Analysis of Key Requirements for Effective Implementation of Biogas Technology for Municipal Solid Waste Management in Sub-Saharan Africa. A Case Study of Kigali City, Rwanda

By

Sylvie Mucyo, B.Sc., M.Sc.

A thesis submitted in partial fulfilment of the requirements of

Abertay University

For the degree of

Doctor of Philosophy

November 2013

I certify that this is a true and accurate version of the thesis approved by the examiners.

Signed………………………………………………. Date………………………………………………….

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To God Almighty for His faithfulness,

To my parents, Viviane Mukamuseruka and Jean Gakwandi

ABSTRACT

Effective management of municipal solid wastes continues to be a major challenge in rapidly growing cities of developing countries. Inadequate waste disposal remains rampant thus posing a serious threat to the environment and public health. The use of biogas technology in the management of municipal solid wastes has become a major focus of interest in developed countries due to its economic value in the generation of energy from biodegradable waste and its ability to divert waste from landfill. The application of the technology in developing countries, in particular sub-Saharan African countries has been a challenge. A major barrier to its implementation in these countries has been attributed to the lack of substantial specific information required in the design of appropriate strategies. This study investigated key factors affecting the application of biogas technology in Kigali City (the capital of Rwanda) with the aim of proffering suitable strategies for effective implementation. The study used an integrated methodological approach interrelating social, technical and economic spheres tools. The study was carried out in three stages. The first stage investigated the availability of suitable feedstock for Anaerobic Digestion (AD) from both domestic and non-domestic sources, household waste management practices and public awareness and attitude towards waste separation at source. Results showed that household food waste was the largest category of waste produced in Kigali City from September 2010 to March 2011, comprising about 74% of total municipal waste produced during this period. This was taken as the average for the City. Socio-economic levels existing in Kigali were found to impact on total waste production with higher production rates occurring in high income households. It was found that households with higher income are more likely to separate waste at source and more willing to pay for waste management services. Incentives, such as free garbage bags, reduced waste charges and economic benefits, with greater focus on poor income communities were found capable of promoting waste separation practice which could effectively enhance the recovery of suitable feedstock. The second stage examined the digestibility and potential energy production from available household food waste and industrial biodegradable feedstocks such as banana and passion fruit wastes. The study also studied the potential effect of operating an AD system under the ambient temperature in Kigali City. Results obtained showed that Kigali ambient temperature of 25^{o}C achieved half methane yields in comparison with the optimum mesophilic operational temperature of 37^{o}C commonly used for large scale AD systems around the world. Results also showed that co-digestion of domestic waste with industrial feedstock can substantially increase biogas yields. The third stage investigated technical requirements and economic viability of operating a biogas plant at 37^{o}C with the available feedstock for the generation of electricity to export to grid and digestate for spreading on land. The annual net energy expected to be generated using the available feedstock was estimated to be 182 kWh/tonne of source-separated waste. Risk analysis revealed that socio-economic needs of communities need to be appropriately integrated to secure the reliability of suitable feedstock in order to ensure project's viability and profitability. It was also found that the development of biogas technology in Kigali could benefit both technically and economically from current Rwandan National key policy objectives related to municipal waste management. All the above mentioned outcome of the research was used to develop a strategic policy-based operational and investment framework for the application of biogas technology in Rwanda.

MAJOR OUTPUT

Mucyo, S., Blackwood, D. and Akunna, J.C. Household solid waste characterisation and public attitude towards source waste separation in Kigali City, Rwanda. Proceedings, *Fourth International Symposium on Energy from Biomass and Waste*, Venice, Italy, 12-15 November 2012

Mucyo, S., Blackwood, D. and Akunna, J.C. Making separate household food waste collection a main stream practice for anaerobic digestion": The case of solid waste management in Kigali City, Rwanda. Proceedings, *Postgraduate research conference*, University of Abertay Dundee, Scotland, 3 October 2012

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ACRONYMS AND ABBREVIATIONS

ACAD	African Carbon Asset Development Facility
AD	Anaerobic Digestion
BIO	Belgian Investment Companies for Developing countries
BMP	Biochemical Methane Potential
CBOs	Community Based Organisations
CDD	Community-Driven Development
CDM	Clean Development Mechanisms
CHP	Combined Heat and Power
DEFRA	Department for Environment, Food and Rural Affairs
DGS	German Solar Energy Society
EAIF	Emerging Africa Infrastructure Fund
EU	European Union
EWSA	Energy and Water Sanitation Authority
FIT	Feed-in Tariff
FMO	Netherlands Development Finance Company
FW	Food Waste
GHG	Greenhouse Gas
GIS	Deutsche Gesellschaft für Internationale Zusammenarbeit
IFDC	International Fertiliser Development Centre
ISWM	Integrated Solid Waste Management
KfW	Kreditanstalt für Wiederaufbau
Level I	Low income residential area
Level II	Middle income residential area
Level III	High income residential area
MINALOC	Ministry of Local Government
MININFRA	Ministry of Infrastructure
MRF	Material Recovery Facilities

MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
NGOs	Non-Government Organisations
NPV	Net Present value
OFMSW	Organic Fraction of Municipal Waste
Other waste	OW
R&D	Research and Development
RDB	Rwanda Development Board
RDF	Refuse-Derived Fuel
REMA	Rwanda Environmental Management Authority
ROR	Rate of Return
RURA	Rwanda Utilities and Regulatory Agency
SC-OFMSW	Separate Organic Fraction of Municipal Solid Waste
SEPA	Scottish Environmental Protection Agency
SNV	Stichting Nederlandse Vrijwilligers (Foundation of Netherlands Volunteers)
SS-OFMSW	Source-separated food waste from domestic sources
SWM	Solid Waste Management
TS	Total Solids
UK	United Kingdom
UNDP	United Nations Development Programme
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
Volatile Fatty Acids	VFA
VS	Volatile Solids
WTP	Willingness To Pay

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

Municipal Solid Waste Management (MSWM) continues to be an increasing concern due to improved lifestyle and population growth in rapidly growing cities. Solid wastes as defined by Tchobanoglous *et al*. (1993, p3) are “all wastes arising from human and animal activities that are normally solid and are discarded as useless or unwanted”. These include organic wastes, inorganic wastes, special wastes or hazardous wastes (Tchobanoglous *et al*. 1993). The EU/UK Waste Management Hierarchy is a major element of European Union and UK waste management policy that has been adopted by most developed countries as an effective environmental tool of integrated waste management (SEPA 2006). The policy includes suitable methods for prevention/minimisation, reuse, material recovery and recycling and disposal to Landfill (Koufodimos and Samaras 2002; SEPA 2006). All the elements of this hierarchy are interrelated and complement each other. The best management option emphasises reducing waste that is disposed of (Tchobanoglous *et al*. 1993).

For most developing countries and in particular sub-Saharan African countries, open dumping still remains the main disposal route thus posing a serious threat to the environment and to public health. Rwanda is no different, in that the most common MSWM problem is one of disposal at designated sites. The available waste information in Kigali indicates that 60% of waste produced per day is collected and disposed at the existing landfill in Kigali City which suggests that the rest is either recycled or deposited at various locations without any form of control (City of Kigali 2007). Nyanza landfill site, presently the main disposal outlet and the only facility in Kigali City, does not meet public health and environmental requirements. It receives both non hazardous and hazardous waste including organic waste which makes up to about 70% of the total waste generated in the City (City of Kigali 2012b). The landfill site would be considered as a semi-controlled dump site, having no lining. A semi-controlled dump site is characterised by an extensive compaction of waste of successive layers separated by an application of a thin covering of soil (Johannessen and Boyer 1999). In such cases, there is high potential for watercourse pollution as there is no control of leachates or of water surface run off (City of Kigali 2007). The state of the site also attracts disease vectors such as flies, vermin, rats and mosquitoes. Furthermore, anaerobic decomposition in underlying layers contribute to the built up of methane gas often causing outbreaks of fire (UNDP 2008), resulting in the emission of polluting gases such as hydrocarbons, sulphur oxides, hydrogen chloride, etc (Tchobanoglous *et al*. 1993; Williams 2005). Elevated piles of wastes with tall sloping sides also pose a significant risk of potential collapse and land slide into the valley (City of Kigali 2012a).

Indeed, the indications are that Kigali City is not practising sustainable Solid Waste Management (SWM) in order to effectively mitigate negative environmental and public health impacts; far from it. According to Coleman *et al*. (2003 p175), "the objective of sustainable waste management is to deal with society's waste in a way that is environmental efficient, economically affordable and socially acceptable". The implication of this definition is that a multidisciplinary approach addressing a broad scope of considerations including economics, sociology and public attitudes, communications, public health, geography, political science, city and regional planning, engineering and conservation is required for the appropriate management of solid waste (Tchobanoglous *et al.* 1993; Al-khatib *et al.* 2010).

1.2 Justification for the research

The insufficient amount of relevant data currently available in Kigali City is a further challenge to the development of an appropriate integrated waste management plan. For example, there is a lack of reliable waste data and insufficient information on public awareness and perception towards SWM. In addition, an inadequate institutional framework, constraints in policy formulation and financial insufficiencies have also been identified as limiting factors to the effective development and implementation of SWM systems in Kigali City (Ministry of Infrastructure 2010). Effective strategies to prevent and to reduce the negative impacts of poor SWM strategies are of vital importance. This includes strategies for waste collection, treatment, recovery and disposal of waste with considerations to environmental benefits, economic optimisation and societal acceptability (Coleman *et al*. 2003).

As already stated, the largest fraction of municipal waste in Kigali is organic, hence the pressing need to find suitable and effective strategies for its management. There exist various methods of treating organic waste including composting, incineration and Anaerobic Digestion (AD).

Composting consists of a breakdown of biodegradable waste by microorganisms in an oxygen environment. The end product is a residue applied as a fertiliser in agriculture and horticulture (Williams 2005). In most developing countries, the turned Windrows system is the most common technique used for composting. This consists of long piles of waste material which are periodically turned to allow aeration (Hartman and Ahring 2006; Tchobanoglous and Kreith 2002). Concerns regarding the emission by composting of considerable amount of methane gas have been raised (Hartman and Ahring 2006). Additional costs are incurred by the large areas of land required and the control of leachate especially with waste material of high moisture content. Thus, green waste is more suitable for composting (Hester and Harrison 2002). A better control of aeration and odour problems, temperature, moisture content as well as mixing rates requires the utilisation of confined reactor systems and associated high energy costs (Williams 1998; Hester and Harrison 2002). Such sophisticated systems lead to increased costs thus making them unsustainable for most developing countries.

Incineration is a direct combustion of waste materials with the additional possibility of the recovery of energy. AD consists of a breakdown of biodegradable waste by micro-organisms in the absence of oxygen, producing biogas and a digestate that can be used as a soil conditioner. Both AD and incineration have the advantage over composting of converting organic waste materials into sources of energy. However, AD is preferred to incineration when dealing with Organic Fraction of Municipal Waste (OFMSW) with high moisture content. Combustion of waste with a high proportion of wet matter requires extra fuel consumption for ignition and sometimes to maintain the incineration process (Williams 1998; Tchobanoglous and Kreith 2002). In addition, the heat necessary to evaporate the moisture content reduces the available calorific value of the waste hence less energy is produced (Williams 1998). Furthermore, the production by incineration of hydrogen chloride and polluting chlorinated residue compounds contained in the MSW poses a threat to the environment, thereby requiring relatively high capital investment in sophisticated technologies for the trap of pollutants (Williams 2005; Hartman and Ahring 2006). In this case, incineration as a treatment for OFMSW would also be uneconomical as an option for developing countries.

Among the three treatment options, AD appears the most cost-effective due its enumerate advantages such as suitability for wet organic waste; limited uncontrolled odour emissions, less land requirement, and limited environmental impacts and possibility of energy recovery and production of soil conditioner in the form of digestate (Zglobisz *et al* 2010). The AD process produces a methane-rich biogas that can be used to generate electricity, heat, fuel and gas. The digestate is a rich source of nitrogen and phosphorus readily available for plants and can potentially be used as an organic fertiliser for plant growth and soil conditioner (Abdullahi *et al.* 2008). The use of AD technology is increasing in European countries especially, Spain, France, Germany, Belgium and Switzerland. It has proven to be effective in treating source separated organics and represents over 27.5% of the total market share of biological treatments in the last 10 years (De Baere 2006). Furthermore, separation of OFMSW for AD application enhances the value of other recyclable materials present in the waste stream. With the use of life-cycle assessment tools, AD has been found to have limited environmental impacts compared to other organic treatment technologies (Mata-Alvarez 2003).

AD development and research in sub-Saharan Africa including Rwanda has mainly been focused on farm-based application using animal wastes as feedstock (Mshandete and Parawira 2009). The technology utilises low-tech smaller reactors such as Chinese fixed dome or low-cost Indian polyethylene tubular digester technology installed at rural households and institutions such as schools and prisons. The technology has been implemented successfully in Asian countries such as India and China and in sub-Saharan African countries such as Tanzania and South Africa where the technology is mainly at household level (Friedrich and Trois 2011; Müller 2007; Mshandete and Parawira 2009). Despite its social, economic and environmental and public health benefits, urban-scale AD technology in Africa remains a challenge.

Municipal AD projects that have been developed in African countries face serious operational problems or have failed mainly due to limited availability of relevant information in the application of the technology at the municipal level and inappropriate prioritisation of management actions (Müller 2007; Friedrich and Trois 2011; Okot-Okumu and Nyenje 2011). This includes lack of substantial information on local social, technical and regulatory requirements in implementing the technology for various types of AD systems. Information on factors influencing public participation to waste management processes such as waste separation at source in developing countries is found lacking. Furthermore, there seems to be insufficient evidence in the available literature (Mbuligwe and Kassenga 2004; Guerrero *et al* 2013), on the impact of local environmental factors such as temperature in the operation of anaerobic digestion plants in sub-Saharan African countries. High capital costs also consist of a major barrier to the development of AD application at commercial scale. This research therefore seeks to develop a framework for assessing the requirements and potential benefits of anaerobic digestion of municipal solid wastes in sub-Saharan African countries using Kigali City as a Case Study. The development of the framework will require analysis of municipal waste production including factors affecting the quantity and quality of solid waste produced, biogas production potential of available solid wastes, the determination of the effect of ambient temperature on potential biogas production and technology selection and the analysis of the economic, technical and social implications of operating AD plant in Kigali.

This study is expected to contribute to the development and assessment of appropriate policies for the improvement of SWM systems and practices. This study will also give objective information for potential investors interested in the application of AD technology as a vital component of sustainable waste management in Kigali City and the rest of sub-Saharan African cities.

1.3 Aim and objectives

The aim of this research is to identify and proffer solutions to the potential challenges of the utilisation of anaerobic digestion technology in sustainable management of municipal solid waste in sub-Saharan Africa using Kigali City, the capital of Rwanda as a case study. With reference to Kigali City, the following objectives have been formulated:

- To review current solid waste management practices and assess public perception towards waste management
- To determine waste characteristics and factors affecting the production of biodegradable organic waste
- To investigate ways of enhancing the quality of household biodegradable waste suitable for AD
- To determine the effect of ambient temperature on methane yield of municipal solid waste
- To evaluate the technical, social and economic requirements of biogas re-use and digestate disposal outlets
- To develop a strategic and operational framework for effective application of AD as a waste management tool

1.4 Research questions

- ➢ What is the current situation with regard to waste management practices in the city of Kigali?

- What is the level of public awareness on the existing solid waste management and the level of participation in waste management practices?
- What is the potential technical, social and economical feasibility of AD application in sustainable waste management in Kigali City?
- What is the current policy and institutional framework and what are the challenges regarding the application of AD and regulatory requirements of its application?

1.5 Research methodology

An integrated research methodology was used to achieve the study aim. A desktop literature review was done to investigate SWM and challenges in developing countries. The experimental research was divided into three stages namely:

- Technical and social data collection including interviews with relevant waste administrators and waste service providers
- Anaerobic digestion laboratory experiments
- A social, technical and economic appraisal of full-scale operation of an AD plant

Food waste was considered as the feedstock for this feasibility study due to its high biodegradability and high potential energy content (El-Mashad and Zhang 2010; Zhang *et al.* 2007; Hartman and Ahring 2006).

1.6 Schematic research plan

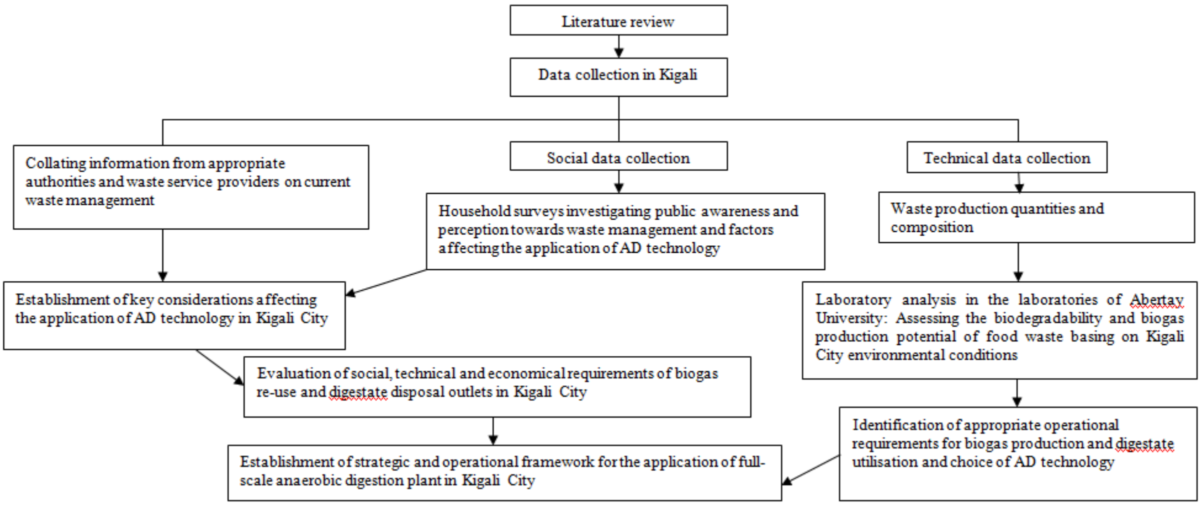

Figure 1 Schematic research plan

1.7 Structure of thesis

Chapter One reviews the status of AD technology in the context of sustainable solid waste management and provides the rationale for the study. Chapter Two provides the concepts of sustainable waste management and provides an introductory and contextual background of municipal waste situation in developing countries as opposed to that of developed countries and discusses the differential waste management approaches in those countries. Chapter Three reviews AD process fundamentals and discusses factors affecting the process efficiency and the challenges for urban scale AD development in sub-Saharan African countries. This chapter also provides a theoretical background of potential strategies and opportunities for its application. Chapter Four reviews SWM systems in Kigali City and critically evaluates the current SWM strategy and examines available support mechanisms for AD development. Chapter Five concludes the literature review and provides a theoretical background for developing a framework for AD as part of an integrated management of municipal solid waste in Kigali City.

Chapter Six presents the methods used in this study to collect and analyse data. An integrated methodological approach combining literature review, qualitative and quantitative field methods was utilised. These consisted of household surveys and interviews, anaerobic digestion laboratory experiments and an economic appraisal of AD implementation for the treatment of organic municipal solid wastes. Chapter Seven and Eight assess the availability of food waste sources in Kigali City and explore various ways of enhancing their potential for AD. In Chapter Nine, bio-methane production potential from food waste and the environmental requirements for biogas production were determined. Chapter Ten evaluates the economic viability of operating an AD plant in Kigali City. Chapter Eleven provides a strategic policy and technical framework for AD application. A summary, conclusions and recommendations are presented in Chapter twelve.

CHAPTER 2

ASPECTS AND DEVELOPMENT OF SOLID WASTE MANAGEMENT

The objective of this chapter is to provide a review of the concepts of sustainable SWM and the state of solid waste management in developing countries and developed countries. This chapter commences with the review of fundamental aspects of solid waste management and moves on to management options in both developed and developing countries with emphasis on differential approaches in these countries and related factors.

2.1 Sustainable solid waste management concepts

The sustainability of solid waste management systems is underpinned by the need of safety in waste disposal and public health protection. Several authors including Coleman *et al.* (2003), Zhu *et al.* (2007), and McDougall *et al.* (2000) have described sustainable SWM in three dimensions of sustainability as socially acceptable, economically affordable and environmentally efficient. Sustainable SWM is characterised by principles and services that are acceptable to the community and responsive to their needs with emphasis on a higher level of service where the need is proven to be greater. A sustainable system for SWM also delivers economic opportunities and services that are cost-effective and suited to local circumstances. It also involves environmentally sound mechanisms that preserve the use of natural resources and reduce pollution of the environment.

2.2 Integrated solid waste management systems

Sustainable solid waste management systems cannot be viewed without the concept of Integrated Solid Waste Management (McDougall *et al*. 2001). Figure 2 shows a structural representation of Integrated Solid Waste Management (ISWM) in the context of developing countries as described by Guerrero *et al.* (2013) in their study on waste management challenges in developing countries. ISWM involves a system that combines various waste streams, waste collection operations with various sorting systems followed by waste management options such as recycling, treatment and final disposal (McDougall *et al.* 2000; Fabbricino 2001; Zhu *et al*. 2007; Bortoleto and Hanaki 2007). The system also includes stakeholders such as government bodies, non government organisations and citizens or service users that partake in waste management processes. The integrated waste management system is also shaped and influenced by local technical, environmental, socio-cultural and economic factors as well as legal and institution factors (Guerrero *et al.* 2013). The objective of integrated waste management is to select and apply suitable techniques and technologies which meet social, politics and finance, economic and environmental conditions (McDougall *et al.* 2000; Fabbricino 2001). This goes hand in hand with the technical capacity to develop systems and properly use environmentally friendly technologies and develop appropriate financial instruments for their implementation (UNEP 2009).

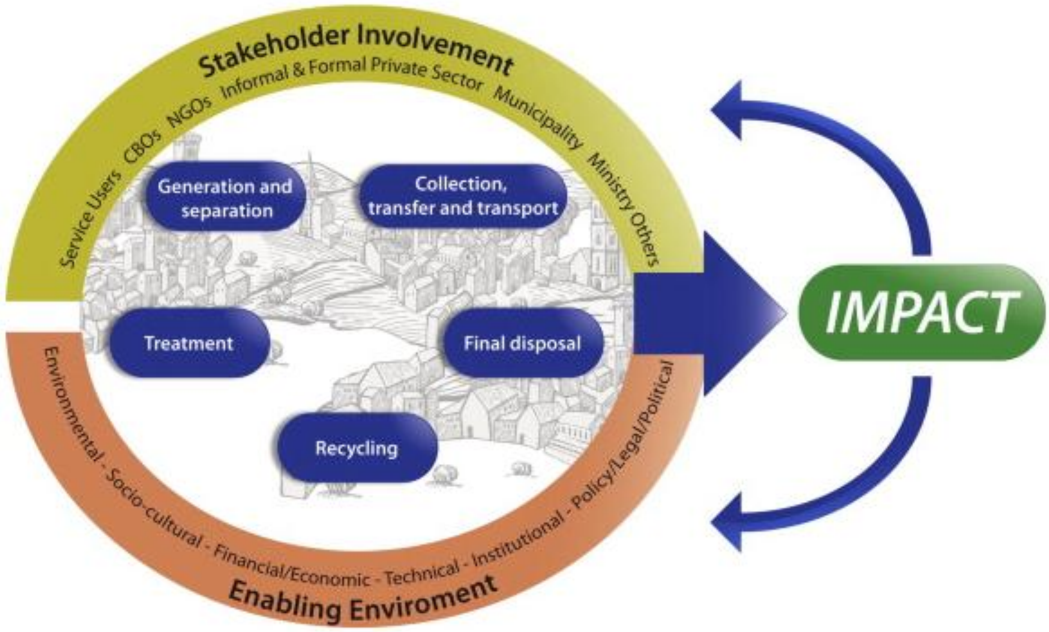

Figure 2 The integrated sustainable waste management model
Source: Guerrero *et al*. (2013)

Depending on local technical capacity and social, political, economic and environmental conditions, the identified waste management options can be implemented individually or in combinations whereby waste of one process serves as the raw material for another (Polprasert 1996; Tchobanoglous and Kreith 2002). Emphasis is placed upon waste separation at source to recover uncontaminated waste material flows in the waste stream to improve the efficiency of the processes thereby increasing the quality of the resulting material (Lens *et al.* 2004). In order to maintain its effectiveness, the collection of source-separated waste depends upon the collaborative efforts of various elements of a community, addressing a range of factors, which would include an up to date knowledge of the waste stream; household education; labour requirements and equipment for collecting and processing waste; policy and strategic planning between private and public financial bodies; local authority management and policy enforcement (Troschinetz and Mihelcic 2009; Refsgaard and Magnussen 2009). While environmental education is commendable, Refsgaard and Magnussen (2009) reported that this may not be sufficient to encourage behavioural change with respect to waste separation at source. Peer pressure, convenience and economic incentives such as reduced waste fees charges have been found to drive waste separation at source (Purcell and Magette 2010). Furthermore, the sustainability of waste management processes critically depends upon the demand of the processed waste products (McDougall *et al*. 2000). More importantly, the effectiveness of SWM systems is enhanced by political targets on waste recovery and the engagement of stakeholders in developing appropriate waste management strategies. The principal players include citizens; public institutions such as local authorities, central government and government agencies; funding bodies, Community-Based Organisations (CBO's) or non government organisations (NGO's) and private waste management companies (Troschinetz and Mihelcic 2009; Kassim and Ali 2006). The roles of stakeholders need to be sufficiently clear, designed and operated through a complementary operational framework in order to optimise the whole system. The system is evaluated through the influence and actions that various stakeholders have on various sectors of solid waste management. Such integrated system will normally necessitate the evaluation of the influence of any management decision on the selected treatment options as this determines the future of waste management in a given region (Fabbricino 2001).

The key areas of ISWM in developing countries include collection of waste produced and disposal to dumping sites or landfill and small-scale waste treatment and recycling processes. The integration of the latter into municipal solid waste management in developing countries is substantially defined in a private economic activity run by an informal sector composed of poor people who collect waste materials from various locations at waste sources, transfer stations and disposal sites in order to extract any remaining economic value and trade them back for reuse and recycling (Scheinberg *et al.* 2011; Wilson *et al.* 2012). Local authorities are mandated by the central government to provide and maintain SWM infrastructure. Local authorities can also contract private companies that manage waste under their supervision (Okot-Okumu and Nyenje 2011). NGO's and CBOs are also an important integral part of the municipal waste management system. CBO's in particular are involved in recycling, collection and drainage cleaning and in the promotion of public engagement to waste management in countries such as Uganda, Tanzania and Ghana (Okot-Okumu and Nyenje 2011; Fobil *et al.* 2008; Kassim and Ali 2006). Unlike CBOs which are less technically skilled and often linked to one particular community, NGO's generally provide technical assistance and funding in the design of appropriate policies and the development SWM systems (UN-Habitat 2011).

2.3 Municipal solid waste management in developed countries and developing countries

MSWM in developed and developing countries is defined by various drivers such as public health, the environment, resource scarcity and the value of waste, climate change, public awareness and participation (Marshall and Farahbakhsh 2013). In general, the key drivers for waste management include public health through the effectiveness of waste collection systems and environmental protection during various processes of SWM such as treatment and disposal, resource management for sustainable use of waste resource through recycling, reuse of materials and organic waste recovery (Wilson *et al*. 2012). Due to variation in waste characteristics, economic development, cultural, socio-economic, political and institutional aspects, SWM in developed countries differ in the approach that must be taken into consideration when compared to developing countries.

2.3.1 Solid waste characterisation

Urban waste mainly originates from residential, commercial establishments, industries, public and private institutions, treatment plant sites and other waste from non established structures that can be described as waste from municipal services. These are from street sweepings, landscaping, parks, recreational areas and construction debris (Shekdar 2009; Williams 2005; Tchobanoglous and Kreith 2002). Construction sites, treatment plant sites, industries and institutions such as schools, hospitals and prisons generally manage their own waste. In general, residential waste has been reported to be the largest component of municipal waste stream with quantities estimated between 55-65% of MSW generation (Tchobanoglous and Kreith 2002). Large amounts are also generated from commercial sources having been estimated at 35-45%.

The average waste generation in developed and developing countries is estimated at 1.43-2.08 per capita per day (kg/c/d) and 0.3-1.44 kg/c/d respectively (Troschinetz and Mihelcic 2009). Figure 3 shows that on average of 19 developing countries from Africa, Asia and South America, waste streams are comprised of 55% of organic material which is twice as much in comparison with developed countries and half the portion of paper and cardboard and similar fractions of glass and plastics (Troschinetz and Mihelcic 2009). Imam *et al.* (2008) reported that food waste, plastics, paper, glass bottles and metals have been the main components of household waste in Abuja, Nigeria. Friedrich and Trois (2011) reviewed municipal solid waste generation in sub-Saharan African countries and found that on average of five countries namely, Nigeria, Botswana, Tanzania, Ghana and Sierra Leone, biodegradable organic fraction consists of approximately 60% of waste produced.

Solid waste characterisation studies investigated the relationship between waste generation and socio-economic factors as these significantly influence the course of SWM (Troschinetz and Mihelcic 2009; Gomez *et al*. 2008; Afon and Okewole 2007; Philippe and Culot 2009; Dangi *et al*. 2011; Thanh *et al.* 2010). Gomez *et al.* (2008) reported the existence of a direct relation between waste generation and income level in Abu Dhabi whilst in Gaborone, the capital city of Botswana, no relationship was found. Troschinetz and Mihelcic (2009) believe that a weak correlation exists between waste generation and income in middle and upper-income countries. According to the authors, the quantity of waste generated can also be influenced by lifestyle and region characteristics. For instance, the Maldives's relatively high waste generation of 2.4 kg/c/d is attributed to its touristic activities. Also, climate and seasonality have been reported to impact on the amount of organic waste being produced due to the availability of a variety of fresh foods and their preparation.

Changes in waste production can also be caused by waste minimisation and reduction policies. Usually observed in developed countries, these policies mainly target manufacturers and industrial activities.

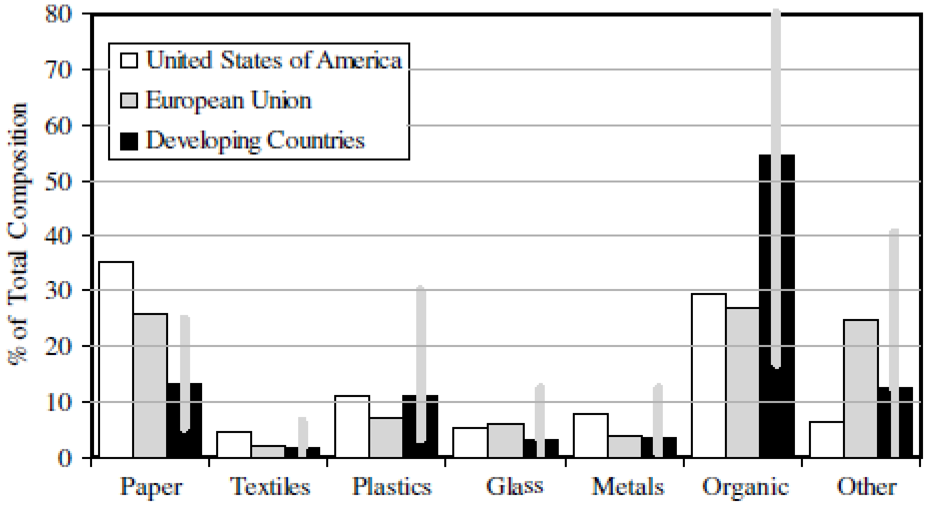

Figure 3. Comparison of solid waste composition of developed countries (United States of America and European Union) against the average of 19 selected developing countries. Vertical bars indicate the range of composition of each material type for the developing countries
Source: Troschinetz and Mihelcic (2009)

2.3.2 Waste handling and collection systems

Waste handling refers to the activities associated with managing the wastes before collection. These include separation at source into various waste components, storage and moving the loaded storage facilities to the point of collection (Tchobanoglous and Kreith 2002). In developed countries, the handling of waste varies depending on housing types. Typically, low-rise building or detached houses use standard wheeled containers, which are loaded and moved to the collection point and returned empty to their storage area. Medium and high rise buildings use plastic bags for waste storage which are loaded in large containers located in outdoor storage area or basement area awaiting collection (Tchobanoglous *et al.* 1993). In developing countries, the quality of waste storage facilities increases with the capacity of the user to afford them. The most common types of storage facilities include old used plastic buckets, used plastic bags or rack sacks. Standard containers are commonly found in high-income areas (Kassim and Ali 2006). Also, women and children are, in general, responsible for the cleanliness of their homes and the handling of waste is their responsibility (El-Hoz 2010; Kassim and Ali 2006).

Waste collection is described as the gathering or picking up of solid wastes from the various sources and hauling them using various means to the location where they are disposed of (Tchobanoglous and Kreith 2002). Both developed and developing countries use co-mingled and source-separated waste collection systems. In developed countries, source-separated wastes systems are being increasingly developed where waste is collected via bring system, drop off system and kerbside collection (McDougall *et al.* 2001). The separation of waste in developed countries is also operated through Material Recovery Facilities (MRF) which utilise automated or manual separation of the commingled or source-separated collected waste. In contrast, solid waste separation activities including waste separation at source are not common in developing countries mainly due to limited technical capacity. In developed countries, waste collection is generally the responsibility of local authorities whereas in developing countries, it is gradually being taken up by the private sector due to inability of local authorities to effectively manage the wastes, as a result of inadequate funding (Troschinetz and Mihelcic 2009; Kassim and Ali, 2006; Henry *et al.* 2006; Imam *et al.* 2008). A study in nine municipalities in Uganda found that between 15-60% of solid waste generated are collected with the highest collection levels in areas served by private companies (Okot-Okumu and Nyenje 2011).

The effectiveness of waste collection is shaped by the infrastructure and technical capacity in place which in turn are dependent upon the level of affluence of the country in question. It has been reported that an estimated less than 50% of population in developing countries is served with waste collection (The World Bank 2011). Both door to door collection and the bring-in systems are used, with the former generally used in planned settlements, and with the latter in unplanned settlements

(Kassim and Ali 2006). While developed countries use sophisticated vehicles for waste collection, developing countries still rely on labour intensive methods (UN-Habitat 2011; Imam *et al*. 2008; Troschinetz and Mihelcic 2009). High-sided open-top trucks, often locally assembled, and manual collection equipments are extensively used in these countries (UN-habitat 2011; Imam *et al.* 2008). The volume of waste often exceeds the capacity of waste collection system. Moreover, the poor conditions of trucks and unavailability of spare parts render them out of service for longer periods (UN-Habitat 2011; Kassim and Ali 2006; Henry *et al*. 2006; Imam *et al.* 2008). Furthermore, high income areas and planned areas receive better service due to highly consistent payment habits of households in these areas and better road access for the collection trucks. Unplanned and low income areas are characterised by meagre or non-existent service due to narrow roadways and low incomes which make it difficult to pay the waste charges (Kassim and Ali 2006; Henry *et al.* 2006; Marshall and Farahbakhsh 2013; Fobil *et al.* 2008). Poor services usually lead to the accumulation of wastes in residential areas resulting in uncontrolled dumping or burning of waste (Okot-Okumu and Nyenje 2011). Fobil *et al.* (2008) in their study on waste collection in Accra, Ghana, informed that paid household waste collection fees consists of less than 10% of the services delivered. In Dar es Salaam City, Tanzania, it has been reported that waste management companies manage to collect less than 50% of the service charge (Kassim and Ali 2006). Okot-Okumu and Nyenje 2011 found that between 15 and 60% of waste generated are collected in Ugandan cities.

Informal waste collection is also typical of developing countries and is carried out by scavengers who are individuals or a group of people who collect recyclable waste such as plastic containers, cans, cardboard and glass via a door to door system using manual collection equipment such as push carts or wheel barrows (Imam *et al.* 2008; Troschinetz and Mihelcic 2009). Scavengers are individuals with poor education and income and mostly operate at dumpsites or transfer stations to sort out recyclable wastes to earn money to buy food or other necessities (UN-Habitat 2011). The working conditions of scavengers are high risk with regard to their health and safety. They can be regarded as part of an informal sector involved in SWM. The informal sector is responsible for most of recycling in developing countries (Scheinberg *et al.* 2011). It has been reported that 2% of the population in Asian and Latin American cities depend on waste picking for their subsistence (Wilson *et al* 2006). It has also been reported that recycling in Abuja, Nigeria is only carried out by scavengers (Imam *et al.* 2006). In Delhi, India alone, it has been reported that 95% of mixed papers, 70% of mixed plastic and metals and 75% of glass was recovered by the informal sector (Friedrich and Trois 2011). According to UN-Habitat (2011), an estimated 15-35% of recyclable waste in developing countries is being recovered by the informal sector. The recovered materials are sold to middlemen who in turn sell them to exporters and large scale manufacturing industries (Imam *et al.* 2008; Troschinetz and Mihelcic 2009). The informal sector is responsible for most recycling in developing countries, however, is not connected to formal municipal recycling initiatives which slows down their effectiveness in delivering good waste management practices (Scheinberg *et al.* 2011; Friedrich and Trois 2011).

In both developed and developing countries, solid waste collection is the most important component of waste management (Tchobanoglous and Kreith 2002; Zglobisz *et al.* 2010; UN-Habitat 2011). Approximately 50 to 80% of total waste management costs in both developed and developing countries are estimated to be spent on waste collection alone (Imam *et al.* 2008; Tchobanoglous and Kreith 2002).

