Potential of biogas production from biowaste in Kenya and its contribution to environmental sustainability

Charles K. Nzila

PhD thesis (2011)

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Thesis submitted in fulfilment of the requirements for the degree of Doctor (PhD) in Applied Biological Sciences

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Dedication

To my dear sister Tanu ...forever in memory......time lapses but your grace is everlasting.

Contents

Abbreviation index

AD	Anaerobic Digestion
AMP	Autochthonic Mixed Population
AOPs	Advanced Oxidation Processes
ASTM	American Society of Materials and Testing
BBE	Biowaste-based biogas energy
BETs	Biowaste energy technologies
BMP	Bio Methane Potential
BVC	Biogas Value Chain
CAMARTEC	Centre for Agricultural Mechanization and Rural Technologies
CAN	Calcium Ammonium Nitrate
CDM	Clean Development Mechanism
CED	Cumulative Energy Demand
CEENE	Cumulative Exergy Extracted from the Natural Environment
CER	Certified Emission Reduction
CHP	Combined Heat and Power
CO_2 eq	Carbon dioxide equivalent
CPF	Chemical Pre-treatment and Fractionation
CSTR	Completely Stirred Tank Reactor
DAP	Di-ammonium Phosphate
DMDO	Dimethyldioxirane
EBR	Energy Breeding Ratio
EnVOC	Environmental Organic Chemistry and Technology
EPP	Energy Payback Period
FERS	Fossil Energy Replacement Saving
GHG	Green House Gas
GWh	Gigawatt hour
HDPE	High-density polyethylene
HRT	Hydraulic Retention Time
ILUC	Indirect land use change
IPCC	Inter-governmental Panel on Climate Change

IPPs	Independent Power Producers
KCl	Potassium Chloride
KIHBS	Kenya Integrated Household Budget Survey
KShs	Kenya Shillings
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
LeAF	Lettinga Associates Foundation
LUC	(Direct) Land use changes
MAP	Mono-ammonium Phosphate
MCSA	Multi Criteria Sustainability Assessment
MCSF	Multi criteria Sustainability assessment Framework
MDG	Millennium Development Goal,
MU_K	Moi University Kenya
NEP	Net Energy Product
NPK	Nitrogen, Phosphate and Potassium
POMS	Peroxymonosulphates
PTFE	Polytetrafluoroethylene
ppmv	parts per million by volume
PU	Polyurethane
PVC	Polyvinyl chloride
REDSEA	Renewable Energy Database System for East Africa
SSA	Sub-Saharan Africa
TOE	Tonnes of oil equivalent
TPF	Thermal pre-treatment and fractionation
TSP	Total Superphosphate
TWh	Terawatt hour
UASB	Up-flow Anaerobic Sludge Blanket
ULV	Ultra Low Volume
VLIR -UOS	Flemish Interuniversity Council – University Development Cooperation

Notation index

$RO_{CH4real}$	Realizable residue methane yield (m^3/yr)
$\sum_{i=1}^{184}(X_i * a_{ij})$	Sum of the product of characterisation factor and amount of resource
RO_{CH4max}	Maximum residue methane potential (m^3/yr)
$\sum_j X_j * m_j$	Sum of the product of characterisation factor and amount of resource
a_{ij}	amount from reference flow *i* (kg, MJ, Nm^3, m^2.a) necessary to obtain product *j*.
a_j	amount of resource *j* (kg, Nm^3, m^2.a)
CDE_{fossil}	Carbon dioxide equivalent for fossil fuel (kg CO_2eq/$Nm^3{}_{biogas}$)
CED	cumulative energy demand (MJ)
$CEENE_j$	cumulative exergy extracted from the natural environment for a product *j* (MJ_{ex})
DM	dry matter ratio
E_{fossil}	Fossil Resource Energy content (MJ/kg)
EBR	Energy breeding ratio
EPP	Energy payback period (years)
FERS	Fossil energy replacement savings ($/ Nm^3)
G_{fossil}	energy content of fossil fuel (LHV of kerosene)
$GHG_{biogas\ prod}$	Green house gas emitted due to biogas production (kg CO_2eq/$Nm^3{}_{biogas}$)
$GHG_{replaced\ fossil}$	Green house gas potential for the fossil fuel replaced by biogas (kg CO_2eq/$Nm^3{}_{biogas}$)
Kitenge	predominantly high ethnic value cotton fabric from Africa
LHV	Lower heating value (MJ/L, MJ/m^3)
P_{fossil}	Price of fossil resource ($/kg)
Q	average annual produce of a given crop (tonnes per yr)
Q_{fossil}	Fossil resource used during biogas production (kg/Nm^3)
R	universal gas constant (8.31kPa.L/mol.K)
RO_{max}	maximum residue output potential (tonnes DM/yr)
RO_{real}	realizable residue potential (tonnes DM/yr)
T	temperature (303K)
V'_{biogas}	biogas volume produced by the substrate (L)
V''_{biogas}	biogas volume in the blank reactor (L)
V_{biogas}	biogas volume (L)
V_{CH4}	methane volume (L or m^3/g VS)
V_h	reactor headspace volume (L)

V_{mol}	molar gas volume at 303K (L/mol)
X_i	characterisation factor of the i^{th} reference flow (MJ_{ex}/kg, MJ_{ex}/MJ, MJ_{ex}/Nm^3, MJ_{ex}/m^2.a)
δ	residue use factor
δ_{fossil}	density of fossil fuel (density of kerosene = 0.81kg/L)
ΔP	change of pressure in the reactor (kPa)
η_{CH4}	fraction of CH_4 in the biogas
β	Residue to crop produce ratio

Chapter 1

General Introduction

1.1 Motivation and aim of the study

The global trends in human development, energy demand and production present an imminent energy crisis as a result of declining quality and quantity of fossil fuels coupled with the unprecedented rising crude oil prices. This unfolding scenario has led to a looming transition towards a biobased economy that demands greater attention to alternative energy sources and revision of existing technologies. It is therefore critical now not only to focus on sustained economic use of the existing limited resources but to identify new technologies and renewable resources that have the potential to cater for the increasing energy demand in addition to possessing other positive attributes such as being sustainable, globally available, easy to exploit as well as having the capacity to positively contribute towards actualization of the United Nations millennium development goals (MDGs).

Biogas technology is one of the biobased technologies that have continued to receive renewed attention coupled with limited protagonism. The major advantages of biogas technology includes its ability to add value to biomass chains by closing material cycles and allowing an improved energy efficiency in addition to its economical feasibility and sustainability potential as well as its ability to meet all the MDGs. Besides, biogas technology is mature and offers a very attractive route to utilize diverse categories of biomass and the inherent biowaste for meeting energy needs as well as contributing to resource and environmental conservation. Biogas is particularly suited for meeting small scale energy needs, can contribute to environmental sanitation and biogas technology is simple enough to avoid production limitations. Consequently most developing countries especially in Africa and Asia have continued to adopt biogas technology in greater numbers.

Accounting for the sustainability of the biogas technology is of great importance when considering the possible role of the technology in the society in general and the biomass cascades in particular. The contribution of biogas technology can vary according to the different scales and substrates that can be used as well as the different end uses of the biogas and digestate. Furthermore, the feasibility of the biogas chain and its configuration as well as the contribution of the alternative fuel replaced by the biogas can vary according to context features. Hence, in order to fully exploit the potential of biogas technology it is important to fully analyse the biogas value chain, establish its potential and evaluate its sustainability. However a lack of methodology in this respect is quite evident and in spite of the maturity of the biogas technology, there are knowledge gaps pertaining to the technological potential and sustainability.

In view of the presented concerns, the main goal of this thesis is to evaluate the potential of biogas production from biowaste and evaluate its contribution to environmental sustainability. The research reviews the biogas value chain, analyses the biowaste energy potential and evaluates the sustainability of biowaste-based biogas energy from a multi criteria perspective.

1.2 Scope and overview of the different chapters

This dissertation has been built as an integration of the state of the art, sustainability assessment framework development, experimental research and systems analysis. The overview of the different chapters and the structure of this thesis research are explained in this part and visualised in Figure 1.1. The state of the art analysis and development of sustainability assessment framework phase was done with the objectives being (i) to gain insight in the biogas value chain and biowaste energy, and (ii) to formulate a sustainability framework for biowaste energy assessment. Both aspects are covered in **chapters 2** and **3**. In **chapter** 2 an analysis of the biogas value chain is done considering the recent advances challenges and opportunities within the main segments of the chain. C**hapter** 3 presents an overview and development of the sustainability assessment framework for biowaste energy assessment. The sustainability concept and the multi-criteria sustainability framework are brought into perspective.

The experimental phase of the thesis derives from two goals, which are (i) to characterise biowaste material for biogas production and (ii) to evaluate the biowaste energy potential from preselected feedstock. The foregoing two aspects are covered in **chapters 4** and **5** of this thesis. **Chapter** 4 presents a characterisation of selected agricultural residues and segregated textile effluents for biogas and nutrient recovery. The gas quality as well as the fertilising characteristics and value of the digestate are explained. **Chapter** 5 goes into further detail and examines the biowaste energy potential in Kenya. The potential of biowaste to spur an energy revolution in Kenya is then evaluated.

In the last part of this thesis, the focus is on the system analysis phase as applied to the multi criteria sustainability assessment of biogas energy. The specific objectives in this case were (i) To develop and apply a multi criteria system in the assessment of biogas sustainability and (ii) To analyse the potential contribution of biowaste-based biogas energy in Kenya considering the cotton industry as a case study. The foregoing aspects are covered in chapters 6 and 7 of this thesis. In **chapter** 6, a multi criteria system focusing on technical, economic and environmental sustainability dimensions is designed and applied to comparatively analyse the common biogas production systems in Kenya. The analysis follows the life cycle sustainability assessment methodology and links the biogas energy to the infrastructures of production. In **chapter** 7 an assessment is carried out on the added value of biowaste valorisation to the environmental profile of the African *Kitenge*. The assessment considers the impacts of valorisation of biowaste to recover energy and nutrients in the form of biogas and digestate respectively within the context of the carbon footprint and cumulative energy demand of the African *Kitenge*. Following the detailed analysis in the preceding chapters, in **chapter** 8 the overall discussion and perspectives are presented.

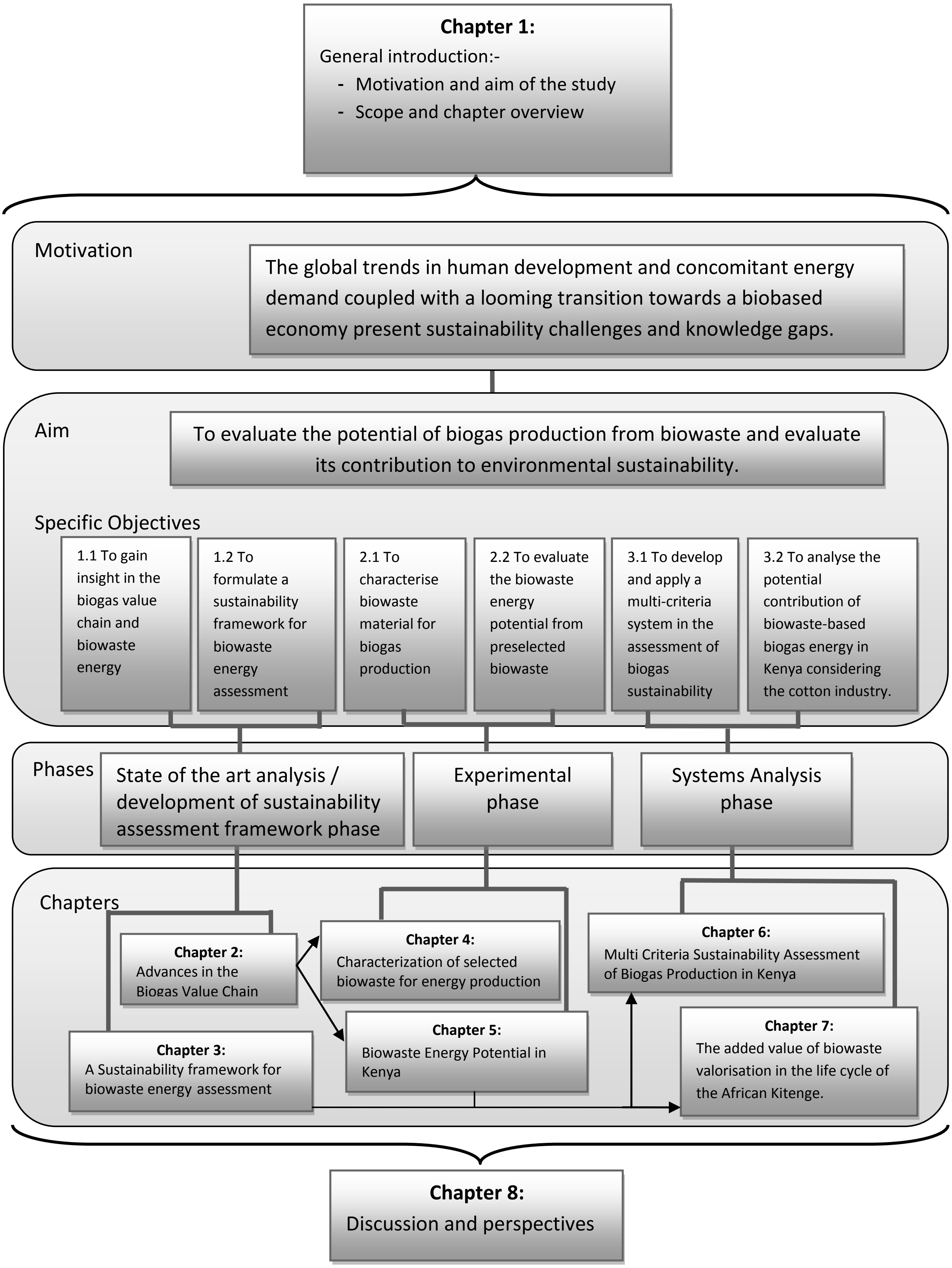


Figure 1.1: General overview and organization of this dissertation

Chapter 2

Advances in the Biogas Value Chain

Abstract

The handling of different cadre of organic matter (feedstock) and subsequent preparation for anaerobic digestion as well as the post-treatment and use of the resultant digestate and biogas broadly constitute the biogas value chain (BVC). The BVC offers many possibilities to convert organic residues, hitherto considered as waste with minimal economic value, into methane and digestate which are respectively high value energy and soil nutrient carriers. The transposition of waste residues from no economic value status into high economic value status has thus necessitated a paradigm shift in the way organic resources (and their residues) are currently handled. In many southern regions, the abundant supply of readily available biomass and the need for secure, affordable, reliable, clean and sustainable energy supply are regarded as some of the key drivers in the exploitation of the BVC. Over the last ten years a lot of insight in the BVC has been witnessed as the fundamental knowledge of anaerobic digestion continue to accumulate. This study evaluates the recent advances in the BVC with a view of highlighting the key challenges and opportunities from a sustainability point of view. The study integrates the BVC production oriented advances with targeted valorisation from the life cycle analysis “cradle to cradle” perspective. One main conclusion is that the BVC as presently constituted suffers from lack of coordination as witnessed by the apparent fragmentation in most of the BVC advances. Consequently while most advances might appear promising from a given BVC fragment point of view, when the entire chain is brought into perspective substantial sustainability issues tend to arise which puts into question the sustainability of the BVC. It is hence opined that substantial sustainability insight for most BVC advances is still required if the BVC is to incontrovertibly remain vital to the sustainable energy matrix.