2.3.3 Treatment technologies

The most developed treatment technologies in developed countries include energy recovery in the form of heat and electricity via anaerobic digestion or incineration. Other technologies include composting (turned windrow, open aerated and in-vessel systems) and the collection of biogas from sanitary landfill for electricity production (Couth and Trois 2012; McDougall *et al.* 2001). The most utilised waste treatment technologies in developing countries include anaerobic digestion and composting which use organic waste as feed material (Couth and Trois 2012). The compost process involves mechanical and manual sorting of waste followed by open-air turned windrow method or pits (Couth and Trois 2012; McDougall *et al.* 2001). Composting activities are limited to more rural and sub-urban areas where space and fields are available. Community composting projects in developing countries are not widespread due to low revenues from the compost sale associated with both poor quality compost resulting from inadequate waste material (Couth and Trois 2012).

Primarily, anaerobic digestion has been used to treat liquid wastes such as manures, organic industrial wastes and sewage sludge and has now been extended to treat organic fraction of municipal solid waste (Mata-Alvarez 2003; McDougall *et al.* 2001). In developing countries, a considerable uptake of AD technology has been observed in rural area with the use of animal waste as feedstock to generate biogas for cooking and lighting and bio-fertiliser for agricultural activities (Mshandete and Parawira 2009). Although large scale AD application for municipal solid waste is commonly applied in developed countries as explained in Chapter 1, its application in developing countries is largely underdeveloped. Anaerobic digestion for the treatment of urban waste is still relatively new. The available AD plants are generally of low technical efficiency as lack of resources and skills hinders the development of more sophisticated systems. The most common digester designs are Chinese fixed-dome and Indian floating-cover digesters (Mshandete and Parawira 2009). The complexity of the technology is also lessened by favourable environmental conditions that characterise these countries whereby tropical and sub-tropical temperatures require no additional heating for AD.

CHAPTER 3

ANAEROBIC WASTE TREATMENT

The objective of this chapter is to provide a review of the science behind anaerobic digestion of organic waste material and aspects affecting its full scale application in the management of municipal solid wastes. This chapter reviews the process fundamentals of anaerobic digestion and factors affecting process efficiency. Challenges for urban scale AD development in sub-Saharan Africa and available strategies and opportunities that can be applicable in effective implementation of anaerobic digestion technology are also discussed.

3.1 Process fundamentals

Understanding of the biochemical reactions involved in AD of organic waste material leading to the formation of methane gas is essential for efficient control of process conditions and in general for operating an AD plant. The reactions are simultaneous and subdivided in four stages namely: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The reactions involved in each stage are catalysed by strict or facultative bacteria strains whereby the products from one group of bacteria serve as the substrates for the next resulting in the biodegradation of organic matter mainly into methane gas and carbon dioxide (Polprasert 1996; Mata-Alvarez 2003).

3.1.1 Hydrolysis

Many organic wastes consist of long-chain organic polymers such as proteins, carbohydrates, lipids, lignin and cellulose (Polprasert 1996). The polymers are broken down to monomers by extracellular specific enzymes produced by a consortium of varied hydrolytic bacteria. These bacteria convert proteins into amino-acids, carbohydrates into simple sugars and lipids into long chain fatty acids which are then dissolved in water and available for acid-producing bacteria. While proteins, lipids and carbohydrates are easily converted by hydrolysis, the extent of degradation of lignin and cellulose can be a limiting factor to AD processes hence the rate of hydrolysis is dependent on substrate characteristics (Mata-Alvarez 2003). Therefore, substrates with woody material are slowly degradable. This stage is also affected by environmental factors both of which are discussed in section 3.2.

3.1.2 Acidogenesis

The monomers released by hydrolysis are converted by bacterial metabolism of acid-forming bacteria also known as fermentative bacteria into hydrogen or formate, carbon dioxide, pyruvate, ammonia, volatile fatty acids, lactic acid and alcohols (Mata-Alvarez 2003; Polprasert 2001). In particular, volatile fatty acids such as acetic, propionic and lactic acids consist of the end-products of bacterial metabolism of protein, lipids and carbohydrates. Carbon dioxide and hydrogen gas are also produced during carbohydrate catabolism (Polprasert 1996).

3.1.3 Acetogenesis

The compounds produced by acidogenesis are oxidised to carbon dioxide, hydrogen and acetic acid (acetate) by the action of obligate hydrogen-producing acetogens (Mata-Alvarez 2003). Also, during this stage, acetic acid is produced from the catabolism of bicarbonate and hydrogen by homoacetogenic bacteria (Lens *et al.* 2004).

3.1.4 Methanogenesis

Methanogenesis consists of the most important stage in anaerobic digestion as it leads to the formation of CH_4. During this stage, methanogenic bacteria use acetic acid, methanol, carbon dioxide and hydrogen to produce methane gas and carbon dioxide. Seventy-percent of methane produced is from acetic acid by acetoclastic methanogenic bacteria making it the most important substrate for methane formation (Polprasert 1996; Mata-Alvarez 2003). Thirty percent is then produced from carbon dioxide and hydrogen by hydrogenotrophic methanogenic bacteria. The latter have a higher growth rate than acetoclastic methanogenic bacteria and both have a slower growth rate than other groups of bacteria present in the process (Lens *et al.* 2004). Furthermore, methanogens significantly depend on hydrolysis and acidogenesis to avail nutrients in usable form (Polprasert 1996).

3.2 Factors affecting process efficiency

Methanogenesis depends on the efficiency of intermediate stages which are also affected by various factors such as substrate characteristics and environmental conditions such as pH, temperature, duration of AD processes and the used AD system (Mata-Alvarez 2003).

3.2.1 Feedstock quality

The level of available nutrients for the microbial population determines the quality of feedstock. This is measured by the concentration of C/N ratio. In general, the content of the nutrient and micronutrient present in the waste is enough for anaerobic digestion (Lens *et al.* 2004). Organic nitrogen is the limiting factor as it is used for microbial cell structure while the energy for growth is obtained through catabolism of carbohydrates (Polprasert 1996). Substrates with high protein content give high nitrogen content hence leading to elevated concentration of ammonia or ammonium ion where the former can become toxic to methanogenesis at higher pH (Banks *et al*. 2011). Another important aspect is the presence in the feedstock of toxic elements such as heavy metals which become acute to changes in pH, temperature or concentration of other substances as they can have synergies with a given inhibitor (Lens *et al.* 2004). Heavy metals and plastics can inhibit bacterial activity and affect the quality of digestate (Mata-Alvarez 2003).

The particle size and surface to volume ratio are also important parameters affecting the feedstock biodegradability and optimisation of processes. A particle size of 25-75 mm is generally recommended (Tchobanoglous *et al.* 1993).

3.2.2 Operating temperature

Temperature is the most important factor for the optimisation of AD processes (Mata-Alvarez 2003; Raposo *et al.* 2012). Degradation rates and yields increase with temperature with optimum at mesophilic temperatures of around 35^{o}C and thermophilic temperatures of around 55^{o}C (Mata-Alvarez 2003). Most anaerobic digesters are operated at these temperature ranges. Thermophilic temperature is reported to offer better yields, however, requires higher control of kinetics especially for waste with high biodegradability whereby acidogenesis can outbalance methanogenesis (Lens *et al.* 2004). Furthermore, systems operated at thermophilic temperatures are highly sensitive to environmental disturbance hence AD processes are often carried out in separate reactors to better control hydrolysis, acidogenesis and methanogenesis (Mata-Alvarez 2003).

3.2.3 Substrate concentration

Substrate concentration is generally expressed in Total Solids (TS) and Volatile Solids (VS) content. The former is the raw estimation of all the organic and inorganic matter content of the waste material sample. Total solids is the residue of the origin material measured after 24 hours drying at 105^{o}C whilst volatile solids consists of the organic TS residue burned and evaporated as gas at 550^{o}C in 2.5 hours (APHA 1992). The concentration of volatile organic matter is usually used to estimate methane production potential from the waste material (Raposo *et al.* 2012). Although digesters typically accept any biodegradable material, the level of digestibility of the material is the key factor if biogas production is the main purpose of AD application (McDougall 2001). Low methane yields are observed with substrates of high lignin content due to low solubility of the compound (Raposo *et al*. 2012).

3.2.4 pH

Process stability is highly dependent on pH value. Excess organic loadings can lower the pH hence inhibiting the activity of methanogens sensitive to high acidic conditions (Mata-Alvarez 2003). A pH below 6 is inhibitory to methanogenic bacteria which has an optimum pH between 7 and 8 (Raposo *et al.* 2012). Acidogenic bacteria which are more tolerant to pH below 6 continue to produce acids faster than the rate at which the slow growing acetoclastic bacteria would utilise them (Polprasert 1996). Therefore, methanogens act as pH regulators by converting volatile fatty acids into CH_4 and other gases. In the beginning of digestion when there is accumulation of acids, the addition of lime and other basic material is added to the digester to obtain a good buffering capacity (Polprasert 1996).

3.2.5 Retention time

The digester performance is also significantly affected by the retention of feedstock in the digester. A short time will allow an accumulation of acids with no methane production by methanogenic bacteria which have a slow growth rate (Polprasert 1996). Thermophilic digesters could go up to 15 days while most mesophilic digesters have a retention time of 30 days.

3.2.6 AD systems

The design of AD system is driven by parameters such as but not limited to feedstock characteristics and the temperature (Mata-Alvarez 2003). With regard to solids concentration of the feedstock, anaerobic digesters can be classified as wet systems for feedstock of total solids around 20% and dry systems for solids above this level (McDougall *et al.* 2001; Mata-Alvarez 2003). Digesters are also classified as mesophilic for those operating between 30 and 40^{o}C and as thermophilic for those operating between 50 and 65^{o}C (McDougall *et al.* 2001).

The wet mesophilic system has extensively been used to treat sewage sludge and animal wastes whereby considerable water is added to reach 3-8% of total solids content (McDougall *et al.* 2001). With this system, occasional mixing may be necessary to prevent hard-scum layer in the digester which would affect homogenous conditions for bacterial action. The control of biological processes can be obtained in stages AD systems. A two-stage process involves the use of one reactor kept at a pH around 6 for hydrolysis and acidification and the second reactor for methanogenesis at the pH of 7.5-8.2 (McDougall *et al.* 2001). The dry system which involves the addition of no or little water to reach 20-40% of TS can be either mesophilic or thermophilic. Anaerobic digestion in semi-dry (10-20% of TS) has been reported to offer a more stabilised digestate and higher methane productivity (Forster-Carneiro *et al.* 2008).

Single stage system as a batch process or continuous process is the most preferred by industrialists. It consists of filling the digester with fresh wastes and sealed until the end of digestion process. It is believed that up to 90% of full-scale plants that are currently operational rely on one-stage dry system due to their simpler design and lower investment costs (Mata-Alvarez 2003). In general, environmental conditions (such as temperature), the end use of the products and the moisture content of the targeted feedstock influence system selection.

3.3 Food waste as feed material

Food waste has been reported to be the largest component of organic MSW (Zhang *et al*. 2007). Food waste from household kitchens and restaurants, food markets and commercial sources generally present the same characteristics. Food waste as feedstock for AD has a high biodegradability compared to other organic municipal solid waste. Due to health and environmental concerns, the bioconversion of food waste for energy generation is becoming economically attractive (Forster-Carneiro *et al.* 2008).

3.4 Biogas yield and utilisation

The characterisation of biogas generation as a function of time can be used to identify the occurrence of inhibition or adaptation (Hansen *et al.* 2004). The biodegradability of feedstock is indicated by methane yields (Zhang *et al.* 2007). Various studies have examined the digestion of food waste under various operating conditions and substrate characteristics which result in varying values of methane production potential. Table 1 presents findings of methane production potential from organic waste obtained from various studies. In full-scale application, the biogas can be efficiently used by burning it directly in engines for Combined Heat and Power (CHP) to produce heat and electricity. Electricity and heating can be used on-site or sold to the grid (DEFRA 2011). The methane can also be cleaned and used as natural gas or vehicle fuel. In most cases, the end use of biogas depends on social, economic and technical local conditions.

Table 1 Methane production potential from food waste

Food waste composition	Methane production potential (ml/g VS)	Operating temperature (^oC)	Retention time	Reference
Boiled rice 10-15% Vegetables 65-70% Meat and eggs 15-20%	489	35	40	Heo *et al.* (2004)
Cooked pasta 22% Cooked meat 9% Lettuce 11% Carrots 3% Potato 44% Milk 11%	492	55	15	Akunna *et al.* (2007)
Vegetable and fruit waste	490	55	60	Forster-Carneiro *et al.* (2008)
Pasta and rice 26% Cooked meat 14% Cooked vegetables 18% Vegetables peelings 22% Fruit peelings 15% Non organic 5%	467-529	37	30	Browne and Murphy (2013)

3.5 Digestate utilisation

The quality of digestate is measured by the level of solids stabilisation, reduced pathogen levels (originating from deceased animals or plants) and absence of toxic elements (Mata-Alvarez 2003). Waste stabilisation increases with decreasing volatile fatty acids (Alburquerque *et al.* 2012). Organic matter removal could reach 87% for waste digested at 35^{o}C (Mata-Alvarez *et al.* 2000). Pathogen inactivation also increases with increasing temperature whereby additional heating is required for mesophilic digesters if not done prior to digestion. Pasteurisation at higher temperatures is required to effectively remove pathogens prior to spreading to land especially if AD is performed at low temperatures (Mata-Alvarez 2003). In general, the temperature for pasteurisation is 70^{o}C. AD may release compounds that are toxic at high levels. These include ammonia contained in the digestate which can be phytotoxic if the digestate is used as soil conditioner (Abdullahi *et al.* 2008).

Generally, it is less expected to gain significant income from the digestate. Mata-Alvarez (2003) reported that the digestate is usually sold at low price or given to farmers in the neighbourhood of the AD plant site. If further costs are made for digestate treatment, then the produced biofertiliser would be sold at higher price.

3.6 Challenges to the application of AD technology for MSWM in sub-Saharan African countries

3.6.1 Social issues

Recovery of waste for any treatment option requires active participation of primary producers of waste. Lack of awareness and education on services and developments in SWM are key barriers to effective participation in good waste management practices in developing countries (Kassim and Ali 2006; Troschinetz and Mihelcic 2009). Often insufficient data on public perception and practices affect the design of appropriate policies especially those that target the recovery of waste (Troschinetz and Mihelcic 2009). Public acceptance of SWM processes and participation such as separating waste at source and payment of waste services are critical (Afroz *et al.* 2009). Households are usually not made aware of their roles and are not given opportunities to contribute in designing suitable SWM practices that affect them or debate on implications of policies and plans (Kassim and Ali 2006; Henry *et al.* 2006; Marara *et al.* 2011). In Dar es Salaam, Tanzania, many households are reluctant to pay due to low income level and lack of awareness (Kassim and Ali 2006).

Waste services can also be driven by the infrastructure in place with better services observed mainly in high income than in low income residential areas. Inadequate waste services in the poor suburban zones of Nairobi have been reported to induce a lack of interest by the public to participate positively in SWM (Henry *et al.* 2006). As a result, uncontrolled disposal of waste at the riversides, waterways and roadsides becomes common practice (Henry *et al*. 2006; Kassim and Ali 2006). Community Based Associations (CBAs) contributed in alleviating the problem and recovering some economic value from waste such as compost from organic waste (Kassim and Ali 2006). These associations are run mainly by poor unemployed individuals and often fail to operate sustainably due to technical and financial constraints.

3.6.2 Technical constraints

Focus on biogas technology research in sub-Saharan African countries has been extensively on agricultural-sourced feedstock and less on the OFMSW (Mshandete and Parawira 2009). Insufficient information and data adversely affect the development of AD across all sectors, including the planning and implementation of appropriate strategies. The Department for Environment, Food and Rural Affairs

(DEFRA) in the UK recognised that cost-effective collection systems that ensure the quality of feedstock are a priority for successful use of MSW as feedstock for AD operations (DEFRA 2009). In most sub-Saharan African countries, access to the right feedstock is problematic due to insufficient waste collection coverage (Kassim and Ali 2006; Henry *et al.* 2006; Imam *et al.* 2008). Ensuring the stability of source-separated waste collection systems in developing countries will remain a challenge.

Most available small-scale digesters are run at local ambient temperatures probably due to relatively high temperatures characteristic of sub-Saharan region and the need to reduce the costs and technical requirements resulting from extra heating (Mshandete and Parawira 2009). Consequently, the amount of biogas generated varies with changing temperatures hence making the whole system, in some cases, unsustainable.

Sub-Saharan African countries with developing economies are characterised with limited human resource with appropriate technical skills. This problem impacts on strategic planning at the institutional level and the operation and maintenance of SWM infrastructure.

3.6.3 Economic and political considerations

Inadequate MSWM in developing countries has been attributed to financial constraints faced by municipalities for the planning of SWM including the upgrading of infrastructure and the improvement of services (Henry *et al.* 2006). The problem is worsened by financial inadequate budget allocation which results in persistent lack of funds. Anaerobic digestion technology for biogas production in sub-Saharan Africa has mainly been promoted and financed by non-governmental organisations and foreign aid agencies (Mshandete and Parawira 2009). The challenge is that low involvement of governments in waste recovery operations in developing countries will always hamper the promotion and development of suitable SWM strategies (Polprasert 1996). Subsequently, the formulation of policies and appropriate strategies that can benefit AD will continue to be delayed. Furthermore, renewable energy technologies in sub-Saharan Africa tend to be high capital intensive which results in preference of low capital intensive conventional technologies (UNEP 2012).

Adding to the lack of enabling business environment, the fact that AD consists of a high capital intensive technology slows the interest of the private sector. Other associated fields of operations also get affected. These include lack of clearly defined roles and collaboration between key stakeholders from the public and private sector and lack of appropriate infrastructure and incentives that enable the operation of various SWM operations (Fobil *et al.* 2008). Furthermore, the generally low priority given to SWM sector by governments also affect capacity building programs in the waste management sector at both the planning level and operation level.

3.6.4 Regulatory challenges

In developing countries, one of the main challenges that continue to affect SWM is the poor design of effective and functional legislative systems (Marara *et al.* 2011). Environmental policies and programs including those in relation to SWM are often designed without considerations to local conditions in terms of public participation, technical and economic requirements. Where available, regulations governing the waste disposal, collection and implementation of SWM projects are not often enforced (Henry *et al.* 2006). Consequently, the implementation of potential waste recovery operations becomes challenging leading to increased costs and financial constraints (Marara *et al.* 2011).

3.8 Current initiatives to encourage effective application of environmental technologies in sub-Saharan African countries

3.8.1 Community-Driven Development

Community-Driven Development (CDD) is defined as the engagement of urban communities in upgrading of urban services (The World Bank 2004). CDD approach has been initiated by World Bank with the aim of giving control of decisions and resources to community groups in urban environments of developing countries. The focus is on poor communities due to their greater vulnerability to environmental problems. CDD operations link communities to private sector and local governments.

CDD approaches have been used to respond to a variety of needs such as water supply and sewer rehabilitation, access roads and storm drainage. Some of these approaches aim at developing community ownership of developmental projects by creating incentives for poor communities. Institutional framework is essential to enable sustainable delivery of municipal services especially waste collection in un-served/under-served communities.

3.8.2 Feed-in Tariff policy in developing renewable energy technologies

In developed countries, the uptake of AD has been enhanced by the introduction of Feed-in Tariff (FIT) policy instrument. The policy provides a guaranteed price for a fixed period to small-scale electricity generators from the produced biogas (DEFRA 2009). The FIT policy has fostered considerably investment in AD in European countries for the generation of electricity and has been considered as the strongest policy in leveraging private investment in sub-Saharan Africa (Zglobisz *et al.* 2010; UNEP 2012). With this policy, market risk is almost reduced as FIT is offered at pre-determined price and over pre-determined number of years. This allows certainty on revenues and projections can be determined which give more assurance to investors

(UNEP 2012). The FIT policy in sub-Saharan Africa has been developed mainly for mobilising private investment in hydropower, wind, solar, geothermal and biomass (UNEP 2012). Anaerobic digestion projects may have not benefited from the policy since most established AD projects are in rural environments and off-grid especially at schools, health clinics and mission hospitals and small scale farms (Mshandete and Parawira 2007; UNEP 2012). The implementation of FIT for AD of municipal waste may initially slow its development due to policy design costs, however, in the long term, may increase its uptake as it has been observed in Kenya for its role in the increase of renewable energy investment (UNEP 2012).

3.8.3 Carbon credit system

Clean Development Mechanisms (CDM) are designed by the United Nations Framework Convention on Climate Change (UNFCCC) to enable emission reduction projects in developing countries by making these countries earn certified emission reduction credits (UNFCCC 2013). These credits can be bought and used by industrialised countries to meet their reduction targets under the 1997 Kyoto Protocol. CDM is therefore established to finance adaptation and emission reduction projects in developing countries that are vulnerable to the adverse effects of climate change (i.e. Parties to the Kyoto Protocol as Non-Annex 1). These include countries of low-lying coastal areas and those prone to desertification and drought and countries that rely on fossil fuel production and commerce for their income. All of the countries in sub-Saharan Africa are designated under the Kyoto Protocol as Non-Annex 1 parties (Couth and Trois 2012). The latter reported that 6.8% of the Greenhouse Gas (GHG) emissions in Africa are from waste. The main GHG emission that comes from SWM is methane gas resulting from anaerobic decomposition of waste at landfill or dumping sites. Such GHG is likely to increase with population growth. Interest in

CDM has been increased in Africa with some projects already in the pipeline such as composting project in Cairo, Egypt (Couth and Trois 2012).

CDM can present a financial opportunity for AD projects owing to the avoidance of methane emissions, the social improvement with the creation of employment, reduced health and environmental risks of inappropriate waste disposal. However, lack of technical, managerial and financial expertise for the design and implementation of the project will have to be circumvented in order to obtain the desired outcome of the policy (UNEP 2012).

CHAPTER 4

SOLID WASTE MANAGEMENT IN KIGALI CITY

This chapter gives an insight into the characteristics of Kigali City and reviews solid waste management systems including management practices. The chapter reviews the key elements of Kigali waste Strategy and implementation of strategies and examines the challenges and the current gaps in the management of wastes. This chapter also reviews the available support mechanisms for the deployment of anaerobic digestion technology in the city.

4.1 Description of Kigali city

Kigali City is the capital and largest city of Rwanda. The City is located in the centre of the country and is one of five provinces of Rwanda (Figure 4). Kigali City is governed by a city council which appoints the executive committee that runs the everyday management of city (Rwanda Gateway 2010). The committee is headed by the Mayor and two deputies, one in charge of economic and financial affairs and a second in charge of social affairs. The City is subdivided into three administrative districts, Nyarugenge, Gasabo and Kicukiro (Figure 5). Each district is subdivided into sectors and each sector into cells. A cell is subdivided into villages commonly called "*imidugudu*". In total, Kigali City has 35 sectors, 161 cells and 1061 villages. The city consists of residential, administrative and commercial districts and small and large industrial entities, built on steep mountains divided by valleys with numerous running streams. According to the City of Kigali, the urban population of Kigali City is currently estimated at around one million inhabiting an area of 730 km^2 (City of Kigali 2012a). The City of Kigali progressively expanded after the 1994 genocide, due to a migration of population in search of better opportunities from rural areas together with returning refugees from other countries. This migration led to a growth of unplanned and informal settlements which suffer from deficiencies in terms of basic infrastructure and services. Kigali City is 70% urban and is surrounded by a sparsely populated rural environment characterised by fields and forests. Approximately 80% to 85% of the Kigali population live in informal settlements (City of Kigali 2008; Durand-Lasserve, 2007). Kigali is situated at an altitude of 1491 meters and its weather is characterised by a tropical highland climate. The country is characterised by four seasons: long rains from mid-March to mid-May; short rains from mid-October to mid-December; short dry season from mid-December to mid-March and a long dry period from mid-May to mid-October (Rwanda Gateway 2010). Over the course of the year, the temperature typically varies from 15^{o}C to 29^{o}C and its average falls between 20 to 21.6^{o}C (City of Kigali 2008). This is of particular interest since it determines ways of handling the waste due to the rapid decomposition of high organic matter generally contained in the household waste (Kassim and Ali 2006).

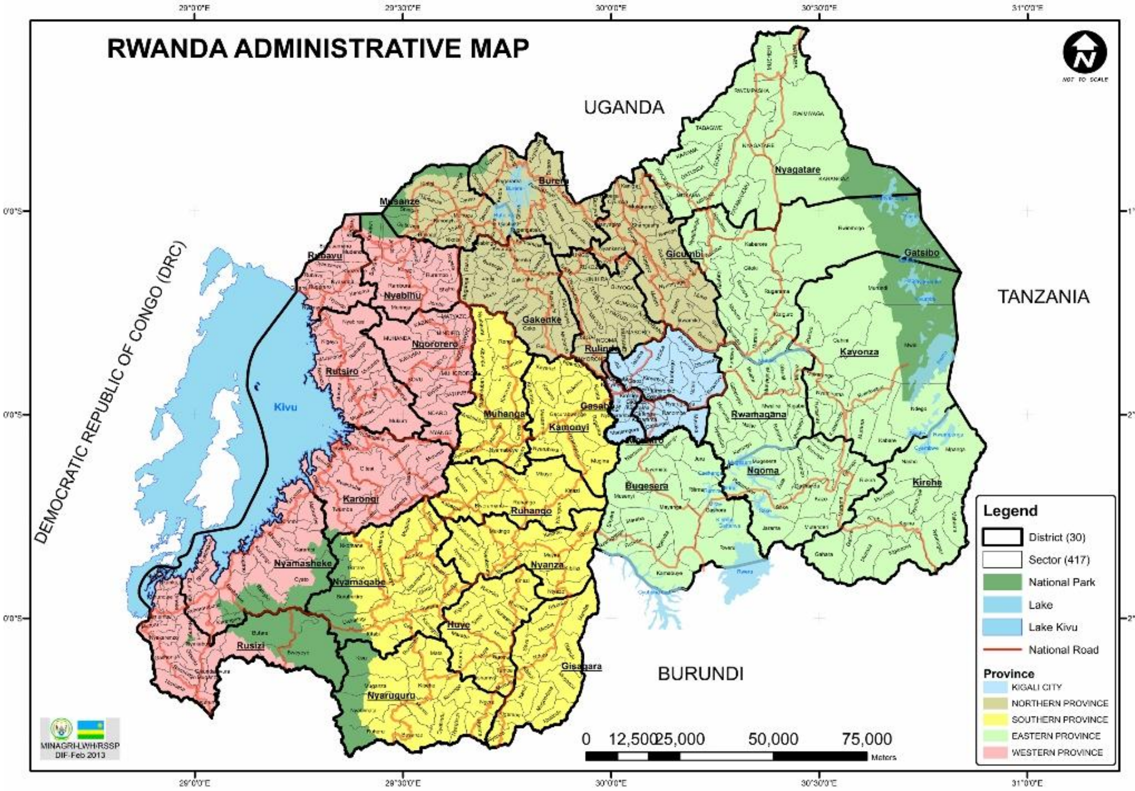

Figure 4 Administrative map of Rwanda
Source: Ministry of Agriculture-GIS (2013)

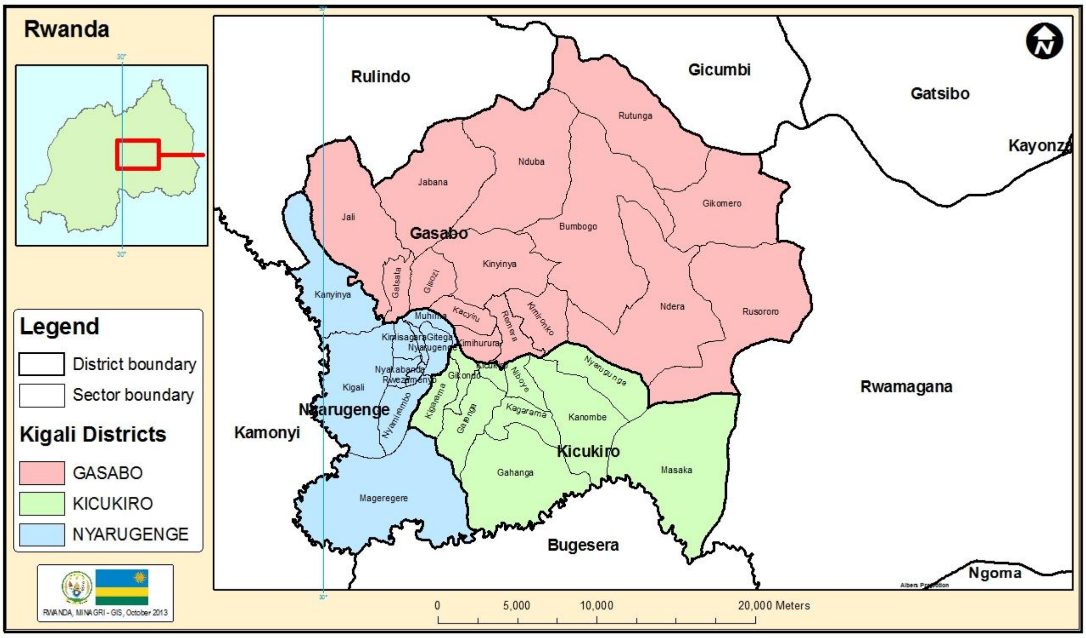

Figure 5 Administrative map of Kigali City
Source: Ministry of Agriculture-GIS (2013)

Figure 6 shows the supervision of waste management in the City is the responsibility of the municipal authority whilst the implementation is managed by district and sector authorities (City of Kigali 2012b). Kigali City has a quite number of similarities with various cities in African countries with regard to SWM practices. These similarities are commonly aspects relating to technical, economical, social and political factors which strongly influence SWM options. The solid waste produced from households in Kigali City undergoes three stages of management: collection, transport and disposal while sorting of waste in order to extract recyclable material takes place at various points in the process.

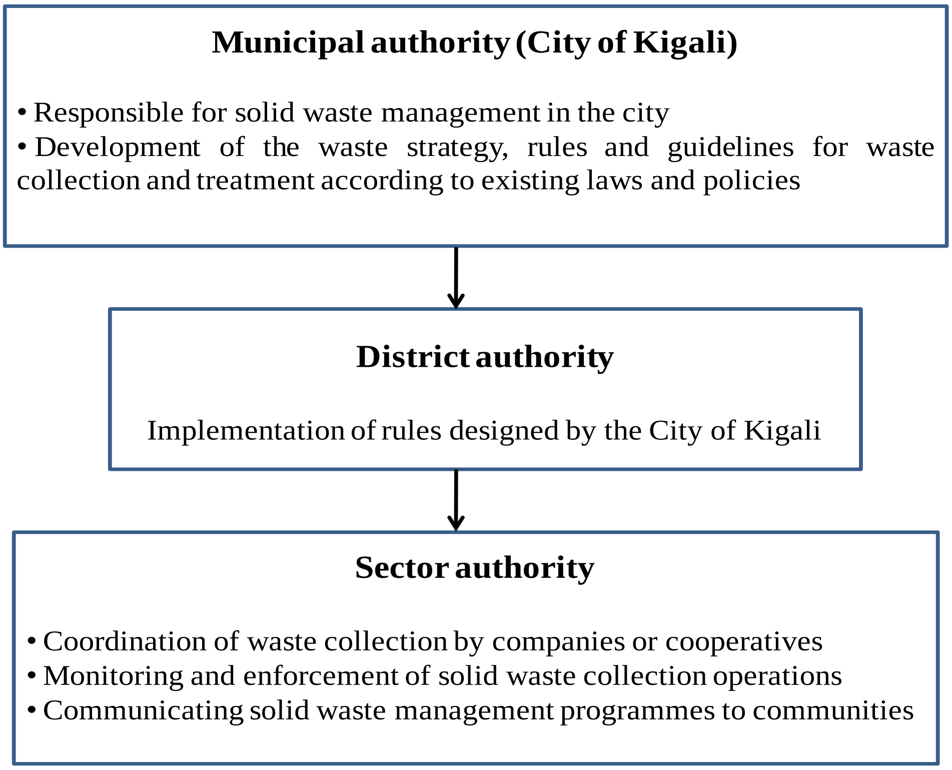

Figure 6 Solid waste management administration in Kigali City
Source: Adapted from City of Kigali (2012b)

4.2 Current solid waste management situation in Kigali City: a review

4.2.1 Waste generation and composition

Solid waste generation in Kigali City is estimated at 450 tonnes per day with 70% of organic waste (City of Kigali 2012b). Household wastes make up 88% of the total municipal waste stream, industrial wastes 9%, commercial wastes 2% and healthcare wastes 1% (City of Kigali 2012b). Except healthcare waste, the composition of other type of wastes from households, industrial and commercial sources is shown in Table 2.

Table 2 Composition of waste by source (percentage in weight) in Kigali City

Weight (%)			
Material type	Households	Commercial	Industrial
Organics	70	75	49
Plastics	5	10	2
Paper	6	5	2
Glass	1	5	6
Aluminium	3	0	2
General	15	5	14
Textile	0	0	5
Iron	0	0	3
Minerals	0	0	17

Source: City of Kigali (2012b)

4.2.2 Waste handling and collection

At household level, the waste is kept at the back of the house in plastic bags or any other material that can serve as a bin such as rack sacs, old plastic buckets or old cardboard cases. The waste is principally mixed at the point of collection (Mugabo and Uwamahoro 2011). A door to door waste collection system is established and is mainly privatised. Cooperatives and private companies have established payment contracts with waste producers. There is no standard pricing with the collection fee which increases depending on the area's socio-economic standing (City of Kigali 2012b). The waste-containing material is placed in front of the house on the day of collection and can stay the whole day under the sun heat or rain and can often end up not being collected on the day. These environmental conditions encourage waste decomposition which consequently produce odour nuisance and attract flies. In poor income communities, where there are often poor access roads, a bring system is used whereby a household member carries the waste to a collection truck located on the street corner, sometimes far from the source of waste generation (City of Kigali 2012b). The local authorities usually subcontract cooperatives for the entire Kigali City to collect the wastes in poor income communities due to difficulties in payment of waste collection fees. The official paid waste collection coverage is currently estimated at 44% of households and the amount of total waste that is collected is estimated at 180 tonnes per day (City of Kigali 2012b). Informal collection in the form of scavenging plays an integral part in the waste management system in Kigali. This consists of a door to door collection of large or small reusable items which are then passed through a trade chain until they are transported to established recycling facilities in Rwanda and neighbouring countries. The recoverable materials include cans or other plastic containers, scrap metals, plastic and glass bottles.

4.2.3 Waste recovery methods

Composting, Refuse-Derived Fuel (RDF) production and plastic recycling are currently being developed as waste recovery methods for municipal solid waste (City of Kigali 2012b). Biogas production via anaerobic digestion is also being developed for the treatment of animal and human wastes especially outside the city in the rural part of Kigali.

4.2.3.1 Recycling

Recycling of plastics and paper are the currently established recycling processes in Kigali. One company in Kigali recycles polyethylene plastics. Garbage bags are sold to customers for waste storage and are salvaged during waste collection and recycled into sheet, garbage bags and tubing (City of Kigali 2012b). Informal recycling also occurs at the landfill as shown in Figure 7, where waste materials such as plastics, metals and paper packaging are sorted and scavenged and pass through a trade chain and exported to other countries such as Uganda and Kenya (City of Kigali 2012a). This activity is mainly practised by women individually or in groups, also described as informal waste collectors. The activities of the informal sector are affected by lack of exposure and proper endorsement from relevant authorities for their role in SWM systems (City of Kigali 2012a). As stated by Scheinberg *et al.* (2011) this situation can largely impact on the informal sector's ability to deliver environmental and economic benefits being a part of ISWM as shown in Figure 2. The expansion of recycling processes in Rwanda is largely affected by technical and by financial constraints such as lack of technical skills for the valorisation of recyclable waste and financial capacity for processing (City of Kigali 2012a). There is no reliable data on current recycling rates in Kigali City.

Figure 7 Waste scavenging at the landfill site in Kigali
Source: The NewTimes (2013)

4.2.3.2 Composting

Composting of organic wastes uses an open windrow system as shown in Figure 8. Composting activities of urban solid waste are not widespread. Composting is labour intensive and a high cost of labour drives the return down (Mugabo and Uwamahoro 2011). Furthermore, it has been reported that composting schemes either large or small in developing countries have failed due to insufficient attention given to marketing and to the research and development of quality of product (Zurbrügg 2002). The current fertiliser marketing system in Rwanda favours the use of inorganic fertiliser where the government has the exclusivity of its importation (Lyambabaje *et al.* 2012). The Ministry of Agriculture partners with wholesalers who make the fertiliser accessible to farmers under various incentives (Lyambabaje *et al.* 2012). Approximately 29.6% of farmers use organic amendment (farm yard manure) alone while 60.8% use both inorganic and organic fertilisers (IFDC 2007). Current challenges include lack and inaccessibility of fertiliser and inadequate supply of the product (Lyambabaje *et al.* 2012; Kelly *et al*. 2001).

Figure 8 Composting activities in Kigali City
Source: REMA (2010)

4.2.3.3 Refuse-Derived Fuel production

Refuse-Derived Fuel (RDF) products in the form of briquettes or pellets are made from agricultural residues and biomass waste. In Rwanda, briquettes are used as a cooking fuel in public institutions such as prisons and schools (City of Kigali 2012b). The most commonly used types of organic wastes include banana peelings, sawdust, rice and coffee husks, bagasse and crop residues (Mwampamba *et al*. 2013; City of Kigali 2012b). Briquettes operations are labour intensive and consist of open-faced natural drying of waste material, shredding, compacting and processing into briquette products using conventional machinery. Most briquettes operations in Kigali have closed down due to poor sales of the finished product (Mwampamba *et al*. 2013). Lack of financial resources for the acquisition of appropriate equipment such as drying machines also hampers the business (City of Kigali 2012b; Young and Khennas 2003). Drying periods during rainy seasons extend the production process thereby affecting market supply of the product. Where machines are available, the costs of drying increases with high moisture content of the waste material and can lead to high costs. There is no available reliable data on the amount of waste diverted to the production of RDF.

4.2.3.4 Anaerobic digestion

Anaerobic digestion for biogas production has been applied for the treatment of human and animal wastes in the rural areas of Rwanda including areas at the outskirts of Kigali City. The technology is not currently used for treating organic municipal solid wastes. Anaerobic digesters have been installed at waste sources for individual rural households, prisons and schools (Safari 2010). The methane gas produced is used for cooking and lighting purposes. Currently, 90% of all energy used by rural households comes from firewood (Safari 2010). In the move to encourage forest conservation and climate change mitigation, the National Domestic Biogas Programme (NDBP) was jointly established in 2007 by the Ministry of Infrastructure (MININFRA) and Netherlands Development Organisation (SNV), an international donor. The move was to increase biogas production from cow dung and reduce (by 40%) the consumption of fuel wood as energy source by the year 2020 and provide an economically sustainable source of energy for Rwandan rural households that have significant livestock (SNV 2012; Landi *et al.* 2013). Other organisations joined such as Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and Energy Water and Sanitation Authority (EWSA) which is under the MININFRA’s authority. These organisations have been responsible for the development, promotion, deployment and maintenance of the NDBP since its creation. Government incentives in the form of technical assistance, subsidies and endorsement for biogas credits from local banks are provided to rural households for the implementation of the biogas programme (SNV 2012). GIZ is no longer participating in the NDBP project since 2011; however, SNV continues to provide technical assistance to the Rwandan government. The programme had an initial budget of $14.1 million to build 15,000 family sized biogas plants throughout the country by 2011. However, the programme has managed to build 2600 household digesters that are currently operational. Since GIZ's financial support ended in 2011, the programme is now funded by only the government and its budget increased to about $14.9 million per annum (Landi *et al.* 2013). About 14,000 citizens including 7120 who are women are beneficiaries of the programme. The development of the programme faces financial, technical and social challenges including low public awareness and engagement (Landi *et al.* 2013).

The biogas digesters are of a fixed-dome design and built underground. They are made of stones, concrete, gravel and sand and operate on batch feeding mode. Table 3 shows the current profile of biogas production from cow manure feedstock and construction costs. There is no available reliable data on digestate quantities from digested manure.

Table 3 Production of biogas from cow manure and related costs for digester installation

Number of Cows	Size of digester (m^3)	Costs of construction ($)	Biogas production (m^3/d)
2	4	1089	1.3
3	6	1340	2
4	8	1591	2.6
5	10	1843	3.3

Source: Internal report (Energy Water and Sanitation Authority 2011)

4.2.4 Disposal practices

The majority of waste generated is deposited by waste management companies at a landfill site, the only facility serving the entire city. The landfill gate fee costs $1.63/tonne (City of Kigali 2012b). Uncontrolled open dumping is also observed especially in water ways and sidewalks of slum areas. Residents often fail to pay the monthly fee waste collection and turn to this practice especially in the rainy season when the waste can be carried away by storm water (City of Kigali 2012b). Also the waste collection service is not proposed in some of these areas due the inability of the households to pay for the services. Uncontrolled dumping particularly poses an environmental and health risks when drainage systems are clogged up by an accumulation of litter in the conduit leading to overflow of waterways and consequently flooding and possible emergence of water borne diseases (Ministry of Infrastructure 2010).

4.2.5 Institutional framework for solid waste management

Solid Waste Management policy falls within the National Policy for Water Supply and Sanitation Services (City of Kigali 2012b). A review of a study by Marara *et al.* (2011) and City of Kigali's report (City of Kigali 2012b) showed that Rwanda has a number of key institutions which have waste management as part of their remits and other institutions that provide advice and technical support. Figure 9 shows the hierarchy of SWM administration in Rwanda. The institutions responsible for the development of SWM policies include Ministry of Health and Ministry of Environment and Natural Resources. Other involved ministries include Ministry of Infrastructure (MININFRA), Ministry of Trade and Industry and the Ministry of Finance and Economic Planning. Government agencies such as Rwanda Utilities and Regulatory Agency (RURA) is responsible for waste licensing, publication of regulations and guidelines for SWM. Rwanda Environmental Management Authority (REMA) is in charge of supervising the implementation of the environmental policy and undertaking environmental impact assessment of major infrastructure projects in both public and private sectors. REMA also coordinates all environmental related issues, provides advice and technical support and gives authorisation to any intended project. Energy, Water and Sanitation Authority (EWSA) under MININFRA provides sanitation and energy infrastructure, assesses related projects and their relevance to both Kigali City and national priorities. The City of Kigali is the municipality authority and is in charge of monitoring the effectiveness of waste collection systems at the district and sector levels, and is allowed to develop its rules according to the existing laws and guidelines.

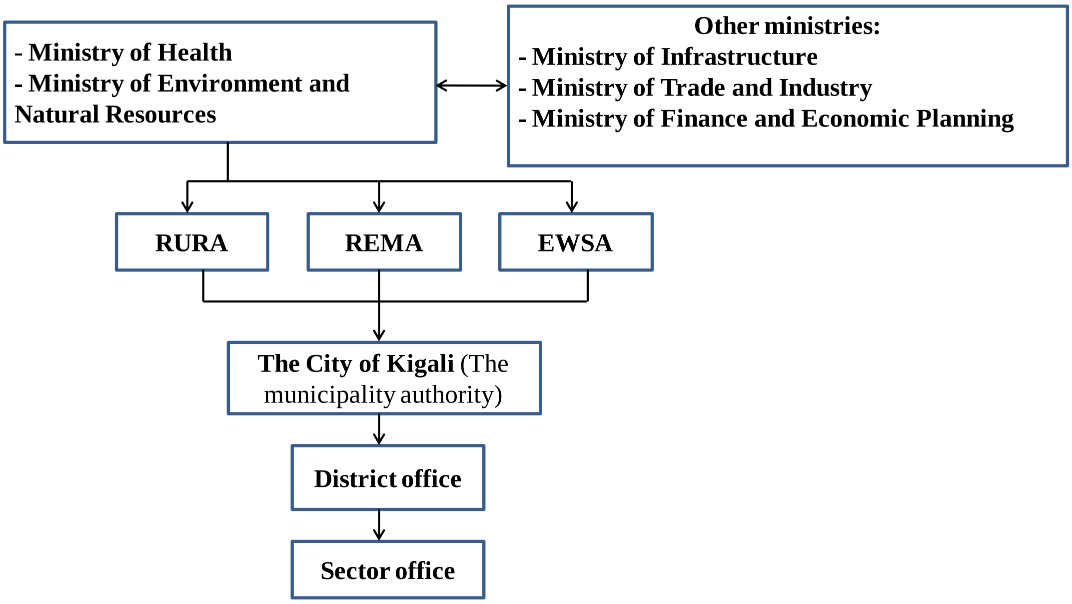

Figure 9 Solid waste management administration in Rwanda
Source: Adapted from City of Kigali (2012b)

The main competent authority in SWM is REMA, however, lacks autonomy to effectively influence the design of suitable SWM strategies and enforce the existing policies and procedures (Marara *et al.* 2011). In reference to Figure 2 in Chapter two, there are some gaps in ensuring sustainable integrated waste management systems in Kigali City. For instance, a lack of procedural framework between institutions has been reported especially in the sharing of information and evaluating sustainable solutions to the waste problem (Ministry of Infrastructure 2010; Marara *et al.* 2011). These tasks are mainly left to households, communities, NGO's, the private sector, community associations and local authorities who have limited technical and financial capabilities (Ministry of Infrastructure 2010). This problem has been attributed to lack of environmental professionals in various sectors of the government and the fact that multi-department management system in delivering environmental solutions in Rwanda is still new (Marara *et al.* 2011). Moreover, the latter found that public participation has not been well integrated in the current regulatory system. This has led to low public environmental awareness, particularly on the responsibilities of various stakeholders (individual, community, etc) in waste management processes. Policy consistency is essential in the viability of solid waste management projects (Marara *et al.* 2011; Zglobisz *et al.* (2010).

4.3 Current Kigali waste strategy and potential development in solid waste management

The Kigali waste Strategy as presented in City of Kigali (2012b) was developed in 2012 and is the first to be ever developed in the country. The Strategy acknowledges that significant improvements need to be made at all waste management sectors. Four waste management options have been designed: a sanitary landfill, an incineration plant for the treatment of hospital and industrial wastes, a composting facility and a recycling facility or sorting facility.

The Strategy stipulates targets to be reached in the waste management sector. It is expected that recycling rates of 45% of produced organic waste and 38% of dry waste will be achieved in 2022. For this, emphasis is placed on developing sorting transits and a manual sorting facility to recover materials of economic value for recycling and composting. The Strategy does not clearly indicate the possible outlets of waste materials recovered in the sorting facility. Some of the potential outlets might include use of plastic waste as raw material by local plastic industries and the exportation of recyclable waste to other countries.

A new sanitary landfill with leachate control and gas collection systems is planned for 2014 at a site located within 30 km from the centre of the City. The landfill is expected to receive waste that is not composted or that has not been recycled.

A composting facility is planned at the same location as the new landfill site and its capital cost has been estimated at $2,315,447. The facility is expected to receive 60,000 tonnes of organic waste and produce compost that will be sold to local farmers. The operation of new landfill site and both the composting and sorting facilities will be outsourced to private contractors

The production of Refuse-Derived fuel pellets from organic waste by the private sector is also expected to divert 1000 tonnes of organic waste both from households and agricultural activities. The produced pellets are expected to be sold at $0.3/kg.

There is less emphasis on developing mechanisms for waste separation at source. Sorting facilities have been found useful for source-separated waste. However, they have been shown to not reduce the risks of waste contamination on their own especially when biological treatment technologies are employed (Mata-Alvarez 2003). The Kigali City Strategy has prioritised composting as the main waste management route of putrescible organic waste. Without proper waste separation, risks of contamination are high which could lead to poor quality waste processed product. Waste separation at source is believed to be by far the most sustainable way of enhancing the potential of waste materials to be processed (Al-Khatib *et al*. 2010). The Strategy reported some successes in implementing waste separation at source in wealthier communities where appropriate facilities for waste separation have been provided. The ability to afford these facilities means that socio-economic factors should be considered when rolling out the practice to other communities. The Strategy also encourages awareness with the use of flyers that show how the materials should be separated. It has been acknowledged that knowledge by the public of the benefits of waste separation can significantly influence separation at source (Refsgaard and Magnussen 2009).

Regarding the treatment technologies chosen for organic waste, the challenge is to seek the most effective technology for managing a particular type of waste. The Strategy on waste recovery only recognises centralised composting and RDF production as the main value recovery potential from organic waste. The Strategy does not specify which waste resource to be treated by each technology. Given that the average moisture content of domestic waste would have to be about 12% before briquetting (Young and Khennas 2003); it is unlikely that RDF production would be an economically viable option from organic municipal wastes which usually contain over 80% moisture content. Furthermore, composting is not particularly suitable for exclusively wet substrates such as food waste or sludges since their structural material will restrict air circulation (McDougall *et al.* 2001). Additionally, in Rwanda and the rest of sub-Saharan African countries, centralised composting of MSW has been reported to be unattractive to potential investors mainly due to poor market development and delayed financial returns (Couth and Trois 2012). In its present form, the Strategy does not demonstrate potential market development strategies for the compost product. The Strategy does not seem to sufficiently seek the most efficient use of organic waste resource in terms of technical, social and economic requirements for its management, the environmental impacts and the overall benefits.

It is the role of the government to harmonise management options targeting organic waste and recommend appropriate strategies that can effectively meet social, environmental and economic benefits. More importantly, with privatisation of waste management operations, the Rwandan government will need to assess those technologies that give assurance to potential investors. Regarding financing of SWM operations by the private sector, the Strategy stipulates tax exemptions for potential investors in recycling and an incentive by the Ministry of Economic Planning and Finance of 10% of capital investment in machinery. However, no specification of incentives was made for private operators involved in waste treatment. In the UK, the significant improvements especially in the expansion of waste recycling activities have been partly been attributed to the setting up of the Waste Strategic Fund (Audit Scotland 2007). Such system will probably be beneficial for Rwanda provided that requisite funding is made available.

The Strategy has not considered anaerobic digestion technology as a management option for municipal solid waste. Experience to date with urban-scale anaerobic digestion in the region has been poor due to technical and economic constraints and due mainly to the relatively poor feedstock quality brought about by none separation of municipal wastes, which may have led to Rwanda's apparent reluctance in recommending the development of the technology.

Installed power generation capacity in Rwanda is at 95 MW from both hydropower and thermal sources which in total represent about 10% of targeted capacity (REMA 2011). Fuel wood is the major source of energy and accounts for 80.40% of total energy consumption which is a threat to the environment. Currently, only 10.1% of the population have access to electricity. The government has a target to reach 50% of population with electricity provision by 2017 (REMA 2011). Proper integration of anaerobic digestion to the overall energy mix can therefore play a significant role in promoting economic development and enhancing the waste management business sector. A more holistic approach to the planning and implementation of anaerobic digestion technology in Rwanda is required since successful application of the technology will depend on existing social and technical capacity conditions. Moreover, the application of anaerobic digestion needs a supportive policy environment that is both financially and technically strategic to smooth out its integration in both the energy sector and the waste sector. There is therefore a need to develop a strategic framework for effective planning and implementation of anaerobic digestion operations. Elements of the strategy will include:

a. Designating suitable feedstock sources
b. Developing community capacity to fulfil the requirements of effective collection and preparation of suitable feedstock
c. Developing technical capacity for the planning and implementation of processes
d. Developing markets for the output products

The four elements will need to be integrated with the local, regional and international policies for effective implementation and the effective utilisation of the limited funding opportunities.

CHAPTER 5

CONCLUSION OF LITERATURE REVIEW

Solid Waste Management (SWM) in developing countries is driven mainly by public health with environmental protection generally not taken properly into account. Effective SWM systems have been shown to meet social needs in addition to being environmentally and economically viable.

Effective SWM strategies will depend upon adequate information on public acceptance, waste characteristics and the economic and social cost of various waste management options. Anaerobic digestion technology for energy generation and bio-fertiliser production (where there is abundance of suitable feedstock) has efficiently proven to be competitive at social, economic and environmental levels. Challenges such as public awareness, availability of suitable feedstock, high capital and running costs and technical constraints associated are key factors to be taken into account in the development of full-scale anaerobic digestion technologies. Anaerobic digestion technology for municipal solid waste in sub-Saharan Africa will be affected by feedstock characteristics and availability, potential uses of biogas and digestate and technical and economic factors. Substrate characteristics will be defined by biodegradability and moisture content of waste whilst technical skills and financial constraints will be influenced by manpower development and government policies.

The collection of suitable waste is the most important factor in ensuring sustainable anaerobic digestion operations. Being the most costly waste management operation as indicated in Chapter 2, it is imperative that direct or indirect mechanisms for effective waste collection are established before development plans for anaerobic digestion application are commenced. In addition to awareness programmes, incentive systems are also likely to improve participation in good waste management practices such as source-separation which will be necessary for cost-effective application of anaerobic digestion technology. Provided that appropriate support by government and non-governmental charitable organisations is provided, the informal waste collection for recyclable waste also has the potential to help develop anaerobic digestion strategies. Hence, mechanisms towards waste handling practices at community level particularly in terms of ensuring the production of high quality feedstock should target those likely to be involved in the informal waste management sector (e.g. poor women and children) who will be able to undertake waste separation.

For Anaerobic digestion to be an integral part of municipal solid waste management in sub-Saharan African countries and in Kigali City (in Rwanda), it is important that waste management policies designed by governments encourage investment in the waste industry. In this regard, waste targets should be appropriate to the available markets for the processed products. Due to constraints in accessing financial resources for capital intensive technologies such as anaerobic digestion, investment in the technology will be driven by the provision of enabling environment for the private sector which includes appropriate policy framework, market development and economic incentives. Government's role in developing anaerobic digestion is crucial for effective implementation.

Little research has been done regarding the development of large-scale anaerobic digestion technology in the management of municipal solid waste in sub-Saharan Africa despite the fact that the technology is widely applied in other parts of the world. A major barrier to its implementation in these countries has been attributed to the lack of substantial specific information required in the design of appropriate strategies. Specific issues include the absence of mechanisms to ensure public awareness and engagement, the availability of suitable feedstock, feedstock digestibility and methane production potential according to local environmental conditions and mechanisms to develop public engagement to anaerobic digestion processes. There is also limited information on the degree to which current applicable policy system can affect the application of the technology. This research is therefore designed to fill in some of these gaps with the aim of reducing these identified obstacles to the application of the technology in sub-Saharan Africa.

This study will use Kigali City as a case study and will adopt an integrated qualitative and quantitative methodological approach interrelating social, economic, environmental and technical spheres to achieve the research aim. Research techniques will comprise of literature review, field surveys, interviews and laboratory experiments. The research project will examine current waste production and characteristics and public awareness and attitude towards waste separation at source with an attempt to estimate feedstock availability for anaerobic digestion and determine factors affecting public/individual waste separation at source. This study will use socio-economic parameters to explore effective mechanisms for collecting source-separated biodegradable waste and will estimate its availability for anaerobic digestion.

Once determined, the composition of suitable feedstock will be used to assess the digestibility and methane gas production potential. The study will also examine the effect of ambient temperature in the operation of an anaerobic digestion plant and evaluate the potentiality of optimising anaerobic digestion processes under Kigali City's specific temperature conditions.

The impact of feedstock availability and its energy potential on the economics of operating an anaerobic digestion plant will also be examined. This study will assess the determinants for effective development of large scale anaerobic digestion technology in Kigali City for the generation of electricity and bio-fertiliser and will explore suitable mechanisms capable of encouraging investment in anaerobic digestion operations.

This study will also attempt to develop a framework for assessing the potential benefits of anaerobic digestion of municipal solid wastes in any given city using Kigali City as an example. The study will therefore provide methodologies and baseline data that can contribute to the use of anaerobic digestion technology for sustainable solid waste management in sub-Saharan African cities and more generally, to the improvement of solid waste management systems in these cities.

CHAPTER 6

MATERIAL AND METHODS

This chapter presents the methods used in this study to collect and analyse the data. Field methods were used to collect relevant data. An integrated methodological approach was used involving household surveys, field observation and interviews with relevant stakeholders, biochemical methane potential tests and economic assessment of AD operations. A literature review was also used to obtain empirical data that were non-available during field studies.

6.1 Social and technical data collection in Kigali City

Two types of surveys were conducted in Kigali City from September 2010 to March 2011, a period that corresponds to the short rainy season (see section 4.1). A waste characterisation survey was conducted to determine the availability of biodegradable waste. A public perception and awareness survey was also conducted to identify gaps and critical factors affecting the application of AD technology in Kigali City.

6.1.1 Survey sites

The waste characterisation survey and the public perception and awareness survey were both conducted in sectors representing urban areas of the three administrative districts. Figure 10 shows catchment areas for household surveys.

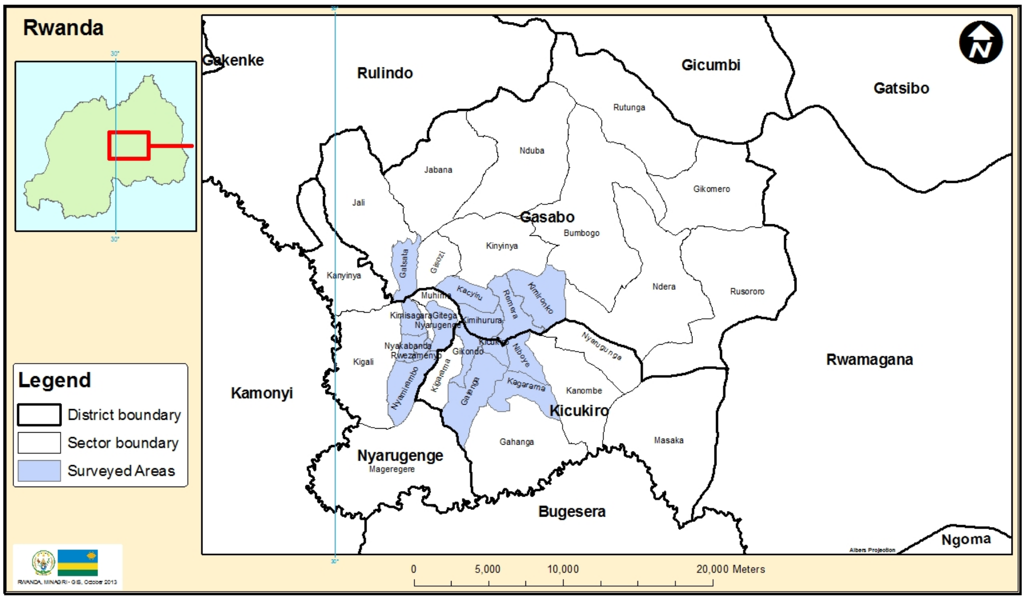

Figure 10 Surveyed urban areas within districts
Courtesy of MINAGRI-GIS (2013)

Methods of direct analysis using socio-economic parameters were used in order to obtain data. Based on an internal report of the Ministry of Local Government (MINALOC 2005), each district is characterised by three socio-economic levels, namely Low income residential area (Level I), Middle income residential area (Level II) and High income residential area (Level III). The sampling areas were therefore classified by range of socio-economic levels. Figure 11 illustrates the three socio-economic levels that characterise Kigali urban areas. Level I is an informal settlement that has developed into a slum area with a substandard housing and of poor quality construction material (Kalimba and De Langen 2007). This area is characterised by poor access roads and basic sanitary infrastructure. Level II is also an unplanned settlement, but the quality of construction of houses varies and includes good quality (cement brick or stone walls), reasonable quality (adobe brick), and poor quality (mud or construction waste material) buildings which features a mixed income composition. Level III is a planned settlement with high-graded houses, paved roads immediately adjacent to houses with all basic sanitary infrastructure services available and in good state of repairs.

Figure 11 Kigali City socio-economic levels showing Level I (Low income residential area); Level II (Middle income residential area) and Level III (High income residential area)
Source: Adapted from Google Earth (2012)

An authorisation to conduct the survey activities was granted by the City of Kigali (Appendix 1) and further notification was made with relevant local authorities for each of the communities. An assistant enumerator was trained on theoretical background of survey methods and survey tools. Catchment areas were also reviewed with the enumerator.

6.1.2 Waste characterisation survey

Although there are different methods of characterising waste, the most common approach is to analyse waste at its point of generation because this method reportedly allows a significant amount of information to be obtained on the nature of the waste generated and its influencing factors (Bandara *et al*. 2007; Bernache-Pérez *et al.* 2001). However, there has been a lack of a formal method for deciding on the appropriate sample size to ensure that the sample selected can provide acceptable representation for solid waste characterisation (Dahlén and Lagerkvist 2008; Al-Khatib *et al.* 2010).

In this study, the total number of households approached for inclusion in the survey was 120 households, from which 75% agreed to participate and the rest formally declined citing reasons such as lack of time or lack of space for keeping waste for a longer period. Thirty households were therefore sampled with 10 households in each of the three social economic levels to represent each of the three districts in Kigali, resulting in a total number of 90 households. Two different coloured plastic bags of 50 kg capacity, one for Food Waste (FW) and the other for Other Waste (OW), a hand weighing scale and a waste data record sheet (Appendix 2) were distributed to each of those households that agreed to take part in the survey. The waste data record sheet was designed to record information on daily FW and OW production. Household size and socio-economic level were recorded by the enumerators at the start of the survey. Respondents were trained on how to separate the waste, weigh the waste and record the data generated everyday during a period of two weeks. Households were being visited regularly by enumerators to verify the progress made in recording the data. Observation of the composition of waste produced was particularly examined during these visits. Seasonality influence on waste production was not particularly examined in this study.

6.1.3 Public perception and awareness questionnaire survey

6.1.3.1 Questionnaire survey design

Questions were developed based on methods described in Purcell and Magette (2010); Refsgaard and Magnussen (2009) and Chakrabarti *et al.* (2009). The questions were designed to obtain data on household socio-economic profile, waste management practices, awareness and perception including attitude to waste separation at source. The questions were presented in two formats i.e. forced choice and open-ended questions. The latter was designed to provide the respondents with an opportunity to give an explanation of their preceding response and freedom to provide a more expansive view of household's opinion on waste management practices. Although forced choice questions are generally used to measure knowledge (Fowler 1995), in this study, they had a role to assess attitudes and to provide factual information. The questionnaire was developed in English language and then translated into Kinyarwanda, the official language of Rwanda. Draft questionnaires were administered in advance to random acquaintances in order to test for problems with language and comprehension of technical terms. In particular, prior to asking the question involving technical words such as treatment technologies, these were first explained literally in language understandable to the respondent. A further pre-test was made in a random local community for the enumerators to familiarise with the questionnaire and identify any potential problems with respondent's comprehension of questions. Suitable changes were made accordingly and a finalised questionnaire was designed (Appendix 2). The pre-testing also allowed finding out technical challenges of the field survey. For instance, it was found that heads of households from Level I and II could be reached at all times whilst those from Level III were most likely to be reached in the evenings after working hours. It was thus decided that more questionnaires would be administered in Level I and Level II during the day and in Level III during evenings in order to complete the survey in the time frame. The responses have been translated and recorded here in English.

6.1.3.2 Sampling procedure

To give a statistical representation of Kigali City population's various socio-economic levels, the number of samples was calculated in proportion to the household data presented in Table 4 which shows the number of households in each socio-economic level for each district. To allow estimation of the proportions with a 95% confidence, the sample size was estimated according to the Equation (1) below (Zar 1999):

$$n = 1.96^2 / 4d^2 \qquad (1)$$

Where n is the sample size and d is the error within which the proportions are estimated. An error of 5% (corresponding to the 95% confidence) was considered in this study. For each district, the size of the sample in each socio-economic level was calculated in proportion to the size of each socio-economic level shown in Table 4.

Table 4 Number and proportion of households by socio-economic level within district**s** of Kigali City

District	Level I	Level II	Level III
Nyarugenge	8,935	26,615	8,516
	20.30%	60.40%	19.30%
Gasabo	6,272	15,463	17,399
	16.00%	39.50%	44.50%
Kicukiro	4,547	11,692	7,492
	19.20%	49.30%	31.60%

Source: Ministry of Local Government (2005)

The questionnaires were distributed in the villages of each socio-economic level. Every first house that starts at a randomly chosen street in the village was invited for inclusion in the survey. Potential respondents were briefed on the survey process and were assured of complete anonymity either verbally or by an informed consent note (Appendix 2). If there was no agreement from the head of household for participation in the survey, the next household on the street would be approached and so on. Reasons for non-participation in the study were noted. Structured interviews were used to prevent incomplete questionnaires and respond to potential questions from respondents in need of clarification. Where an immediate face to face interview was not possible, a more suitable time would be arranged or a questionnaire would be left for collection by the enumerator in the following days. The total number of households invited for inclusion in the survey was 468. The response rate was 91.45%. Therefore, the total number of households surveyed was 428. The distribution of households surveyed from each socio-economic level within each district is shown in Table 5.

Table 5 The number of sampled households in the three socio-economic levels according to districts

Districts	Level I	Level II	Level III
Nyarugenge	35	125	23
Gasabo	36	57	64
Kicukiro	17	44	27
Total	88	226	114

6.1.4 Field observation of waste management practices

By walking along the streets of residential areas and various locations in Kigali City, a field observation was carried out in order to obtain information on waste disposal practices, waste physical composition, existing waste storage systems and space availability. Relevant photos were also taken (Appendix 3).

6.1.5 Interviews with stakeholders

To obtain information on current waste management practices and factors affecting waste recovery for AD, interviews were conducted with various waste service providers, representatives of the City of Kigali office and public institutions such as Rwanda Environment Management Authority (REMA) and Rwanda Utility Regulatory Agency (RURA). The interviews also provided information on interactions between relevant institutions in municipal SWM and service providers. The interviews consisted of informal meetings and conversations. The topics discussed during the interviews were as follows for which specific questions are presented in appendix 4:

- Organisation of SWM practices from waste collection to final disposal for various waste sources
- Major challenges to all sectors of SWM, i.e. collection and transportation, treatment and disposal
- State of solid waste management in various areas of the City
- Challenges in enforcement of regulatory requirements for the management of waste

Waste service providers, representatives of the City of Kigali office were also consulted to obtain information on the quantity of waste produced (from sources other than households) and waste disposal practices of these sources. These other sources include hotels and restaurants, public markets, supermarkets and institution buildings. Waste data on food processing industries was unavailable and efforts to obtain information directly from the industry operators were unsuccessful. The Ministry in charge of industrial activities was also not able to provide information on waste except the number of current food processing industries and their processed products.

6.1.6 Data analysis

Data from both surveys were analysed using the statistical package, SPSS v.18. Descriptive statistics were used to analyse household waste production and SWM practices and relationships between variables were investigated using General Linear Models (Fox 2008). Specifically, a General Linear Model (GLM) with district (three variables), socio-economic level (three levels) and household size as explanatory variables were applied to analyse and predict waste production (FW and OW), which was introduced in the model as a dependent variable. The district variable and socio-economic level were introduced in the model as factors, while household size was introduced as covariate. Interaction between the different explanatory variables was also incorporated in the model, and a model selection was carried out based on the Akaike Information Criterion (AIC) selection criterion (Fox 2008). Post-hoc multiple comparison tests based on Tukey's test were further applied when necessary, to compare waste production between districts.

A chi-square test for independence (Zar 1999) was used to analyse the data generated by the public perception and awareness questionnaire survey in order to investigate relationships between attitude towards SWM practices and socio-economic level as reflected by the household type.

6.2 Biochemical Methane Potential experiments

The objective of this experimental study was to determine the Biochemical Methane Potential (BMP) of typical composition of food waste produced in Kigali City and the effect of Kigali climatic conditions on digestibility and BMP. Kigali City's average annual temperature ranges between 20^{o}C and 21.6^{o}C with minimum temperature reaching 14^{o}C and maximum 26^{o}C (City of Kigali 2008). A temperature of 37^{o}C is the most common digestion temperature of AD systems in the world, therefore BMP tests at 37^{o}C compared with those at 25^{o}C considered as the ambient temperature of Kigali City. This section describes the material and methods used for assessing the digestibility and BMP of various feedstocks that can be obtained in Kigali City. This includes a description of experimental designs and analytical methods. This study adapted the procedures described in Abdullahi *et al.* (2008); Hansen *et al.* (2004); (Raposo *et al.* (2011); Akunna *et al*. (2007); Zhang *et al.* (2007) and Gunaseelan (2004).

6.2.1 Feedstock selection

6.2.1.1 Typical household food waste

Since experiments were run in the University of Abertay Dundee laboratories, it was impractical to import food waste from Kigali. Shops that sell similar types of food as in Kigali were found in Dundee and it was then necessary to simulate food waste composition for Kigali. A total of four households living in Dundee, two from Rwanda and two from Kenya were invited to participate in the survey and volunteered to provide food waste samples. They were asked to consume the type of food they would normally eat in their respective countries for a period of one week and were provided with financial support to purchase the food since exotic goods are in general relatively more expensive in Dundee. The volunteers were asked to separate biodegradable from non-biodegradable waste. The source-separated food wastes were collected from these volunteers and taken to the Public Health Engineering laboratory of University of Abertay Dundee for the experiments. The feedstock was separated into components.

6.2.1.2 Industrial feedstock

Two types of feedstocks from industrial sources were selected to compare their digestion performance in comparison to food waste under similar environmental conditions. East African Highland cooking Banana (*Musa acuminata*) and Passion fruit (*Passiflora edulis*) were selected due to their national commercial importance, their availability for collection and their relative abundance in Kigali City. Banana is the leading staple food and cash crop for the production of industrial beverages whereby annual per capita consumption is estimated at 258 kg (Jagwe *et al*. 2011). Passion fruit is one of the most important commercialised fruit and processed to produce soft drinks (JE Austin Associates 2009). The bananas and passion fruits were obtained from grocery shops in Dundee, Scotland for the BMP tests.

6.2.2 Preparation of feedstock for BMP tests and source of inoculums

Separate samples of mixed food waste, banana and passion fruit waste peels were weighed before being oven-dried at 75^{o}C for 24 hours in order to determine the dry matter content. The dried samples were separately ground using a kitchen blender to reduce the particle size up to ≤ 1 mm. The ground samples were stored in labelled plastic containers, sealed and kept at room temperature until used.

An active mesophilic anaerobic digested sludge was collected from the Hatton municipal domestic waste water treatment plant (Hatton, Angus, UK) was used as the source of inoculum.

6.2.3 Experimental design: Batch reactor system

BMP tests were conducted using a 500 ml glass bottle equipped with rubber septum and a screw cap as shown in Figure 12. The bottles were prepared in triplicate and were used as batch reactors. Cultures were prepared with inoculum and substrate volume ratio of 4:1 respectively to make up 300 ml of liquid volume. The bottles were tightly closed with a rubber septum caps (Fisher, UK) before being placed in their respective incubators. Blank reactors and reactors containing waste samples were placed in the incubators set at 25^{o}C±1^{o}C and 37^{o}C±1^{o}C respectively. The reactors were incubated for 50 days during which the reactors were shaken on a daily basis to allow mixing of the substrate. Using a 100 µl sample lock syringe (Hamilton Sample Lock syringe, Model 1710SL, 26281 SIGMA-ALDRICH, UK), the gas was sampled from the headspace of the reactors through the rubber septum as illustrated in Figure 12. The pressure lock was closed before the syringe was redrawn from the reactor headspace. The pressure in the bottles was monitored by observing the shape of the rubber. Significant pressure built up was released by inserting a hospital syringe in the rubber septum and gas released by displacement of the syringe was added to cumulative biogas production.

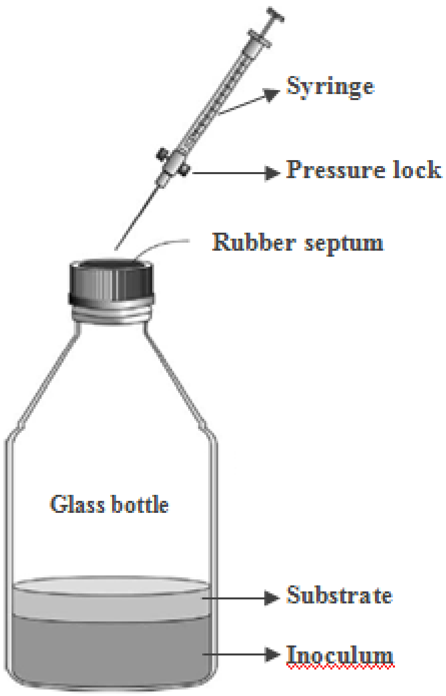

Figure 12 Illustration of reactor and biogas sampling with a sample lock syringe
Source: Adapted from Hansen *et al.* (2004)

6.2.4 Analytical methods

6.2.4.1 Measurement of methane gas

Methane gas yields were determined by Gas Chromatograph (HEWLETT PACKARD 5890 Series II Gas chromatograph) equipped with an AT-Alumina Stainless Steel Capillary column. Oven, injector and detector temperatures set at 50^{o}C, 120^{o}C, 150^{o}C respectively. Helium gas was used as the carrier gas at a flow rate of 7 ml/min with a final hold of 3 min. Standard of 10%, 30%, 50% and 100% of methane gas were used for calibration.

6.2.4.2 pH value

No pH correction was performed during the whole experiment. After the end of incubation period, the pH of all samples was measured using a *Sension* 3 laboratory pH meter (HACH, USA) to determine the levels of acids in the sample. The pH meter was calibrated with standard buffers of pH values of 4; 7 and 10 before measuring pH values of samples.

6.2.4.3 Ammonium nitrogen and C/N ratio

Waste samples were sent to Mylnefield Research Services of the James Hutton Institute in Dundee, Scotland for the measurements of total carbon and total nitrogen. After the 50-day incubation period, samples were measured for ammonium nitrogen ($NH4^{+}$-N) levels. Samples were prepared in triplicate. For this, a sample from each reactor was transferred in a labelled eppendolf tube and was centrifuged for 20 min at 5600 rpm (Centrifuge A14, JUAN SA). A sample of supernatant was transferred in a new labelled eppendolf tube. The concentration of NH_4^{+}-N was determined using the LCK 303 (HACH-Lange, USA) cuvette tests. A spectrophotometer (DR 5000, HACH Lange) was used to measure the concentration by reading the absorbance at 694 nm.

6.2.4.4 Volatile fatty acids and estimation of methane gas potential

The concentration of Volatile Fatty Acids (VFA) measured as acetic acid equivalent was measured in the liquid phase of cultures after the incubation period. Samples were centrifuged in eppendorf tubes at 6400 rpm for 6 min and the supernatant was analysed immediately. VFA were analysed by esterification of carboxylic acids present in the supernatant using the methods described in Montgomery *et al.* (1962). The concentration of acetic acid expressed as mg/l was then determined by spectrophotometry at a wavelength of 495 nm on a basis of three series of samples measured in triplicates. In order to estimate the methane production potential from the accumulated VFA of the sample, the concentration of acetic acid was converted to methane gas using the stoichiometric equation (2) shown below (Akunna *et al.* 2009):

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad (2)$$

1 mole (60g) 1 mole = 22.4 litres (at standard temperature and pressure)
1 mole =22.04 litres (at room temperature, 20^oC)

i.e. 1 g of acetic acid can produce up to 400 ml of methane gas at room temperature (20^{o}C) and pressure (1atm), N.