Redrafted from: Charles Nzila, Jo Dewulf, Henri Spanjers, Henry Kiriamiti and Herman van Langenhove. The Biogas Value Chain - A Review of Recent Advances, Challenges and Opportunities. Biomass and Bioenergy (under review)

2.1 Introduction

2.1.1 General perspectives of the biogas value chain

The 21st century has been characterised by unprecedented awareness in the realms of social, economic and environmental sustainability. Moreover it is now common knowledge that the planet earth can no longer sustain the human way of life indefinitely. Climate change in general and global warming in particular are widely regarded as the major threat to the environment. Consequently there are concerted efforts globally to urgently mitigate global warming. The preservation of natural resources, reduction of greenhouse gases and sustainable use of green energy are some of the key fronts being employed for combating climate change. In this perspective, biogas technology is widely regarded as a vital tool due to its recognised social, economic and environmental benefits. The production and use of biogas has become a topical issue in the last decade (Deublein and Steinhauser 2008, Nzila et al. 2010, Ranalli 2007, Sims 2004, Yu Liu 2008) though way back in 1630 BC Babylonians had knowledge of “marsh gas” produced from decaying organic matter (Sims 2004). However, significant valorisation of the biogas only materialised in 1895 (The University of Adelaide 2010), when biogas from anaerobic digestion was first recovered for use in street lamps in Exeter, England as well as during the Second World War when energy supplies were extensively reduced. Over the years the biogas technology has continued to be exploited to convert organic residues, hitherto considered as waste with minimal economic value, into methane which is a higher value energy carrier. The transposition of waste residues from no economic value status into high economic value status has thus necessitated a paradigm shift in the way organic resources are currently handled (Nzila et al. 2010).

The handling of different cadre of organic matter (feedstock) and subsequent preparation for anaerobic digestion as well as the post-treatment and use of the resultant digestate and biogas broadly constitute the biogas value chain (BVC). The BVC offers many possibilities to stabilize and add value to biomass through anaerobic digestion thus producing energy and organic fertilizer in the form of methane and nutrient rich digestate respectively. Besides, the stabilizer organic matter is also believed to exert an important impact on soil fauna as well as soil fertility. Over the last ten years a lot of insight in the BVC has been witnessed as the fundamental knowledge of anaerobic digestion continue to accumulate. A generalised and simplified scheme of the BVC (Figure 2.1) comprises of 5 segments namely collection and handling of feedstock substrates, storage, pre-treatment, fractionation and anaerobic digestion, post treatment and energy and nutrient recovery from the end products. Depending on the nature and composition of the feedstock substrates (biowaste, industrial by-products, and energy crops) the delivered material must frequently undergo extensive pre-treatment and fractionation steps so as to remove contaminants besides rendering them suitable for efficient anaerobic digestion. Post treatment of the anaerobic digestion products through stabilisation of the digestate and biogas cleaning and upgrading facilitates safe use of the digestate as bio fertilizer as well as efficient use of the biogas as an energy carrier having several applications such as production of heat and electricity as well as in transportation.

The performance of the BVC is highly dependent on systems conditions especially the type of feedstock as well as biogas and digestate reuse (Berglund and Borjesson 2006). Technically, the sustainability of the BVC depends to a large extend on the overall performance of the entire chain as a single unit hence poor performance of any of the chain's segments has an adverse effect on the whole chain. Anaerobic digestion is however the backbone of the BVC owing to its capability to convert biowaste and other organic matter into high value energy and nutrient carriers. The higher utilization efficiency of the anaerobic digestion products render the process to have more eminence than the conventional means of waste disposal whereby large quantities of biomass energy are wasted because of low utilization efficiency (Nzila et al. 2010, Yu et al. 2008).

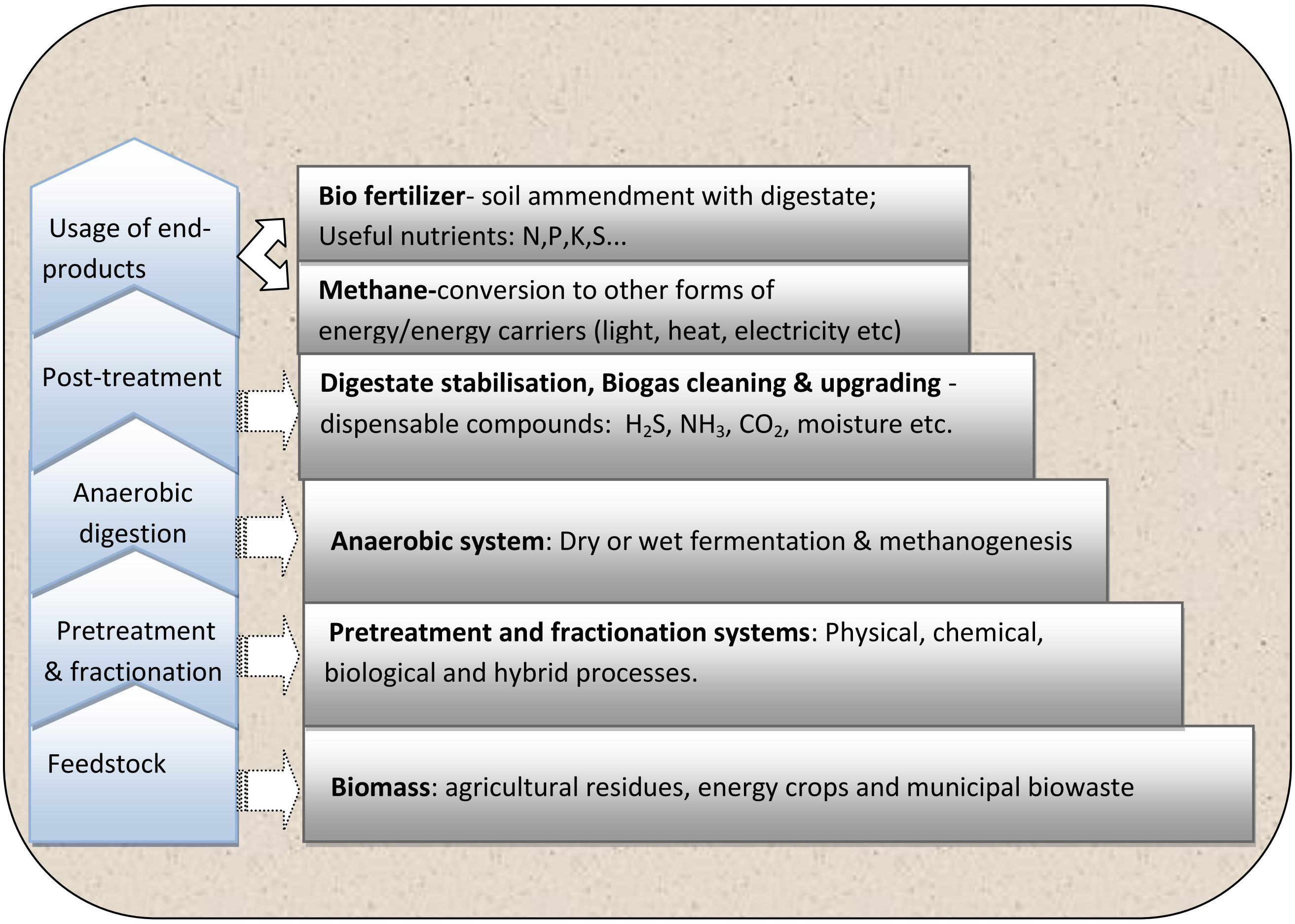
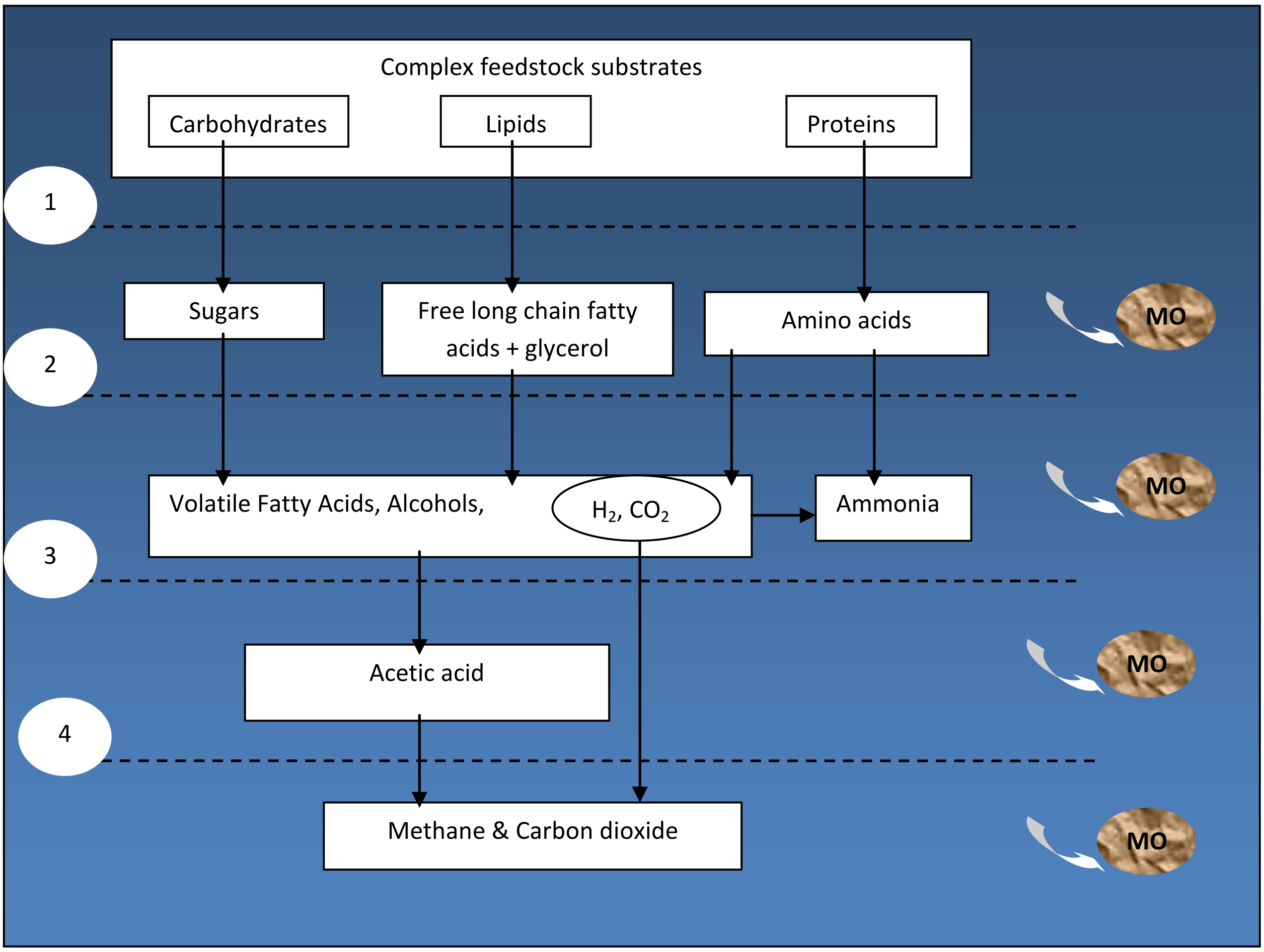


Figure 2.1: A simplified scheme of the main segments in the Biogas Value Chain.

Currently anaerobic digestion is generally agreed to consist of a series of stepwise reactions which are catalysed by mixed groups of prokaryotes such as bacterial and Achaea species through which organic matter is converted to the main products that is methane and carbon dioxide (Figure 2.2). The complex organic matter (carbohydrates, lipids and proteins) are initially disintegrated and hydrolysed (step 1; pH 5-6) to oligomers or monomers (simple sugars, free long chain fatty acids, glycerol and amino acids), which are then metabolised by fermentative bacteria (step 2; pH 5.5-6.7) with the production of hydrogen (H_2), carbon dioxide (CO_2), ammonia, alcohols (methanol and propanol) and volatile fatty (organic) acids from preceding acetate, propionate and butyrate. The volatile fatty acids, other than acetic acid, are converted to methanogenic precursors (H_2, CO_2 and acetic acid) by the syntrophic acetogen bacteria (step 3; pH 5.5-6.7). Finally during the methane (CH_4) synthesis phase (step 4; pH 6.6-8.0), the methanogenic organisms produce CH_4 from the preceding simple molecules.



(MO = microbial biomass)

Figure 2.2: Simplified schematic representation of the anaerobic digestion steps (Deublein and Steinhauser 2008, Ranalli 2007)

Normally all the serial metabolization steps are rate controlled by the slowest members of the consortia. The entire anaerobic digestion process thus proceeds as long as each subsequent class of organisms processes the organic intermediates at least as fast as they are produced. Accumulation of any inhibitory substances, unbalanced nutrient composition and the quality of the substrate in general have a considerable influence on the dynamic equilibrium of the bacterial species involved in anaerobic digestion. Nevertheless through the biochemistry pathways of anaerobic digestion and methane gas production (Deublein and Steinhauser 2008, Ranalli 2007) the BVC offers many possibilities to stabilize and add value to low value organic material thus producing clean energy and organic fertilizer in the form of methane and nutrient rich digestate, respectively. Besides, BVC systems bring about a net reduction of greenhouse gas emissions because methane emissions that would otherwise result from land filling as well as uncontrolled decay of biowaste are avoided (Nzila et al. 2010, Taherzadeh and Karimi 2008).

Over the last decade much insight in the BVC has been gained as fundamental knowledge of anaerobic digestion continued to accumulate. Several reviews dealing with the separate segments of the BVC have been published. Sahlstrom (Sahlstrom 2003) investigated the end product segment of BVC by reviewing the survival of pathogenic bacteria in organic waste used in biogas plants with a view of providing a means of assessing the bio security risk associated with using digested residue as fertilizer. Other studies have reviewed the lower segments of BVC in the very recent past and indeed considerable efforts seem to have been dedicated to advancements in the lower segments of the BVC (Bagge et al. 2005, Beszedes et al. 2009, Carrere et al. 2008, Gautam et al. 2009, Sahlstrom 2003, Taherzadeh and Karimi 2008, Ward et al. 2008, Yadvika et al. 2004, Yuan and Bandosz 2007). In addition, Table 2.1 presents a categorization of different studies on separate parts of the chain. Sustainable advancements in the BVC however demand seamless harmony among the separate chain segments thus any progress in the lower segments should translate into enhanced value at the upper segment without any undue shift of environmental, economic or social burden. The major challenge thus becomes the development of the ability to sustainably and effectively convert the intrinsically variable feedstock at the bottom segment of the BVC into value added useful products at the top segment of the BVC as efficient as for example the current petrochemical refinery but without duplication of its inherent negative impacts.

Table 2.1

Categorization of selected literature in terms of the BVC segment investigated

Investigated BVC component	Remarks	Reference
Feedstock pre-treatment and anaerobic digestion	Technological factors such as energy balance, CO_2 emission and requirements for downstream processing need to be factored when selecting pre-treatment techniques.	(Beszedes et al. 2009, Carrere et al. 2008, Mtui G. Y. S. 2009, Taherzadeh and Karimi 2008, Ward et al. 2008, Yadvika et al. 2004)
Feedstock pre-treatment and usage of end product (digestate)	There are bio security issues associated with the use of digestate due to the presence of recalcitrant spore – forming bacteria as well as bacterial recontamination and re-growth after pasteurisation and anaerobic digestion. Concerns have been reported pertaining to prevalence of increased mosquitoes after the installation of biogas plants.	(Bagge et al. 2005, Gautam et al. 2009, Sahlstrom 2003)
Usage of end product (biogas)	There are waste handling concerns associated with waste products of biogas cleaning.	(Lei et al. 2007, Yuan and Bandosz 2007)

In most domestic biogas projects in many developing countries there is a general consensus for fixed dome, floating drum and the plug flow through (tubular) biogas reactors as the major anaerobic digester designs of choice. However due to the fragmented manner in which the BVC has been presented in the past and the apparent lack of clear benchmarks, it is currently not possible to agree on for instance the most appropriate way of enhancing biogas production or using the biogas. A typical case is the fact that while some pre-treatment processes significantly enhance biogas production, they simultaneously either render the digestate unfit for soil amendment or leave behind a very large footprint of primary fossil energy (Zhao et al. 2009). Similarly, some BVC aspects such as the non valorisation of digestate do not translate into significant savings in avoided emission of CO_2. The present study thus strives to address these concerns as transparently as possible, and to the best of our knowledge, it is the first one to integrate the lower and the upper segments of the BVC. The objective of the present work is thus to evaluate the recent advances in the BVC with a view of highlighting the key challenges and opportunities from sustainability point of view. Hence, the study integrates the production oriented advances with targeted valorisation from the life cycle analysis “cradle to cradle” perspective.

2.1.2 Recent advances in the biogas value chain

Feedstock is essentially the cogwheel of the BVC with the lignocellulosic and animal manure based feedstock being the most abundant in nature. Worldwide there is an estimated annual production of 10 – 50 billion dry tons of lignocellulosic biomass accounting for about 50% of the global vegetal biomass yield (Galbe and Zacchi 2002) with an estimated methane potential of 50 – 250 billion cubic metres or 174 – 870 TWh of electricity (Acaroglu et al. 2005, Nzila et al. 2010). The recent advances in the biogas value chain can be viewed from two intrinsic perspectives namely BVC - production oriented advances and BVC - valorisation based advances (Figure 2.3) whereas the linkage between the two perspectives can be expressed in terms of their technical, economic and environmental sustainability which constitute the vertices of the sustainability triangle.

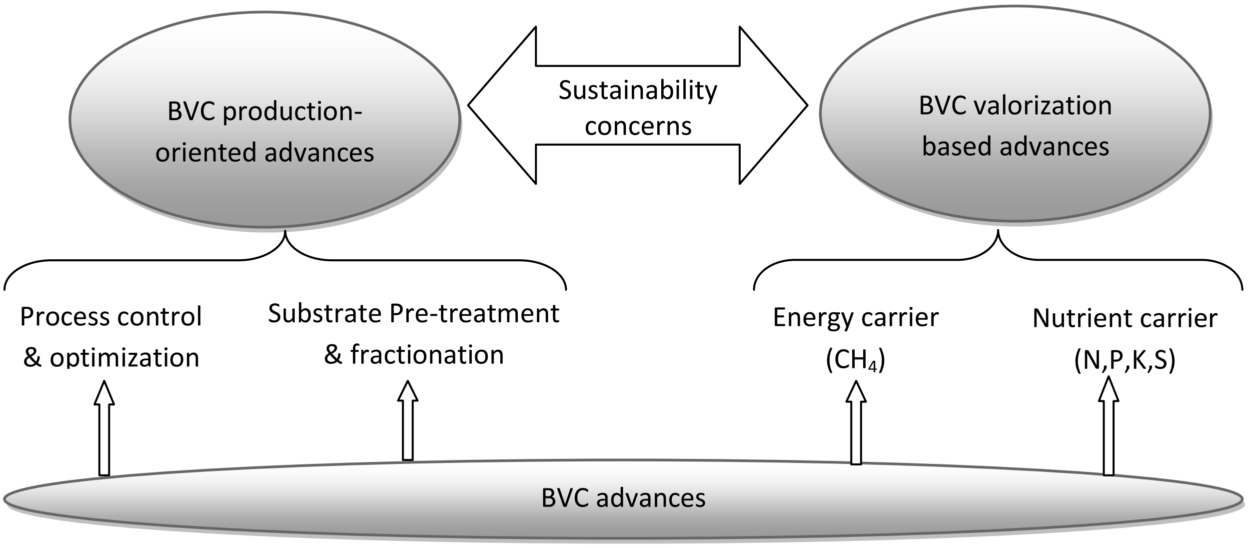


Figure 2.3: Inter-linkage of the advances in BVC

There are several advances in biogas production however the most important ones can be further classified into substrate pre-treatment, fractionation, process control and optimization whereas the most important advances in biogas valorisation can be explained from the viewpoint of biogas and digestate as sustainable energy carrier and organic fertilizer, respectively.

2.2 BVC - production oriented advances: substrate pre-treatment and fractionation

2.2.1 The role of feedstock pre-treatment and fractionation in a BVC

In the perspective of value addition, the BVC is strongly influenced by feedstock restrictions such as substrate complexity, quality, quantity, year-round cost-effective availability as well as pre-processing needs. During the anaerobic digestion step of complex substrates such as lignocellulosic biomass, hydrolysis is normally considered to be the rate limiting step. Consequently in a typical BVC, biogas production depends for the most part on the biodegradability and hydrolysis rate of the complex substrate (Fernandes et al. 2009). Adequate substrate digestibility and homogeneity is thus a principal requirement in anaerobic digestion systems. The feeding of homogenous substrates to the anaerobic digester allows undisturbed mass transfer between solid particles, liquid and gaseous phases inside the digester. Moreover, the biogas bubbles formed are thus immediately released from the cells or aggregates. Feedstock pre-treatment helps to avoid detrimental effects of pH variations, high concentrations and inherent inhibitions thereby enabling rapid biodegradation of the substrate. Feedstock fractionation on the other hand may serve to disintegrate and increase the surface area of the substrate thus enhancing its reactivity with the mixed consortia of enzymes during anaerobic digestion thus leading to enhanced biogas production. On a molecular level pre-treatment and fractionation may also help to “unlock” otherwise unbiodegradable molecules and make available smaller degradable molecules (Figure 2.4). Hence, depending on the anaerobic digestion system used (wet, dry or semi dry) as well as substrate composition and physical state (Ranalli 2007) fairly different degrees of substrate pre-treatment and benefits thereof can be attained.

After mechanical separation and milling, the biomass substrate must be pre-treated or fractionated with a view of enhancing the otherwise rate limiting hydrolysis step of anaerobic digestion. The basic pre-treatment technique is substrate equalisation by dilution. Other extended pre-treatment and fractionation techniques can be broadly classified as physical, chemical, biological and hybrid processes. Physical pre-treatment techniques include mechanical comminution and thermal disintegration. Based on prevailing practices, other less common physical pre-treatment techniques include steam explosion, ultrasonic, microwave and irradiation disintegration. Chemical pre-treatment techniques include chemical pre-hydrolysis, Advanced Oxidation Processes (AOP) and Solvent Processes. The main biological pre-treatment techniques include ensiling and enzymatic hydrolysis whereas hybrid pre-treatment techniques entail different combinations of physical, chemical and/or biological pre-treatment techniques.

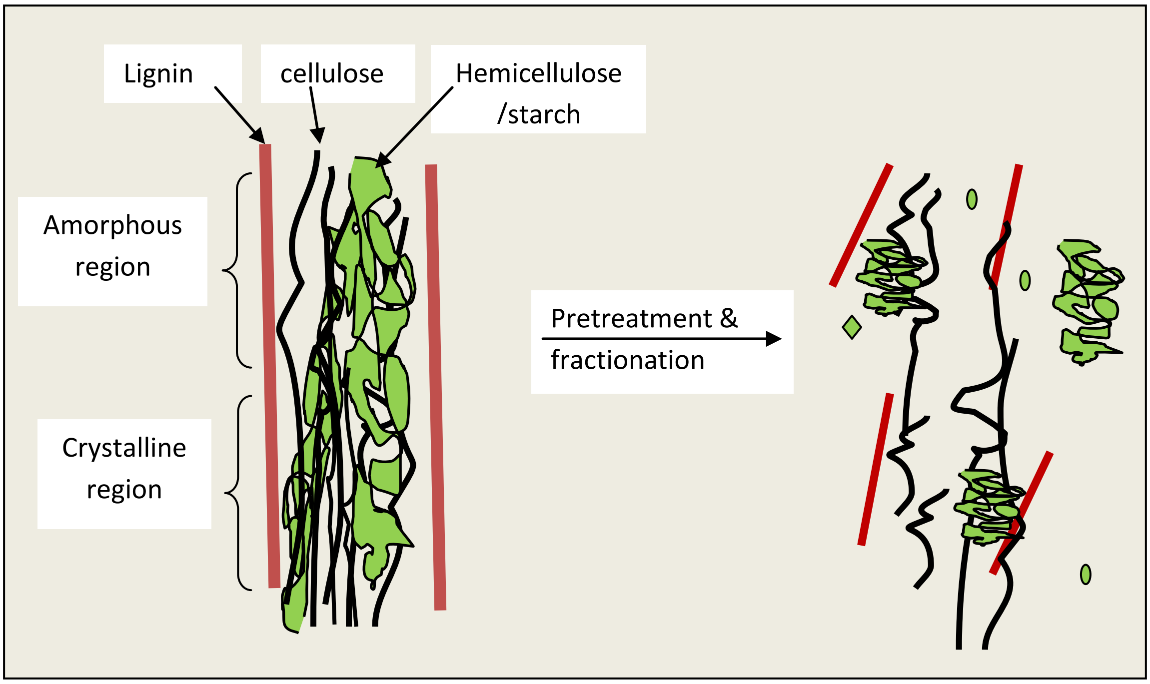


Figure 2.4: Feedstock pre-treatment and fractionation

2.2.2 Physical pre-treatment and fractionation techniques

(i) Mechanical fractionation

Some substrates such as the bulky, fibrous or lignocellulosic type demand homogenisation and size reduction or fractionation via chopping or crushing of coarse and bulky materials (De Sousa et al. 2004, Guerra et al. 2006, Mani et al. 2004, Mtui G. and Nakamura 2005, Qi et al. 2005) so as to achieve faster biodegradation besides mitigating the clogging of piping systems, scum formation and formation of bottom layers which reduces the effective reactor volume. Other benefits of mechanical comminution include increased surface area which facilitates any subsequent physicochemical and biochemical pre-treatments and fractionation. Biomass mechanical comminution techniques that have proved to be successful based on research evidence include mechanical chopping (De Sousa et al. 2004), hammer milling (Mani et al. 2004), grind milling (Mtui G. and Nakamura 2005), roller milling (Qi et al. 2005), vibratory milling (Guerra et al. 2006) and ball milling (Mtui G. and Nakamura 2005, Mtui G. Y. S. 2009). A comparison of the different biomass mechanical comminution techniques (Table 2.2) on the basis of their relative merits and demerits (in terms of respective energy requirements, yield, bulk density and moisture loss in the feedstock among other aspects) shows that a careful consideration is necessary when choosing the requisite technique for feedstock comminution. For instance milling can be employed to alter the inherent ultra structure of lignocelluloses hence increasing the surface available for enzymatic fractionation besides lowering the degree of crystallinity of the feedstock thus consequently making the material more amenable to hydrolysing enzymes. Mechanical comminution has proved to be suitable for applications at full-scale biogas plants with reported increase in Bio Methane Potential (BMP) in terms of methane yield (ml CH_4/gVS) of up to 25% being reported for lignocellulosic substrates (Hartmann et al. 2000). However the process suffers from two main drawbacks namely significant energy requirement and inability to remove lignin which restricts the access of the hydrolysing enzymes to cellulose besides inhibiting cellulose enzymes. Furthermore substrate shearing, as opposed to mechanical comminution, has been shown to be the one responsible for effective "unlocking" of substrates for anaerobic digestion. However since not all biogas feedstock are suitable for shearing it is therefore necessary to combine mechanical comminution with other fractionation techniques such as thermal, chemical and biological pre-treatment so as to effectively enhance biogas production in the BVC. Nevertheless, in spite of the rather common full-scale application of mechanical comminution, the technology is generally considered to be energy intensive.