6.2.4.5 Total and Volatile solids

Total Solids (TS) and Volatile Solids (VS) were measured according to Standard Methods (APHA 1992). Samples were prepared in triplicate. TS of a representative liquid sample were measured gravimetically by oven-drying the sample to a constant weight for 24 hours at 104^{o}C. The volume of the analysed sample was measured and TS were calculated in g/l using the equation (3):

$$TS = [(A - B) * 1000] / V_{sample} \qquad (3)$$

Where A is the weight of the dry residue and dish (in grams), B the weight of the dish in grams and V_{sample} the volume of the sample in ml. The dry residue produced by TS analysis was ignited in a furnace at a temperature of 550^{o}C for 2.5 hours until a constant weight was obtained. The concentration of volatile solids was calculated using the equation (4):

$$VS = [(A - C) * 1000] / V_{sample} \qquad (4)$$

Where C is the weight of the ash residue and dish (in grams) after ignition. Volatile solids were also expressed as a percentage of TS. The VS of the samples were measured before and after the incubation period.

6.2.4.6 Determination of methane gas production

Based on the volume of the reactor headspace and the concentration of methane gas measured by the gas chromatograph, the volume of methane produced by the substrate was determined. The amount of gas sampled from the reactors was less than 0.8% of the headspace and considered insignificant to change the headspace pressure. The measurements including the methane releases were converted to standard temperature and pressure (STP: ^{o}C and 1 atmosphere) according to equation (5). The actual temperature (T_m) and atmospheric pressure (P_m) were recorded at the time of methane gas measurement (X_m). Cumulative methane gas production was then calculated as a function of time. The net cumulative methane volumes from the various waste samples were corrected by subtracting the mean cumulative methane volume of the blank samples. Methane yields were calculated by dividing the corrected methane volumes by the mass of VS (g) added to each reactor. The VS content in sample reactors after digestion was determined by subtraction of the VS content of blank reactors from the VS content of sample reactors.

$$X_{STP} = X_m * \left(T_{s\tan dard} * P_m\right) / \left(T_m * P_{s\tan dard}\right) \qquad (5)$$

Source: Hansen *et al*. (2004)

6.3 Economic assessment of AD operations

This study applied the economic evaluation techniques described by Rogers (2001) and Levy and Sarnat (1994). The methods for data collection were adapted from Harris *et al*. (2006). Relevant AD operations were first defined in terms of the type of technology, the sizing and the siting of the plant. Related capital expenditures, operation costs and benefits were determined with respect to Kigali local conditions. The major components of the economic model include community data and other waste sources; feedstock data and parameters; feedstock collection; methane production and energy value; plant sizing and financial model output.

6.3.1 Location and description of a suitable site for AD plant

Rapport *et al.* (2008) advised that a digester treating municipal solid waste should be co-located with a landfill, a composter or a MRF to reduce costs and simplify permitting regulations. A suitable site for the AD plant was therefore investigated taking into consideration these and other factors such as the distance from waste sources, sites accepting the waste and the AD products disposal outlets. It was thus necessary to access documentation on infrastructure planning for Kigali City. A report on Kigali City sub-areas planning informed that a waste treatment facility is planned at a site located in the outskirt of Kigali City, at approximately 30 km from the City centre (City of Kigali 2010). Figure 13a shows the location of the site as planned by the municipality. The surface area of the facility is 30 hectares with 9 hectares planned for a sanitary landfill and the remaining surface area for potential developments in waste treatment and recycling (City of Kigali 2010).

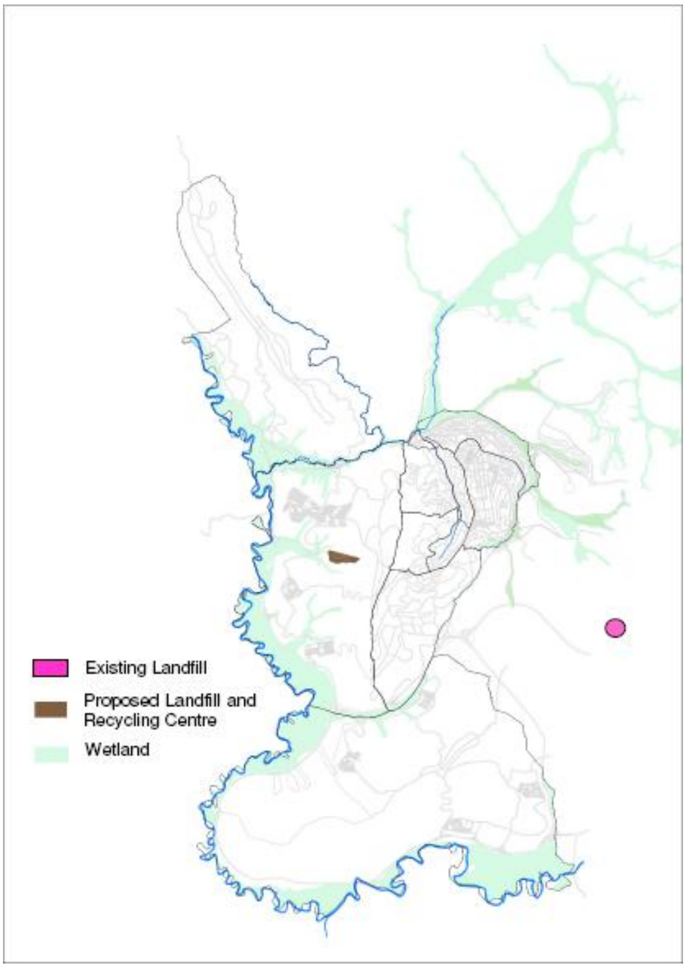

Figure 13a Location of the New Landfill and Recycling centre as planned by the municipality in Nyarugenge district
Source: City of Kigali (2010)

A subsequent field investigation was made with representatives of City of Kigali administration. As shown in Figure 13b, the site is easily accessible from a major road and is not adjacent to any urban development surrounded by forests which can be considered as disposal outlets for digestate (Figure 13c). The nearest grid connection through a medium voltage system (30 kV) is at 1 km from the site. A map representing the energy infrastructure such as electricity map is currently unavailable.

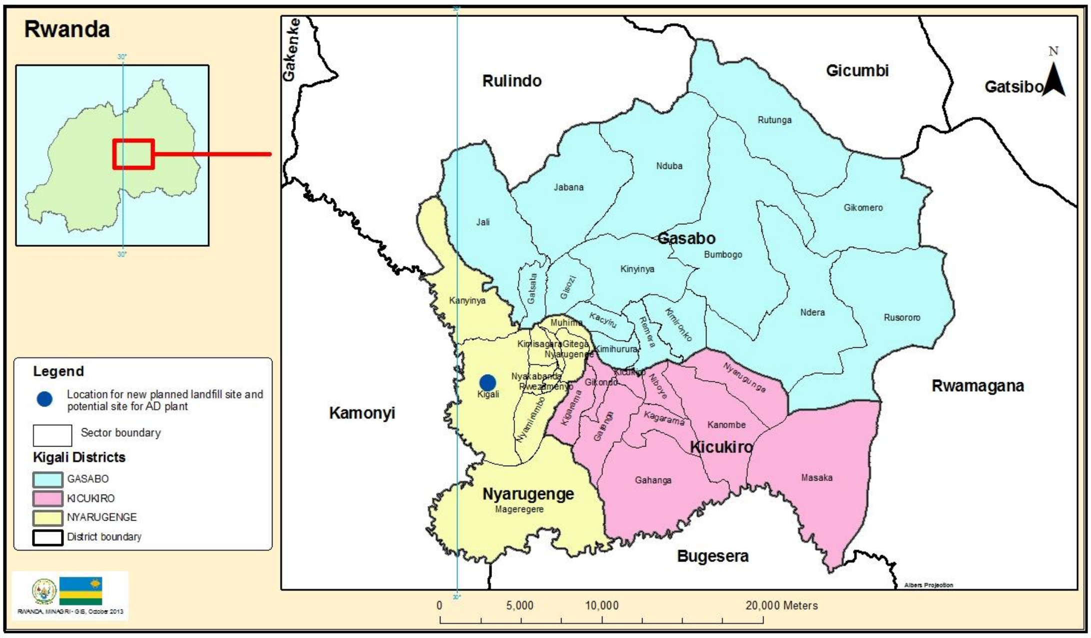

Figure 13b Location of the new landfill and recycling centre and potential site for AD plant in Kigali City
Source: Ministry of Agriculture-GIS (2013)

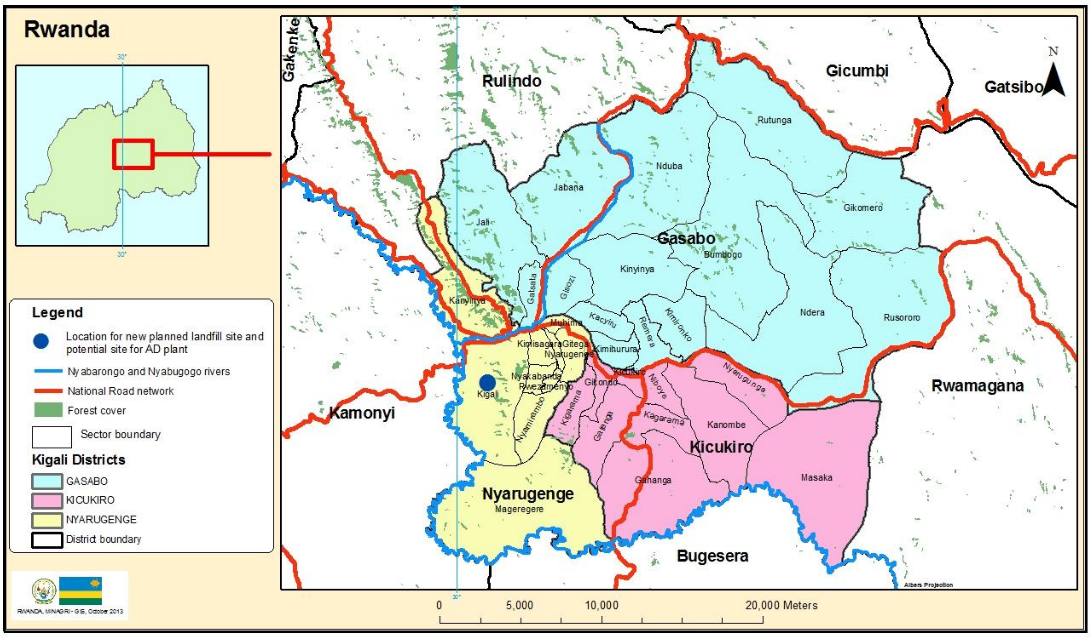

Figure 13c Potential site for AD plant and major road network and available local forest land for spreading of anaerobic digestate
Courtesy of Ministry of Agriculture-GIS (2013)

6.3.2 Collection and calculation of cost and income information of AD operations

Information on the cost and income of AD operations was obtained through interviews and literature review. Capital costs and technical operations costs and benefits were estimated based on the number of households likely to participate in AD operations, the food waste capture rate and the proposed location of the AD plant. The incentives likely to affect the costs and benefits were also identified. Both the costs and the benefits of AD operations are set out in US dollars and conversion from Rwandan currency to US dollars was calculated using the Xe currency converter (Xe 2013).

6.3.2.1 Interviews with private operators and relevant institutions

Interviews in Kigali City were conducted with waste service providers and institutions such as City of Kigali, Energy Water and Sanitation Authority (EWSA), Rwanda Utilities Regulatory Agency (RURA), Rwanda Environment Management Authority (REMA), International Fertiliser Development Centre (IFDC), Ministry of Agriculture (MINAGRI) and Rwanda Development Board (RDB) to obtain information on available incentives for energy project developers.

Interviews with four waste service providers in Kigali City provided cost information on awareness tools, waste collection labour, primary waste storage facilities, and transportation of waste from sources to the AD plant site. Average costs were calculated.

Due to little development in the AD technology for MSW in Kigali City, it was necessary to collect data in Scotland that was not available in Kigali. This data comprised of the equipment used in building an anaerobic digestion plant and related costs. The Lochhead AD development in Fife, Scotland was used as a model of large scale commercial AD plant due to lack of information in Kigali City on the operational planning of such development. Apart from labour costs, it is assumed that there is little difference in the costs of equipments since most of the materials will likely to be imported. A field visit of the Lochhead AD plant site and an interview were arranged with Fife Council, the official developer of the Lochhead AD plant.

a. Awareness tools

In this study, a leaflet was selected as an awareness tool designed to educate households on proper waste storage and waste separation at home and inform on waste processing activities being operated by the waste manager. The average cost of a leaflet per household was determined hence the total cost of leaflets was calculated.

b. Primary waste storage facilities

The cost of primary waste storage facilities was determined by calculating the cost of garbage bag per household per month. The costs were estimated for low, middle and high income households likely to participate in waste separation practice.

c. Waste collection labour

The cost of labour was calculated by determining the average wage per labourer per month, the number of labourers and number of households serviced. The cost of labour per household in a month can thus be calculated.

d. Waste transportation

The capacity of a truck in tonnes and the cost per tour were determined hence the cost per tonne and the total costs for transporting waste generated in a year.

e. Grid connection

The cost information for the national electricity grid connection was provided by the Energy and Water Sanitation Authority (EWSA) in Kigali. The cost of connection is dependent on the type of support poles and the distance between the plant and the point of grid connection.

f. Identification of AD plant cost elements

The cost of AD plant infrastructure was calculated based on the amount of food waste inflow that is collected annually and the potential methane gas production. Further enquiries with Lochhead AD plant developer provided information on operational planning of the AD plant and its capital costs (Personal communication, John White, 23 November 2012). Technical operations of the AD plant site were adapted for Kigali City.

g. Benefits

The benefits considered in this study are revenues from waste collection service and sales from the produced electricity. The total benefits for waste collection are calculated based on the waste charges per household and the household's socio-economic level. Electricity sales are dependent on the available FIT. Non-monetary benefits were qualitatively analysed based on current Kigali local conditions.

h. Incentives

The incentives identified and used in this study are tax exemptions applicable to all renewable energies, FIT and acquisition of government land free of charge to potential developers in renewable energy (RURA 2012). The available FITs were developed for hydropower projects and set according to plant capacity with $0.118/kWh and $0.123/kWh for plant capacities of 1 MW and 750 kW respectively. Tax exemptions include investment plant allowances of 50% of the invested amount in the first tax period of use of such asset which in this case removes corporation tax payment in the first year of operations. The income on waste collection is not taxable and seven percent is deducted in the tax period for projects employing >900 people.

6.3.2.2 Literature review

The lack of information from field investigations in Kigali City and in Scotland was circumvented by consulting the literature on AD developments of similar type and scale. The costs of some of AD plant infrastructure were calculated based on the information provided in German Solar Energy Society (DGS) and Ecofys (2005); Mata-Alvarez (2003) and Banks *et al*. (2011).

6.3.3 Financial modelling

Household food waste capture rate and the Feed-in Tariff (FIT) were identified as values susceptible to change. Feedstock quantity and FIT were therefore identified as variables for which a change would impact the economics outcome of the project. Scenarios of household food waste capture rates were designed based on the results from household surveys. Various scenarios of household food waste capture rates with variable FIT for the electricity output were therefore considered and the project's costs and revenues were calculated. An Excel spreadsheet was designed for the calculation and compilation of financial data (Appendix 7).

Sensitivity analysis in this study was used as a decision support technique to identify which alternative AD project scenarios are viable and likely to be chosen by a private operator. The Net Present value (NPV) was used as the indicator to determine whether the project is viable and profitable enough to be considered a worthwhile investment (Harris *et al*. 2006). Sensitivity of the NPV to possible changes in both household food waste capture rates and FIT was evaluated. According to the equation (6), the NPV is calculated by discounting the future net cash flow at a rate which reflects the value of alternative use of the funds summing them over the life of the project and deducting its initial capital investment (Levy and Sarnat 1994):

$$NPV = \sum_{t=1}^{n} S_t / (1+k)^t - I_o \quad (6)$$

Where:

S_t: the expected net cash flow at the end of year t

I_o: the initial investment outlay

k: the discount rate or the minimum annual rate of return on new investment

n : the project's duration in years

Sensitivity of the NPV to variable return rates was also determined. Only, the return rates for which NPV is positive were considered. A minimum acceptable rate of return relative to investments in renewable energy projects in Kigali was determined as 14% (Personal communication, Alex Mutware, 12 February 2013) and was used to assess economically desirable project scenarios (Rogers 2001).

Since, one cannot fully describe an investment project in terms of monetary costs and income (Levy and Sarnat 1994), an additional sensitivity test was conducted by analysing the impact of adverse changes in the major components of costs and income of the AD project. These are numerically large components or small essential components that are very important for the design of the project. In this regard, capital costs and operation costs for AD plant, waste collection costs and gross revenues from both waste services and electricity sales at the current FIT were considered as key variables for which NPV is sensitive. The sensitivity of NPV was therefore analysed for changes in the variables with an increase or a decrease by 15% using a return rate of 14%. The impact of change of one variable to the NPV thus the viability of project scenario was evaluated using the initial estimate of the values of each of other variables. It was assumed that the operation costs vary with changing values of waste capture rates while other variables remain unchanged. The comparison of the various scenarios of waste capture rates using the NPV determined which investment would be the most attractive to the AD project developer.

Risks to project's viability were also evaluated by identifying sources of adverse changes in key variables of the economic model thereby resulting into financial losses and estimating the likelihood of occurrence and impacts of those changes to project's viability. The likelihood of occurrence and impact were rated on a scale of 1-5 and expressed as follows:

1= Very low; 2= Low; 3= Medium; 4= High and 5= Very high

Risk was then calculated using Equation (7) below by multiplying scores of likelihood and impact.

$$R = L * I \qquad (7)$$

Source: Kotek and Tabas (2012)

Where *L* is the likelihood of occurrence of undesirable situation and *I*, the severity of impact of that situation to project's viability. The importance of risk was evaluated using the following scale:

1-3= Non significant; 3-7= Low significance and 8-25 = Significant

Practical financial mitigation strategies against these changes were investigated through a literature review on funding resources available regionally and internationally that could be beneficial and applicable to AD technology for MSWM in Kigali City.

CHAPTER 7

DETERMINATION OF WASTE CHARACTERISTICS IN KIGALI CITY

7.1 Introduction

Solid waste characterisation is one of the key elements in finding the most appropriate and viable strategies for managing waste (Al-Khatib *et al*. 2010). Information gained from waste characterisation can be used to determine the available waste market for treatment and to design policy instruments and practices for waste management. This includes the design of strategies for educating the public and raising their awareness with regard to the benefits of proper waste management practices. The design of strategies for an integrated waste management plan for AD will require waste specific data including waste composition, quantities and information on factors affecting waste generation. This chapter aimed to provide detailed analysis of municipal solid waste including factors affecting the quantity and quality of solid waste produced with a particular focus on easily biodegradable waste such as food waste.

7.2 Methodology

A household survey was carried out to collect quantitative and qualitative data on waste production in three districts of Kigali City, Nyarugenge, Gasabo and Kicukiro. Interviews with relevant stakeholders were also conducted to collate additional information on waste characteristics in Kigali City as described in Section 6.1.1 and 6.1.2.

7.3 Results and discussion

7.3.1 Urban household waste characteristics

Household waste is generally composed of leftover food and fruit, inedible parts of vegetables, and peels of fruits, potato and cooking bananas with large quantities of the latter and vegetable wastes. Other types of waste found were garden waste, dirt or ash, plastic and glass bottles, plastic packaging, aluminium cans, paper, cardboard and batteries.

Food waste (FW) formed the largest proportion of the total waste representing 74% by wet weight. These findings are consistent with Kigali landfill waste composition data which estimates Kigali production waste to be made up of 71% of biodegradable and 29% of non biodegradable waste (City of Kigali 2012a).

Table 6 shows the results for total household waste generation and the number of residents per household. The average household size was 5.4 with a total daily waste generation of 3.3 kg per household (3.3 kg/h/d) and 0.61 kg per person (0.61 kg/c/d) with 0.45 kg/c/d of FW and 0.16 kg/c/d of OW. The production rate obtained is similar to previous estimations based on 2005 landfill data, where per capita waste generation was estimated to be about 0.6 kg (City of Kigali 2007). Waste results from this study are also similar to comparable countries. A recent study reviewing waste generation in sub-Saharan African cities reported; 0.55 kg/c/d for Uganda (Okot-Okumu and Nyenje 2011); 0.55-0.58 kg/c/d for Abuja, Nigeria; 0.4 kg/c/d for Accra, Ghana and Dar Es Salaam, Tanzania and 0.45 kg/c/d for Freetown, Sierra Leone and with an overall average for African developing countries as 0.44 kg/c/d (Friedrich and Trois 2011).

Waste stream in Kigali consists of a high quantity of food waste, this trend being a general characteristic of developing countries (Troschinetz and Mihelcic

2009). A possible explanation of this may be the consumption habits, where households have the habit of cooking fresh meals for breakfast, lunch and dinner. The consumption of fresh unprocessed food in developing countries is more common than packed foods, with the latter being mostly imported and thus more expensive and generally associated with more opulent lifestyles. Using the population data presented in Table 4 (section 6.1.1) and household survey results in Table 6, overall, the quantity of household food waste generation in Kigali urban areas was estimated to be 269 tonnes per day.

Table 6 Household waste production in Kigali City

Description	Average household size	FW [a] (kg/h/d) ± SD	FW (kg/c/d) ± SD	OW [b] (kg/h/d) ± SD	OW (kg/c/d) ± SD	TW [c] (kg/h/d) ± SD	TW (kg/c/d) ± SD
Level I	5.9	1.6 ± 1.3	0.28 ± 0.2	0.6 ± 0.7	0.1 ± 0.5	2.2 ± 1.7	0.38 ± 0.2
Level II	5.3	2.3 ± 2.0	0.44 ± 0.3	0.3 ± 0.2	0.06 ± 0.04	2.6 ± 2.1	0.5 ± 0.3
Level III	5.2	3.4 ± 1.3	0.65 ± 0.3	1.7 ± 2.3	0.29 ± 0.1	5.1 ± 3.9	0.94 ± 0.3
Total population	5.4	2.4 ± 1.9	0.45 ± 0.3	0.9 ± 1.5	0.16 ± 0.3	3.3 ± 2.9	0.61 ± 0.5

[a]Food Waste; [b]Other Waste; [c]Total Waste

7.3.2 Effect of socio-economic level and household size on waste production

7.3.2.1 Food waste production

Table 6 shows that FW production in high income household (Level III) was significantly higher than that from other levels (p-value<0.001 for Level III compared to Level I, and p-value=0.023 for Level III compared to Level II), while Level I and Level II are not significantly different (p-value=0.175). Bandara *et al*., (2007) and Gomez *et al*. (2008) also observed higher production of organic waste in higher income households in sub-urban municipality areas in developing countries of Sri Lanka and in Chihuahua Mexico, respectively.

By combining the effect of socio-economic level and household size on FW production as shown in Figure 14, it was found that the rate of FW production increases significantly with household size in Level II and Level III (p-value=0.011 and p-value=0.003 respectively) while in Level I, household size has little effect on FW production (p-value=0.405). Using data shown in Table 4 (section 6.1.1) and Table 6, Figure 15 was produced and shows that household FW production from Level II households is higher than those obtained from Level I and Level III.

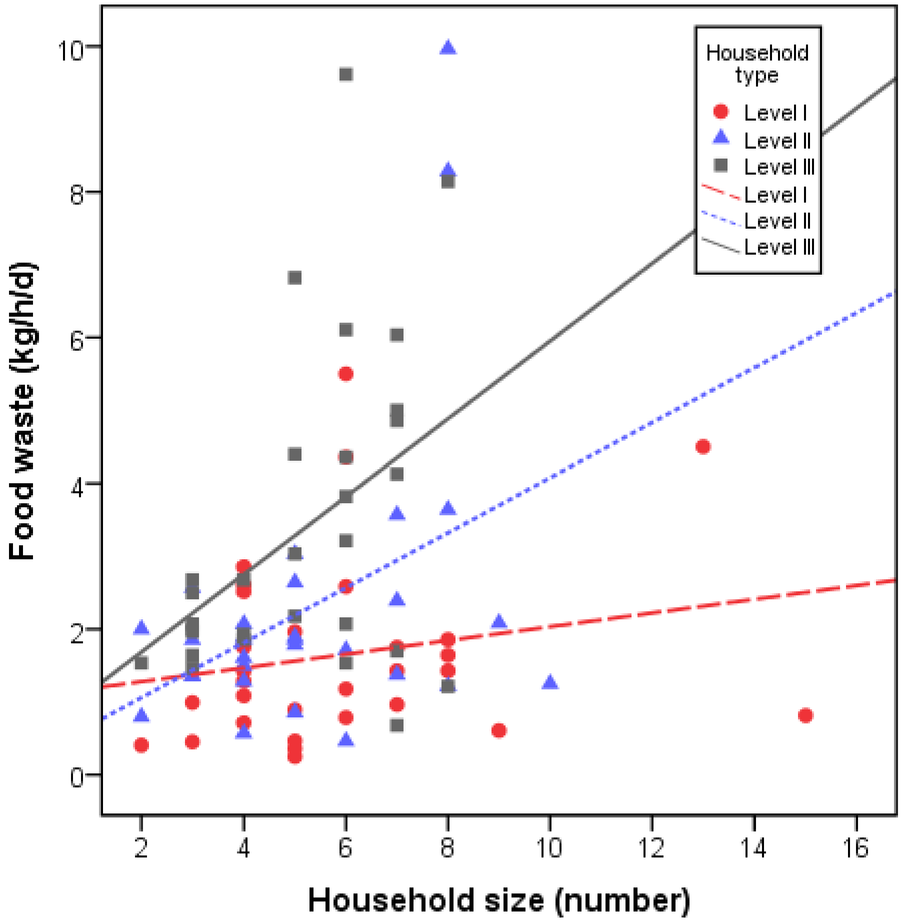

Figure 14 Relationship between food waste production and household size in the various socio-economic levels

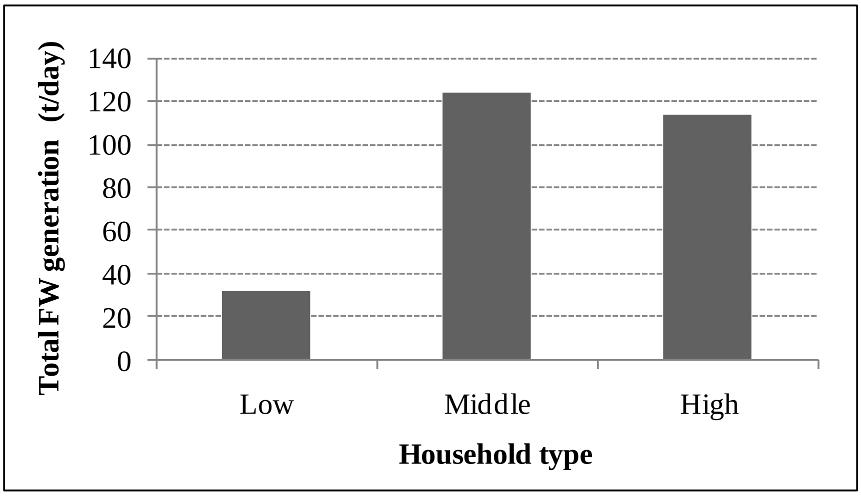

Figure 15 Household Food Waste (FW) production rate in the various socio-economic levels

7.3.2.2 Production of Other Waste (OW)

Table 6 shows that the production of OW is greater in high income household compared to other levels (p-value=0.003 for Level III compared to Level I, and p-value<0.001 for Level III compared to Level II). Results also revealed that the production of OW in Level I and Level II households are not significantly different (p-value=0.405). Additionally, as shown in Figure 16, household size has no effect on the production of OW (p-value=0.979) in various socio-economic levels. Using the data presented in Table 4 and Table 6, it was found that the production of OW in Level III is higher than those obtained from other levels as shown in Figure 17.

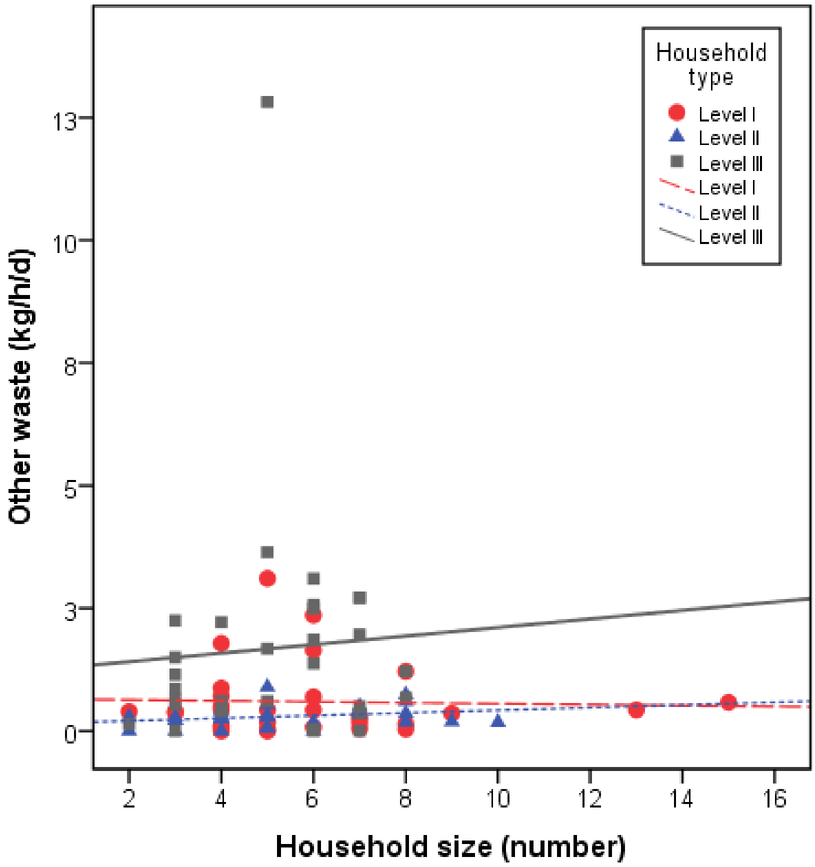

Figure 16 Relationship between the production of other type of waste and household size in various socio-economic levels

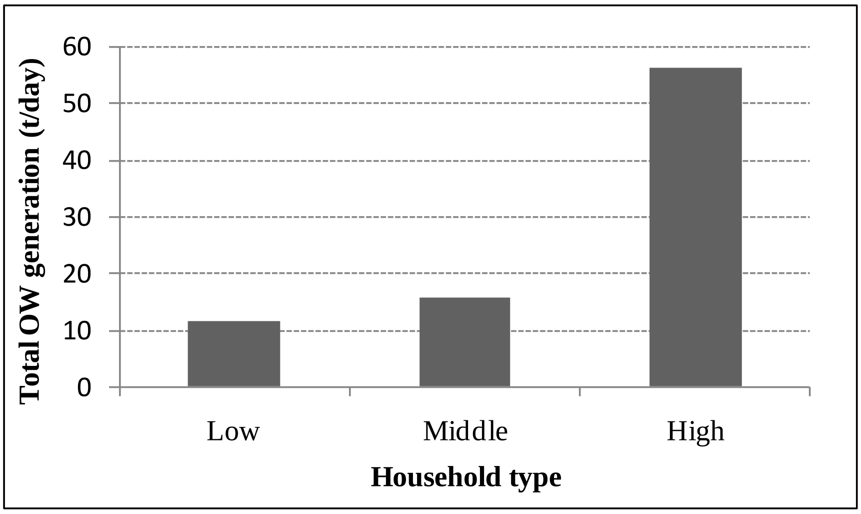

Figure 17 Household production rate of Other Waste (OW) in various socio-economic levels

7.3.3 Household waste generation rates in districts

Figure 18 shows that Nyarugenge district produces a higher quantity of household FW than other districts, followed very closely by Gasabo district and that the lowest quantity is found in Kicukiro district. Similar results were observed for OW. A statistical analysis of the results showed that the differences in waste production across the districts are not significant (p-value=0.504 for FW, and p-value=0.485 for OW respectively). Nyarugenge district is composed of more low and middle income households whilst Gasabo has more of high income households (As shown in Table 4, section 6.1.1) which suggests that the variation in socio-economic groups within districts is less likely to result in a significant variation in the total waste stream from one district to another.

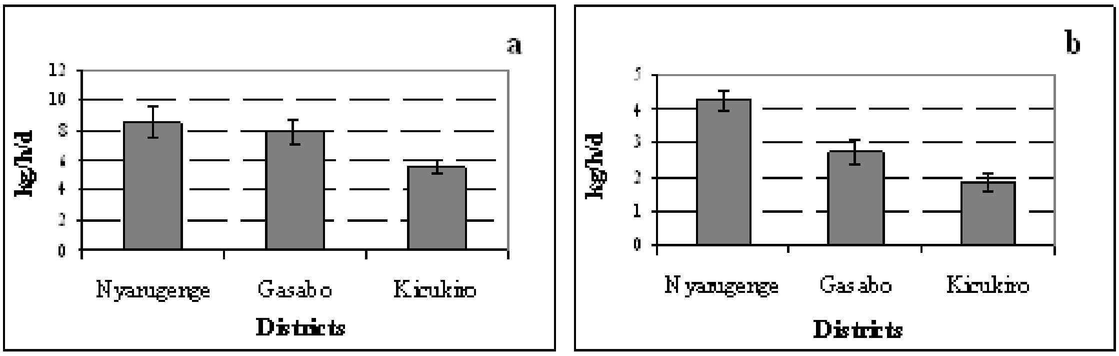

Figure 18 Daily mean food waste (FW) production (a) and other waste (OW) per household (b) in districts. The bars indicate mean values of 14 days waste generation ±SE, n=30

7.3.4 Potential food waste availability from other MSW sources

Information from interviews revealed potential waste sources for anaerobic digestion and feedstock availability. Major sources include commercial establishments such as hotels, restaurants, market places and food processing industries. The waste produced from public markets is currently landfilled whilst most commercial establishments deal with local farmers who use the food waste as animal feed. Educational institutions also produce high quantities of biodegradable waste; however, these establishments convert their own waste to compost or animal feed. A major hotel or a restaurant can produce about 1,000 and 500 kg/d of food wastes respectively. A major public market can easily produce 5,250 kg/d of vegetable and fruit wastes. In particular, a restaurant can produce an average of 178 kg/d of passion fruit peels as a by-product of juice processing. Other establishments include commercial and office buildings which can produce up to 45 kg/d and 21.6 kg/d of wastes respectively. These establishments are considered to provide separated waste fractions at the point of collection. Regarding industrial wastes, Kigali has 12 operational agro-based food processing industries. These include industries that process grain mill products, sugar cane, prepared animal feeds, fruit beverages, dairy products and cereal processing. However, field investigations provided insufficient information on the quantities produced from food processing industries. The available estimations were made by the City of Kigali (2012a) of a drink processing industry which could produce up to 27 tonnes /month of biodegradable waste.

Table 7 shows estimates of quantities of suitable waste from selected sources which can be available for an anaerobic digestion facility. With this type of feedstock, it is important to secure reliable supply of feedstock through legal contracts between anaerobic digestion plant developers and the establishments to prevent risks of waste diversion.

Table 7 Potential food waste availability from various sources

Source	Food waste (t/year)
Public Markets	11,340[a]
Hotels	1,080[b]
Restaurants	900[c]
Office buildings	23.3[d]
Supermarkets	129.6[e]
Drink Processing Industry	3,863
Total	17,336

[a]Waste generated from 6 major public markets
[b]Waste generated from 3 major hotels
[c]Waste generated from 5 major restaurants
[d]Waste generated from 3 major office buildings
[e]Waste generated from 8 major supermarkets

7.4 Conclusion

This chapter has provided adequate qualitative and quantitative information about waste production in Kigali City including factors affecting the quantity and quality of solid waste produced. The rate of waste production per capita per day of 0.61 kg for Kigali City found in this study was largely similar to other reported waste generation rates in other sub-Saharan African cities. Overall, the average household waste generation was found to be 3.3 kg per day. The average household waste has an average food waste of 74% and 26% of other types of waste. On average per day, a person produces 0.45 kg of food waste and 0.16 kg of other types of waste.

Waste production was characterised through the use of socio-economic factors in order to effectively quantify the availability of waste for Anaerobic Digestion. It was found that household daily waste production from high income area is greater than those from other lower socio-economic levels. Furthermore, no significant difference is found between middle and low income household. It was also found that food waste production increases with household size only in middle and high income households. The differences in household waste production between socio-economic levels imply that waste management strategies for the purpose of providing feedstock for an Anaerobic Digestion facility would be community-specific.

This chapter only shows waste quantities in Kigali City but does not inform on waste capture rates for Anaerobic Digestion. For this, information on alternative waste management routes is required and the assessment of waste collection systems in place. The next chapter will determine current competing waste management routes and the practicality of collecting source-separated food waste from households and other non-domestic sources.

CHAPTER 8

DETERMINATION OF STRATEGIES FOR COLLECTION OF GOOD QUALITY FOOD WASTE FOR AD IN KIGALI CITY

8.1 Introduction

In Kigali City, waste separation at source is still in the early stage of development and the waste is principally mixed at the point of collection (Mugabo and Uwamahoro 2011). In addition, there has been no substantial information on effective mechanisms for the recovery of organic waste. It has been shown that effective implementation of waste collection and separation at source is a primary step in lowering capital investment in the waste management industry (Uiterkamp *et al.* 2011).