(ii) Thermal pre-treatment and fractionation (TPF)

Feedstock TPF is principally geared towards controlled heat disintegration or fractionation of the ultra chemical structure of various kinds of substrates using a wide range of temperatures ranging from 60 to 270°C. Generally the technology is among the widely investigated topics as a strategy for enhancing the hydrolytic step of anaerobic digestion as well as control of disease vectors in the digestate (Sahlström Leena et al. 2008). Feedstock TPF at temperatures between 100 and 190°C for 20 minutes to 1 hour are the most common with a reported enhancement in terms of methane yield (ml CH_4/g COD_{in}) of between 25% and 76% for both batch and CSTR mesophilic and thermophilic setups at 20 to 40 days HRT (Bougrier C. et al. 2005, Bougrier C. et al. 2006, Bougrier Claire et al. 2008, Bruni et al. 2010, Carrere et al. 2008, Mladenovska et al. 2006, Sustec 2010, Valo et al. 2004). Treatments applied at temperatures below 100°C are considered as low temperature TPF whereas treatments at temperatures above 100°C are considered as high temperature TPF. Generally, feedstock TPF is essentially a necessity for the BVC during winter time due to low hydrolysis rate at low temperature however in most southern tropical regions the average temperatures are rather moderate thus the technology is still not considered to be essential hence it has not yet gained a foothold. Nevertheless from sustainability point of view, feedstock TPF is seen to be energy intensive hence necessitating the need to balance the energetic expense with the increment in biogas production. Any energy expenditure during TPF at the lower end of the BVC system must be balanced with the energy gain as extra biogas production at the upper end of the BVC system (Bruni et al. 2010). Besides, CO_2 emissions as a result of feedstock TPF should also be factored and balanced with avoided emission of CO_2 during the use of the biogas and digestate.

Table 2.2

Merits and demerits of different biomass mechanical fractionation techniques for biogas production feedstock

Fractionation technique	Merits	Demerits	References
Mechanical chopping	• Less moisture loss (<0.5%) • Applicable to both dry and wet materials.	• High energy costs, • Does not facilitate shearing of the feedstock	(De Sousa et al. 2004) (Hartmann et al. 2000)
Hammer milling	• Higher product bulk density • Versatile-able to process a wide range of materials	• Higher moisture loss (1-3%) • Higher risk of dust explosion • High energy costs	(Mani et al. 2004)
Grind milling	• Higher product surface area.	• Not effective on wet materials • Higher risk of dust explosion High energy costs	(Mtui G. and Nakamura 2005)
Roller milling	• High output per kWh • Less moisture loss (<0.5%)	• Low bulk density • Not effective on fibre or 2-dimensional materials	(Qi et al. 2005)
Vibratory milling	• High product bulk density	• Low output per kW • High energy costs	(Guerra et al. 2006)
Ball milling	• Applicable to both dry and wet materials	• Higher energy costs • High tendency of cellulose recrystallization after milling	(Taherzadeh and Karimi 2008)

2.2.3 Chemical pre-treatment and fractionation (CPF)

Feedstock CPF is oriented towards the application of chemicals for swelling, solubilisation and hydrolysis of BVC feedstock prior to anaerobic digestion. There is a wide variety of compounds used in CPF such as swelling agents, dilute acids, organosolvents, oxidants, etc. Generally, feedstock CPF for renewable energy generation in the form of biogas has for a long time been considered to be economically unattractive due to the high price of chemicals in comparison to the low economic value of the resultant biogas energy (Pavlostathis and Gossett 1985). Moreover, some chemicals such as organic solvents are thought to have possible negative effect on subsequent (biochemical) fermentation / methanogesis process. However, the current increased demand for renewable energy sources and concomitantly increasing energy prices leads to a renewed interest in CPF (Fernandes et al. 2009). The recent advances in feedstock CPF for biogas production are mostly oriented towards chemically induced hydrolysis, advanced oxidation and solvent processes.

(i) Chemical hydrolysis and fractionation processes

Chemical hydrolysis and fractionation process of feedstock refers to the controlled use of alkaline or weak acid media at either elevated or room temperature to hydrolyse and fractionate the feedstock. Alkaline fractionation entails the use of alkaline solutions such as NaOH (Neves et al. 2006a, Qi et al. 2005), $Ca(OH)_2$ or ammonia to remove lignin and hemicelluloses from the complex feedstock and convert the resultant cellulose into the corresponding alkali-cellulose that is more readily accessed by enzymes. While the removal of lignin greatly enhances cellulose accessibility by enzymes, the presence of lignin in the anaerobic digestion broth is reported to impede methanogenesis (Taherzadeh and Karimi 2008) hence a careful balance of lignin solubilisation and cellulose hydrolysis and fractionation is required so as to mitigate inhibition of methanogenesis by lignin. When alkaline hydrolysis of feedstock is carried out at low temperatures the process takes a relatively long time and requires high concentration of the base. Several studies have pointed out that alkaline hydrolysis is the best known method for enhancing the biodegradation and methane production from complex materials such as the wide array of feedstock used in BVC systems(Lin et al. 2009, Neves et al. 2006a). Acid hydrolysis on the other hand necessitates the use of weak acids as catalysts to hydrolyse the complex polymers of BVC feedstock such as cellulose and hemicellulose polymers into simple sugars such as hexose and pentose (the so called C6 and C5 sugars). The feedstock conversion into sugars greatly enhances the biomethanation process. Unlike alkaline hydrolysis, acid hydrolysis is not effective in dissolving lignin, but it sufficiently disrupts the lignin structure hence increasing susceptibility of cellulose to enzymatic hydrolysis. The effectiveness of chemical fractionation in a BVC system depends largely on feedstock factors such as lignin content as well as the potential for the formation of secondary biodegradation inhibitors such as ferric iron (van Bodegom et al. 2004), humic and fulvic acids (Steinberg et al. 2008).

(ii) Advanced Oxidation Processes

Advanced Oxidation Processes (AOPs) are basically a set of processes which make use of (chemical) oxidants whereby the main mechanism involve the generation of highly reactive free hydroxyl radicals (°OH) in sufficient quantity to affect the structure of both organic and oxidisable inorganic components. The °OH whose oxidation potential is 2.33 V is effective in destroying organic compounds because it is a reactive electrophile that reacts rapidly and non-selectively with nearly all electron-rich organic compounds (Stasinakis 2008). Once generated the °OH can attack an organic compound (R) by radical addition (Eq. 1), hydrogen abstraction (Eq. 2) and electron transfer (Eq. 3) (SES 1994). The AOPs can therefore completely mineralise organic matter to carbon dioxide and water which is not desired in BVC, and hence it is typically not necessary to operate to this level.

$$R + HO^{\circ} \rightarrow ROH \qquad (1)$$

$$RH + HO^{\circ} \rightarrow R^{\circ} + H_2\,O \qquad (2)$$

$$R^{n} + HO^{\circ} \rightarrow R^{n-1} + ROH^{-} \qquad (3)$$

There are many processes able to generate the highly reactive °OH species and the most common ones are:

- Chemical advanced oxidation processes using hydrogen peroxide (H_2O_2), ozone (O_3) or combinations of O_3 and H_2O_2, hypochlorite, Fenton's reagent (Fe^{2+}/H_20_2) etc. Combination of ozone with catalyst commonly referred to as heterogeneous catalytic oxidation processes (HCO) is a relatively new area that is gaining interest from both the research community and industry.
- Ultra-violet (UV) enhanced oxidation such as UV/O_3, UV/H_2O_2, UV/air, and photo catalysis (UV/catalyst (TiO_2)).
- Wet air oxidation and catalytic wet air oxidation (where air is used as the oxidant).

BVC feedstock pre-treatment by means of AOPs is designed to break down and open up the complex structure of organic matter rendering it easily accessible by the hydrolytic as well as fermentative bacteria. Generally the advanced oxidation of organic matter is essentially a balance between solubilisation and degradation. The main reagents of AOP reactions in BVC feedstock fractionation are ozone, hydrogen peroxide and air/oxygen in well defined dosages and combinations in neutral, acidic or alkaline media. In this perspective three main categories of AOP do suffice namely elevated temperature wet oxidation, ambient temperature wet oxidation and peroxidation.

(a) Elevated temperature wet AOP

The elevated temperature wet oxidation involves subjecting the feedstock material to hot water and an oxidising agent such as air, ozone or oxygen (Lissens et al. 2004). The operating temperatures are normally above 120°C (typically 148 – 200°C) for a period of about 30 minutes. In addition to oxidative reactions, the process leads to the formation of organic acids both of which serve to solubilise and degrade the complex organic polymers causing further fractionation thus making it predisposed to enzymatic hydrolysis. Elevated temperature wet oxidation can be carried out in both acidic and alkaline media (Silverstein et al. 2007). However the alkaline wet oxidation treatment comparatively yields less anaerobic biodegradation inhibitors such as phenols, furfural and furans (Martín et al. 2007). Lissens (Lissens et al. 2004) investigated the effect of wet oxidation on methane yield from several biowaste pre-treated by wet oxidation at temperatures of 185 – 220°C and oxygen pressure of 0 – 12 bar for 15 minutes prior to full-scale anaerobic digestion. The wet oxidation process is reported to have increased methane yield by approximately 35-40%. Similar findings were reported by (Liu H. W. et al. 2002) after steam fractionation of municipal Solid Waste (MSW).

(b) Low temperature wet AOP

Oxidation of BVC feedstock can be carried out at ambient temperature with the help of powerful oxidising agents such as ozone, peroxyacids, nitric and nitrous acids, chromates and permanganate ion. Ozone is the most preferred low temperature wet oxidising agent hence the process is commonly referred to as ozonation and it is one of the processes used to solubilise biological sludge (Bougrier C. et al. 2007). During pre-treatment and fractionation of the complex BVC feedstock, ozone reacts directly and selectively with the unsaturated bonds while at the same time it decomposes and generates radicals that oxidise the organic matter thus leading to solubilisation and mineralisation. As a consequence of the ozone treatment, the BVC feedstock becomes more accessible to microorganisms (Hyung et al. 2000). The main parameters for BVC feedstock ozonation are feedstock moisture content, particle size and ozone concentration in the gas flow. The optimum moisture content for effective ozonation is normally 30% while the optimum ozone dosage is around 0.15 g O_3/g TS or 2.5 g O_3/L (Bougrier C. et al. 2007) above which it causes a decrease in biogas yield. Ozonation is regarded as a promising BVC feedstock fractionation technique because apart from its potent disinfecting properties, the method does not leave acidic, basic or toxic residues in the treated material. Beszedez (Beszedes et al. 2009) investigated biogas production of ozone pretreated canned maize sludge and reported a 800% increase in methane production (mL/g DM) with a net energy product per gram of dry matter (NEP/g DM) balance of + 2000 J/g thus implying that the ozonation treatment was associated with an energy increase. However, ozonation of BVC feedstock might be expensive because a large amount of ozone is required (Sun and Cheng 2002) and since most ozone generators consume 7 kW/kg O_3, therefore economic sustainability is not foreseen.

(c) Peroxidation

Peroxidation refers to the use of peroxides for the fractionation of a substrate. The technique has been extensively investigated and it has been applied in industrial and domestic wastewater treatment especially in post treatment (Ahmadi et al. 2005, Badawy and Ali 2006). The free radical chemistry of peroxidation is quite complex however the classical mechanism of autoxidation i.e., the radical-chain process involving the three sequences of initiation, chain propagation and termination suffices to simplify the process. Peroxidation of feedstock causes substantial fractionation via solubilisation that is not accompanied by the production of the biodegradation inhibitors such as phenols, furfurals and furans as in the case with wet oxidation (Martín et al. 2007) thus the process improves the susceptibility of cellulose to enzymatic hydrolysis. Several peroxidation techniques have been applied with great promise: from the well-known Fenton peroxidation (Neyens and Baeyens 2003) to novel reactions involving peroxymonosulphate (POMS), dimethyldioxirane (DMDO) (Dewil et al. 2006), sodium hypochlorite/hydrogen peroxide mixture (Day and Chung 2009) and alkaline peroxide. The major benefit of BVC feedstock fractionation via peroxidation includes increased biogas production ranging from 75% for Fenton treatment to 150% for DMDO treatment (Mishima et al. 2006, Saha and Cotta 2007). Generally in BVC feedstock pre-treatment and fractionation, AOP offer several advantages over biological or physical processes including (Mishima et al. 2006, Saha and Cotta 2007)

- The absence of secondary detectable wastes or probably unknown intermediates
- The ability to handle fluctuating flow and compositions of feedstock
- Unattended operation
- Improved disinfection of the BVC digestate

However the relatively high capital and operational cost of the AOPs (compared with biological and other chemical treatment) due to the use of costly chemicals and the high energy consumption as well as the suspected formation of unknown intermediates which could be toxic remain unsolved (Stasinakis 2008). Besides, the application of AOPs in the BVC is largely confined to laboratory trials only. Consequently the sustainability of AOPs as applied to the BVC is still a matter of conjecture.

(iii) Solvent processes

Solvent processes are techniques that employ the principle of differential solubilisation and portioning of the organic matter cell wall through disruption of the hydrogen bonding between micro fibrils. When applied on lignocellulosic feedstock, solvent fractionation facilitates the extraction and or decomposition of lignin and possibly hemicelluloses. When organic solvents or their aqueous solutions are used, the technique is commonly referred to as organosolv process. The most common organosolv processes are alcohol, organic acid and organic peracid as well as acetone pre-treatments and fractionation (Akgul and Kirci 2009, Brosse et al. 2009, Xu et al. 2006). The organosolv process has been widely investigated especially in the realm of pulp and ethanol bio refinery however it is regarded as being too expensive for feedstock fractionation at the moment. Organic solvents are generally expensive besides they inhibit hydrolytic enzymes hence they should be removed from the pre-treated feedstock before enzymatic hydrolysis but this leads to increased energy consumption. Consequently, in spite of the fact that organosolv fractionation provides an alternative for effectively increasing the enzymatic digestibility of lignocellulosic feedstock its application in the BVC system is not foreseen in the near future. For a detailed review and evaluation of the organosolv pre-treatment process the reader is referred to Zhao *et al.* (Zhao et al. 2009).

2.2.4 Biological pre-treatment and fractionation techniques

(i) Ensiling

Feedstock ensiling is the basic biological pre-treatment technique which facilitates conservation and storage of substrates. The technique of ensiling entails chopping of fresh crop matter and compacting in airtight silos whereby the autochthonic mixed population (AMP) of lactic acid bacteria and yeasts produces well degradable organic acids, but because of the low pH (about pH 4) the process is preserved from further microbial activity. However, after pH correction of the feedstock, the microbial process is reawakened during the subsequent anaerobic digestion whereby the hydrolysis and fermentation step tends to proceed faster thus making ensiled BVC feedstock suitable for biomethanation. The ensiling temperature has been found to influence subsequent biomethanation whereby ensiling of beet leaves at 5°C for up to 6 months was reported to enhance biomethanation by up to 39% as opposed to 6% biomethanation increase reported for similar ensiling at 10°C (Parawira et al. 2008).

Application of silage additives such as enhanced AMP cultures has began to take centre stage in ensiling of anaerobic digestion feedstock due to the need to enhance the ensiling process, increase storage stability of the silage as well as reduce the growth of yeasts, fungi and clostridia. Feedstock silage additives complement and enhance the existing natural process by lowering the pH values in silage and, in properly stored feed, preventing the growth of decomposition bacteria and fungi. Most bacteria-based silage additives are dosed in ultra low volumes (ULV) typically ranging from 10 to 100 ml per ton of fresh feedstock. Generally the ULV range of dosage serves to lower the cost of enhanced ensiling.

(ii) Microbial / Enzymatic fractionation

Microbial fractionation is a biochemical technique that utilizes both enzymes and fungi to degrade and solubilise the feedstock through selective delignification. Consequently a wide variety of some microbial communities such as bacteria, yeast and fungi strains are of interest in the biogas value chain because they enhance biogas production (Yadvika et al. 2004). Enzymatic fractionation utilizes both hydrolytic and oxidative enzymes derived mainly from bacteria and fungi. Three different types of enzymes are required to fractionate cellulosic feedstock. Endo-cellulase enzymes attack the non-crystalline regions of the feedstock chain to produce oligosaccharides. On the other hand exo-cellulase enzymes attack the chain ends producing cellobiose whereas β-glucosidase enzymes attack both oligosaccharides and cellobiose to produce glucose. Similarly, white, brown and soft rot fungi are used to predigest complex feedstock such as lignocelluloses whereby the brown rots are specific to cellulose, while white and soft rots are generally specific to both cellulose and lignin. The hydrolytic and oxidative enzymatic reactions are mainly carried out at 30 – 45 °C with low enzyme loading rate at reaction time of 6 – 26 hours (Mtui G. Y. S. 2009). The recent advances in biological pre-hydrolysis involve the design and use of highly efficient enzymes such as cellulase mixtures (Gusakov et al. 2007, Hui et al. 2008, Kristensen et al. 2009, Sathitsuksanoh et al. 2009, Silverstein et al. 2007, Zhang et al. 2009), cellulolytic strains of bacteria like actinomycetes and mixed consortia (Yadvika et al. 2004) and fungal-bacterial consortium (Li et al. 2002). Enzymatic hydrolysis of feedstock is generally geared towards various levels of cellulose fractionation (Kristensen et al. 2009, Yachmenev et al. 2009). However since lignin is not attacked by most enzymes and therefore shields the cellulose during hydrolysis (Jameel et al. 2008, Mansfield et al. 1999) enzymatic hydrolysis using optimised pre-treatment factors, recombinant enzymatic strains as well as possible recovery of the otherwise expensive enzymes still requires further scientific insight so as to acquire a foothold in the biogas value chain.

2.2.5 Hybrid pre-treatment and fractionation techniques

Hybrid pre-treatment is generally a combination of different physical, chemical and/or biological pre-treatment techniques with the aim of synergistically optimising the capacity presented by the individual techniques. The most common hybrid pre-treatment techniques which include the hydrothermal and thermo chemical pre-hydrolysis as well as the less common bio-thermo-chemical fractionation are discussed below.

(i) Hydrothermal fractionation

Hydrothermal fractionation refers to the process of subjecting feedstock, especially carbohydrates and lignocellulosic materials, to steam or hot water (above 160°C) normally under high pressure (above 20bar) as typically applied in the CAMBI^{TM} process (Anaerobi Digestion 2010). The process serves to solubilise and degrade the feedstock (Jin and Enomoto 2009) thus enlarging the accessible and susceptible surface area which in turn makes it more acquiescent to hydrolytic enzymes. The commonly used techniques of hydrothermal fractionation include hot water fractionation and steam-based fractionation (Liu H. W. et al. 2002).

Hot water hydrothermal fractionation, commonly referred to as Liquid Hot Water (LHW) hydrolysis entails subjecting the material to hot water under high pressure for a short duration of time. The optimum LHW conditions are reported as 220°C, 2 minutes residence time and at most 5% solid concentration. The LHW process causes hydration of cellulose and removal of hemicelluloses and some portion of lignin hence making the material amenable to biomethanation. LHW hydrolysis has been extensively applied in the pulp industry for several decades however the technique is yet to find a foothold in biogas production.

Steam-based hydrothermal fractionation also referred to as steam hydrolysis entails steaming with or without explosion (auto hydrolysis) (Alfaro et al. 2009). Steam explosion hydrolysis gives better results than steaming without explosion and it involves subjecting the material to steam under high pressure and hence high temperature for a short duration of time. Typical steam explosion conditions of pressure, temperature and time are respectively 15 – 22 bar, 160 - 260°C and 2 seconds to 20 minutes (Liu H. W. et al. 2002, Taherzadeh and Karimi 2008). The process of steam explosion is widely investigated and documented with approximately 40% improvement in methane yield being reported(Liu H. W. et al. 2002). Moreover, the potential of combining steam explosion with mechanical and or chemical treatment with a view to effectively enhancing anaerobic digestion and hence biogas production has been demonstrated in the production of biogas from activated sludge (Bougrier C. et al. 2006, Bougrier Claire et al. 2008, Mladenovska et al. 2006).

The advantages of hydrothermal fractionation include:

- The process is environment friendly since it does not necessarily require chemicals hence less production of neutralization residues.
- The fractionation reactors are comparatively cheap since they don't have to be made of chemical corrosion resistant materials.
- Size reduction of the feedstock is not obligatory hence the technique helps to avoid the highly energy demanding feedstock size reduction operation.
- The hydrothermally degraded material provides a rapid burst in methane production without a significant lag phase.
- It facilitates the sanitation of the feedstock through pathogen destruction.

The main disadvantage of hydrothermal fractionation and pre-treatment emanates from the elevated temperature of the pre-treated feedstock which may pose problems in subsequent biological pre-treatment such as enzymatic fractionation as well as during anaerobic digestion especially at mesophilic conditions hence necessitating an additional step for temperature correction.

(ii) Thermo chemical fractionation

Thermo chemical fractionation generally entails the synergetic incorporation of chemicals such as alkalis and sometimes acids into thermal pre-treatment of BVC feedstock in order to accelerate the rate limiting hydrolysis process and improve the biodegradability and hence the final biogas production of the substrates (Bruni et al. 2010). During anaerobic digestion of the raw lignin-rich feedstock, the cellulolytic enzymes hardly have access to the cellulose thus leading to retardation or even complete prevention of hydrolysis (Fernandes et al. 2009). Specialised pre-hydrolysis processes such as thermal and chemical techniques are particularly essential for effective pre-treatment of complex substrates such as the lignin encrusted cellulose which is hitherto fairly resistant to anaerobic degradation.

Chemical fractionation of lignocellulosic feedstock for renewable energy generation in the form of biogas is long considered to be economically unattractive due to the high price of chemicals in comparison to the low energy costs (Fernandes et al. 2009). However the application of thermo chemical fractionation drastically reduces the chemical usage besides the fractionation can be performed at temperatures lower than those employed in thermal pre-treatment alone, thus lowering the overall fractionation cost. Table 2.3 presents the optimum thermo-chemical fractionation conditions for various BVC feedstock classes based on the inherent lignin content. Fractionation of feedstock by means of NaOH and CaO might be interesting but it is generally constrained by either high temperature requirement or the need for a long residence time. On the other hand, fractionation by means of ammonia NH_4-N does not yield substantial biogas enhancement. Consequently fractionation by means of $Ca(OH)_2$ appears to be quite promising due to lack of chemical residue coupled with substantial methane enhancement, however large quantities of the chemical are required which essentially raises serious concerns from sustainability point of view.

Table 2.3

Optimum thermo/chemical fractionation conditions for selected chemicals

Chemical		**Temp.**	**Time**	**Feedstock**	**% CH_4**	**Remarks**	**References**
Formula	***Concentration***	**(°C)**	***(hrs)***	**lignin content**	**enhancement**		
NaOH	0.08 - 0.3 (2%)	190	0.33	Low	73% - 83%	Cheap, provides pH buffering	(Carrere et al. 2008, Lin et al. 2009, Neves et al. 2006a, Zheng et al. 2009)
$Ca(OH)_2$	10%	85	16	High	142%	Cheap and requires low temperatures	(Fernandes et al. 2009)
CaO	6 – 8%	15	600	High	59%	Leaves no chemical residue	(Bruni et al. 2010)
NH_3-N	3	120	0.66	Low/High	28%	Generates substantial inert COD	(Fernandes et al. 2009, Mladenovska et al. 2006)

Notes: concentration in g/gTS unless otherwise stated; CH_4 quantification based on m^3CH_4/KgVs

(iii) Bio-thermo-chemical fractionation

Combination of biological with both thermal and/or chemical treatments in the so called hybrid or compound pre-treatment techniques has not been sufficiently researched. Nevertheless, commercially available enzymes such as laccase, cellulase and hemicellulase (Bruni et al. 2010) can be used in a series-wise combination with steam and chemical pre-treatment of feedstock for biogas production. Improvement in biogas production (ml CH4/g VS) of up to 60% has been reported.

2.3 BVC - production oriented advances: Process control and optimization

2.3.1 Control of BVC process parameters.

(i) Substrate availability and consistency

Biogas production depends strongly on the physical state, composition and consistency of the used substrates. Theoretical gas production and composition can be computed from the input substrates in terms of proportional composition of proteins, fats, starch sugars and crude fibre (Table 2.4). Generally for micro organism (MO) nutrition, proteins and fats are easier to degrade whereas cellulose and hemicelluloses are difficult to degrade and lignin is not degradable. The control of substrate composition and presentation is thus essential in ensuring consistent biogas production. For proper solubilisation of organic materials in a BVC system, the ratio between solids and water should be 1:1 on unit volume basis. If the substrate mixture is too diluted there is a tendency of increased scum formation whereas if it is too thick, the flow of gas can be impeded.

Table 2.4

Theoretical polymer COD equivalent, biogas yield and composition (Nzila et al. 2010)

Substrate	Structural formula	COD equivalent	Biogas yield (L/g)	% CH_4	%CO_2
1g Carbohydrates	$C_6H_{12}O_6$	1.07g COD	0.75	50	50
1g Lipids	RCO_2H	2.91g COD	1.25	68	32
1g Proteins	$(C_4H_{1.6}O_{1.2})x$	1.5g COD	0.70	71	29

(ii) Digester seeding

Acetogenic and methanogenic bacteria are naturally present in organic waste albeit in small quantities although these microorganisms may be absent in case of certain pre-treatment techniques. However the acetogens proliferate faster than the methanogens that tend to develop rather slowly. Since it is essential to have a dynamic balance between the different microbial consortia during anaerobic digestion and methane production, it is therefore prudent during BVC digester start up to add a certain amount of seed sludge, up to 50%, from another digester as an inoculum. Seeding of the digester drastically reduces the start up period thereby ensuring prompt production of biogas.

(iii) Nutrients

Nutrients including N, P, K and trace elements such as nickel, cobalt, molybdenum, iron etc, are essential to enable the build-up of MO biomass. Different substrates contain the essential nutrients in various proportions with animal manure being widely regarded as one of the best mediums to supply the essential nutrients. However, excess of certain elements such as NH_4^+, Na, Cu, Ni etc, can be toxic since they inhibit bacterial metabolism hence curtailing or lowering methane production. For example, presence of NH_4^+ from 50 to 200 mg/L stimulates the growth of microbes, whereas its concentration above 1500 mg/L produces toxicity.

(iv) pH value

Methane producing bacteria are very sensitive to pH levels outside their optimum range. Generally it is essential to maintain the pH of the digester between 6 and 7 so as to ensure maximum methane production. Any pH levels below or above the optimum pH window drastically reduces or completely curtails methane production.

(v) Temperature

Methane production is influenced by temperature to a great extent since the enzymatic activity of the bacteria is largely temperature dependent. The methanogens are inactive in extreme low temperatures (under 10°C) whereas extreme elevated temperatures (over 70°C) cause destruction of the bacterial enzymes. The effect of extreme low temperatures can be mitigated by raising the temperature through heating of the digester as well as proper insulation of the digester. Temperature is thus a critical factor especially during the initial stage of methane formation however once metabolism occurs, the exothermic reaction becomes helpful for methane production. The commonly used temperature for mesophilic and thermophilic digestion are 25 – 40°C and 45 – 55°C respectively. Satisfactory gas production takes place in the mesophilic range with the optimum temperature being 35°C.

(vi) Anaerobic condition

Methanogenic microorganisms are strict anaerobes therefore BVC digesters should be made totally airtight so as to prevent the microbial consortia from becoming metabolically inactive as well as to avoid undue loss of the produced biogas and emission of methane to the atmosphere.

(vii) Volatile Fatty Acids (VFA) concentration

The concentration of organic VFA's such as acetic, propionic, butyric and valeric acid in the substrate leachate determines the potential and rate of methane production of the substrate. The amount of extraction of organic content from the substrate indicates its digestion pattern, i.e. its potential and suitability for anaerobic digestion. Therefore the characteristics of leachate in terms of specific VFA concentrations have a significant effect on the digester performance.