This chapter identifies gaps and key factors affecting the collection of source-separated biodegradable waste for AD and investigates ways of enhancing its effectiveness for AD in Kigali City.

8.2 Methodology

Methods for collecting the required data were developed taking into account both the technical and human aspects of SWM such as the activities of waste service providers, household practices (e.g. waste separation and disposal) and public attitude and awareness towards waste management practices. Information on all these was collated through interviews with relevant authorities and a household questionnaire survey. Detailed description of the methods is found in sections 6.1.2. and 6.1.3.

8.3 Results and discussion

8.3.1 Socio-economic characteristics of respondents

The average household size in the questionnaire survey was 5.9. The majority of respondents were adult women which made up of about 69.4% of the total respondents. Regarding the level of literacy of the respondents, overall, 36.3%, 34.8% and 24.3% had higher education, secondary education and only primary education respectively. About 4.7% of respondents do not have formal education. The distribution across various socio-economic levels showed that 44.3%, 26.5% and 4.4% of respondents in Level I, II and III respectively had only primary school education and that up to 11.3%, 32.7% and 72.8% of respondents in Level I, II and III respectively had university degrees.

Regarding occupation, overall, 29% of respondents were casual workers or unemployed. Broken down by levels, 47.7%, 34.1%, 4.4% of respondents in Level I, II and III respectively were unemployed or casual workers. About 7% of respondents in Level I claimed to be in business whilst 15.5% and 34.2% were identified in Level II and III respectively. Generally, most respondents in Level III are highly educated and are involved in relatively lucrative economic activities.

8.3.2 Public awareness towards waste management

8.3.2.1 Concern over waste management problems

Survey respondents were asked to rate the level of importance of various challenges associated with the current SWM practices. As shown in Figure 19, it was found that "*high costs*" of SWM and "*lack of information on economic benefits of waste*" are not as important problems as "*poor waste collection*", "*lack of safe disposal facilities*" and "*ignorance of waste impact on the environment*" with latter considered as the most important problem. The respondents' opinion on SWM problems are informed by their experiences in their immediate environment. Moreover, as often observed in similar conducted types of surveys (Purcell and Magette 2010), respondents do not usually make association between various SWM aspects, in this instance, economic benefits of waste and safe waste disposal facilities. With regard to the high costs associated with SWM, respondents do not think cost is a serious problem probably because SWM is perceived as only waste collection and disposal which might be regarded as requiring minimum investment.

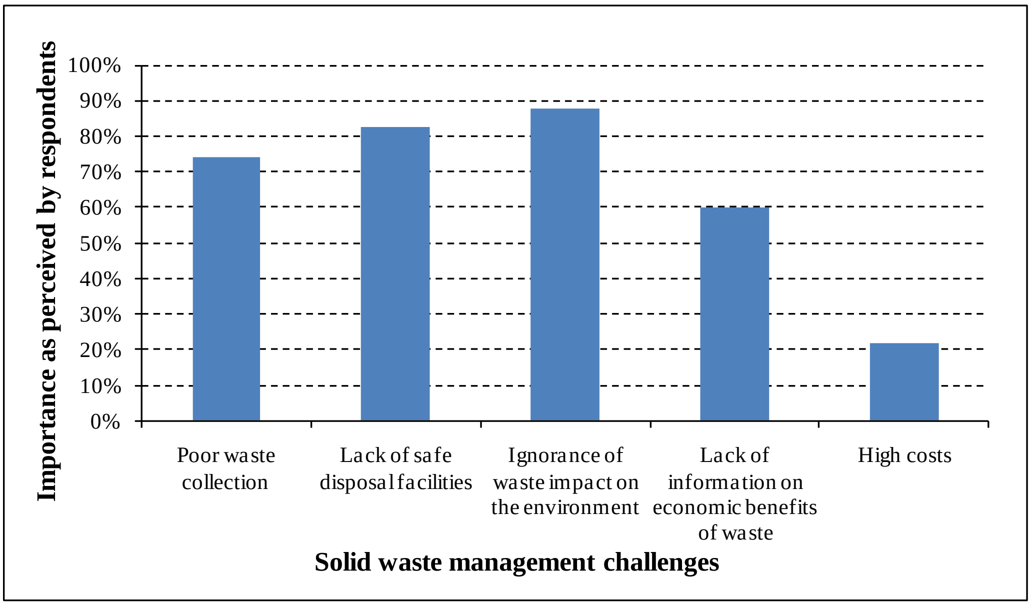

Figure 19 The level of importance of various challenges on current SWM practices as perceived by respondents

8.3.2.2 Rating of the importance of SWM options

Figure 20 shows how various SWM options are strongly perceived as a priority in the future of SWM programs. Overall, increasing waste recycling was viewed to be the most important option closely followed by anaerobic digestion. Although more than 80% strongly believe that recycling, anaerobic digestion and composting are preferred options in the future of SWM, a considerable number of respondents (78% and 58.9%) also believed that the use of landfill was important and that reducing its use should not be considered a priority. Incineration was regarded by respondents as a polluting option and as discussed by McDougal *et al*. (2001), any facility seen as such is likely to result into the rejection of the system. Respondents expressed their concerns on the fate of waste in the absence of landfills. The results indicate that respondents do not link landfill diversion with waste conversion technologies. While respondents may recognise the need for waste conversion technologies, the positive attitude towards the continued use of landfill describes a population locked into a system shaped by habits and historical institutional structures. Similar observation was made by Marshall and Farahbakhsh (2013) in their study on systems approaches to integrated solid waste management in developing countries. This perception around SWM can be a significant barrier to the implementation of waste separation initiatives.

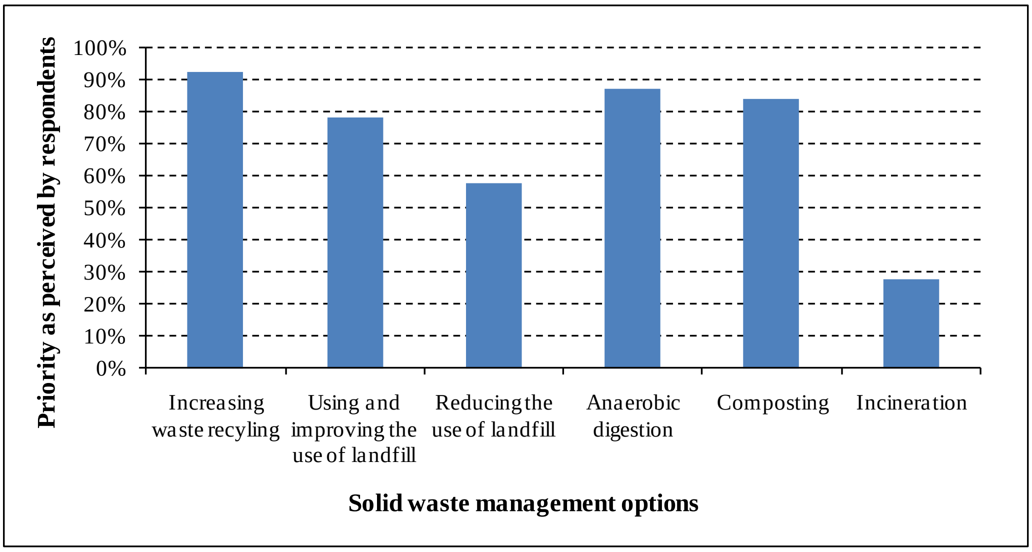

Figure 20 Priority of solid waste management options in the future of solid waste management as perceived by respondents

8.3.3 Socio-economic status and waste separation behaviour

Figure 21 presents various reasons that were cited by respondents for separating and not separating waste in households. The results also helped to determine various end routes of waste hence giving an insight into options for waste recovery for AD and the amount of waste likely to be collected. Respondents in group A do not separate waste indicating that they have nothing to gain from the practice. Respondents separated waste for various reasons such as protecting collectors against sharp objects (B); composting (D) and animal feeding (I); reuse (F) and removal of items such as scrap metals, cans and bottles for waste scavengers (H). Respondents also separated biodegradable from non biodegradable at the request of waste collectors (C). Segregation is done by 58.4% of households irrespective of waste recycling schemes. Respondents in group E and G do not separate waste due to lack of time and a belief that the responsibility of waste separation lies with the waste service provider respectively. This variability in responses indicates low public awareness regarding the purpose of waste separation and overall benefits of the practice. Overall respondents dedicated to source-separation of wastes counted for 15.2% of those surveyed. There was no statistical relationship between waste separation behaviour and socio-economic level as also observed by Troschinetz and Mihelcic (2009).

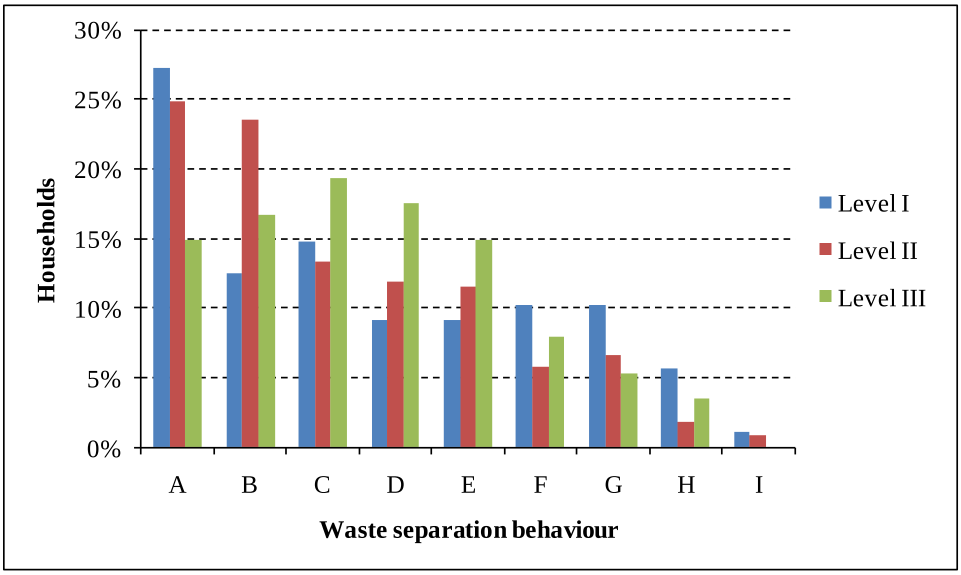

Figure 21 Waste separation behaviour in households according to socio-economic level. A: No segregation, all is waste and not profitable; B: Sort glass and metal debris to protect waste collectors; C: Sort biodegradable from non biodegradable waste at the request of waste operators; D: Sort waste for home composting; E: No segregation, the waste operators sort the waste; F: Sort waste for reuse; G: No segregation due to lack of time; H: Sort items for waste scavengers; I: Sort waste for animal feed

Considering the relatively high amount of biodegradable organic waste produced in households, the results on waste separation practice indicate that recovery and harnessing of this resource is still underdeveloped in Kigali City. Results also show that other waste management routes competing with AD for biodegradable waste include home composting and animal feed. Overall 12.9% of households compost their waste and 0.7% keeps the waste for animal feed. Therefore, approximately 86.4% of households can potentially provide biodegradable waste for AD. Based on the data shown in figure 10, the proportion of households that can potentially provide feedstock for AD has been estimated as 89.8%, 87.2% and 82.5% of the total population respectively from low, middle and high income residential areas. Using the data presented in Table 4; Table 6 and Figure 21, overall, the quantity of household food waste available that can be captured for AD has been estimated as 230 tonnes per day.

8.3.4 Socio-economic status and attitude towards waste management

8.3.4.1 Waste service and householder satisfaction

Overall 82.9% of households are serviced with a door to door waste collection and principally privatised with private waste operators. It was found that 51.7% of the participants considered the waste service as being moderately good. Chi-Square test of independence showed that satisfaction over waste services was significantly influenced by the socio-economic level of respondents (P=0.038). Overall, 47% of the households surveyed were not satisfied with the current service which they deemed as "poor", citing low frequency and absence of waste collection. This was mainly observed in middle and low income residential areas where poor access roads and low returns are likely to discourage service providers since their income is based on user fees. The situation is accentuated by the fact that many households fail to pay the monthly waste collection fee, causing waste collectors to cease their operations in the neighbourhood. The City of Kigali (2012) also reported poor waste services in Nyarugenge district which has a higher number of low income households as shown in Table 4. As a result many households in this area resort to dumping especially in water channels as shown in Figure 22. This situation poses a threat to public health and eventually undermines efforts to incorporate household SWM initiatives and recover waste from households. Similar situation has been observed in other sub-Saharan African countries such as Kenya (Henry *et al*. 2006) and Uganda (Okot-Ukumu and Nyenje 2011). Information from interviews with service providers also indicated that registration and licensing of waste management companies without proper financial and technical capacity and the failing of local authorities to enforce legal contracts were contributing factors to poor waste service delivery in some areas of Kigali City (Appendix 4).

Figure 22 Uncontrolled dumping in low income residential area (Level I) due to lack of waste collection service

8.3.4.2 Willingness to pay for improved services

Improved services imply regular schedules and better facilities for waste collection. Chi-Square test showed a significant relationship between Willingness to Pay (WTP) and socio-economic level ($P<0.001$). Figure 23 shows that WTP for improved services increases with socio-economic level. Similar results were also observed by Afroz *et al.* (2009), Chakrabarti *et al.* (2009) and Okot-Okumu and Nyenje (2011). The results imply that it would be difficult to implement and enforce successfully the payment system for waste collection in low income areas. Another level of accountability beside the payment system is therefore essential for improving waste collection in low income areas.

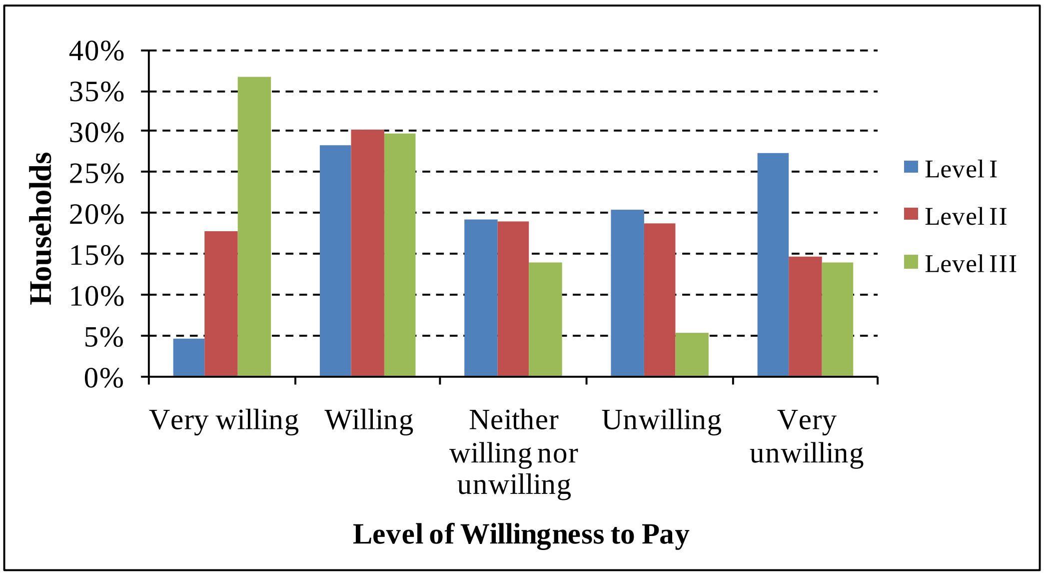

Figure 23 Level of willingness to pay for improved services in low (Level I), middle (Level II) and high income households (Level III)

8.3.4.3 Drivers for waste separation at source

Figure 24 shows the different types of motivation that would encourage respondents to separate waste in their households. It has been found that organised recycling programmes (D) and availability of free garbage bags (B) would be highly encouraging to respondents in Level III whilst most respondents in Level I and II needed more information on the benefits that can be gained from complying with good SWM practices (E). The results seem to suggest that households with lower income will likely to be more motivated to separate waste with the expectation of obtaining economic benefits from sustainable SWM practices whilst higher income households are more inclined to improving waste collections systems for health and environmental benefits. A chi-square test analysis also showed a significant association between household type and motivation to waste separation (p-value=0.001).

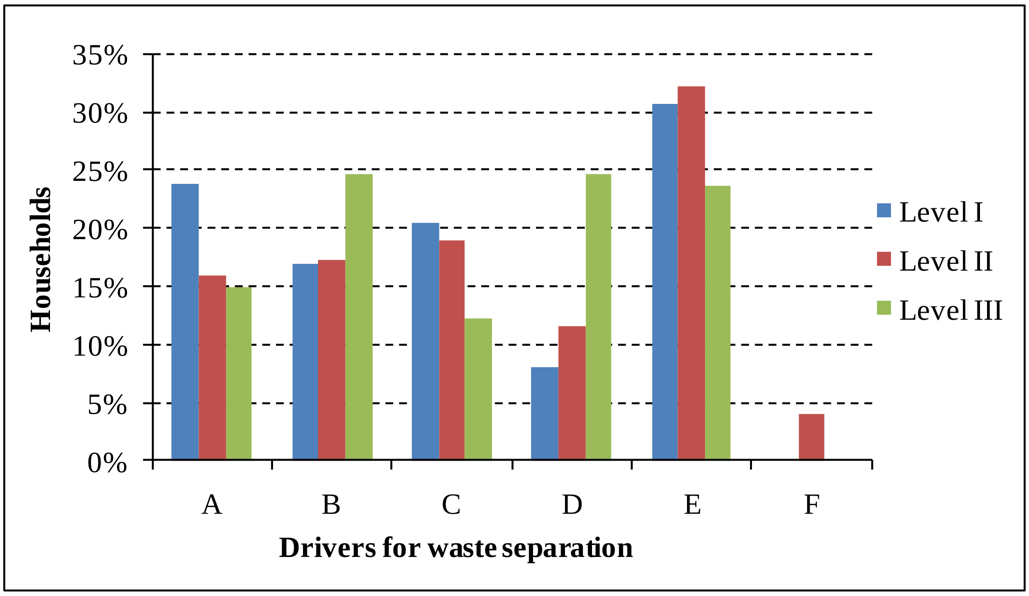

Figure 24 Drivers for waste separation in various socio-economic levels. A: Lower waste collection bills; B: Free garbage bags; C: Frequent schedule for waste collection; D: Organised recycling programmes; E: More information on the benefits of Solid Waste Management; F: None, no time to segregate

8.4.4. General discussion and recommendations

Information obtained from interviews indicated that with a combination of factors such as low waste service returns, lack of economic drivers and landfill being the cheapest route for waste disposal, less attention is given to improving waste management practices. Additionally, composting and production of RDF which are currently common in Kigali City and the rest of sub-Saharan African countries, have not been able to effectively encourage waste separation at source. Consequently, the economic gains and the demand for RDF and compost products are relatively low. These SWM options do not provide enough incentive for waste service providers to invest in technologies and improve on waste collection systems. Security in the demand for the output product such as electricity from methane gas can be an important factor for stimulating investment in AD. Provided that a financial system for AD development is available, the potential to collect food waste as a segregated fraction in Kigali City will require a strong partnership between local authorities, communities and AD developers. Results obtained from the household survey showed that there is a need to drive community participation in appropriate waste disposal practices and waste separation at source. Education and awareness programmes alone do not seem to be sufficient in securing suitable feedstock for AD unless appropriate incentives or remuneration mechanisms according to community specific needs are provided. It has been observed that incentives including rewards for sorted waste can encourage household waste separation (Shaw and Maynard 2008). In Kigali City, incentives would be appropriate especially in situations of deterring factors generally claimed by waste producers such as the level of effort involved, space availability and time constraints. The potential to collect suitable feedstock for AD as a segregated fraction from non-domestic sources such as commercial establishments and industries is high compared to households. Using the information obtained from this study, a potentially viable scenario for the collection of source-separated household waste in Kigali City is proposed:

a. AD project developer and communities

In this scenario, payment and incentive systems would be established. The scenario considers that both middle and high income areas would be subjected to a payment system. Households from low income areas would be exempted from waste collection fee and garbage bags free of charge for all socio-economic levels would be provided.

Revenues from commercial sources and from high income areas would be used to subsidise service in low income areas. Households in low income areas who have developed a habit of not paying the waste fees may not be significantly influenced with this type of incentive. In this case, additional incentives may be necessary to increase their interest and promote ownership of AD project. Incentives such as point-based food vouchers, also considered as a payment scheme, can be introduced for the poor urban communities. This would consist of a system of points for which a household receives upon waste correctly separated and brought to the waste collection point at a specified time. A certain amount of points collected by the household for a specific period of time will allow the householders to spend on food products in partnering stores. Similar compensation/payment system has already been applied in biodiversity conservation policies for communities' adjacent protected areas in Rwanda (Nielsen and Spenceley 2011) and could strategically be adapted in SWM programmes. However, financing of this type of compensation will require more than AD project financial gains to ensure its sustainability.

Educational and awareness leaflets for waste separation at source would be produced by the AD project developer and distributed to every household. The leaflets will provide clear information as to what should be put in the garbage bags and the ultimate purpose of waste separation practice for AD processes. An example of the leaflet is shown in Appendix 5. It is also necessary to give a promotional message that brings to the attention of households on the incentives available for them in return for good waste separation practice.

It is hoped that if the practice of waste separation at source is well established and effective, its potential can be enhanced by the influence of peer pressure among individuals or households in the community. Moreover, with the creation of employment that comes with AD project, the perception around waste separation would become significantly positive with time.

b. Role of local authorities

A partnership between AD project developer and local authorities needs to be established. The local authorities should endorse all AD operations at community level and facilitate communication between the communities and the AD developer. The local authorities should also monitor the implementation of waste separation at source and increase awareness about the benefits of waste separation and AD by targeting larger audience such as young people at local schools and in various community women associations [since it has been observed that housewives play a major role in the management of household waste in developing countries and are the most responsible of the cleanliness of their homes whereby disposal of waste is one of their daily responsibilities (El-Hoz 2010)]. With proper training, women associations might also conduct awareness programmes and could be rewarded in return. Regular consultative meetings between the communities, the AD project developer and local authorities should be established to ensure participation of all parties concerned hence allowing for collective actions in decision-making regarding systems operations and optimisation.

8.6 Conclusion

Household waste management practices were examined to identify the available options in the management of waste for Anaerobic Digestion purposes. Results showed that home composting and animal feed are currently alternative waste management routes for biodegradable waste. Taking into consideration the diversion of organic wastes to both outlets, the quantity of household food waste available for anaerobic digestion has been estimated to be about 230 tonnes per day. This chapter has also investigated the ability of household incentive-based systems to improve practices and enable investment in anaerobic digestion technology for economic, social, environmental and health benefits to the local community. The study also found that the socio-economic status of households significantly affect public attitude towards waste management practices, and the level of potential household participation in waste management at the community level. It was also found that willingness to pay for improved services increased with income level. The results showed that the expectation of economic gains would be efficient to drive poorer households to waste separation practice whilst expectation for improved waste collection systems would be appropriate to motivate wealthier households to waste separation at source. The results can inform the formulation of strategies for collecting source-separated waste based on the two identified indicators: willingness to pay and motivation to waste separation. Appropriate strategies for source waste separation need to be tailored to the specific needs of the given community or region. While offering incentives to all socio-economic levels is commendable, additional investment effort in the form of compensation schemes in poor income communities is required to sustainably secure collection of source-separated waste. Although the implementation of such incentives may be costly, the fact that they are beneficial to environmental protection and poverty alleviation efforts may attract funding from climate change mitigation policies or welfare policies.

Along with household incentives, public awareness programmes targeting anaerobic digestion should be educational and subject-specific with emphasis on broad understanding of sustainable Solid Waste Management technologies and individual and community responsibilities. Assuming the organic material for anaerobic digestion is correctly sorted and collected, the opportunities arising from its use for anaerobic digestion are expected to largely benefit the Kigali City’s various communities in particular and the government strategic policies on health and environment. The addition of feedstock from other non-domestic sources to household wastes could also increase the energy potential obtained from anaerobic digestion.

The next chapter will assess the potential energy production from available feedstock, the environmental requirements for biogas production and methods in the maximisation of energy value from the wastes.

CHAPTER 9

DETERMINATION OF METHANE PRODUCTION POTENTIAL OF SOURCE-SEPARATED FOOD WASTE FOR KIGALI CITY

9.1 Introduction

The conversion of organic fraction of municipal solid waste (OFMSW) to energy is now a major focus of interest for economic gains and environmental benefits and for a sustainable waste management perspective (Hierholtzer and Akunna 2012; Akunna *et al.* 2007). The measurement of the Biochemical Methane Potential (BMP) is an indicator of anaerobic biodegradability of the organic material. The performance of BMP assays depends on various factors that include waste characteristics and operational temperature. Important aspects of substrate characteristics include volatile solids concentration which provides an estimation of the organic content of the waste material. Other aspects include C/N ratio which is an important parameter in estimating possible ammonia inhibition and nitrogen deficiency for the microbial community that degrade the waste, and the substrate particle size which may affect the degradation rate of the waste (Abdullahi *et al.* 2008).

Temperature is by far the most influential environmental factor in AD processes where methanogens seem to strive at temperatures between 30-40^{o}C and 45-60^{o}C with optimum at around 37^{o}C and 55^{o}C (Raposo *et al.* 2012). Most AD studies have focused on these temperature ranges. Toxic elements such as heavy metals and plastics that can affect AD process and digestate quality are potentially low especially in source-separated waste (Browne and Murphy 2013; Zglobisz *et al*. 2010). It is in this regard that source-separation of food waste has been drawing significant interest for compliance with regulatory requirements of digestate disposal to agricultural land in various European countries (Browne and Murphy 2013; Banks *et al*. 2011).

Regarding operating conditions in sub-Saharan Africa, there is little information on the effect of local environmental factors such as temperature for operating an AD plant in these countries. Since Kigali City's temperature ranges from 15 to 29^{o}C throughout the year (City of Kigali 2008), this study will investigate the effect of Kigali ambient temperature of 25^{o}C on digestion performance of source-separated waste in comparison with an alternative 37^{o}C which will require the use of some of the methane produced to increase the temperature thereby reducing the net energy production. The performance on BMP potential will therefore determine full economic benefits for full-scale application in Kigali City that is discussed further in Chapter 10. BMP tests were carried therefore carried out to estimate methane potential of source-separated food waste available in Kigali City and determine the effects of operating an AD system at ambient temperature rather than at 37^{o}C.

9.2 Methodology

Section 6.2 provides a detailed description of methods used. The food samples collected from households in Dundee for BMP tests comprised of potato peelings (40.92%); mixed vegetables cuttings and peels (26.59%); meat remains (17.97%); fruits composed of avocado, mango and banana (7.26%); bread remains (2.98%); corn cob (2.84%) and tea leaves (1.41%). The components were found to be similar to the physical composition obtained from Kigali waste characterisation survey (Section 7.3.1). The performance of anaerobic digestion of waste samples was measured by investigating the effect of temperature on BMP and solid reduction.

9.3 Results and discussion

9.3.1 Substrate characteristics

Table 8 shows the characteristics of waste sample used in the study. The food waste contained 19% of TS and 90.12% of VS which are within the typical ranges for this type of waste (Browne and Murphy 2013). The C/N ratio of 14 is similar to literature values (Browne and Murphy 2013; Zhang *et al.* 2007; Mata-Alvarez, 2003). The C/N ratio of passion fruit waste is 26 and is within the typical range required by anaerobic bacteria (Mata-Alvarez 2003) whilst that of banana was 55 indicating that nitrogen addition will be required prior to digestion.

Table 8 Feedstock characteristics

Characteristic	Banana peels	Passion fruit peels	Mixed food waste
Total solids (%)	15.6	15	19
Volatile solids (%)	91.03	85.45	90.12
C/N	55	26	14

9.3.2 Solid reduction

Table 9 shows net VS reduction (net of blank results) results after 50 days of digestion. The values obtained for FW are comparable to 78% of VS destruction obtained by Wang *et al*. (2005) at 35^{o}C after 25 days of digestion. No comparison could be made for other types of feedstock used in this study for temperature conditions of 25^{o}C as little relevant information was available in the literature.

Table 9 Net volatile solid reduction in feedstock

	Net VS destruction (%)	
Waste sample	25^{o}C	37^{o}C
Banana peels	54	74
Passion fruit peels	47	57
Mixed food waste	85	89

9.3.3 Methane gas production

Figure 25 shows that after 50 days of digestion, cumulative methane gas yields from digested food waste at 37^{o}C were approximately twice than that achieved at 25^{o}C. As shown in the figure, methane production at 25^{o}C was relatively low and steady in the first five days and increased from the sixth day to reach its optimum at Day 23 of digestion and remained constant until the end of digestion period. Similarly, methane production at 37^{o}C increased steadily until day 23 and remained constant until the end of digestion period (50 days). Digestion of food waste at 37^{o}C gave a cumulative methane production of 398 ml g^{-1} VS_{added} and a specific methane gas yield of 448.2 ml/g $VS_{removed}$. Methane gas production at 25^{o}C was 207 ml/g VS_{added} and a specific methane yield of 243 ml/g $VS_{removed}$ was obtained. The results are consistent with other published results. Browne and Murphy (2013) showed methane yields of 396 ml/g VS_{added} for FW digested for 30 days at 37^{o}C whilst Heo *et al*. (2004) obtained 489 ml/VS_{added} after 40 days at 35^{o}C. For higher temperatures, Zhang *et al*. (2007) obtained 435 ml/gVS after 28 days of digestion at 50±2^{o}C. Currently, there seems to be insufficient information in the available literature on anaerobic digestion of food waste at 25^{o}C.

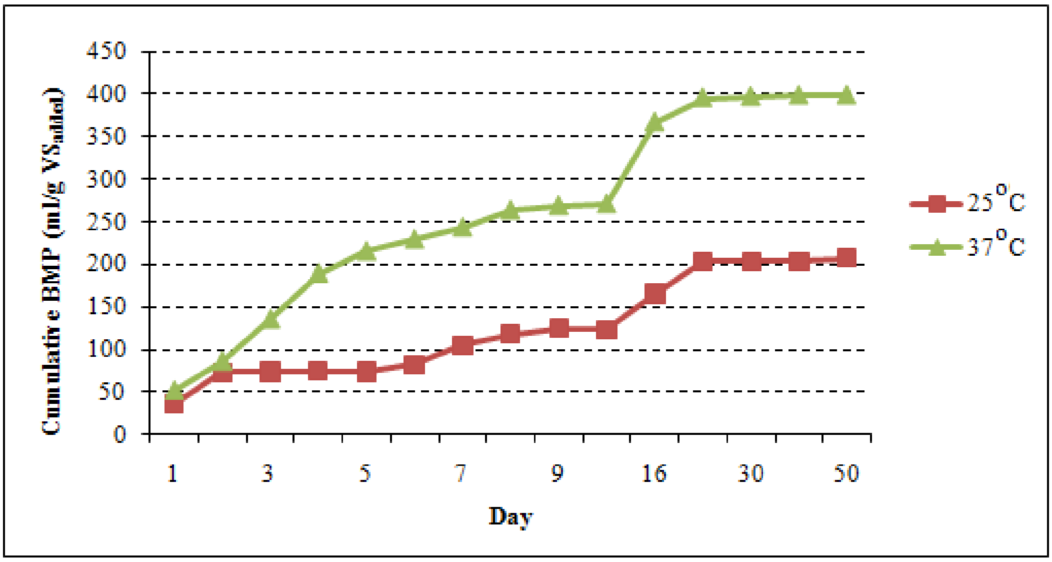

Figure 25 Cumulative methane gas production potential from digestion of mixed food waste at 25°C and 37°C

The digestion performance for banana peels is shown in Figure 26. Banana peels incubated at 25°C and 37°C gave cumulative methane yields of 83.71 ml/g VS_{added} and 325.71 ml/g VS_{added} respectively. Specific methane yields of 140.17 ml/g $VS_{removed}$ at 25°C and 398.74 ml/g $VS_{removed}$ at 37°C were obtained. The literature provides different values for banana waste peels digested at 37°C. Gunaseelan (2004) reported values ranging from 223 to 336 ml/g VS_{added} while Raposo *et al.* (2012) reported 374-409 ml/g VS_{added} of banana waste peels.

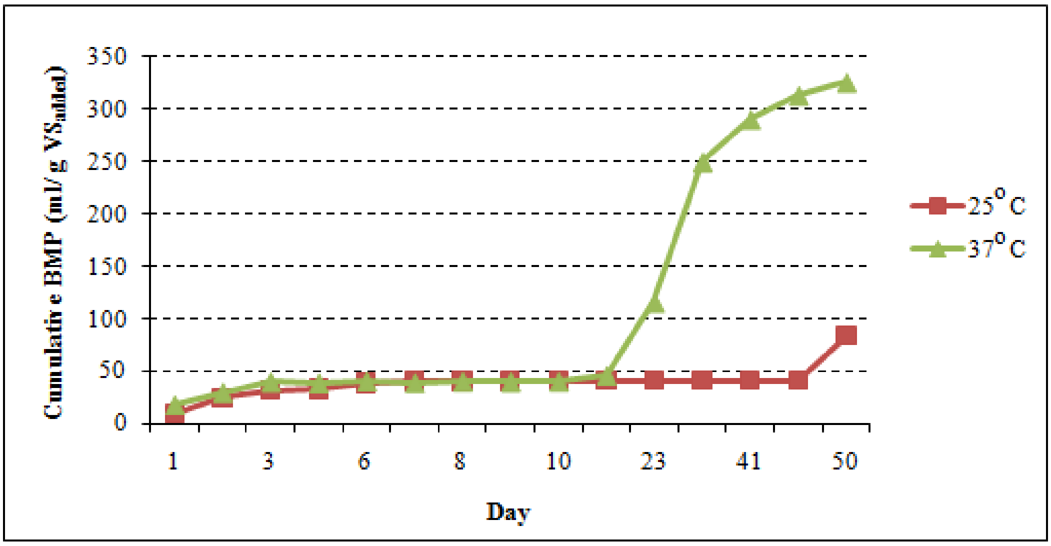

Figure 26 Cumulative methane gas production from banana waste peels at 25°C and 37°C during

Figure 27 shows results of anaerobic digestion of passion fruit waste. The digestion of passion fruit waste methane yields of 216.39 ml/g VS_{added} and 323.83 ml/g $VS_{removed}$ at 37°C. The digestion of passion fruit waste at 25°C failed due to inhibition by acids accumulation.

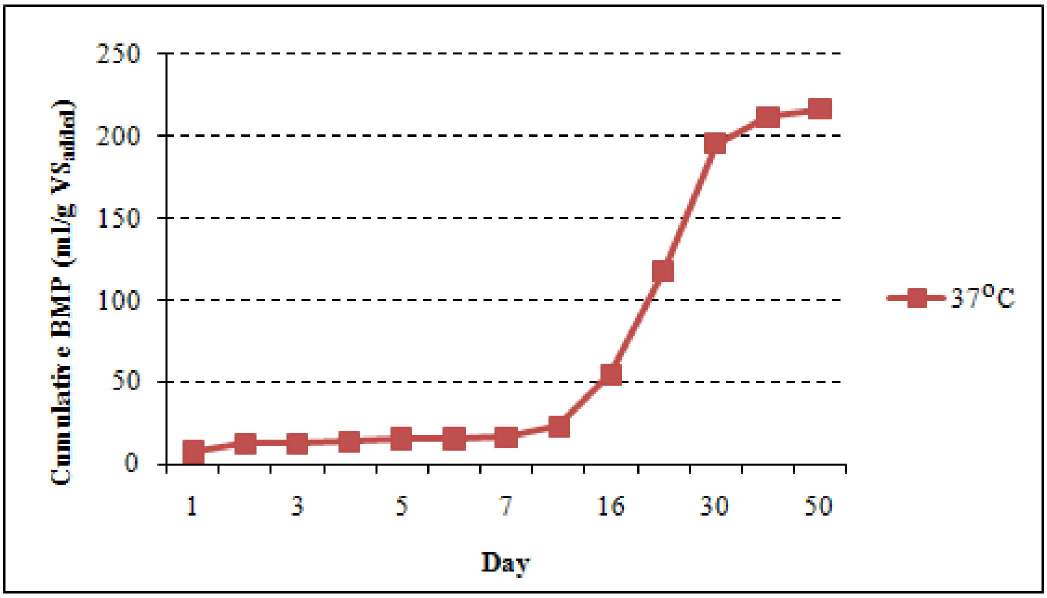

Figure 27 Cumulative methane gas potential of passion fruit waste at 37°C

For all types of feedstock used in the experiments, the optimum BMP was achieved on Day 23-30. It can therefore be assumed that 30 days would be an appropriate retention time in operating AD plant for the feedstocks used in the experiments.

9.3.4 Methane gas potential of volatile fatty acids accumulation after digestion

Table 10 shows VFA accumulation of various types of feedstocks at 25°C and 37°C at Day 50 of anaerobic digestion period and the corresponding methane gas potential (converted using equation 2, section 6.2.3.4). As shown in the table, VFA accumulation is higher at 25°C for all the wastes which suggests that the retention time for sufficient conversion of VFA to methane gas should be increased.

Table 10 VFA accumulation and methane production potential of food waste, banana waste and passion fruit waste after digestion period of 50 days

	VFA (mg/l)		BMP(ml/g VS)	
	25^{o}C	37^{o}C	25^{o}C	37^{o}C
Mixed Food waste	55	14	16	7
Banana waste	2798	91	153	11
Passion fruit waste	2789	190	146	13

9.3.5 Estimation of maximum methane gas production potential

The maximum methane gas production potential for each feedstock was estimated using the methane gas production during the incubation period and the potential methane gas production theoretically converted from VFA accumulated in the cultures after the incubation period. As shown in Table 10, the remaining VFA concentrations in food waste samples seemed to increase little amounts of methane gas at both 25^{o}C and 37^{o}C. Moreover, the maximum value of methane potential at 37^{o}C was found to be twice higher than at 25^{o}C which demonstrates that effective anaerobic digestion can be achieved with 37^{o}C with a retention time of 30 days.