2.3.2 Process optimization

(i) Phased digestion

Phased digestion is a multi-step process where two-stage reactors or more are employed with a view to optimising the anaerobic digestion conditions. The digestion either takes place with both stages carrying out the same reactions but with different retention times or with the first stage only for the hydrolysis and acidification steps and the other for the methanogenic step. BVC systems that employ phased digestion do not require strict control of pH during the first stage hence hydrolysis and acidification are permitted to proceed to maximum completion thus supplying the methanogenic step with plenty of VFAs and alcohols.

(ii) Co digestion

At present many BVC projects in most developing countries are based on the singular use of animal manures (bio methane potential 0.15 – 0.35 m^3/kgVS) as the principal feedstock for the biogas digesters. Consequently, there is a concurrent general tendency to limit the propagation of BVC technology to livestock owners only thus excluding a bigger population especially in the rural regions where agricultural and other organic residues (bio methane potential 0.18 – 0.8 m^3/kgVS) are in abundance. Moreover in Africa, there seems to be insufficient knowledge and hence experience in the conversion of substrates other than the conventional manure (Mshandete A., Kivaisi, A. et al. 2004, Nzila et al. 2010). However, confining the BVC technology to a single feedstock limits the overall potential of the system. Therefore, there is a great need for biogas research and development aimed at enhancement of biogas process using efficient cost effective high rate bioreactors and different biogas feed stocks other than conventional animal manures used in traditional BVC systems (Mshandete A. M. and Parawira 2009). Co-digestion of organic wastes as a multi-feedstock process optimization technology is increasingly being applied in BVC systems for simultaneous treatment of several solid and liquid organic wastes. The multi-feedstock BVC approach has been under investigation in several developed countries (Nzila et al. 2010) where it has been reported to exhibit tremendous potential (Table2.5). The main advantages of this technology are improved methane yield because of the supply of additional nutrients from the codigestates, more efficient use of the BVC bioreactor and the production of nutrient rich digestate. Other advantages include increased digester buffering ability, dilution of inhibiting components that might be present in one of the feedstock as well as improved digestate quality. Co-digestion of organic fractions of municipal solid waste, sisal leaf decortications residues, coffee hulls with chicken manure or fish waste or cow dung manure improved the digestibility of the materials resulting in increased methane productivity (Mshandete A., Kivaisi, A. et al. 2004).

Table 2.5

Process optimization techniques, methodology and results

Process optimization technique	Methodology	Results	References
Co digestion in a single phase reactor	Simultaneous digestion of barley waste and kitchen waste at 40% and 60% ratios by mass respectively	methanation as a % of theoretical BMP: 92% (control 83%), litres CH_4 /kgVS 432 (control363), %TS reduction: 92 (control 83), %VS reduction: 75 (control 61)	(Neves et al. 2006a)
Co digestion in a two- phase reactor	Simultaneous digestion of potato waste and sugar beet waste leaves in a two phased hydrolysis and methane filter reactors (10 & 2.6 m^3 respectively)	Digestion of individual substrates gave gross energy yields (CH_4) of 2.1-3.4 kWh/kg VS; Co-digestion yielded up to 60% higher CH_4 yield	(Parawira et al. 2008)
Phased digestion	Two-stage methane production from animal manure and household waste	21% higher methane yield over the conventional one stage process.	(Liu D. W. et al. 2006)

2.3.3 Application of additives

Several biological, biochemical and chemical additives such as biomass, microbial strains and micro and or macro nutrients respectively have been known to enhance the production rate of a BVC bioreactor or increase the speed of start up, which ultimately improves biogas plant performance significantly. For effective and high production of biogas in a BVC system especially those based on animal dung and biowaste, many biological additives such as succulent plants or algae, soybean curd residue water hyacinth and lemon grass have been added in the digester with great promise in methane enhancement of up to 63% (Mshandete A. M. and Parawira 2009, Sahlstrom 2003, Satyanarayan et al. 2008, Yadvika et al. 2004).

2.4 BVC- valorisation based advances: Biogas and digestate valorisation

2.4.1 Biogas as a sustainable energy carrier

The valorisation of biogas offers various direct and indirect benefits key among which is the replacement of fossil based energy. Biogas is widely regarded as an energy carrier and since a typical biogas plant can utilise locally available organic raw materials the biogas energy can be regarded as being cheaper and reliable as compared to fossil fuels. The main uses of biogas as an energy source are found in cooking, lighting, refrigeration, biogas-fuelled engines, and electricity generation. However to unlock the energy potential in the biogas it is essential to upgrade it to preferably grid quality prior to valorising it into the various forms of energy (Figure 2.5). Upgrading of the biogas entails cleaning and removal of contaminants such as moisture, particulate matter, hydrogen sulphide, ammonia, carbon dioxide, etc. However, biogas upgrading is considered to be parasitic from energy sustainability point of view. Nevertheless, with proper management of the various BVC segments preceding biogas usage it might be possible to ameliorate the need for upgrading through minimization of the contaminants or production of biogas devoid of the typical contaminants.

In the recent past, the valorisation of biogas has developed tremendously from the conventional lamps, stoves and heaters to more specialised engines and fuel cells with the limitation being on the efficiency of converting the biogas energy to secondary forms of energy such as mechanical power and electricity.

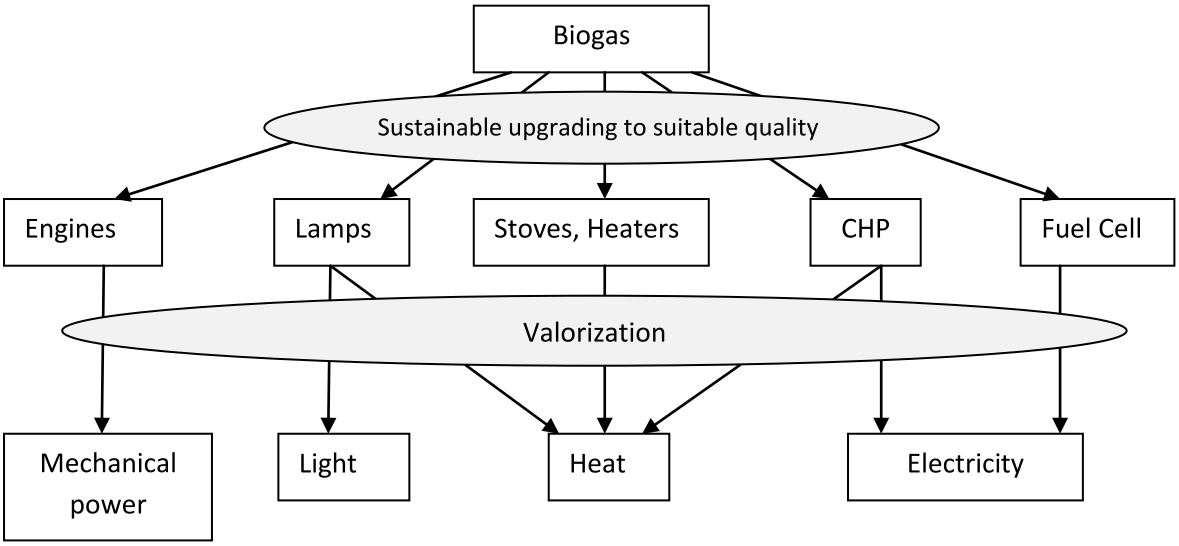


Figure 2.5: Valorisation of biogas as a sustainable energy carrier.

Moreover, the specialised application of biogas necessitates specific packaging such as compression and storage as well as a high level of biogas purity. The chemical composition and properties of raw biogas and the requirements for various applications are presented in Tables 2.6 and 2.7. Since most of the possible contaminants in the biogas such as ammonia, sulphides as well as halogen compounds originate from the feedstock, there is need to explore increased use of those feedstock devoid of the contaminant precursors. Similarly there is need for the biogas upgrading technologies to be adoptive so as to avoid “quality giveaway” since for example direct use of biogas in engines may not need the same quality of biogas as fuel cells or grid injection.

Table 2.6

Chemical composition of biogas, concentrations and properties of the components (Ranalli 2007).

Component	Concentration in raw biogas	Properties
CH_4	50-75% (v/v)	Energy carrier
CO_2	25-50% (v/v)	Corrosive, especially in presence of water
H_2S	0-5,000 ppm (v/v)	Corrosive, SO_2 - emissions during combustion
NH_3	0-500 ppm (v/v)	NOx - emissions during combustion
Siloxanes	0-50 mg/m^3	Engine damage (sands off) in CHP
N_2	0-5 % (v/v)	Decreases heating value
Water vapour	1-5 % (v/v)	Corrosive

Table 2.7

Biogas requirements for various applications (Amrit et al. 2009)

Details	Size	Consumption	Biogas Composition		
		Gas m^3(STP)/hr	CH_4%v/v	NH_3 ppm	H_2S ppm
Biogas engine	per HP/hour	0.40	30-60%	<20	< 5
Biogas lamp	1 mantle	0.07 – 0.08	> 30%	<100	< 1000
Kitchen Stove	2 ” diameter	0.33	> 30%	<100	< 1000
Biogas heater / boiler	ND	0.15 – 0.40	> 30%	<20	< 1000
CHP engine	per unit kWh	0.56	> 60%	<20	< 5
Fuel cell	per unit kWh	45	> 96%	< 1	< 2

Key: ND = not defined

There are biogas CHP units capable of processing biogas at higher H_2S and NH_3 levels (such as 400ppm and 100ppm respectively for H_2S and NH_3) without causing operational problems in biogas engines / CHP units. Nevertheless, the said operational ability is obviously at variance with the increased engine down times due to maintenance work; shorter maintenance intervals and hence higher maintenance costs; reduced service life of individual components as well as the increased air emissions which might contravene some national emission standards (Ranali 2007; European Commission 2010).

2.4.2 Digestate as a sustainable organic fertilizer

Anaerobic digestion draws carbon, hydrogen and oxygen out of the substrate whereas the essential plant nutrients (N, P, and K) remain, at least in principle, in place. The composition of fertilizing agents in digested slurry depends on the source material as well as the storage conditions of the digestate (Paavola and Rintala 2008). The suitability of the digestate as a sustainable organic fertilizer can therefore be manipulated within certain limits. Generally the volume of the source material remains unchanged, since only some 35 - 50% of the organic substances (corresponding to 5 - 10% of the total volume) are converted to gas. Fermentation reduces the C/N-ratio by removing some of the carbon, which has the advantage of increasing the fertilizing effect. Another favourable effect is that organically fixed nitrogen and other plant nutrients become mineralized and, hence, more readily available to the plants. Compared to the source material, the digestate is usually highly disintegrated, has a finer, more homogeneous structure, which makes it easier to spread on agricultural land besides having a higher potential as a viable source of humus in the soil.

(i) Fertilizing characteristics of digestate

The fertilizing properties of digested slurry are determined by how much mineral substance especially nitrogen (N), phosphorous (P) and potassium (K), and trace elements it contains. In lateritic as well as tropical soils under continuous cultivation, the NPK content is of prime importance. In addition, the organic content of digested slurry improves the soil's texture, stabilizes its humic content, intensifies its rate of nutrient-depot formation and increases its water-holding capacity. However, it should be noted that a good water balance is very important in organically fertilized soil since a shortage of water can wipe out the fertilizing effect. Very few data on yields and doses are presently available with regard to fertilizing with digested slurry, mainly because sound scientific knowledge and information on practical experience are lacking in this very broad domain.

The digested effluent from biogas plant commonly referred to as digestate or bio-slurry has proved to be high quality organic manure rich in concentrated nutrients, plant hormones and enzymes as well as humus essential for plant growth. There are multiple advantages that accrue with the use of digestate. The digestate increases the proportion of nitrogen available for plant growth (Gerin et al. 2008) thereby stimulating plant growth especially in their early vegetative stages consequently increasing agricultural production by up to 20 – 30 %. Besides, when the digestate is used for crop production it leads to a reduction in the use of chemical fertilizers and hence a sustainable increase in farm income. However the digestate benefits are counterbalanced by the energy balance of the BVC system which is estimated to become negative when the distance between the AD system and the source of feedstock and hence the point of use of the digestate exceeds 100 km thus necessitating the parasitic use of the biogas or fossil fuels for transportation (Borjesson and Berglund 2006).

(ii) Hygiene aspects of the digestate

Health and sanitation is of primary concern to BVC systems. Anaerobic digestion kills off (causes high pathogen fatality) or at least deactivates certain pathogens and worm ova, though the effect cannot necessarily be referred to as hygienization (Table 2.8). Ninety-five percent of the ova and pathogens accumulate in the scum and sediment in case of incomplete anaerobic digestion. In tropical regions most BVC systems operate at the mesophilic temperature range hence there is a potential risk of the accumulation of ascaris ova and colititre in the digestate. Besides the sulphite reducing clostridia are neither affected by anaerobic digestion nor storage of the digestate (Paavola and Rintala 2008). In addition, weed seeds normally remain more or less unaffected. Nevertheless when anaerobic digestion is well carried out, the digestate is practically odourless and does not attract flies.

Table 2.8

Survival time (days) and fatality rate (log reduction) of pathogens in different biogas plants (Kumar et al. 1999, Paavola and Rintala 2008, Wagner et al. 2008)

Bacteria	**Thermophilic digestion (53-55°C)**		**Mesophilic digestion (35-37°C)**		**Psycrophilic digestion (8-25°C)**	
	Days	Log reduction	Days	Log reduction	Days	Log reduction
Salmonella	1-2	> 4	7	> 4	44	> 4
Shigella	1	> 4	5	> 4	30	> 4
Poliviruses	X	X	9	> 4	X	X
Schistosoma ova	Hours	> 4	7	> 4	7-22	> 4
Hookworm ova	1	> 4	10	> 4	30	1
Ascaris ova	2	> 4	36	2	100	0.5
Colititre	2	< 0.003	21	< 0.003	40-60	< 0.003
Clostridia	20	ND	35	ND	90 - 270	ND

Key: X = no data reported; ND = no detectable fatality

2.5 Comparative sustainability analysis of biogas enhancement techniques

The most conspicuous feature of the biogas enhancement techniques reported in literature is their cross cutting nature and influence on the entire BVC. However the quest for the ideal pre-treatment technology remains largely unresolved. Owing to the diversity of the biogas enhancement techniques and their influence on the entire BVC it is not always correct to compare the potential of different techniques by a singular criterion such as the current use of economical and/or technical factors only without the need to refer to other parameters such as social and environmental burden and renewability potential. Pre-treatment cost represents one of the highest variable cost in a bio refinery (Sousa et al. 2009) however in addition to the cost of additives and/or chemicals, the energy requirements associated with temperature, pressure, mixing, water utilization and chemical recovery are all important factors to consider when selecting a pre-treatment technology. Similarly, the biogas enhancement threshold associated with the pre-treatment and the effect of the pre-treatment on the quality of the biogas and digestate are equally important. Moreover the emissions associated with the pre-treatment provide useful environmental yardstick for the evaluation of the ideal pre-treatment technology. Indeed most biogas enhancement techniques carry a renewability burden owing to their associated greenhouse gas emissions. Any suitable comparative analysis tool for BVC pre-treatment technologies should therefore take into consideration all the inputs, outputs and emissions associated with the technology (Figure 2.5) including the accruing societal benefits. To this end, a comprehensive evaluation of the pre-treatment step in a BVC should take into account the effects of the pre-treatment on the entire BVC. A suitable application of the life cycle concept to supplement cost and or technological aspects can suffice in the consideration for the ideal pre-treatment technology. In this context Figure 2.6 present an expanded system boundary suitable for the consideration of the optimal pre-treatment technology. Besides, a comparative analysis of different biogas enhancement techniques is presented in Tables 2.9 and 2.10. A general relative approach for different pre-treatment and fractionation techniques is presented in Table 2.9. This approach might be sufficient for initial screening of different pre-treatment techniques however it might be regarded as being quite simplistic hence too limited for making an informed decision during the evaluation of BVC pre-treatment techniques. A more detailed comparative approach is employed in Table 2.10 where the potential of different biogas enhancement techniques is compared against the associated use of fossil primary energy as well as the avoided emissions of carbon dioxide. The avoided emissions could be calculated by assuming that 1 joule of biogas prevents the CO_2 emission of the combustion of 1 joule of fossil primary energy (petrol, diesel or coal) taking into account any additional greenhouse gas emissions associated with the biogas enhancement technique.

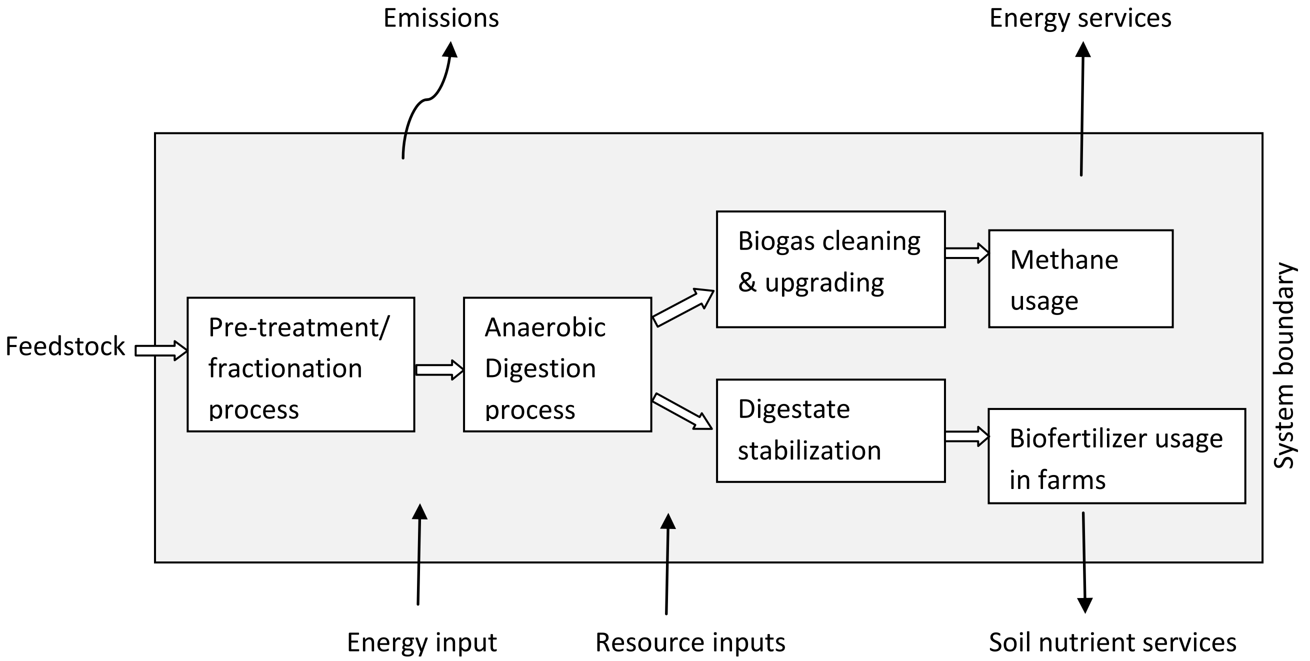


Figure 2.6: Overview of the expanded system boundary in the evaluation of pre-treatment and fractionation technologies for anaerobic digestion. The arrows represent material flows, energy flows and emissions from the system.

Table 2.9

Comparative analysis of the different physical, chemical, biological and hybrid pre-treatment and fractionation techniques.

Pre-treatment / fractionation technique	**Physical**		**Chemical**	**Biological**		**Hybrid**		
	Mechanical fractionation	Thermal	Chemical processes	Ensiling	Microbial /enzymatic	Hydrothermal	Thermo-chemical	Bio-thermo chemical
Fundamental principle	Feedstock size reduction	Thermal disintegration of feedstock	Chemical disintegration of feedstock	Microbial feedstock disintegration		(Pressurised) thermal / chemical / microbial disintegration of feedstock		
Targeted modification	Physical size reduction	breakdown of micro fibrils	Reduction of molecular mass and chemical cell hydrolysis	Bio-chemical cell hydrolysis and breakdown of micro fibrils		Cell hydrolysis and breakdown of micro fibrils	breakdown of micro fibrils and reduction of molecular mass	Bio-chemical cell hydrolysis , breakdown of micro fibrils and reduction of molecular mass
Cost estimation	Moderate	High	Very High	Negligible	Minimal	High	Moderate	Moderate
Status	Full scale	Full scale	Lab scale	Full scale	Lab scale	Full scale	Full scale	Lab scale
Remarks	Does not rapture nor shear the feedstock	Might require additional cooling stage	Expensive due to high cost of chemicals	Requires extra storage facilities		Parasitic energy consumption, Might require additional cooling stage		

Table 2.10

Comparative analysis of selected feedstock, BMP, biogas enhancement thresholds and environmental load

Biogas Feedstock	**Animal manure**	**Municipal Solid Waste**	**Household solid waste**	**Fruit & vegetable waste**	**Farm residues & biowaste**	**References**
Typical BMP (m^3/tonne VS)	**150 – 600**	**400 – 900**	**470 – 1100**	**300 – 600**	**300 – 1000**	(Bougrier C. et al. 2006, Bruni et al. 2010, Callaghan et al. 2002, Fernandes et al. 2009, Neves et al. 2006a, Neves et al. 2006b, Nzila et al. 2010, Ranalli 2007)

Biogas Enhancement Technique	**Biogas enhancement thresholds** [a]			**Environmental load** [b]		
	Average	High value	Low value	Primary fossil energy requirement (kJ)	Avoided emissions (kg CO_2 eq/m^3CH_4)	
Physical treatment						
- **Mechanical fractionation**	17%	25%	8%	High	Negligible	(Bruni et al. 2010), (Hartmann et al. 2000)
- **Thermal hydrolysis**	51%	76%	25%	High	Minimal	(Bougrier C. et al. 2006)
Chemical treatment	80%	100%	59%	Moderate	Low	(Neves et al. 2006a)
Biological treatment						
- **Ensiling**	23%	39%	6%	Minimal	High	(Parawira et al. 2008)
- **Microbial treatment**	33%	33%	ND	Minimal	High	(Bruni et al. 2010)
Compound treatment						
- **Hydrothermal hydrolysis**	40%	38%	6%	Moderate	Moderate	(Liu H. W. et al. 2002)
- **Thermo chemical**	22%	69%	24%	Moderate	Moderate	(Fernandes et al. 2009)
- **Bio-thermo-chemical**	47%			Moderate	Moderate	(Bruni et al. 2010)
Process optimization						
- **Nutrients addition (micro/macro)**	76%	92%	60%	Negligible	High	(Parawira et al. 2008), (Neves et al. 2006a)
- **Co digestion**	78%	96%	59%	Negligible	High	(Callaghan et al. 2002), (Mshandete A., Kivaisi, A. et al. 2004)

a : based on ml CH_4/g Vs b : qualitative ND: no data reported

2.6 Challenges in the biogas value chain and their mitigation

2.6.1 General overview of challenges in the BVC

The BVC system is manifested with ingrained operational and incidental challenges that run through the entire BVC segments and which if not addressed adequately might lead to incomplete realization of the benefits anticipated from BVC projects. The following synopsis considers the most important challenges along the major segments of a BVC system that might hinder full realization of the BVC in the sustainable energy matrix as well as in agricultural application and presents the appropriate mitigation measures.

2.6.2 Feedstock sourcing, preparation and handling challenges

The sourcing, preparation and subsequent handling of different cadre of BVC feedstock for anaerobic digestion broadly constitute a comprehensive range of challenges. During the general use of biomass for energy production, land use competition with food and feed production is widely considered a potential key barrier to exploiting the BVC potential in many countries (Fischer et al. 2007) however the exploitation of biowaste as feedstock for biogas production (Nzila et al. 2010) is seen as a potential means for mitigating this challenge. On the other hand, transportation and handling costs are generally significant for all BVC feedstock since these costs can account to over €20 per tonne of the delivered feedstock (Berglund and Borjesson 2006). It is therefore essential to embrace a decentralised BVC approach whereby the biogas plants are located in areas of excess BVC feedstock. In this way transportation costs become minimised while simultaneously providing the best chance for maximum biogas supply year round. In addition determination of the suitability and bio methane potential (BMP) of any given feedstock requires thorough characterisation which in turn presents another set of challenges owing to the diversity within and across the different BVC feedstock. It is well acknowledged that the suitability and BMP parameters of the feedstock determines, to a certain extent, both design and economic details of a biogas plant (Angelidaki et al. 2009, Kaparaju et al. 2010) however these variables cannot be easily estimated especially in most southern regions due to non availability and fragmentation of essential data. Potential biomass productivity of individual BVC feedstock available in the southern regions and the associated energy yields need to be calculated and the results tabulated by aggregate land cover classes for ease of reference.

2.6.3 BVC anaerobic digestion system challenges

The main factors affecting the microbial activities in an anaerobic digester are highlighted under BVC process control and optimization (section 3). During anaerobic digestion, the control of the process parameters presents a multi faceted challenge especially for small scale domestic digesters which lack mechanical mixing and inbuilt process monitoring mechanisms. In the absence of mechanical mixing, the stirring up of the digester contents is predominantly attained through gas production. However lower gas production causes insufficient mixing which leads to poor substrate – biomass contact thus leading to lower gas production and hence a vicious cycle. Another inherent challenge is the maintenance of digester temperature at the optimum range especially during the cold (winter) season when most digesters have been known to stop gas production. Many attempts such as direct heating by means of biomass or fossil fuel, solar and biogas as well as indirect heating using heat from compost pile have been fronted as possible means for raising the digester temperature during the cold season. It should however be noted that some systems are simple but less effective while others are more effective but costly. Nevertheless, the control of heat losses through the digester walls, roof and floor is paramount so as to eliminate the need for external heating of the digester. Moreover, apart from incorporating a rain shelter, comprehensive heat insulation of the digester during the construction phase integrated with the compost pile might suffice as efficient and inexpensive means for maintaining the appropriate digester temperature.

2.6.4 Biogas post-treatment handling and usage challenges

The main challenges during biogas post-treatment and handling are those concerned with biogas purification and subsequent storage. The predominant forms of post-treatment aim at removing the main pollutants such as moisture, carbon dioxide, ammonia, halogenated hydrocarbons, siloxanes and hydrogen sulphide. The required degree of purification based on methane content is dependent on the expected end use of the biogas as presented in Figure 2.7. Boilers, lamps and biogas stoves do not have a high gas quality requirement. However for efficient operation of the gas nozzles it is preferable to remove hydrogen sulphide and condense water vapour from raw biogas failure to which there is formation of highly corrosive sulphurous acid in the condensate. The removal of water often leads to substantial removal of hydrogen sulphide.

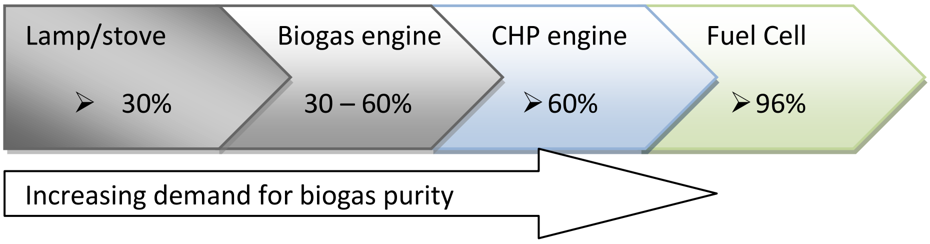


Figure 2.7: Biogas requirements (in % CH_4) for different applications.

On the other hand, specialist biogas applications such as CHP engine and methane fuel cells demand systematic purification, upgrading and compression of the biogas. However, comprehensive upgrading of biogas to over 96% purity (for fuel cells) necessitates specialist and costly operations besides the additional energy consumption. Nevertheless the upgraded biogas is considered to be one of the cleanest fuels with minimal impacts to human health and environment.

2.6.5 Digestate post-treatment, handling and usage challenges

The digestate of a BVC system should have a useful purpose and hence benefit should be derived from its production. The high nutrient content of digestate makes it suitable as organic fertilizer as well as for soil amendment and landscaping. The use of digestate depends on its quality thus some chemical, biological and physical attributes of the digestate can present serious challenges which must be addressed prior to the extraction of maximum benefits from the digestate.