As shown in Figure 28, VFA accumulation in banana and passion fruit wastes at 25^{o}C were found to increase the methane gas potential which suggest that the effect of the lower temperature is mainly on the conversion of the acid to methane retention time. Hence, the size of the digester for banana and passion fruit waste peels digested at 25^{o}C will need to be increased to ensure maximum production.

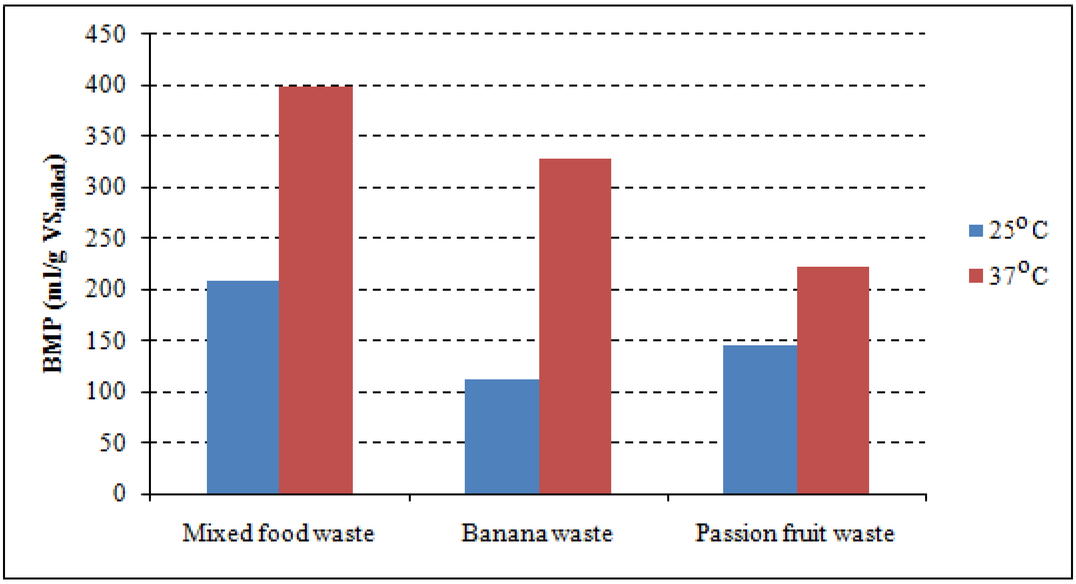

Figure 28 Maximum methane gas production potential of food waste, banana waste and passion fruit waste at 25°C and 37°C

9.4 Conclusion

The aim of this chapter was to evaluate the digestibility of the selected feedstocks. This study investigated the effect of temperature on anaerobic digestion process. Results show for all feedstocks that digestion at 37°C is approximately twice more effective than that of 25°C.

Anaerobic digestion of food waste samples achieved maximum methane yields of 209 ml/g VS_{added} and 399 ml/g VS_{added} respectively at 25°C and 37°C. The obtained C/N value of 14 was also an indication that digestion of food waste can be carried out without nutrient supplement. Anaerobic digestion of feedstock from industrial sources also showed similar pattern with higher methane yields at 37°C during digestion. Banana waste peels achieved maximum methane yields of 112 ml/g VS_{added} and 328 ml/g VS_{added} respectively at 25°C and 37°C. The methane yields of passion fruit at 37°C were found to be 221 ml/g VS_{added}. Methane gas production at 25°C was inhibited by acids accumulation; however, its maximum potential was estimated at about 146 ml/g VS_{added}. Optimum BMP for all types of waste were obtained on Day

23-30. These results show that acid accumulation is the main consequence of lower temperature digestion. This can only be reduced by high temperature digestion (at 37^{o}C) or longer digestion time at 25^{o}C which will require the increase of digester capacity thus increasing land requirements. Industrial sources can also offer healthy supply of feedstock such as banana and passion fruit wastes which can significantly enhance anaerobic digestion potential of feedstock from domestic and commercial sources.

CHAPTER 10

ECONOMIC FRAMEWORK FOR SUSTAINABLE APPLICATION OF AD TECHNOLOGY FOR KIGALI CITY

10.1 Introduction

The economic sustainability of AD technology lies in its capacity to function efficiently over a long period of time by delivering both attractive returns on investment over a specified period of time. The main purpose of AD technology is energy recovery for its wider economic benefits (DEFRA 2011). However, high capital costs and lack of understanding of the market have been the main constraints for AD development globally.

Energy, being one of Rwanda's priority investment sectors (Safari 2010), would be the key driver in investing in AD technology. The Rwandan government has been initiating measures and policies for the growth of low carbon development with significant progress in the electricity sector with a target of using 90% of electricity from renewable sources (RDB 2012). The establishment of Feed-in Tariff (FIT) policy is one of the tools for encouraging renewable energy investment with hydropower source as the precursor of the policy. This means that the development of other renewable energy sources could lag behind due to difficulties in adapting the regulatory framework that was principally designed for hydroelectricity injection. Furthermore, it has been pointed out (IFDC 2007; Kelly *et al*. 2001) that the lack of financial resources and mechanisms for developing organic fertiliser use in Rwanda reduces the scale and the extent of activities of producers and distributors hence resulting in less availability and less demand of the product. The lack of marketing system for organic fertiliser and the consequent challenge of assessing the current demand would make it therefore difficult to evaluate the financial business of digestate. The options for digestate management have to be assessed in terms of the market value of digestate and the pre-treatment and handling costs such as dry matter separation, storage, transportation and the available land for disposal.

The decision to invest in AD technology for MSW requires information that include feedstock availability, the type of technology, the siting of the plant, sources of income and the market size, financial incentives or possible subsidy schemes, the regulatory requirements and the cost and revenue information (DGS and Ecofys 2005). It is practically difficult to get the ideal input data for the decision model therefore, the use of sensitivity tests in economic appraisal of projects is essential in exposing the risks resulting from changes to final result and identifying where the focus should be for a potential developer (Rogers 2001; The Andersons Centre 2010).

In chapter 7, a waste characterisation survey was carried out in order to obtain household waste production rates in Kigali City. Other potential waste sources for AD were also identified and include commercial establishments, office buildings and industries. In chapter 8, a public perception and awareness questionnaire survey was also carried out to evaluate the practicality of waste separation at source. In chapter 9, anaerobic digestion tests were used to determine methane gas potential from source-separated food waste and other types of organic feedstock that are amenable to AD in Kigali. Chapter 9 also identifies the economic implications of operating AD systems at 37^{o}C and 25^{o}C. This chapter aims to assess the technical requirements and economic viability of AD technology application for electricity generation and digestate utilisation in Kigali City. This chapter provides an insight into the technical aspects of operating an AD plant for Kigali City with a system operating at an optimum mesophilic operational temperature of 37^{o}C and the economic viability without additional external revenue streams. The available feedstock for AD is reviewed and the costs and benefits of AD operations are discussed.

10.2 Methodology

Information obtained from the public perception and awareness questionnaire survey and the waste characterisation survey was used to quantify the maximum available waste material for AD. The amount of biodegradable waste in the household waste stream and the alternative management routes which are likely to compete with AD were taken into considerations in the estimation of the total amount of available household biodegradable waste. Since the collection of source separated waste depends on voluntary public participation to waste separation practice, Willingness to Pay (WTP) for improved services is considered a key parameter in estimating the realistic amount of waste material that is likely to be collected for AD. This assumption is based on the belief that WTP indicates general waste awareness and concern of environmental problems, both which are drivers to effective participation in waste management activities. The proportion of households that are “very willing” and “willing” to pay for improved services (Figure 23) was considered as the maximum household participation rate for waste separation at source. The ideal maximum waste capture rate was then estimated using household food waste data from each socio-economic level. Various waste capture rates were estimated and represent project scenarios (Appendix 6). For each project scenario, the following parameters were estimated:

- Methane production rate and energy value
- Capital costs and operation costs
- Revenues from both electricity sales and waste collection

The scenario of using the digestate as soil conditioner for locally available forest land without commercialisation was also studied.

The NPV was calculated at a Rate of Return (ROR) of 14% under the available FIT of $0.118/kWh. The analysis considers 20 years as an expected lifetime of the plant. The methods used for collecting the cost and income information used in the economic model are described in detail in section 6.3 and calculation of the required data including dimension and costs of AD plant facilities is presented in Appendix 7.

As described in section 6.3, sensitivity of project's viability (based on the NPV) to changes in feedstock quantity, FIT and ROR was analysed. The NPV was calculated net of tax. The viability of projects scenarios were assessed over a range of ROR. Further sensitivity tests of NPV to an error of 15% of major costs and gross revenue components were examined to assess any incurred risks. The impact of change of one variable to the NPV was thus evaluated whilst other variables were kept constant under a minimum acceptable rate of return of 14% and the available FIT.

10.3 Results and discussion

10.3.1 Determination of household food waste available for AD

As discussed in section 8.3.2, the amount of food waste available in the waste stream can be recovered from 89.8%, 87.2 %, and 82.5 % of households respectively in low, middle and high income residential area. Within socio-economic levels, in total, the percentages of households that are "very willing" and "willing" to pay for improved services are 33%, 48% and 66% respectively for low, middle and high income households (Figure 23). These percentages were assumed to represent the actual maximum household participation rate for waste separation at source. Using the population data presented in Table 4 and the waste data in Table 6, the maximum source separated food waste for AD is estimated and presented in Table 11.

Table 11 Estimation of food waste available in the household waste stream and the maximum waste capture rate

	Low income area	Middle income area	High income area	Total
[a]Total number of households	19,754	53,770	33,407	106,931
[b]Number of households with food waste collection	89.8%	87.2%	82.5%	
	17,739	46,887	27,561	92,187
[c]Food waste/hh (kg)	1.6	2.3	3.4	
Total food waste available (kg/d)	28,382	107,840	93,707	229,930
[d]Number of households correctly sorting	33%	48%	66%	
	6,519	25,810	22,049	54377
Total separated food waste (kg/d)	10,430	59,362	74,965	144,758
[e]Overall % of sorted food waste				63

[a]Population data derived from Table 4
[b]Availability of food waste in the household waste stream, data derived from Figure 16
[c]Waste data derived from Table 6
[d]The proportion of households that are willing to pay for improved services, data derived from Figure 18
[e] Estimated maximum waste capture rate

10.3.2 Scenario building of food waste capture rate and availability of food waste

As discussed in section 8.3.4.a., the recovery of waste from low income areas is expected to be higher once the incentive system is operational. Results on willingness to pay and motivation to waste separation at source also suggest greater participation rates in high income areas. However, within the middle income area which features a mixed income, households with a low income may not accept to separate waste and pay for waste services. A similar observation was made by Tukahirwa *et al*. (2013) and Afroz et *al*. (2009). Consequently, the proportion of households participating in waste separation might be reduced compared to other socio-economic levels. Possible scenarios of waste capture rates are therefore created to take into considerations these behavioural changes. Having obtained the maximum capture rate of 63% of available

230 tonnes household food waste, various capture rates based on decreasing amount of source-separated food waste collected from each socio-economic level were calculated with higher decrease from middle income area. The calculated percentages represent project scenarios and were determined as 10%; 20%, 25%, 35%, 45%, 55% with the maximum capture rate as 63%.

Each project scenario has an additional feedstock collected from commercial establishments, industries and office buildings as presented in Table 12. The selected sources could amount to 47 tonnes per day. Table 12 summarises the waste data including the availability of volatile solids (VS) content of the waste (see section 9.3.1).

Table 12 Sources and feedstock availability for the AD plant according to projects scenarios

Constant values							
Dry matter content	19%						
VS content	90.12%						
Household waste capture rate /Project scenario	10%	20%	25%	35%	45%	55%	63%
SS-OFMSW[a] (t/y)	8,760	16,973	21,170	29,200	37,960	45,990	52,836
SC-OFMSW[b] (t/y)	17,336	17,336	17,336	17,336	17,336	17,336	17,336
Total quantity of waste by wet weight (t/y)	26,096	34,309	38,506	46,536	55,296	63,326	70,172
Total volatile solids content (t/y)	4,468	5,875	6,593	7,968	9,468	10,843	12,015

[a]Source-separated food waste collected from domestic sources
[b]Separated food waste collected from non domestic sources

10.3.3 Technical design of AD operations

In order to secure reliable feedstock, optimise services and ensure control of additional costs or savings, the AD project developer would also be in charge of waste collection service in addition to the operation of the AD plant and management of the digestate. Assuming the AD plant will be operated at 37^{o}C, Figure 29 illustrates the AD project layout developed in this study. This scenario is based on findings obtained from this study, site visits of AD facilities and interviews with plant managers in the

UK and the literature on AD operations of similar type and scale. The AD plant site comprises of a reception hall for the incoming waste equipped with mechanical pre-treatment facilities; fourteen concrete parallel digestion tunnels operating in batch system at 37^{o}C for a retention time of 30 days, a silo for biogas storage; four pasteurisation tunnels for digestate treatment at 70^{o}C for one hour for effective pathogen removal; two post-digestion halls with the capacity of storing the digestate for two months before spreading on forest land; cleansing of biogas and safety equipment and a Combined Heat and Power (CHP) unit with energy efficiency of 57% and 33% respectively for heat and electricity. In the beginning, heating of digesters is provided by external energy sources until the plant has generated sufficient biogas to produce the required heating. After digestion, the digestate is removed from the reactor where 10% is re-circulated and mixed with new fresh incoming feedstock.

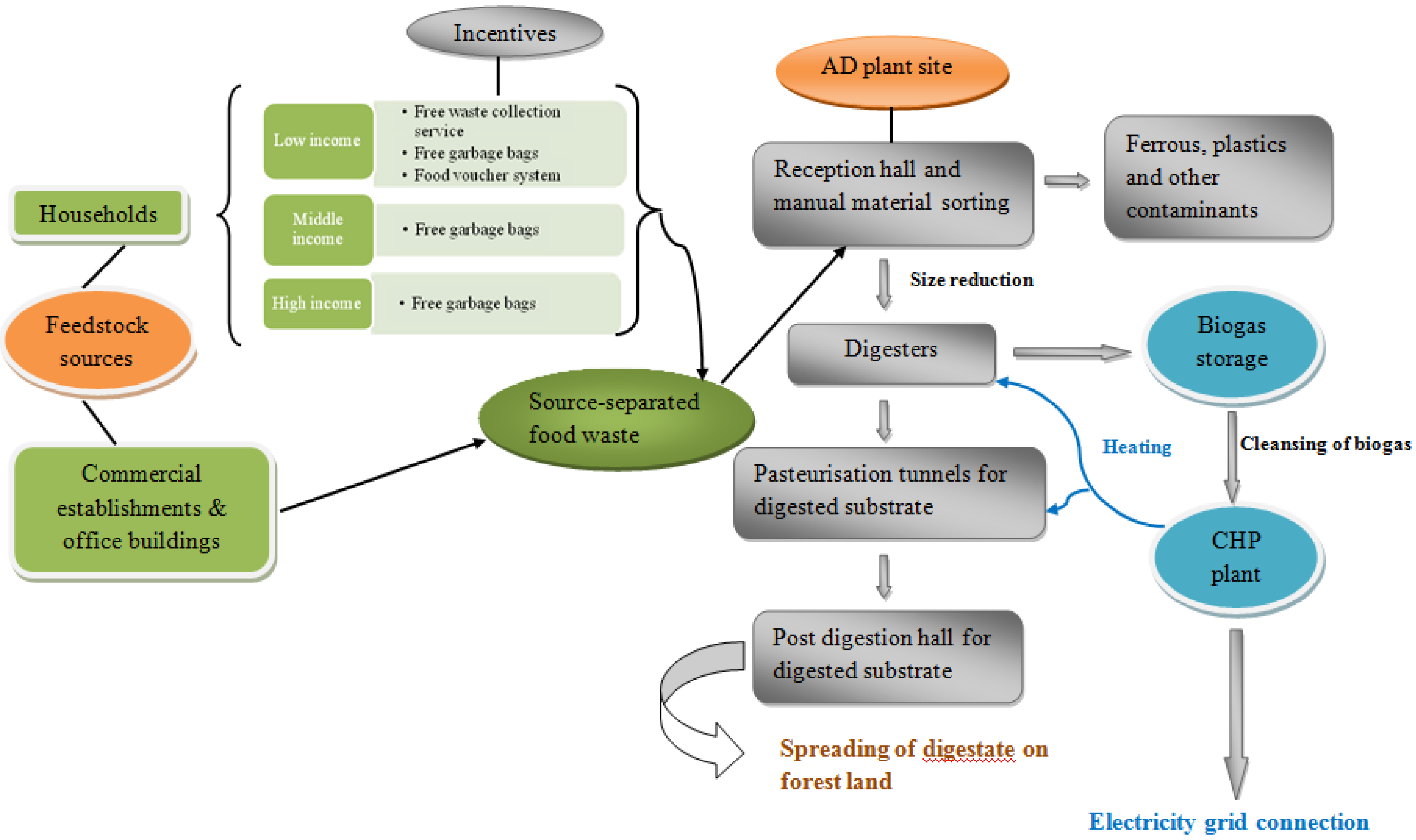

Figure 29 Technical layout of AD operations

10.3.4 Economic evaluation of AD operations for various scenarios

10.3.4.1 Energy generation, capital expenditure and operating costs

In Chapter 9, gross methane potential from food waste digested at 37^{o}C was found to be 398 m^3 per tonne of volatile solids. Gross methane production potential was therefore calculated as 68 m^3/tonne of collected food waste and the net methane gas output as 61 m^3/tonne (Appendix 7). The net electricity for export to grid was calculated as 182 kWh/tonne of collected food waste. It was found that the cost of installing an AD plant is $4,605,135 (Appendix 7). Mbuligwe and Kassenga (2004) estimated $3.991 million for a similar project of 15,600 tonnes of annual capacity in Dar es Salaam, Tanzania.

Overall, the cost of feedstock collection represents the major expenditure for the AD project annual costs (Appendix 7). Figure 30 shows the cost of producing electricity for various project scenarios which represent the sum of discounted operation costs (at a discount rate of 14%) per 1 kWh of electricity produced over 20 years plant lifetime. As shown in Figure 30, production costs increase with an increase in feedstock supply although the difference is not large. It was found that a project with a capacity of 38,506 tonnes per year (tpa) would cost $2.46/kWh. A similar project in the UK of approximately 38,000 tpa with a discount rate of 10.7% over 25 years of lifetime would cost approximately $0.93/kWh (Zglobisz *et al*. 2010). Using the same model, an AD project of 38,506 tpa in Kigali (25% of household waste capture rate) could cost $3.2/kWh (Appendix 8). There is insufficient data in the available literature on detailed cost information of AD projects in sub-Saharan Africa.

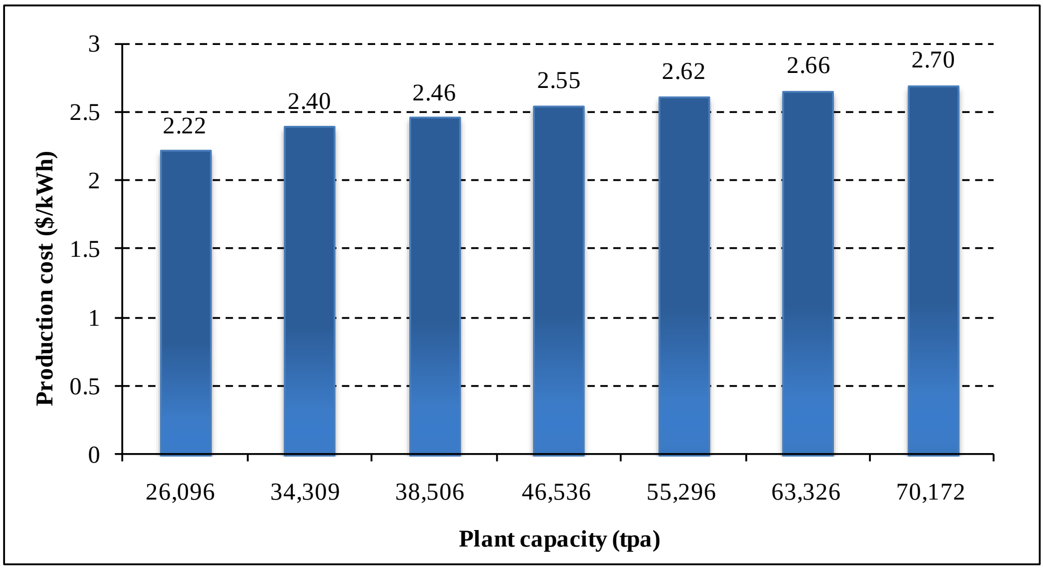

Figure 30 Cost per unit of electricity output for various projects scenarios as reflected by annual waste tonnage throughput

10.3.4.2 Sensitivity analyses for AD projects scenarios

A. Revenues from AD operations and non-monetary derived benefits

Figure 31 shows that an AD project with less than 35% of household waste capture rate was not viable under any of the FIT scenarios. A project with 25% of waste capture rate could yield a positive return if the current FIT is increased by 30%.

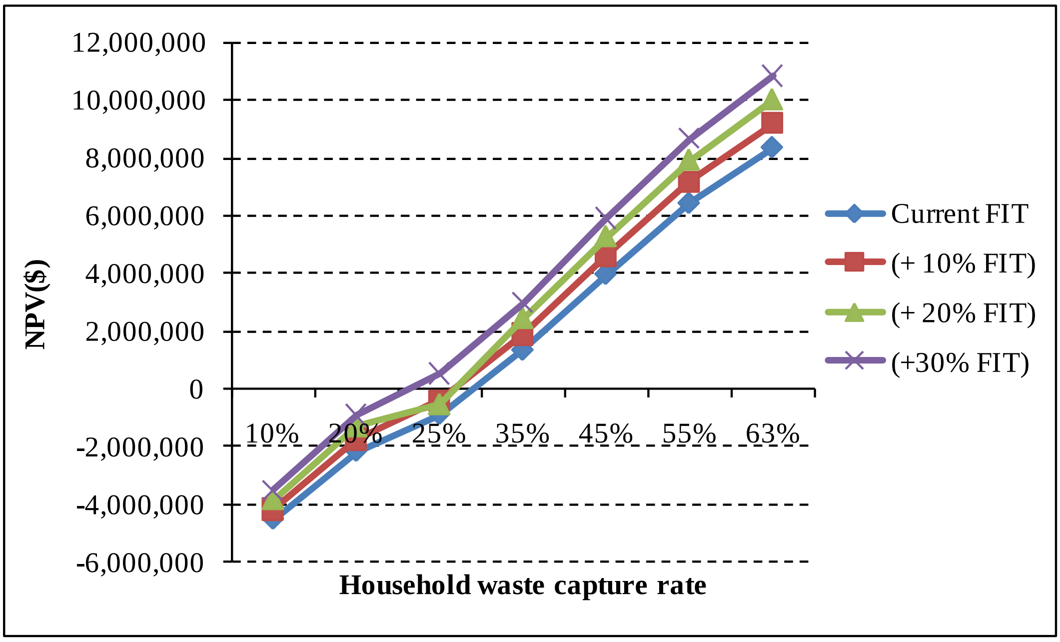

Figure 31 Viability of projects scenarios as reflected by household waste capture rates under different FIT and a ROR of 14%

Figure 32 shows the NPV of AD project scenarios. It was found that a project of 46,536 tpa (35% household waste capture rate) could yield a NPV of $29/tonne and $119/tonne for projects with 70,172 tpa. A study in the UK, Zglobisz *et al*. (2010) found that a business of 25 years of plant lifetime with a discount rate of 10.7% and 38,400 tpa could yield a NPV of $104.198/tonne when incentives are applied such as Renewable Obligation Certificates (ROCs). Using the same model, a project of 38,506 tpa (25% household waste capture rate) in Kigali could yield a NPV of $3.65/tonne (Appendix 8). Profitability from an AD project in Kigali can be increased by the provision of substantial incentives. For example, the NPV could increase to $50.41/tonne if the FIT is increased by 30%.

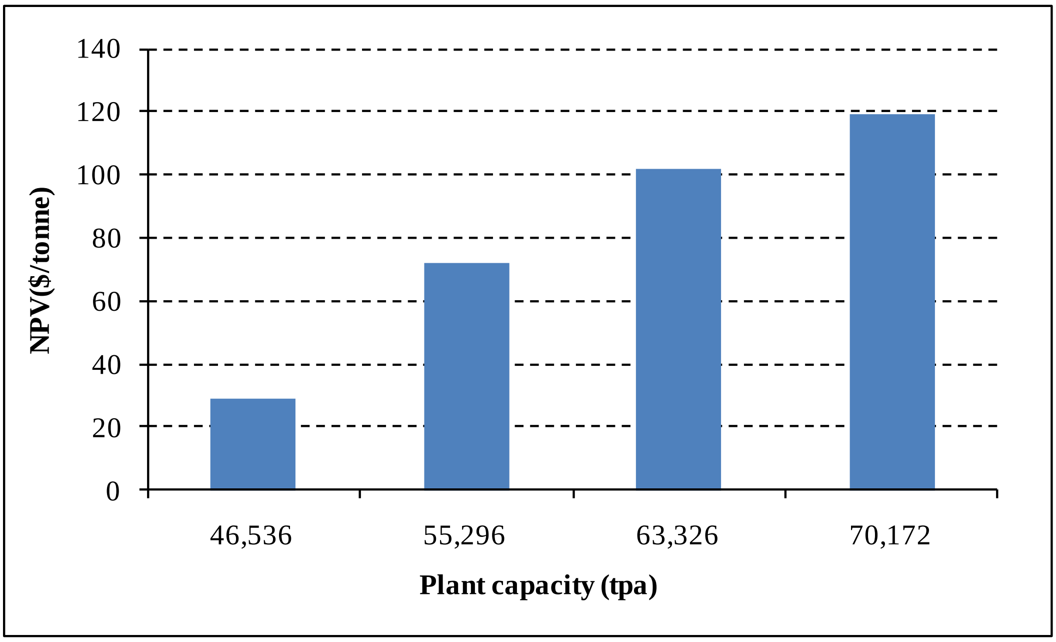

Figure 32 NPV per tonne for different projects scenarios as reflected by the annual tonnage throughput

The development of AD technology for Kigali City can deliver substantial non-monetary benefits. Table 13 summarises key benefits that can be derived from AD application obtained through a qualitative analysis of the findings obtained in this study. Some immediate benefits include landfill diversion hence extending its lifespan, employment opportunities and environmental education through sustainable practices such as waste separation at source. The use of AD also contributes to the reduction of greenhouse gas emissions by generating a renewable energy and by landfill diversion of biodegradable waste emitting methane gas.

Across all projects scenarios, the AD projects would employ as minimum as 563 workers and as maximum as 1019 workers for household waste collection activities only (Appendix 6) and would divert as much as 52,836 tonnes per year of waste from landfill.

In Rwanda, power consumption is 720 kWh per person per year (Safari 2010). Using the household data (section 8.3.1) and results on potential electric power generation from the produced methane gas (Appendix 7), it can be estimated that the AD plant has the potential to generate enough electricity to power approximately 1996 households with the least viable scenario (46,536 tpa) and 3009 households with the best viable scenario (70,172 tpa).

Table 13 Non-monetary benefits derived from potential anaerobic digestion development and application in the management of municipal solid waste in Kigali City

Indicators	Non-monetary benefits
Education	- Increased public awareness about environmental problems - Community environmental education through sustainable practices
Public health	- Landfill diversion - Water pollution control through control of inadequate disposal of waste - Increased sanitation in residential areas
Quality of life	- Increased employment and poverty alleviation - Mitigation of aesthetic and odour problems arising from inadequate waste disposal - Increased public access to electricity
Social repercussions	- Job creation - Improved Solid Waste Management services for poor income communities - Promotion of gender equality by mobilising women in the job market
Economic development	- Land use management through landfill diversion - Diversification of energy sources - Capacity building and job creation - Private sector development
Investment	- Creation of services and industries in relation to Anaerobic Digestion technology - Private sector development
Environmental protection	- Land use conservation through recycling of nutrients - Reduction of greenhouse gas emissions - Water pollution control through landfill diversion and control of inadequate disposal of waste

B. Effect of variable FIT and ROR on NPV

Figure 33 shows the sensitivity of projects' viability to variable FIT and ROR. A project with 25% waste capture rate is unlikely to be viable unless there is substantial increase in FIT with a return rate of less than 16%. At higher ROR, a project of 35% household waste capture was only viable at higher FIT scenarios. Only projects with 45% waste capture rate and higher capture rates are viable at all evaluated scenarios. For minimum waste capture rates, viable scenarios depended on FIT.

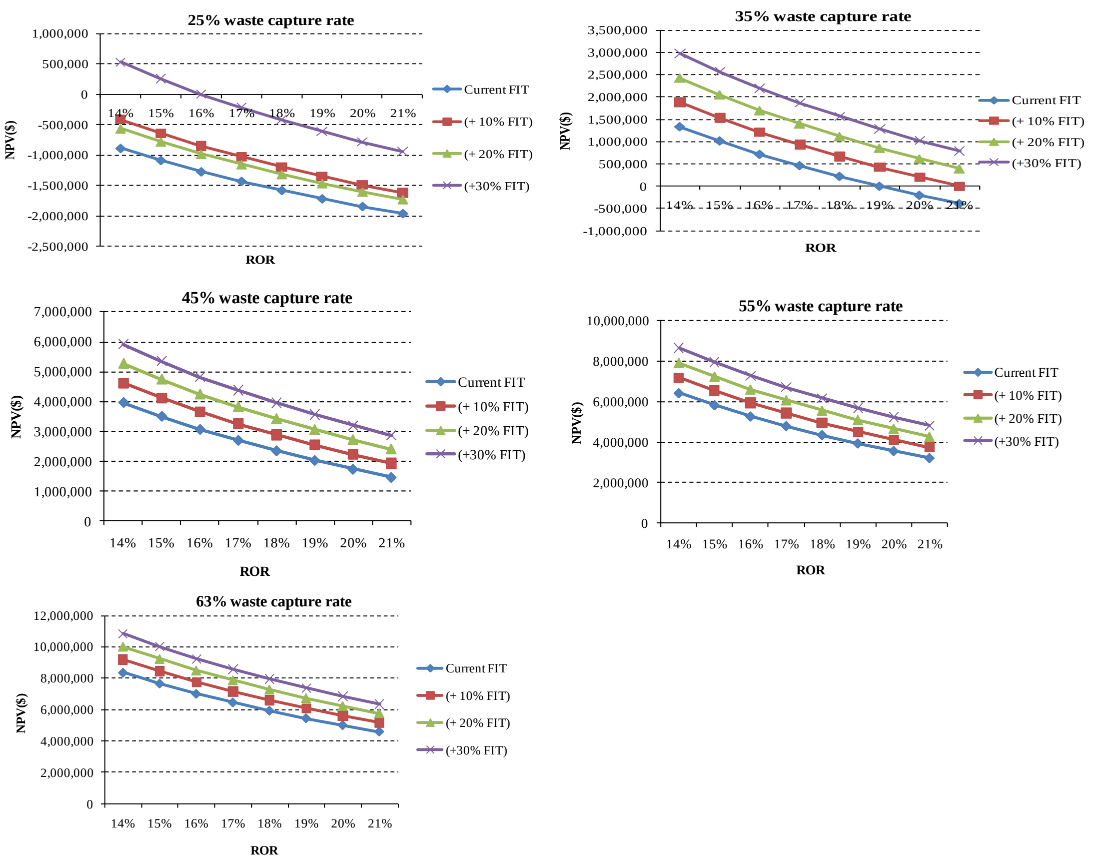

Figure 33 Sensitivity of project's viability as reflected by household waste capture rate with variable FIT and ROR

C. Risk analysis

Figure 34 shows the viability of project scenarios to adverse changes in key variables of major cost components and gross revenues. These are waste collection costs and revenues, capital costs and AD plant O&M costs and decrease in electricity sales. Using the current FIT of $118/kWh for electricity and an acceptable ROR of 14%, the impact of (adverse) changes in key variables with an increase or a decrease by 15% on the NPV was determined. It was found that the viability of all project scenarios is most sensitive to changes in waste collection costs and waste collection gross revenues. The finances on feedstock supply could be a limiting factor as the movement of its costs causes major changes on the NPV of project scenarios. Furthermore, it is unlikely that the costs of waste collection would reduce especially if there is feedstock competition for composting and the use of incentives such as free waste collection to maintain feedstock supply. The reduction in waste collection revenues also has a large impact on NPV of projects with more than 35% of household feedstock supply compared to other variables. The results also demonstrated that reduction in electricity sales can be risky for project scenarios with less than 45% of household waste capture. Project scenarios of less than 45% of household waste capture rate present high risks for the project uptake.

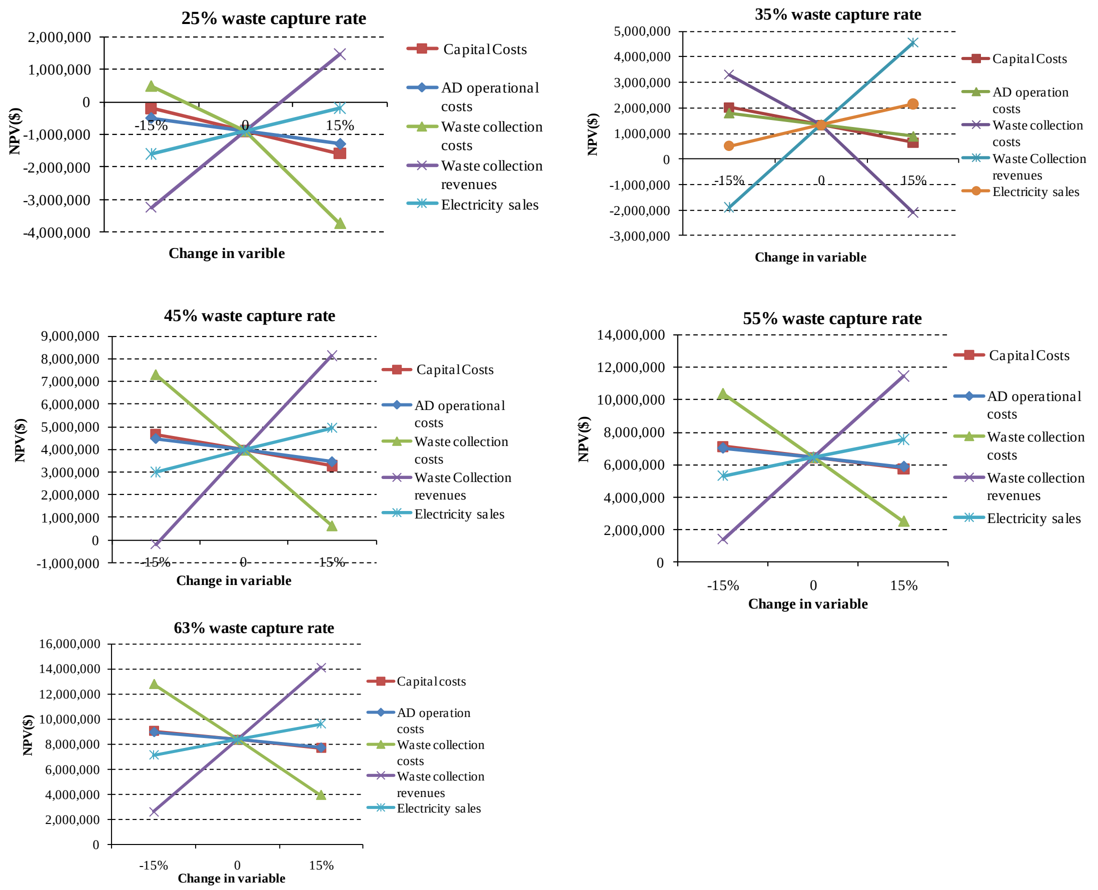

Figure 34 Sensitivity of project's viability to changes in key variables using a FIT of $0.118/kWh and ROR of 14%

10.3.4.3 Source of adverse changes - Qualitative analysis

Increase in capital costs

Capital costs might be increased by the increase in construction costs, the solely importation of AD plant equipment, legislation requirements and high transaction costs.

Increase in waste collection costs

The increase in waste collection costs might be due to various factors:

- Sorting facilities (e.g. garbage bags) representing a significant part of a substantial fraction of waste collection costs in the order of 40% for all viable scenarios, followed by transportation costs and labour costs. Labour costs are the most likely to increase than other cost elements.

- Labour costs are likely to increase in low income areas, where bring in system might take a long time to implement requiring more of a door to door waste collection system hence increasing the number of workers.
- Costs for awareness promotion programmes are likely to increase with public campaigns adding to the estimated costs for door-to-door awareness campaign.

Decrease in waste collection revenues

A reduction in waste collection revenues might be caused by a delay or no payment of waste collection bills by contracted households.

Increase in AD operation costs

The increase in costs may originate from:

- The collection of unsuitable waste and extra costs for pre-treatment
- The provision of heating during system start up
- External provision of inoculum for a fast start-up digestion
- The use of chemicals for process stability
- Extra costs for digestate management such as transportation costs and costs for additional treatment of digestate

Decrease in electricity revenues

A decrease in electricity revenues is unlikely to be caused by a lower FIT as this would most probable to be increased with proper adjustment. A decrease in electricity sales for the project scenarios might be due to:

- A slow system start up and technical disruptions in AD processes
- Methane gas leakages from the plant before and after digestion
- Digestion of unsuitable waste leading to less methane gas production

Table 14 shows potential levels of risks to project's viability identified in this study. In some cases, the occurrence of these risks in cost and revenue elements such as AD plant operation costs or electricity sales can be high but not sufficiently to make the project unprofitable as shown in Figure 34. The adverse changes in waste collection costs and waste collection revenues present major risks to project's viability compared to other costs and revenue elements. Therefore, mitigation strategies against these risks need to prioritise on the development of effective waste collection systems.

Table 14 Sources of adverse changes in cost and revenue components and qualitative risk evaluation

	Variables														
	Capital costs			Waste collection costs			Waste collection revenues			Plant operation costs			Electricity revenues		
Sources of change	**Likelihood**	**Impact**	**Risk**	**Likelihood**	**Impact**	**Risk**	**Likelihood**	**Impact**	**Risk**	**Likelihood**	**Impact**	**Risk**	**Likelihood**	**Impact**	**Risk**
Cost of sorting facilities	–	–	**–**	5	5	**25**	–	–	**–**	–	–	**–**	–	–	**–**
Transportation costs	–	–	**–**	5	4	**20**	–	–	**–**	–	–	**–**	–	–	**–**
Labour costs	–	–	**–**	5	4	**20**	–	–	**–**	–	–	**–**	–	–	**–**
Awareness costs	–	–	**–**	3	2	**6**	–	–	**–**	–	–	**–**	–	–	**–**
Delay of payment of waste service	–	–	**–**	–	–	**–**	4	5	**20**	–	–	**–**	–	–	**–**
No payment of waste service	–	–	**–**	–	–	**–**	3	5	**15**	–	–	**–**	–	–	**–**
Construction costs	4	2	**8**	–	–	**–**	–	–	**–**	–	–	**–**	–	–	**–**
Solely importation of equipment	4	2	**8**	–	–	**–**	–	–	**–**	–	–	**–**	–	–	**–**
Legislation requirements	3	2	**6**	–	–	**–**	–	–	**–**	–	–	**–**	–	–	**–**
Transaction costs	4	2	**8**	–	–	**–**	–	–	**–**	–	–	**–**	–	–	**–**
Collection of unsuitable waste and pre-treatment	–	–	**–**	–	–	**–**	–	–	**–**	3	1	**3**	–	–	**–**
Provision of heating from external sources	–	–	**–**	–	–	**–**	–	–	**–**	5	1	**5**	–	–	**–**
External provision of inoculum	–	–	**–**	–	–	**–**	–	–	**–**	5	1	**5**	–	–	**–**
Use of chemicals	–	–	**–**	–	–	**–**	–	–	**–**	3	1	**3**	–	–	**–**
Digestate handling costs	–	–	**–**	–	–	**–**	–	–	**–**	3	2	**6**	–	–	**–**
Technical disruption	–	–	**–**	–	–	**–**	–	–	**–**	–	–	**–**	3	2	**6**
Methane gas leakage	–	–	**–**	–	–	**–**	–	–	**–**	–	–	**–**	2	2	**4**
Digestion of unsuitable waste	–	–	**–**	–	–	**–**	–	–	**–**	–	–	**–**	3	2	**6**

Risk: 1-3= Non significant; 3-7= Low significance and 8-25 = Significant

Considering the elevated costs in securing suitable and sufficient feedstock, the high capital costs and the discussed investment risks, it is possible that lenders may stipulate higher ROR than the value considered in this study. The exclusive reliance on project revenues to mitigate the financial risks is unlikely to sustainably finance the system or encourage greater uptake in the AD industry without substantial external funding to allow for unanticipated costs. The risks are also increased by a lack of appropriate policy-based investment framework and thus can give place to less capital intensive conventional energy technologies.

10.3.4.4 Mitigation strategies against financial pressure

In the UK, the Department for Environment, Food and Rural Affairs (DEFRA) identified important challenges in the expansion of AD technology. These include AD developer’s lack of awareness of a variety of funding sources available for AD development (DEFRA 2011). This issue is common in AD industry and therefore not limited to the UK. The application of AD technology can deliver social, environmental and economic benefits which are embedded in sustainable development objectives for which various funding mechanisms are made available for their implementation. It is thus imperative to highlight the available local, regional and international financial opportunities that could accelerate the development of AD technology for MSWM in Rwanda and other sub-Saharan African countries. Key mechanisms are summarised in the following sections.

A. Local support mechanisms

Mechanisms to tackle financial constraints in developing AD technology for MSW in Rwanda can be mainstreamed from the national strategy on Climate Change and Low Carbon Development (REMA 2011) and the City of Kigali Development plan (City of

Kigali 2012c). The strategies bring together policies from various key areas of national development. Although these are several, those that can provide financial opportunities for AD development for MSW include sanitation, gender equality, cities and the built environment sector and environmental protection in particular climate change mitigation. The implementation of these policies is generally funded by a range of multilateral development donor funding bodies such as World Bank, African Development Bank, European Union, Public Private Infrastructure Advisory, Private Infrastructure Development Group, Special Climate Fund and Adaption Fund and UN agencies. The funds are managed by the government and financial assistance for AD development could be paid out through public-private partnerships and grants.

Sanitation

Sanitation policy goal is to increase access to potable water through water security efficiency and conservation. AD can complement this objective by mitigating the effects of inadequate waste disposal such as water pollution and potential flooding resulting from clogging of water drainage systems. AD also offers the possibility of co-digestion of solid waste with sewage sludge. Funding can be sourced from policy stakeholders such as Rwanda Natural Resources Authority (RNRA), Ministry of Natural Resources (MINIRENA), Ministry of Infrastructure (MININFRA), EWSA, MINAGRI and municipal districts and would address costs associated with the improvement of waste collection systems.

Cities and Built Environment sector

The government seeks to promote the development of waste reduction and carbon reducing projects in the Built Environment sector. The available public funding exists through public venture capital and equity capital provided by the National Bank of

Rwanda or the Ministry of Economic planning and Finance (MINECOFIN) and could assist in leveraging capital costs.

Low carbon development and environmental protection

The government of Rwanda through Rwanda Environment Management Authority (REMA) has developed a National Fund for the Environment known as FONERWA. The fund aims to promote "Rwanda's green growth and climate resilience strategy" for which objectives are to achieve low carbon energy supply, social protection and improved health. Beneficiaries include public and private sector, civil society, research institutions and communities. Targets areas for funding include research and development and technology transfer. Others include the implementation in the areas of renewable energy and energy efficient technology and pollution management including public environmental education. The policy allows a venture capital loan fund, lines of credit, public equity capital by the National Bank of Rwanda. The funding could assist with the capital expenditure or lessen the operational financial risks associated with feedstock logistics and AD plant processes.

Gender equality

The objective of the national gender policy is to promote gender equality in the development process including women empowerment and poverty reduction. This is implemented through the integration of gender equality into the policies, programmes, activities and budgets in all sectors and at all levels. The policies include the promotion of gender equality in building capacity in waste recycling activities (City of Kigali 2012c). AD development can mobilise women and provide employment in AD-related SWM activities. Additionally, SWM and in particular informal recycling of waste is one of gender sensitive practices where women are particularly active. AD development could improve the working conditions of women in effective collection of source separated waste. Funding can be obtained from United Nations Development Program (UNDP) and United Nation Environmental Program (UNEP) and could address logistics of improving waste collection and separation practices.

B. Regional and International support mechanisms

The most important financing mechanisms can be obtained from Climate Finance specifically designed for developing countries and aimed at adaption and mitigation projects that can reduce the impacts of climate change (UNDP 2013). Other significant funding can be obtained from investment groups that invest in higher risks markets to promote economic growth and poverty reduction through infrastructure development projects (Private Infrastructure Development Group 2013). The relevant possible financing mechanisms that can be applicable to private investment in AD development include grant, equity, capital markets and technical assistance in the sectors of renewable energy, waste management, low carbon and adaptation to climate change. Financial assistance could address the capital costs and the optimisation of AD operations especially waste collection costs and the O&M costs for the AD plant. The most relevant funding sources are summarised as follows:

- African Carbon Asset Development Facility (ACAD) for projects located in Sub-Saharan Africa and involved in renewable energy; climate change mitigation and waste management. Available funds amount to $ 87.1 million.

- Kreditanstalt für Wiederaufbau (KfW) Development and Climate Finance for climate-relevant investments in developing countries and industrialised countries. The criteria for which AD qualifies include renewable energy, low carbon and waste management. The funding amount is variable.

- Clean Development Mechanisms (CDM) which provides funding for emission-reduction projects in developing countries by allowing the trade of carbon credits. AD project is eligible for its contribution in reducing greenhouse gas emissions. The funding addresses full adaptation cost to address the adverse effects of climate change. Access to funding requires the endorsement of government of the receiving country. The project can apply up to $1 million.

- Emerging Africa Infrastructure Fund (EAIF) which provides long-term foreign currency to infrastructure projects located in sub-Saharan Africa. The EAIF finances private companies involved in green projects, for refurbishment, upgrade or expansion of existing facilities. Eligible sectors include energy supply including generation, transmission and distribution. The EAIF's aim is to make a lasting impact on the development of sub-Saharan Africa's infrastructure by facilitating economic growth directly or indirectly and contributing to poverty alleviation in the region. With a debt fund of up to US $ 753.2 million, the EAIF can invest in a project of 15 years lifetime for a range between US$10 million (or equivalent) to US$ 30 million (or equivalent). The funding does not require a political risk cover.

- Netherlands Development Finance Company (FMO) which supports sustainable private sector growth in developing and emerging markets by investing in private companies in the field of energy, agribusiness, food and water. Funding can be provided through loans, equity, mezzanine, guarantees and capital markets. Available funds amount to € 5.9 billion (or equivalent) as of year 2011 and a portion of the capital needed for the eligible project can be financed.

- Belgian Investment Companies for Developing countries (BIO) in the support of private sector for growth and sustainable development with the aim of achieving the Millennium Development Goals in those countries. BIO finances private infrastructure projects for the increase in energy and water access.

10.4 Conclusion

Using the results obtained from household surveys, the collection of source-separated feedstock for Anaerobic Digestion was modelled according to socio-economic levels. It was found that out of 230 tonnes available for anaerobic digestion per day, a maximum of 63% of household food waste could be captured for anaerobic digestion. Another 47 tonnes per day could be supplied by commercial establishments and office buildings. The net electric power production from the plant has been estimated to be 182 kWh/tonne of source-separated waste.

Various household waste capture rates were modelled in this study and these are represented as project scenarios. The sensitivity of Net Present Value to changes in key variables has also been evaluated. It has been found that projects with less than 35% of household waste capture rate are not viable under all evaluated scenarios, thus requiring a change in Feed-in Tariff and Rate of Return. Only projects of over 45% of household feedstock supply would be attractive to the investor regardless of the electricity price and the considered rate of returns. Possibilities of co-digestion with organic wastes from other waste streams such as abattoirs and food processing industries have not been considered in this study, although the practice would increase the anaerobic digestion potential, and increase investment attractiveness.

It has been shown that financial incentives such as Feed-in Tariff scheme can effectively enhance investment in Anaerobic Digestion provided that appropriate tariffs are established. However, high capital costs could be a major barrier for the uptake. With the assumption that the Anaerobic Digestion project is fully financed from its revenues, the adverse increment changes in waste collection costs and decrease in both waste collection revenues and electricity sales would make the viable projects less profitable and could lead to a financially unsustainable venture. Increment changes in waste collection costs present the highest risks for project viability and are likely to result from increased labour costs, incentive costs, transportation costs and costs of awareness programmes.

This study has indicated the strategic role that anaerobic digestion could play in the implementation of key Rwandan national development policies in the areas of sanitation, cities and built environment, gender equality and climate change mitigation. Benefits that can be generated by the application of anaerobic digestion technology for municipal solid wastes include landfill diversion of the largest fraction of waste hence contributing to land use management; energy generation; land conservation from digestate utilisation; reduction of greenhouse gas emissions; employment opportunities and capacity building. These benefits could be used as selling points to access funding from governmental and non-governmental bodies. For this, an effective regulated financial framework specifically designed for anaerobic digestion should be established between government bodies on one hand and donors on the other hand in order to meet the policies' objectives. The framework should also feed into the review of existing waste policies that target organic waste and the set up of priorities for the waste produced. Financial assistance can be sought from international climate finance where significant funding is available for development projects particularly in developing countries. The funds could be used to leverage capital expenditure or address the financial constraints of day to day Anaerobic Digestion operations in particular the logistics of collecting source-separated waste.

CHAPTER 11

DEVELOPMENT OF A STRATEGIC POLICY AND TECHNICAL FRAMEWORK FOR THE APPLICATION OF ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTES

11.1. Introduction

Progress is being made in Sub-Saharan Africa with farm-based AD technology for the conversion of farm waste products into energy as a strategy for rural development (Mshandete and Parawira 2009). However, the challenge is to link AD development initiatives for urban waste management and to design an effective financing framework to support its development. Although AD technology is one of the technologies that have a sufficient track record in the European Union as far as renewable energy is concerned, hydropower, solar power and geothermal energy are the established technologies in sub-Saharan Africa that currently attract large pool of funds (UNDP 2012). Lack of understanding of the relationship between bio-waste to energy technologies and relevant national policies objectives seem to be the main constraint to developing AD in sub-Saharan Africa. This chapter attempts to propose a framework for mobilising resources in developing and applying anaerobic digestion technologies for the management of municipal solid wastes in Kigali City. In regard to the AD plant layout presented in section 10.3.3, this chapter also contributes in the provision of guidelines to prevent pollution of air, ground and surface water and protect public health during anaerobic digestion plant operations.

11.2 Methodology

Results presented in Chapter 8 and 10 established suitable mechanisms for the application of AD technology in the management of municipal solid waste. These include mechanisms for the applicability of effective collection of source-separated waste and potential financial resources to address technical and financial constraints in the development and operations of anaerobic digestion technology. In this chapter, the conclusion and recommendations from Chapter 8 and 10 were used to establish the principal actors and their role in designing and applying effective strategies for AD application in the social, political, institutional, economic and technical domains.

11.3 Influencing trajectory of funding resources

It is important to view AD technology within the context of macroeconomic evaluation. As previously mentioned (Table 13, section 10.3.3.2), the management of MSW using AD technology benefits public health efforts by landfill diversion and safe waste disposal and offers low carbon and resource-efficient economy with increased waste recycling opportunities and the provision of renewable energy and bio-fertiliser. Other benefits that can arise with AD development include the generation of new industries and services and associated employment opportunities. Rwanda's strategic priorities for its sustainable development targets specifically poverty reduction, capacity building, gender equality, sanitation, land use management and conservation, agriculture and rural development and the use of renewable energies which are reflected in AD's potential benefits. Rwanda's commitment to the use of AD technology should therefore be viewed in AD's benefits. Figure 35 shows an illustration of a proposed integrated policy and technical framework developed from the results of this study that can govern and shape deployment of AD technology for the treatment of municipal solid wastes. From this figure, two strategic roles emerge with regard to the financing of AD development. Firstly, the government should be able to advocate the leverage of important funding for investment in urban based clean energy projects. In this regard, the government should play the advocacy role towards lenders and other external funding bodies on behalf of private developers. It has been found that significant external funding resources for investment in clean energy in Africa are directed at the rural poor due to their distant location to nearest power grids. It is noteworthy that Rwanda relies heavily on donor funding in the financing of public sector activities within the various sectors of national importance. An investment plan for AD should be drawn from a combination of policy-based operations in strategic areas of national priority sectors mentioned above. This can be made possible by the establishment of a specific fund for AD secured from the finances made available within these policies. The government should also entice investors by establishing an appropriate regulatory and financial framework for AD within these areas. The regulatory framework should also facilitate swiftness of the issuing process of operating permits and other compliance documentation.

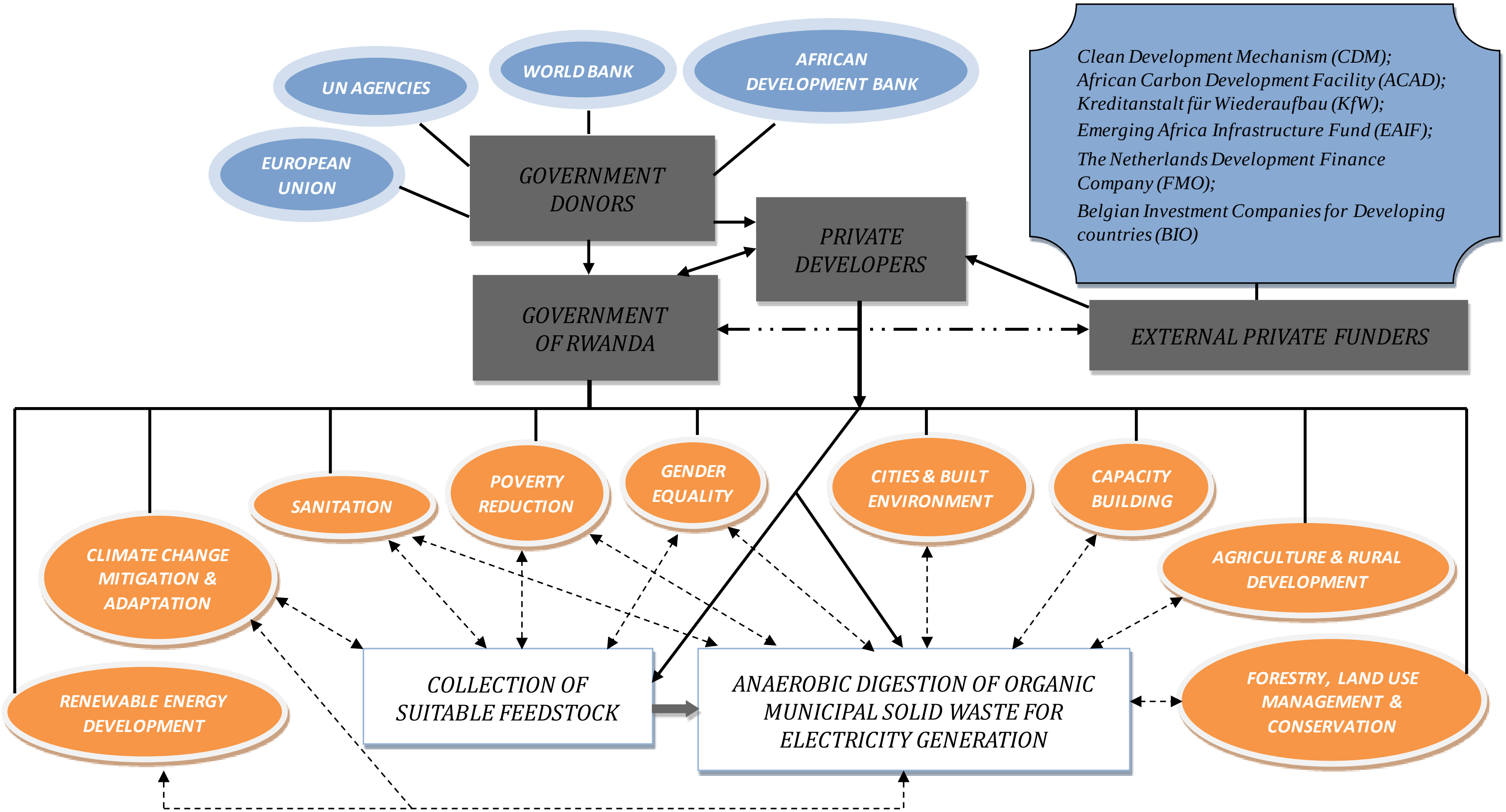

Figure 35 Proposed strategic policy and technical framework for the deployment of AD technology in the management of municipal solid wastes in Kigali City

Legend:

———	Constituent	←·→	Potential cooperation	(grey box)	Funding source entities
←→	Public-Private partnerships	→	Capital flows	(blue box)	Anaerobic Digestion-based operations
←- -→	Policy-based operations funding	(orange oval)	Rwandan national priority sectors		

The available financial resources should address grants or partnerships; guaranty funds and subsidies, low carbon credentials and funding for developing AD-specific mechanisms or policies. Areas of intervention should include:

- Developing financial instruments such as appropriate Feed-in Tariff for electricity generated by AD processes and tax exemptions for the importation of renewable energy infrastructure
- Building technical capacity by incorporating renewable energy skills in the existing education curriculum
- Developing strategies for digestate commercialisation that include support for R&D and raising public awareness about the use of the product
- Integrating AD development with land use management and forestry owing to its capacity to strategically improve sustainable land management efforts through landfill diversion, reduction of environmental impacts resulting from landfill use and land conditioning through digestate utilisation
- Integrating AD development with gender Equality and Skills development policies targeting women and women environmental groups where available

Considering the current positive global political and financial environment on climate change and renewable energy use, linking AD technology of municipal solid wastes with climate-sensitive policies would be a long term strategy to overcome the potential financial constraints and encourage investment in the technology.

11.4 Regulatory considerations

Project developers operating a waste disposal or a recovery operation have a legal obligation to hold a permit from competent authorities. The permit is issued upon fulfilment of regulatory requirements for the installation and operation of waste treatment facilities. Anaerobic digestion processes could be harmful to the environment and human health if not controlled by permitting regulations. The regulations are developed for the installation and operations of anaerobic digestion plant planned for the treatment of the organic fraction of municipal solid waste for electricity generation. The regulations comprise of measures to be taken to prevent public health risks and pollution on air, land and water resulting from anaerobic digestion operations conducted at the site. Taking into account the technical design of AD operations developed in this study and the social, economic and environmental conditions of Kigali City, the following guidelines were developed:

10.4.1 AD plant site

Anaerobic digestion plant site should be located at a safe distance from residential areas. The plant site should include a laboratory among its premises. The laboratory should be equipped with appropriate facilities to carry out necessary analyses including waste characteristics and output products.

11.4.1.1 Waste handling at reception hall

a. Reception hall

- A list of permissible wastes for anaerobic digestion should be established.
- Only garden waste excluding branches, kitchen/food waste should be approved for treatment.
- The reception hall should be covered and should have an impervious surface with a drainage system that allows collection of leachate from the incoming waste to the the digester.
- The hall should have two units, one for sorting out potential contaminants and another for size reduction.

- The air in the hall potentially contains a high density of spores of secondary pathogens. A ventilation system should be installed to ensure fresh air is continuously fed into the hall via a biofilter sucking the air. To prevent contact, inhalation or any other health hazard, the workers sorting manually the waste should always be equipped with appropriate safety wear.
- After the sorting of contaminants such as plastics, metals, packaging, glass and other non biodegradable wastes, these should be assembled and taken to the recycling centre. At this stage, the composition of waste that enters the digester should be determined.
- The main parameters for process control such as dry solids, volatile solids and pH should be analysed in the laboratory prior to digestion.
- Preventive measures such as fences must be taken against birds, rodents and insects on site.

b. AD plant

- The waste must remain in the digester for a minimum of 30 days. Control procedures and appropriate equipment for temperature and pH control should be available.
- Regular monitoring of any potential spillage.
- Monitoring and control of potential biogas leakage should be done regularly. An anti-flare gas system should be on-site.

11.4.1.2 Biogas storage

- The biogas storage facility should be near as possible to the digester.
- The biogas produced should be measured for methane content.

- Safety measures should be taken to prevent gas leakage in situation of disasters such as flooding.

11.4.1.3 Pasteurisation

- Anaerobic digestion plants treating organic municipal solid waste should be equipped with pasteurisation units. The digestate should remain in the pasteurisation hall for a minimum of 1 hour and heated at 70^{o}C.

- The digestate should be tested for pathogens before and after pasteurisation.

11.4.1.4 Digestate storage halls

- The digestate should be stored for a maximum of two months
- The halls should be covered to prevent birds, rodents and insects on site and equipped with biogas collection system for any remaining gas and a ventilation system for odour prevention.

- A procedure for analysing the end products (Biogas and digestate) should be made available and conducted in the on-site laboratory.
- Digestate should be tested for pathogens such as *Salmonella* and *Enterobacteriaceae* prior to disposing on land.

11.4.1.5 Spreading of digestate

- Digestate generated from non-separated waste shall be classified as waste and subject to regulations applying on general waste.

- Digestate which is not pasteurised should be classified as waste
- Digestate which has been pasteurised should be classified as waste until a competent authority classifies it as good quality to be spread.

- Digestate which has been pasteurised should not be used on land or disposed of by other means unless it is used for soil conditioning or other beneficial purposes. The digestate shall be classified as waste otherwise.

11.5 Conclusion

The aim of this chapter was to establish a strategic operational framework for the application of anaerobic digestion technology in the management of municipal solid wastes. The framework incorporates current local and international policy system for which objectives are directly affected by the application of anaerobic digestion in Kigali City.

Findings from this study showed that a greater emphasis must be put on source-separated waste collection to increase the potential of anaerobic digestion. This study has also shown that incentive-based systems are more likely to encourage waste separation at source. The private sector in charge of waste services and waste recovery in Kigali is not equipped financially, politically, legally and lacks appropriate awareness mechanisms to support the SWM industry including anaerobic digestion technology. Developing effective waste collection systems that will allow greater capture of suitable feedstock and the application of the technology will be costly and would need consolidated financial mechanisms from anaerobic digestion operators, the government and the external funding groups. In particular, the government will play a central part in creating the enabling environment for urban-based biogas technology application. The framework will facilitate the design of feasible strategies under local conditions that will attract investment in biogas technology as well as developing solid waste management systems. These strategies include financial incentives such as subsidies, grants, tax exemptions, Feed-in tariff, appropriate regulatory requirements, and integration of anaerobic digestion technical requirements with current local policy objectives such as those under renewable energy development, land use management and forestry, agriculture, gender equality and skills development.

CHAPTER 12

SUMMARY, CONCLUSION AND RECOMMENDATIONS

This chapter was developed in the following manner. A summary of key findings obtained in this study commences this chapter. Then, a conclusion is presented in section 12.2 in which the objectives are reviewed and the extent to which they were achieved. This study's contribution to knowledge is presented in section 12.2.1. Finally, recommendations for future research work were developed in response to limitations that had been identified in this study and are presented in section 12.4

12.1 Summary

The role of AD in Municipal Solid Waste Management has attracted little attention in sub-Saharan African countries. This research was carried out to evaluate the social, technical and economic requirements for the development of AD technology as part of a system approach for the management of organic municipal solid waste in sub-Saharan Africa using Kigali City as a case study. Field studies that included household surveys and interviews to relevant waste managers were conducted to investigate the current waste management situation in Kigali and to identify challenges that might impact the application of AD. The collection of source-separated waste is identified as a critical factor in enhancing AD potential for energy generation and digestate management. Household waste production, public awareness and attitude towards waste separation at source were found to be dependent on socio-economic levels existing in Kigali City. Biochemical methane production experiments were carried out in order to estimate the methane production potential of source-separated food waste and other types of food processing wastes likely to be used as feedstock for the AD project. The experiment also aimed at determining the effect of operating temperature on the design and operation of AD systems in Kigali. Finally, the economic viability of operating an Anaerobic Digestion plant was assessed and its sustainability was evaluated through a strategic operational framework.

Based upon household survey findings depicting the current waste management situation in Kigali City, there is a total of 269 tonnes per day of food waste available representing 74% of total household wastes and the rest represents dry recyclable waste. These figures are consistent with previous estimations based on landfill waste (City of Kigali 2012a). The study also showed that socio-economic factors at household level significantly impact on waste production and its availability for AD. It was found that food waste production increases with household socio-economic level whereby higher income household produce greater waste levels than middle and low income households. Low income households have the lowest food waste production however; waste levels were not statistically different from those in middle income households. Results also showed that food waste production increases with household size only middle and high income households whilst no effect was found for other type of wastes in any household type. The prediction of waste production rates through the use of socio-economic factors is important to strategically estimate feedstock availability for AD.

The availability of waste for AD gives consideration to competing waste management routes. Results on waste separation behaviour in households showed that home composting and the production of animal feeds are the current waste management routes for food waste in particular. This reduces the amount of feedstock available for AD to about 230 tonnes per day. Considering that low and middle income households represent the vast majority of population in Kigali City and live in unplanned settlements or slums, this study demonstrates that poor income among the population could affect the recovery of waste for AD. It was also found that 41% of households are less satisfied with waste management due to poor waste collection services. Lack of road access in both middle and low income areas discourage service providers thereby extending the services to other areas which result in irregular waste collection and uncontrolled open dumping. Poor income communities also often turn to this practice in order to avoid paying the monthly waste collection fees. This particularly poses an environmental problem when drainage systems are clogged up by an accumulation of litter in conduits leading to overflow of waterways and consequently flooding and often the emergence of water borne diseases. The problem is exacerbated by the fact that waste collection service is mainly based on user fees which hardly cover costs for collection thereby making the business unsustainable.

This study also demonstrated that public participation in SWM is correlated to socio-economic level. It was found that household's willingness to pay for improved services increased with socio-economic level. Motivation to adopt waste separation practice is also driven by socio-economic level. Low and middle income households are more interested in the economic value of SWM while higher income households seemed more interested in waste storage facilities and organised recycling programmes. Although high income households are more willing to pay for additional costs related to improved systems, it was found that incentives such as free waste storage bags would highly motivate their participation to waste separation at source. Other studies have also shown that incentives for sorting waste are the most preferred options to encourage household waste separation (Shaw and Maynard 2008). It is clear from the findings that incentive-based systems would encourage participation to waste separation at source. In particular, socio-economic schemes would be suitable for developing effective source-separated waste collection systems in poor income communities. Possible strategies identified in this study include free waste collection service and food voucher incentive system. These incentives can ensure sustained desirable practices towards waste management. The incentive-based systems should be coupled with appropriate communication strategies. The study also revealed that the public is inclined to promoting waste conversion technologies, public health and environmental protection and yet does not recognise the role of landfill diversion in promoting waste conversion technologies. More emphasis is therefore required in designing clear subject-specific awareness and education programmes that can drive public participation in sustainable waste management practices. It is essential that awareness programmes highlight the degree to which waste separation affects SWM processes.

Based on the assumption that willingness to pay for improved services demonstrated household's willing to participate in desirable SWM practices, the proportion of wastes available for AD was considered to be predominantly from those households that have expressed their willingness to pay for improved services. Using the waste and the population data obtained from this study, the amount of waste likely to be captured was calculated for each socio-economic level and totalled on overall capture rate of 63%. Since the quantity of collected waste is subject to change, various waste capture rates were modelled with decreasing quantities and these represented AD project scenarios. Relevant potential non-domestic sources of feedstock for AD were also identified, providing a total of 47 tonnes produced every day from food processing industry, restaurants, hotels and public markets as well as canteens of office buildings.

In order to determine the effect of Kigali climatic conditions in operating an AD plant, biochemical methane production experiments were carried out at two temperatures, $25^{o}C$ and $37^{o}C$; with $25^{o}C$ representing Kigali ambient temperature versus 37^{o}C, the most common temperature for AD operations worldwide. Cumulative BMP from the digestion of source-separated food waste and common non-domestic feedstocks were estimated. Waste peelings of cooking banana and passion fruit were selected due to their abundance in Kigali City. Optimum cumulative BMP of feedstocks were obtained on Day 23-30. Methane production potential of food waste was found to be 207 ml/g VS_{added} and 398 ml/g VS_{added} respectively at 25^{o}C and 37^{o}C. Regarding other feedstocks, methane production potential of banana waste was estimated at 112 ml/g VS_{added} and 328 ml/g VS_{added} respectively at 25^{o}C and 37^{o}C while that of passion fruit was found to be 146 ml/g VS_{added} at 25^{o}C and 221 ml/g VS_{added} at 37^{o}C. Acid accumulation was the main consequence of lower temperature digestion which may have hampered methane gas production. This can be circumvented by longer periods of retention time to allow digestibility and maximum degradation which would require the increase of digester size in order to give similar yield as at 37^{o}C. This study has also shown that co-digestion of feedstock from domestic and commercial sources with feedstock from industrial sources (banana and passion fruit waste) can enhance volumetric biogas production.

The economic viability of AD project scenarios was assessed using 37^{o}C as the operating temperature for the AD plant for feasibility analysis at conditions beyond 25^{o}C operating conditions. The analysis was based on changes in feedstock quantities under a variable FIT and ROR. Using the NPV as the criteria for project's viability, it was found that projects with less than 35% of household food waste capture would not be viable. Using a minimum acceptable rate of return of 14% and an available FIT of 0.118/kWh, the sensitivity of NPV of viable scenarios to adverse changes of 15% in key variables was examined. Significant risks to project's viability simulated changes in waste collection costs, waste collection revenues and electricity sales. Projects with 35% of household waste capture were not viable under adverse changes in waste collection costs and waste collection revenues. The investment risks are considered safe with 45% or more of household food waste capture. Key variables that can be subject to adverse changes have been identified and these include capital costs, waste collection revenues and costs, AD plant operation costs and electricity sales. The adverse changes in the last three variables are related to inadequate quality of collected feedstock.

Furthermore, access to capital finance and challenges in the collection of a suitable feedstock are identified as major factors that can delay the development of Anaerobic Digestion for municipal solid waste in sub-Saharan Africa. Sources of capital finance and financial resources for assisting the development of an effective AD project have also been identified in this study. Some of these sources are embedded under current Rwandan national policies. The application of AD for bio-conversion of organic municipal waste benefit local policy objectives in national priority sectors such as sanitation, climate change mitigation, public health, capacity building and poverty reduction. Key potential benefits from AD development include employment opportunities; reduction of greenhouse gas emissions through the generation of renewable energy and landfill diversion of methane gas emitting waste; public health protection and water pollution control from effective waste collection and treatment. Despite these benefits, it appears that investor awareness and interest are limited probably due to poor promotion of the technology amongst relevant stakeholders in both the public and private sectors. The core factor may lie in the current structural design of political and financial systems surrounding solid waste management options in Rwanda which have to be reformed. These will need to be selected according to profitable markets thus requiring appropriate policy arrangements. In this context, a road map for successful implementation of anaerobic digestion will need to be driven and shaped by national energy policy. The strategy can also largely benefit from the international policy system on the use of renewable energy and climate change.

There also exist various local and international financial mechanisms available under the priority sectors mentioned in the above paragraph that could leverage capital funding and finances for developing effective systems for AD application. In particular, important private and public funding is available for projects and programmes that address the adverse effects of climate change. A policy-based financial framework specifically designed for AD by the government and external funding bodies and/or donors as key stakeholders developed from the findings of this study could help to stimulate best practices and private investment in waste collection and treatment. The funding could address subsidies, grants, public-private partnerships, and appropriate Feed-in tariff and tax exemptions. More importantly, the strategic role of the government is essential for the implementation of full scale AD application as most private funding bodies such as CDM require endorsement by governments for eligible projects.

12.2 Conclusion

This study identified and analysed the key requirements in the application of the biogas technology for the management of the organic fraction of municipal solid wastes in sub-Saharan Africa. Using Kigali City, the capital of Rwanda as a case study, the study aimed to evaluate the key challenges and proffer solutions in the application of Anaerobic Digestion technology as part of an integrated management of municipal solid. The objectives of the study were: (i) to review current solid waste management practices and assess public perception towards waste management; (ii) to determine waste characteristics and factors affecting the production of biodegradable organic waste; (iii) to investigate ways of enhancing the quality of household biodegradable waste suitable for AD; (iv) to determine the effect of ambient temperature on methane yield of municipal solid waste; (v) to evaluate the technical, social and economic requirements of biogas re-use and digestate disposal outlets; (vi) to develop a strategic and operational framework for effective application of AD as a waste management tool.

A waste characterisation survey and a public perception and awareness survey and interviews with relevant stakeholders were conducted in order to achieve the first three objectives. The obtained data from household surveys was analysed using statistical models such as Generalised Linear Models, Post-hoc multiple comparisons and Chi-square tests to determine relationships between key variables to examine public awareness and perception towards solid waste management and practices, in particular factors affecting waste separation at source; effect of socio-economic factors on both waste production rates and the recovery of suitable feedstock for anaerobic digestion. The findings were presented in Chapter seven, eight and nine and the conclusions drawn from this investigation are as follows:

(1) With regard to practices and public awareness towards waste management, this study has shown that clear subject-specific awareness programmes are required to improve public participation to solid waste management processes. The socio-economic level of households have a significant impact on public attitude to waste management whereby those of high socio-economic status are more willingness to pay for improved services. A significant relationship was also found between socio-economic level and motivation to segregate at source whereby households with low income would be motivated to separate waste with the expectation of obtaining economic benefits whilst higher

income are more inclined to adopt improved waste collection systems. These findings showed that understanding the socio-economic status of residents is vital in assessing feedstock availability and quality for an effective anaerobic digestion.

(2) This study has also shown that food waste composed of about 74% of household waste. Total waste production rates also relate to household socio-economic level with greater rates in high income households. Current household disposal routes for organic fraction of municipal solid waste include home composting and animal feed production. From these findings, the estimations for the quantity of feedstock potentially available for anaerobic digestion were obtained. Non domestic feedstock sources, such as public markets and commercial establishments were also identified and quantified.

(3) It was also found that recovery rates for waste materials can be increased by adopting practices likely to encourage source separation for a given area and for an appropriate waste collection system. Community-specific interventions in the form of remunerative incentives with greater focus on poor income communities have been found to be capable of improving waste separation practice and hence result in the recovery of suitable feedstock for anaerobic digestion.

From the above, it is clear that the first three objectives have been achieved.

To achieve the fourth objective, biochemical methane potential tests were carried out to determine the digestibility of available source-separated food waste and methane gas potential under Kigali's average daytime ambient temperature of $25^{o}C$. It was found that anaerobic digestion at $25^{o}C$ yielded 50% lower quantities of methane gas compared with the yield at the optimum operating mesophilic temperature of $37^{o}C$.

Operation of anaerobic digestion plant at 25°C will therefore require about twice the reactor capacity to in order achieve similar yield as at 37°C. Anaerobic digestion operation at 37°C will incur additional costs in heating requirements whilst operation at 25°C will increase pressure on land requirements.

The fourth objective of this study has thus been achieved.

For the fifth objective, the viability of anaerobic digestion technology in the management of municipal solid waste was assessed. Various scenarios were designed by considering the social, technical and economic factors obtained in this study (see objectives 1 to three above). Using viability indicators such as Net Present Value, conditions for effective anaerobic digestion projects were identified. The key findings are as follows:

(1) Sensitivity analysis showed that only projects with 45% or more of available household food waste present lower financial risks. Higher risks to project's viability have been found to be associated with the collection of appropriate feedstock.

(2) The financial anticipated risks such as high capital costs and costs of collecting the appropriate feedstock including incentive systems are likely to remain and delay the development of anaerobic digestion for municipal solid waste in sub-Saharan Africa if strategic policy objectives specifically designed for anaerobic digestion are not provided. It has been shown that funding opportunities from both the public and private sectors can be drawn from current key Rwandan national policy objectives that benefit from the application of biogas technology as it is done in developed countries such as the European Union.

From the above, it is clear that this study has developed a feasible viable scenario and has provided the requirements of a full-scale application of biogas technology for electricity production and digestate utilisation. The fifth objective has thus been achieved.

The work undertaken to achieve all the five objectives outline above, has provided information required for achieving the sixth objective, which involved the establishment of a strategic operational and investment framework for the application of anaerobic digestion technology for Kigali City. The framework brings together key actors and their specific roles:

(1) Private developers for the collection and operation of an anaerobic digestion plant

(2) Specific external private funders involved in socio-economic development projects and climate change mitigation strategies in developing countries for the provision of grants and loans to private developers

(3) The government of Rwanda for the provision of operational framework incorporating appropriate financial instruments and regulations under current national priority policy objectives which benefit from the various operations of anaerobic digestion technology.

The developed model can be used to tackle challenges that are likely to delay the development of anaerobic digestion. It can therefore be said that the sixth objective has been achieved.

12.2.1 Contribution to knowledge

To the best of author's knowledge, this research is the first of its kind to be conducted in Rwanda and for Kigali City, and in other sub-Saharan African urban cities. This research has provided feasible planning, design and operational characterisation techniques for effective implementation of AD technology for municipal solid wastes in sub-Saharan Africa.

The research also established a broad understanding of relationships between socio-economic factors and the management and recovery of municipal solid wastes.

Solid Waste Management options in sub-Saharan Africa have also tended to be sector-specific with limited cross-sectoral engagement beneficial to countries with limited resources. This study has thus provided a model for investing and operating anaerobic digestion technologies in sub-Saharan Africa under conditions of limited resources.

The findings of this study will appeal to a wide audience, scientists and engineers in both public and private sector establishments involved in municipal waste treatment and management, particularly in areas with limited financial resources.

12.4. Recommendations

The time allocated for this research has not allowed tapping into other relevant areas of research, such as:

- Seasonal availability of domestic waste production and recovery
- Determination of the quantities and composition of organic wastes from non domestic sources such as abattoirs and various food processing industries in Kigali City and their seasonal availability
- Options available for the disposal and agricultural reuse of digestate
- Establishment of ways to integrate scavengers in sustainable waste management practices
- Evaluation of the effectiveness of various types of incentives for encouraging waste separation at source.

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APPENDIX 1

Republic of Rwanda
City of Kigali

24/09/2010

3315/ 24 September 2010

TO WHOM IT MAY CONCERN

This is to give to Ms Sylvie MUCYO is a Rwandan, Full-time PhD student at the University of Abertay Dundee, the authorization to conduct a field survey and undertake waste data collection in Gasabo, Kicukiro and Nyarugenge Districts as part of her research work on "Assessing the potential role of anaerobic digestion in sustainable management of household wastes in Kigali City".

Kindly provide her with any assistance that she might need in relation to her research work.

Sincerely,

f Kigali City.

City of Kigali, B.P.3527 Kigali, Tél. 250-57-2255 / 57-6967 /57-5958 & Fax 250-57-3684 www.kigalicity.org

APPENDIX 2

Public perception and awareness questionnaire

Area:

District:

Household type:

Household size:

Gender of the interviewee:

Job type/occupation:

Education level:

Q1. a) How important is waste management to you and your household? (please tick one)

- Very important
- Important
- Moderately important
- Not important
- Indifferent

b) Why?

Q3. Do you know that some components of household waste can provide economic benefits?

- Yes
- No

Q4. Which of the waste components listed below is economically beneficial (tick more than one)

- Cardboard and newsprints
- Wood
- Grass
- Bottle
- Aluminium cans
- Food and kitchen waste
- Clothes

Q5. What are the potential economic values that can be obtained from waste? (tick more than one)

- Fertiliser in the form of compost
- Energy, in the form of methane gas for household cooking
- Re-use of materials
- Recycling of materials
- Don’t know

Q6. a) What materials do you separate from other waste?

- Cardboard and newsprints
- Wood
- Grass
- Bottle
- Aluminium cans
- Food and kitchen waste
- Clothes
- None

b) Why?

Q7. Among the following incentives what would motivate you to separate the various components of waste in order to support the answer given in Q 5? (Tick more than one)

- Lower waste disposal bills if offering a separate waste collection
- Availability of more garbage bags
- Frequent and respected schedule for waste collection
- Organised recycling programmes with collection of bulky items
- More information on the benefits of waste management

Q8. Is there a waste collection service for your household?

- Yes – please go to Q 9
- No - please go to Q 11

Q9. a)Who is in charge of collecting your waste?

- Local authority
- Private waste collector

b) How frequent is waste collection?

Q 10. a) How would you rate the waste management service serving you?

- Excellent
- Very good
- Moderately good
- Not good
- Distasteful

b) Why?

Q11. Why is there no waste collection service for your household?

- No means to pay for collection service

- House location not accessible
- Presence of a dumping site in the neighbourhood
- No service offered
- Other (please specify)

Q12.a) Do you feel you should pay to dispose waste?

- Yes
- No

b) Why/ why not?

Q13. a) How often do you use the following facilities?

1= Always 2=Very often 3= Occasionally 4 = rarely 5 = never

Type					
Garbage bag collection by private company	1	2	3	4	5
Garbage bag collection by local authority	1	2	3	4	5
Disposal in common roll on container (at the market place, in the neighbourhood)	1	2	3	4	5
Dumping site in the neighbourhood	1	2	3	4	5
Waste transfer site in the neighbourhood	1	2	3	4	5
Occasional bulky item collection	1	2	3	4	5

Q14. a) How are you concerned with any of the following facilities?

1= Very concerned, 2= concerned, 3= somewhat concerned, 4= indifferent 5= not concerned

Type					
Garbage bag collection by private company	1	2	3	4	5
Garbage bag collection by local authority					
Disposal in common roll on container (at the market place, in the neighbourhood)	1	2	3	4	5
Dumping site in the neighbourhood	1	2	3	4	5
Waste transfer site in the neighbourhood	1	2	3	4	5
Occasional bulky item collection	1	2	3	4	5

b) Please list your concerns if any? And why if not?

Q 15. In your opinion, how serious are the following waste management problems facing Kigali City?

1= Very serious, 2= serious, 3= somewhat serious, 4= No opinion, 5= Not serious,

Poor waste collection service	1	2	3	4	5
Lack of safe disposal facilities	1	2	3	4	5
Ignorance of waste impact on the environment	1	2	3	4	5
Lack of information on material recovery methods and benefits	1	2	3	4	5
High costs	1	2	3	4	5
Other (please specify)	1	2	3	4	5

Q16. How willing are you to pay more for an improved household waste management?

1=Very willing, 2=willing, 3= neither willing or unwilling, 4= unwilling 5= very unwilling

Q17. a) Where do you get most of your information on waste management issues?

- Environment groups/organisations
- Media (television, radio, newspapers)
- Local authorities
- Umuganda (community service)
- Government agencies/law
- Leaflets
- None
- Others (please specify)

Q18. What waste management issues would you like more information on?

Q19. When it comes to household waste, what is your opinion on the importance of following priorities for Rwandan waste management policy over the next few years?

1= Very important, 2= important, 3 = moderately important, 4= of little importance 5= unimportant

Increase recycling facilities	1	2	3	4	5
Improve and use landfill	1	2	3	4	5
Reduce landfill	1	2	3	4	5
Reduce food waste disposal and convert it to energy	1	2	3	4	5
More composting	1	2	3	4	5
Introduce incinerators	1	2	3	4	5
No further action	1	2	3	4	5

Waste data record sheet

Household type:

Household size:

Area:

District:

Day of waste collection:

Week 1

Waste type	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Food waste								
Other waste								

Week 2

Waste type	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Total
Food waste								
Other waste								

Informed consent note

Dear participant,

Thank you for giving us your time and consideration. This research intent is to investigate your knowledge about solid waste management and your views about waste management practices here in your neighbourhood and in Kigali City in general. This research will contribute to provide strategies for the improvement of solid waste management in Kigali City. Here are some statements you would like to consider before answering the questions:

1. You will not benefit from this research either by money or other offers
2. You have the right to decline to participate in this research
3. You have the opportunity to withdraw at any stage of the research
4. You are given full confidentiality of your responses in this questionnaire
5. You are given full anonymity, your name is not asked and is not required for this research

May you have any queries, my contact details are the following

Names: Sylvie Mucyo from the University of Abertay Dundee, Scotland

KIST, Mobile phone:[redacted]

Thank you.

APPENDIX 3

Waste disposal practices and waste storage systems

Nyanza landfill site

Uncontrolled dumping on side paths and in drains

Biodegradable and non biodegradable wastes in rack sacs and plastic bags

APPENDIX 4

Interview questions with waste service providers

Theme	Questions to service providers
Organisation of SWM practices from waste collection to final disposal for various waste sources	1. What types of equipment used for waste storage and collection? If trucks are used, how many does your company possess? 2. Is waste separated at source? 3. How often do you collect the waste? 4. What is the mode of payment? 5. What waste treatment methods does your company have and who are the customers?
Major challenges to SWM in Kigali City	1. What problems do you face regarding waste generation, collection and transportation, treatment and disposal? 2. What do you see that slows down the development of waste management systems in Kigali City?
Challenges in enforcement of regulatory requirements for the management of waste	1. How do you interact with institutions that have waste management in their responsibilities? 2. How is compliance of regulations and guidelines by households and service providers monitored? 3. What are the reasons for non-compliance if any?
State of solid waste management in Kigali City	How do you see the future of waste management in Kigali City?

Responses of waste service providers to interview questions under various themes

Theme	Statements of service providers
Organisation of SWM practices from waste collection to final disposal for various waste sources	- We collect waste from households, restaurants, pubs, office buildings and supermarkets using trucks for transportation - We collect waste from households, restaurants, pubs and markets using two trucks and wheelbarrows. These are used in areas with no access road

	- We use trucks for waste collection. Wheelbarrows which are especially used in areas with no road access - Rack sacs are mainly used for waste storage in middle and low income households and the waste is mixed - We sell plastic bags to our clients for waste storage. We salvage the plastic bags upon collection and recycle them into new products. We provide different coloured plastic bags: black for organic waste, blue for plastic, metal and glass, yellow for paper and cardboards. Waste separation at source is not always practiced - The mode of payment depends on the frequency of waste collection which is also measured by the quantity of waste produced and the location from waste source to the disposal site. The fee also increases with the social standing of the area - Waste is sorted at a transfer station and organic wastes composed of banana peels and sugar cane peels are processed into briquettes. These are sold to prison institutions - We only process waste into compost when we have the market
Major challenges to SWM in Kigali City	- There is a lack of standard payment for household waste collection that the resident should pay to private companies and this slows down our business - We lack technical and financial capacity to produce briquettes that could satisfy the available market. We only manage to process 276 tonnes of briquettes per year for one prison institution - People are not faithful in paying waste collection fees. Others refuse to use the service and most of these are the ones that dump waste in undesignated areas

Challenges in enforcement of regulatory requirements for the management of waste	- Some companies are registered and licensed without the fulfilment of permitting regulations which lead to disorganised waste collection systems. This problem result into poor service in certain areas and accumulation of uncollected waste - There is no regular follow-up by relevant authorities of the implementation of existing rules and guidelines concerning waste services at household level. Monitoring is mainly observed for commercial entities such as restaurants and hotels - Fines are not issued for non-compliance as there since there are no measures to control clandestine dumping - There are no specific regulations to protect the citizen against the harmful effects of waste
State of solid waste management in Kigali City	- We have regular interactive meetings with local authorities from where we operate. Often conflicts arise between local authorities and companies and decisions are made without mutual agreement. These meetings occur without a regulatory representative to put up strategies that could improve our services. There should be consultation between all stakeholders, public sector, private sector and the civil society. The meetings could help in exposing the problems and finding solutions collectively which can improve the existing policies. - We lack financial capacity to upgrade our services. Access to bank loans is limited since local banks are not familiar with waste management industry. - Currently, there is no NGO’s that is engaged in solid waste awareness campaigns or educational programmes on the subject. NGO’s role in SWM can improve solid waste management practices.

APPENDIX 5

Educational and awareness leaflet for waste separation at source

The need for waste separation at home! Let your food waste be a source of electricity generation and contribute in protecting the environment and public health from the harmful effects of waste

What kind of organic waste to sort out together?

Organic waste to be sorted in the same garbage bag:

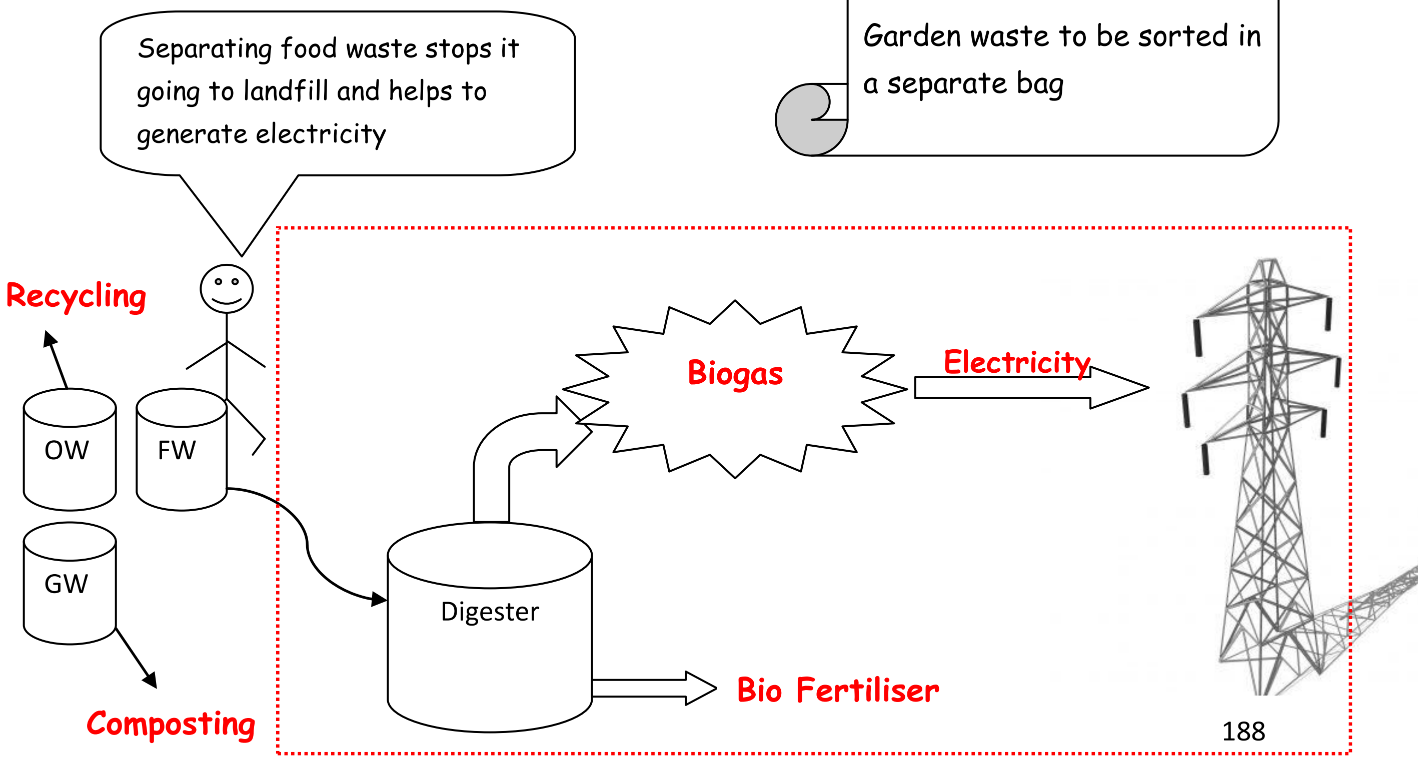
- Peelings of fruits
- Vegetable peels and cuttings, tuber peels
- Spoilt vegetables and fruits
- Cooked and uncooked meat, bones and fats
- Bread, egg shells
- Used tea leaves, tea bags and coffee grounds
- All cooked left-over food

Do not mix!!!

Other type of wastes to be sorted in the same garbage bag:

- Plastic bags
- Glass, bottles and cans
- Cardboard, newspapers and papers
- Nappies or sanitary waste
- Batteries
- Pharmaceuticals and cosmetics
- Ash and sand

Garden waste to be sorted in a separate bag



APPENDIX 6

Table 1: Scenario building of household food waste capture rate

Social economic level	X_1	X_2	X3	X4	X5	X6	X7
Low income area	1000	2500	3000	5000	7000	9000	10430
Middle income area	3000	9000	15000	25000	35000	45000	59362
High income area	20000	35000	40000	50000	62000	72000	74965
Total (kg/d)	24,000	46,500	58,000	80,000	104,000	126,000	144,757
% of source separated food waste	10	20	25	35	45	55	63
Number of households	9,015	17,467	21,787	30,051	39,067	47,331	54,377

X= waste capture rate variable

Cost information for waste collection

$1= 615 RWF (Xe 2013)

Average household waste collection costs

Labour requirements: 2400 households are served by 45 labourers. Average cost per labourer is $65 per month.

Costs of waste collection are shown in Table 2.

Table 2: Annual waste collection cost

Description	**Data ($/ tonne)**	**Annual cost ($) per household**
Waste collection from waste source to disposal for a distance between 15 -30 km	17.88	
Labour		14.63

Other costs concern the application fee for waste collection licence is $8.38 while the licence costs $25.16.

Worst case viable scenario of 30,051 households served and best case scenario of 54,377 households served (Table 1) will require 563 labourers and 1020 labourers respectively.

Awareness tools and garbage bags

Leaflets are often used by waste management companies to educate the public about good SWM practices. The Average cost for a leaflet is $0.37. A garbage bag for waste collection costs $39 per year per household.

Income information for waste collection

Table 3: Revenues from household waste collection (SS-OFMSW)

Socio-economic level	**Total revenue ($/hh)**
Low[a]	68
Middle	88
High	156

[a]Low income area is exempted from payment of waste collection service

Table 4: Revenues from SC-OFMSW collection (Hotels, restaurants, canteens, markets, supermarkets, Drink processing industry)

Source	**Number of selected sources**	**Annual revenue per unit ($)**	**Total annual revenue ($)**	**Total annual revenue ($/tonne)**
Major institution/canteen	3	390	1,170	
Major Restaurant/Hotel	8	585	4,680	
Major public market	6	12,683	76,098	
Major Supermarket	8	390	3,120	
Drink processing industry	1	1171	1,171	
Total income			86,239	5

Dimensions of AD plant equipments, capital costs and operation costs

1) Shaft shredding system for food waste

A shaft shredding system that process food waste with density > 1050 kg/m^3 and moisture content of 83% and with an output of 20 mm costs £62,300 or $98,276 (quote from UNTHA Shredding Technology).

2) Digesters

Lochhead AD development requires 14 concrete tunnel digesters for 46,000 tonnes/yr of feedstock and full capital costs for 1 tunnel equal to £85,185 ($136,296)

Feedstock inflow of 46,536t/yr requires 14 tunnels and total capital costs of $1,908,144

3) Digester volume (m^3) = substrate (m^3/yr) x [Retention time (days)/365] (German Solar Energy Society and Ecofys 2005)

Density of food waste = 0.75 t / m^3

With TS = 19%, the feedstock volume = 0.25 m^3/t

1 m^3 cost $60.3

A retention time of 28 days usually requires post-digestion storage time of 2 months.

Required digester volume = 11,634 x 30/365) = **956 m^3**

4) Post-digestion storage $_{(m3)}$ = Substrate $_{(m3/yr)}$ x [Required storage time (months)/12] – Size of digester $_{(m3)}$ (German Solar Energy Society and Ecofys 2005)

Required post-digestion storage = 11,634 m^3 x (2/12) – 956 m^3 = **983 m^3**

Total Costs = 60.3 ($/$m^3$) x 983 m^3 = **$59,275**

There are two post-digestion halls which comprise of an enclosed aeration hall to stabilise digestate removed from digesters and a storage hall for digestate after being treated in the pasteurisation halls. A reception hall is also of similar size and of similar costs.

5) Size of biogas storage $_{(m3)}$ = Daily biogas production (m^3/day) x storage capacity for CHP use (German Solar Energy Society and Ecofys 2005)

With 65% of methane gas,

Required size of biogas storage = 13,367 m^3/d x (20/100) = 2,673 m^3/d

Average costs= $73.58/ m^3 ; Total costs = 2,673 m^3 x $ 73.58/ m^3 = $196,679

6) Capital and O&M costs for AD facilities

In this study, CHP gas engine will be operational for 8500 hours. O&M costs = 0.009p/kWh (Department of energy and climate change 2013)

Operation and maintenance costs for other AD facilities are estimated separately at 3% of total investment costs (DGS and Ecofys 2005; Mata-Alvarez 2003) minus project development costs.

7) Other equipments

- Desulphilisation: 350Euro ($ 455)
- Condensate trap: 6,000-10,000 Euro (average: 8,000 Euro = $10,400)

(DGS and Ecofys 2005)

8) Heat demand of the plant

DGS and Ecofys (2005)

Heat demand of the digester (MJ/yr) = Mass of substrate (t) x Specific heat (kJ/kg/K) x (T digester – T fresh) x 130%

Specific heat of the substrate is equal to that of water = 4.2 kJ/kg/K; average temperature of the fresh heat is 15^{o}C; 3.6 MJ/kWh

Heat demand (MJ/yr) = 70,172 x 4.2 x (37–15) x 130% = 8,429,097 MJ/yr

= 2,341,416 kWh /yr

9) Connection to the national grid

Connection through medium voltage system (Example: 30kV) costs $50,000 per km using wooden poles. The distance between the AD plant site and the grid connection point is approximately at 1km.

Table 3: Feed-in Tariff for hydropower plants

N^{o}	Tariff (in USD)per kWh	Plant installed capacity
1	16.6 cents	50 KW
2	14.3 cents	200 KW
3	12.9 cents	500 KW
4	11.8 cents	1 MW
5	8.7 cents	3 MW
6	7.2 cents	5 MW
7	6.7 cents	10 MW

10) Transportation of anaerobic digestate

A digestate amount equal to 90% of the feedstock volume is produced by anaerobic digestion. The digestate will be sprayed on forest land, at approximately 1000 m from the plant site. The unit cost of transportation is $\$11/m^3$.

11) Insurance and taxes

- The annual costs for insurance of the installation are estimated at 0.5% (for circumstances beyond one's control of total installation costs (DGS and Ecofys 2005; Mata-Alvarez 2003).

- Corporate income tax is 30% of taxable business profit (Rwanda Revenue Authority no date)

12) Incentives provided in the income tax law (nº 16/2005 on direct income)

- **Investment allowance (Article 26**): An investment allowance of 50% of the invested amount in new or used assets is deductible in the first tax period of purchase and or of use of such asset if the business is located outside Kigali or falls within the priority sectors determined by the Investment code such as energy.

Therefore, plant tax allowances would be $4,774,577 x 50/100 = $2,387,289

- **Profit tax discount (Article 41):** seven per cent discount (**7%**) if the investor employs more than nine hundred (900) Rwandans and if only the investor maintains the employees for at least six months during a tax period.

Source: Rwanda Revenue Authority (no date)

13) Project development

- Costs include licence fees, contracts and consultancy services. The costs were estimated taking into account project of similar scope in Rwanda such as the development of sanitary landfill and recycling centre. Approximately $50,000 is estimated for project development

Source: UNDP (2012)

APPENDIX 7

ECONOMIC MODEL							
Constant values							
Anaerobic digestion process type	Batch						
Technical life time (years)	20						
Retention time (days)	30						
Operating temperature (oC)	37						
TS (%)	19						
VS (% of TS)	90.12%						
Degradation of VS (%)	88.00%						
Methane potential (m^3/ton VS_{added})	398						
Household food waste capture (%)	63	55	45	35	25	20	10
Annual food waste collection							
Households	54,377	47,331	39,067	30,051	21,787	17,467	9,015
SS-OFMSW (t)	52,836	45,990	37,960	29,200	21,170	16,973	8,760
SC-OFMSW (t)	17,336	17,336	17,336	17,336	17,336	17,336	17,336
SS-OFMSW+SC-OFMSW annual flow (t)	70,172	63,326	55,296	46,536	38,506	34,309	26,096
Feedstock volume (m^3)	17,543	15,832	13,824	11,634	9,627	8,577	6,524
SS-OFMSW+SC-OFMSW annual VS (t)	12,015	10,843	9,468	7,968	6,593	5,875	4,468
Annual collection costs							
Awareness costs ($/hh)	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Total awareness costs							

	20,119	17,512	14,455	11,119	8,061	6,463	3,336
Labour costs ($/t)	15	15	15	15	15	15	15
Total labour costs	1,052,585	949,890	829,440	698,040	577,590	514,628	391,440
Waste storage facilities costs ($/hh)	39	39	39	39	39	39	39
Total waste storage facilities costs	2,140,279	1,845,911	1,523,609	1,172,007	849,705	681,229	351,602
Transportation costs ($/t)	18	18	18	18	18	18	18
Total transportation costs	1,254,681	1,132,269	995,328	837,648	693,108	617,553	469,728
Tax on waste collection ($)	0	0	0	0	0	0	0
Total ($)	4,467,664	3,945,583	3,362,832	2,718,814	2,128,464	1,819,873	1,216,106
Anaerobic Digestion							
Annual amount of VS fed into digester (tonnes)	12,015	10,843	9,468	7,968	6,593	5,875	4,468
Gross annual methane gas yield	4,782,154	4,315,587	3,768,353	3,171,370	2,624,136	2,338,081	1,778,410
Gross methane gas yield (m^3/tonne)	68						
CHP efficiency (%)	90	90	90	90	90	90	90
Net annual methane gas output (m^3)	4,303,939	3,884,029	3,391,518	2,854,233	2,361,722	2,104,273	1,600,569
Energy value (MJ/m^3)	36	36	36	36	36	36	36
Energy value (MJ)	154,941,804	139,825,031	122,094,636	102,752,386	85,021,991	75,753,830	57,620,472
Energy value (MJ/kWh)	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Net energy potential (kWh)	43,039,390	38,840,286	33,915,177	28,542,330	23,617,220	21,042,731	16,005,687
Energy (CHP)							

Operational hours	8500	8500	8500	8500	8500	8500	8500
Heat utilisation efficiency (%)	57	57	57	57	57	57	57
Electricity utilisation efficiency (%)	33	33	33	33	33	33	33
Annual Process heat (kWh)	24,532,452	22,138,963	19,331,651	16,269,128	13,461,815	11,994,356	9,123,241
Digester heat demand (MJ/yr)	8,429,097	7,606,719	6,642,156	5,589,904	4,625,341	4,121,137	3,134,652
Digester heat demand (kWh)	2,341,416	2,112,978	1,845,043	1,552,751	1,284,817	1,144,760	870,737
Digester heat loss (30% of digester heat demand)	702,425	633,893	553,513	465,825	385,445	343,428	261,221
Residual heat production (kWh)	21,488,612	19,392,092	16,933,094	14,250,551	11,791,553	10,506,168	7,991,284
Electricity potential (kWh)	14,202,999	12,817,294	11,192,008	9,418,969	7,793,683	6,944,101	5,281,877
Onsite electricty use (%)	10	10	10	10	10	10	10
Onsite electricty use (kWh)	1,420,300	1,281,729	1,119,201	941,897	779,368	694,410	528,188
Net Electricity production (kWh)	12,782,699	11,535,565	10,072,807	8,477,072	7,014,314	6,249,691	4,753,689
Net energy exports (kWe)	1,504	1,357	1,185	997	825	735	559
Net energy export (kWh/tonne)	182						
Digestate							
Whole digestate (m^3) (90% of feedstock volume)	15,789	14,248	12,442	10,471	8,664	7,719	5,872
Whole digestate disposed (minus 10% recirculation)	14,210	12,824	11,197	9,424	7,797	6,947	5,284
Capital costs for AD facilities ($)							
Land	0						

Reception hall	59,275							
Mechanical pretreatment facilities/shredder	98,276							
Digestion tunnels ($136,296/tunnel)	1,908,144							
Pasteurisation tunnels	545,184							
Post-digestion halls ($59,275 per hall)	118,550							
Biogas storage	196,679							
Other equipments including safety measures	10,855							
CHP plant ($1258/kWe)	1,254,607							
Grid connection	15,000							
Civil works	13,000							
Subtotal	4,219,570							
Engineering and construction (8% of hardware costs)	337,566							
Subtotal	4,557,135							
Project development	50,000							
Total ($)	4,607,135							
Annual running costs of the AD plant								
O&M (3% of capital costs)	136,714							

Annual O&M for CHP ($0.01/kWh)	430,394	388,403	339,152	285,423	236,172	210,427	160,057
Annual insurance (0.5% of total installation costs)	22,786						
Digestate transportation costs ($11/m^3)	156,309	141,059	123,172	103,659	85,772	76,422	58,129
Total ($)	746,202	688,961	621,823	548,582	481,444	446,349	377,685
Gross annual income on waste collection							
SS-OFMSW collection service ($)	5,710,830	4,970,844	4,102,919	3,156,092	2,288,166	1,834,478	946,828
SC-OFMSW collection service ($/tonne)	5						
SC-OFMSW collection service ($)	86,239						
SC-OFMSW+SS-OFMSW collection ($)	5,797,069	5,057,083	4,189,158	3,242,331	2,374,405	1,920,717	1,033,067
Electricity price-Current FIT ($/kWh)	0.118	0.118	0.118	0.118	0.123	0.123	0.129
Annual electricity sales	1,508,358	1,361,197	1,188,591	1,000,294	862,761	768,712	613,226
(+ 10% FIT)	1,659,194	1,497,316	1,307,450	1,100,324	949,037	845,583	674,548
(+ 20% FIT)	1,810,030	1,633,436	1,426,310	1,200,353	1,035,313	922,454	735,871
(+30% FIT)	1,960,866	1,769,556	1,545,169	1,300,383	1,121,589	999,326	797,194
Allowance 50% of capital investment	2,303,568						

APPENDIX 8

__**Running costs discounted at 14% over 20 years of plant life time**__

Discount rate	14%							
Waste capture rate		**63**	**55**	**45**	**35**	**25**	**20**	**10**
Year	PWF	5,213,866	4,634,544	3,984,655	3,267,396	2,609,909	2,266,222	1,593,791
1	0.88	4,573,567	4,065,389	3,495,312	2,866,137	2,289,393	1,987,914	1,398,063
2	0.77	4,011,901	3,566,131	3,066,063	2,514,155	2,008,240	1,743,784	1,226,371
3	0.67	3,519,211	3,128,185	2,689,529	2,205,399	1,761,614	1,529,635	1,075,764
4	0.59	3,087,027	2,744,022	2,359,236	1,934,561	1,545,275	1,341,785	943,652
5	0.52	2,707,919	2,407,037	2,069,505	1,696,983	1,355,505	1,177,005	827,765
6	0.46	2,375,367	2,111,436	1,815,355	1,488,582	1,189,039	1,032,460	726,110
7	0.40	2,083,655	1,852,137	1,592,417	1,305,773	1,043,017	905,667	636,938
8	0.35	1,827,768	1,624,681	1,396,857	1,145,415	914,927	794,445	558,718
9	0.31	1,603,305	1,425,159	1,225,313	1,004,750	802,568	696,881	490,103
10	0.27	1,406,408	1,250,140	1,074,836	881,360	704,007	611,299	429,915
11	0.24	1,233,691	1,096,614	942,839	773,123	617,550	536,227	377,119
12	0.21	1,082,185	961,942	827,051	678,178	541,710	470,375	330,806
13	0.18	949,285	843,809	725,484	594,893	475,184	412,610	290,181

14	0.16	832,706	740,183	636,389	521,836	416,828	361,938	254,544
15	0.14	730,444	649,283	558,236	457,751	365,639	317,490	223,285
16	0.12	640,741	569,547	489,681	401,536	320,736	278,500	195,864
17	0.11	562,053	499,602	429,545	352,224	281,347	244,298	171,810
18	0.09	493,029	438,248	376,794	308,969	246,796	214,297	150,711
19	0.08	432,482	384,428	330,521	271,025	216,488	187,979	132,202
20	0.07	379,370	337,217	289,930	237,741	189,901	164,894	115,967
PW		34,532,115	30,695,189	26,390,893	21,640,391	17,285,765	15,009,483	10,555,888
Electricity exports (kWh)		12,782,699	11,535,565	10,072,807	8,477,072	7,014,314	6,249,691	4,753,689
Feedstock(tonnes)		70,172	63,326	55,296	46,536	38,506	34,309	26,096
Production costs ($/kWh)		2.70	2.66	2.62	2.55	2.46	2.40	2.22
Investment costs ($/kWh)		0.36	0.40	0.46	0.54	0.66	0.74	0.97
Investment costs ($/t)		65.65	72.75	83.32	99.00	119.65	134.29	176.55
Production costs ($/t)		492.10	484.72	477.27	465.02	448.91	437.49	404.50

Running costs discounted at 10.7% over 25 years of plant life time

Discount rate	10.70%							
Waste capture rate		**63**	**55**	**45**	**35**	**25**	**20**	**10**
Year	PWF	5,213,866	4,634,544	3,984,655	3,267,396	2,609,909	2,266,222	1,593,791
0	1.00	4,607,135						
1	0.90	4,709,906	4,186,580	3,599,508	2,951,577	2,357,641	2,047,174	1,439,739
2	0.82	4,254,658	3,781,915	3,251,588	2,666,285	2,129,757	1,849,299	1,300,577
3	0.74	3,843,413	3,416,364	2,937,297	2,408,568	1,923,900	1,670,550	1,174,867
4	0.67	3,471,917	3,086,146	2,653,385	2,175,762	1,737,940	1,509,079	1,061,307
5	0.60	3,136,330	2,787,847	2,396,915	1,965,458	1,569,955	1,363,215	958,723
6	0.54	2,833,180	2,518,380	2,165,235	1,775,481	1,418,207	1,231,450	866,056
7	0.49	2,559,331	2,274,959	1,955,949	1,603,867	1,281,126	1,112,421	782,345
8	0.44	2,311,952	2,055,067	1,766,891	1,448,841	1,157,296	1,004,897	706,725
9	0.40	2,088,485	1,856,429	1,596,108	1,308,800	1,045,434	907,766	638,415
10	0.36	1,886,617	1,676,991	1,441,832	1,182,294	944,385	820,023	576,707
11	0.33	1,704,261	1,514,897	1,302,468	1,068,017	853,103	740,762	520,964
12	0.30	1,539,531	1,368,471	1,176,574	964,785	770,644	669,162	470,609
13	0.27	1,390,724	1,236,198	1,062,849	871,531	696,155	604,482	425,121
14	0.24	1,256,299	1,116,710	960,117	787,291	628,867	546,054	384,030

15	0.22	1,134,869	1,008,771	867,314	711,193	568,082	493,274	346,910
16	0.20	1,025,175	911,266	783,482	642,451	513,172	445,595	313,379
17	0.18	926,084	823,185	707,752	580,353	463,570	402,525	283,088
18	0.16	836,571	743,618	639,343	524,257	418,763	363,618	255,726
19	0.14	755,710	671,742	577,545	473,584	378,286	328,471	231,008
20	0.13	682,665	606,813	521,721	427,808	341,722	296,722	208,679
21	0.12	616,680	548,160	471,293	386,458	308,692	268,042	188,509
22	0.11	557,073	495,176	425,739	349,103	278,854	242,133	170,288
23	0.10	503,228	447,313	384,588	315,360	251,901	218,729	153,828
24	0.09	454,587	404,077	347,414	284,878	227,553	197,588	138,960
25	0.08	410,648	365,020	313,834	257,342	205,558	178,489	125,528
PW		44,889,891	39,902,094	34,306,740	28,131,344	22,470,564	19,511,520	13,722,086
Electricity exports (kWh)		12,782,699	11,535,565	10,072,807	8,477,072	7,014,314	6,249,691	4,753,689
Feedstock(tonnes)		70,172	63,326	55,296	46,536	38,506	34,309	26,096
Production costs ($/kWh)		3.51	3.46	3.41	3.32	3.20	3.12	2.89
Investment costs ($/kWh)		0.36	0.40	0.46	0.54	0.66	0.74	0.97
Investment costs ($/t)		65.65	72.75	83.32	99.00	119.65	134.29	176.55
Production costs ($/t)		639.71	630.11	620.42	604.51	583.56	568.71	525.83