BVC feedstock exclusively from agricultural origin can contain heavy metals, inorganic fertilizer residues, pathogens, seeds, transmissible spongiform encephalopathy (TSE) as well as persistent organic contaminants such as pesticide residues and antibiotics. Industrial and household waste BVC feedstock can contain aromatic, aliphatic and halogenated hydrocarbons as well as TSE. Other physical impurities such as plastic, rubber, metal, glass, ceramics, sand, stones and undigested cellulosic material such as wood and paper are also common. These impurities can inevitably find their way into the digestate and can cause damage to the environment besides resulting to new routes of transmission of pathogens and diseases between animals, humans and the environment. Presence of these contaminants in the digestate is highly likely to cause a negative public perception of the BVC besides their removal necessitates increased operational costs. Quality control and source segregation of the BVC feedstock is therefore essential since digestate post-treatment is not as effective in removing contaminants as compared to the elimination of potential contaminants at the source thereby avoiding the formation of further secondary or intermediate contaminants.

2.6.6 Technical challenges

The selection of the most appropriate biogas plant design in most southern regions is still a matter of conjecture, largely being determined by the prevailing designs in the region. Typical design criteria include space, existing structures within the household compound, cost minimization, substrate availability and the energy needs of the plant owner. However owing to the fragmented manner in which the scarce information on biogas systems in many southern countries has been presented in the past (Nzila et al. 2010) and the apparent lack of clear benchmarks, it is currently (2010) not possible to agree on for instance the most appropriate biogas system to implement in most countries. Consequently because of the existing diversity in eco-efficiency and digester design considerations, it is imperative that the relative merits and demerits of each design be widely and readily available, and presented in a transparent and uniform manner so that stake- holders can make informed decision on which system to implement based on their needs (Demirbas 2007, Ramesohl et al. 2006) thus a comprehensive sustainability assessment can adequately suffice for this purpose. Other technical challenges presented by the digestate include emissions and odour due to post methanation as well transportation of the digestate to the point of end use in the case of centralised digesters. To mitigate these challenges it is essential to employ decentralised digesters as well as incorporate compositing in the BVC.

2.7 Future prospects

2.7.1 Biogas upgrading to grid quality: perspectives and prospectus for scrubbing, compression and storage

Biogas is an important source of renewable raw methane however in most instances especially in developing countries presently; it can only be used at the place where it is produced. There is therefore an apparent need to make biogas transportable which can be done by compressing the gas in cylinders (Clarke 2008). However the presence of incombustible contaminants such as CO_2, H_2S and water vapour components reduce its calorific value and make it uneconomical to compress and transport to longer distances. It is therefore only viable to compress the biogas after the removal of the contaminants.

CO_2 scrubbing from biogas

A variety of processes that have been developed for removing CO_2 from natural gas in petro-chemical industries are being increasingly employed for CO_2 scrubbing from biogas. Generally several basic mechanisms are involved to achieve selective separation of gas constituents. These may include physical or chemical absorption, adsorption on a solid surface, membrane separation, cryogenic separation and chemical conversion. While most of these processes present promising prospects for CO_2 scrubbing from biogas their application is wrought by their level of complexity, environmental sustainability and cost challenges owing to the present economic value of biogas. Nevertheless, the physical absorption method is less complicated, requires fewer infrastructures and is cost effective. Indeed water scrubbing method is popular for CO_2 removal in biogas plants in Sweden, France and USA however results show that 5-10% CO_2 remain in the biogas after scrubbing (Kapdi et al 2005).

Scrubbing of H_2S

The different processes that have been developed for H_2S removal can be classified into two general categories namely dry and liquid phase oxidation respectively. The dry oxidation with stoichiometric quantities of air/oxygen (usually 2-6% oxygen) is capable of lowering H_2S concentration to less than 50ppm however substantial care is necessary to avoid overdosing of air since biogas in air is explosive in the range of 6-12% depending on methane content. Dry oxidation by means of adsorption of H_2S using iron oxide (iron oxide pellets or iron oxide covered wood chips) or activated carbon is also popular. However the application of wood chips is very popular owing to the low cost of the product as well as the possibilities of regenerating the iron filter. The liquid phase oxidation process on the other hand is primarily used for the treatment of gases containing relatively low concentration of H_2S. The process can be classified into (a) physical absorption process by use of solvents such as water or NaOH; (b) chemical absorption process by use of iron salt solutions such as iron chloride ($FeCL_3$); (c) biological process by use of a bio scrubber such as the bio trickling filter (van den Bosch, 2008). All the methods of H_2S removal are generally suitable and economically viable for large-scale digesters however the use of bio scrubber or $FeCL_3$ (which can be dosed directly to the digester slurry) are particularly most suitable for small scale digesters and H_2S removal to levels lower than 10 ppm are possible.

Biogas compression and storage

Biogas containing mainly methane cannot be stored easily since at ambient temperature it does not liquefy under pressure (critical temperature and pressure required are -82.5 °C and 47.5 bar respectively). Nevertheless, compressing the (scrubbed) biogas increases pressure to the level required to overcome resistance to gas flow, concentrates the energy content and reduces the storage requirements. Integrated units with facilities for scrubbing, compressing and storing have been developed in a number of developed countries such as Belgium, German, Denmark, Sweden, Australia and New Zealand (Clarke 2008). In addition the compressed biogas has also been supplied to the national gas grid in The Netherlands.

2.7.2 Methane fuel cells against the backdrop of efficiency

Various types of fuel cells have been developed for different fuel sources (Van herle et al. 2004) with (bio) hydrogen being undoubtedly the fuel of choice. However in the recent past biogas has been analysed as a fuel for phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC) as well as the polymer electrolyte membrane fuel cells (PEMFC) (Bove and Lunghi 2005, Schmersahl et al. 2007, Van herle et al. 2004). Similar to bio-hydrogen, biogas production and utilization in methane fuel cells provides an opportunity for a clean and reliable option for decentralised residential energy supply. The use of biogas in fuel cells with combined heat and power generation presents a reliable and environment friendly alternative to replace conventional power generation with fossil fuels. The biogas-fuel cell technology has the advantage of being a comparatively cost-effective domestic regenerative energy source coupled with high electrical efficiency and low pollution as compared to motor engines. Indeed the use of biogas in modified hydrogen fuel cells has been demonstrated (Schmersahl et al. 2007) and a typical biogas-fuel cell system with biogas processing system is shown in Figure 2.8.

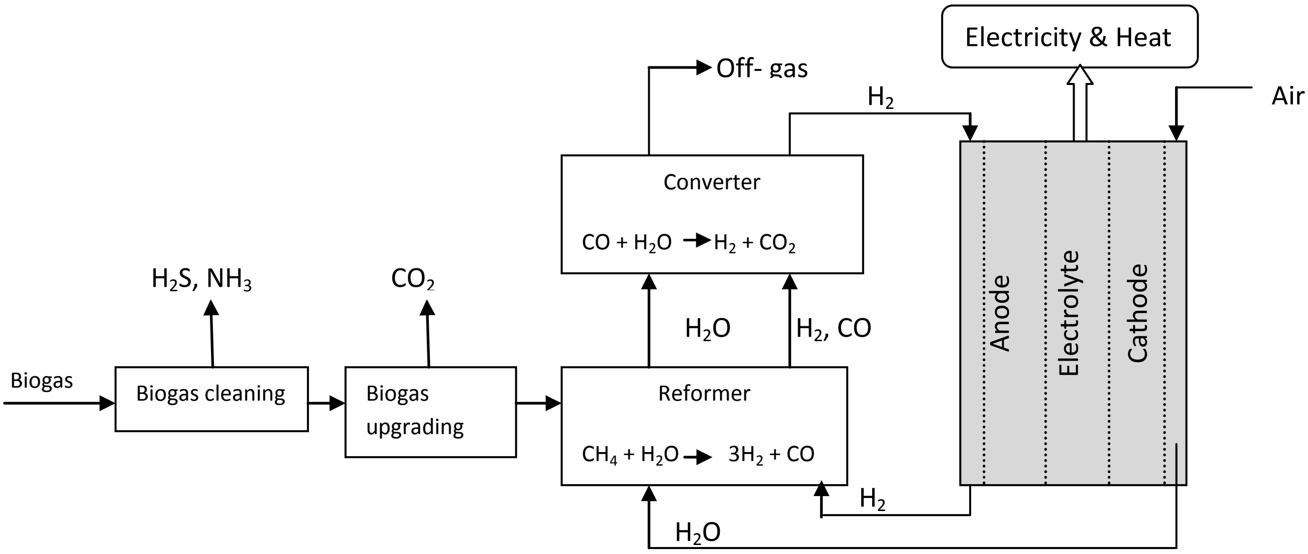


Figure 2.8: General scheme of a biogas fuel cell system

Generally, biogas fuel cells tend to require very high biogas methane density (>96%) hence the need for biogas cleaning and upgrading. Consequently, the use of biogas in fuel cell systems requires adaptation and optimization so as to eliminate the various inherent harmful components and hence reform the biogas into hydrogen for subsequent conversion to electricity and heat by the fuel cell. Conversely, a hydrogen purity of as low as 50% is sufficient for an efficient and stable operation of PEMFC (Schmersahl et al. 2007). In this connection, it appears that for fuel cell applications, the BVC can be made more efficient by streamlining it towards the production of hydrogen instead of methane. This calls for a paradigm shift in the way the BVC is currently constituted. Subsequently there is a need to perform a comprehensive sustainability assessment of biogas-fuel cell systems with a few to establishing the balance of emissions, their impacts as well as the exergetic balance of the entire system and the trade-offs therein since it can be envisaged that biogas reforming for use in fuel cells could be exergetically inefficient. Moreover, fuel cell technology as presently constituted is deemed to be rather expensive yet less efficient when compared to the conventional CHP systems.

2.8 Conclusions

The BVC system presents virtually unlimited opportunities for stabilising and adding value to organic resources. The recent advances in the biogas value chain can be viewed from two intrinsic perspectives namely BVC - production oriented advances and BVC - valorisation based advances. However, the BVC as presently constituted suffers from lack of coordination as witnessed by the apparent fragmentation in most of the BVC advances. Besides it is observed that Research advances and diversity decrease along the biogas production chain. Nevertheless, based on the published literature, the current BVC valorisation advances appear to lag behind the BVC production advances.

Various BVC production oriented advances especially those geared towards substrate pre-treatment appear to be rather too specific thus focusing on the alteration of the substrate structure and enhancement of biogas production with minimal regard to energy requirements and or quality of the resultant digestate. Similarly some advances in the BVC valorisation such as the niche applications in fuel cells appear to demand rather very stringent gas quality requirements thus occasioning the need to re-evaluate the suitability of BVC in such niche applications. Besides while the viability of most BVC advances might appear promising from a specific aspect, sustainability concerns tend to emerge when the scope is enlarged to encompass the entire BVC thus occasioning further reassessment of the sustainability of BVC. Nevertheless, the continued in-depth understanding of biogas substrates and the nutrient value of the digestate as well as reported breakthroughs in simple and efficient biogas treatment such as bio scrubbing render BVC to be quite useful as a source of energy and soil nutrients. However the apparent lack of coordination in the BVC imply that substantial sustainability insight for most BVC advances is still required if the BVC is to incontrovertibly remain vital to the sustainable energy matrix.

Acknowledgements

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Chapter 3

A Sustainability assessment framework for biowaste energy

Abstract

Sustainability and sustainable development are broad concepts that have continued to attract increased attention within the public and private sector thus gaining a broad acceptance as the guiding principle for both public policy and corporate strategies. *Sustainability is a technical balance between the present and future interests.* However, there are challenges in the implementation of the sustainability concept owing to the multi-dimensionality of the sustainability goal coupled with the complexity of socio-economic and biophysical systems. Sustainable energy exemplifies such a panorama. In this chapter, while focusing on sustainable energy, a framework is designed for comparing the environmental, technical and socio-economic performance of different biogas systems. Furthermore, an approach for operationalizing the designed framework is proposed.

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3.1 Introduction

Energy including renewable and geologic storages is an essential input to global sustenance and development. The world's energy consumption is estimated to increase exponentially from the current 22 billion kWh yr^{-1} to 53 billion kWh by 2020 (Omer 2008). Such escalating demand could place significant strain on the current energy infrastructure and potentially damage the environment via emission of toxic chemical pollutants, greenhouse gases like CO_2 and other air pollutants (Omer 2008, Wang et al. 2009). These cause climate change and environmental pollution of air, water and land which in turn has a negative impact on the planet as well as the health and living quality of humans. The effects of global warming, diminished natural resources, uneven distribution of energy resources, rising energy prices and hence increased energy demand constitute an energy crisis of global magnitude. The crisis demands an immediate paradigm shift in energy policies with a view of not only revising the existing technologies but paying greater attention to alternative energy sources. Thus, there is a need to identify new technologies as well as alternative renewable and environmental friendly sources of energy. The development of cost-effective renewable energy technologies for energy production is a priority for many private firms, research centres and governments. Availability of secure, affordable, reliable, clean and sustainable energy supply is therefore regarded as one of the key drivers of development and enhancement of the quality of life. To this end, biofuel technology has been identified as quite a promising technology (Cardona and Sanchez 2007, Kondili and Kaldellis 2007) due to its potential of being a significant source of energy.

Nevertheless, renewable energy contributes as much as 20% of the global energy supplies worldwide. Over two thirds of this comes from biomass use, mostly in developing countries. While some of the global energy supplies are unsustainable, the potential for energy from sustainable technologies is great. Biowaste energy technologies (BETs) such as biowaste based biogas, bio ethanol and biodiesel are some of the technologies widely regarded as being sustainable.

3.2 Biomass and biowaste energy

Biomass which comprises any organic matter such as plants and animal waste is one of the oldest energy resources and raw material known to man and an important contributor to the world economy. The biomass that is produced for any specific application can be referred to as primary resource whereas any biomass without a specific application as well as the residue from primary resources can be broadly regarded as a secondary resource. Biowaste can thus be defined as secondary resource biomass. From this perspective, biowaste can be seen as a biomass by-product without immediate value and whose disposal could incur economic and or environmental cost. Generally biomass is per definition renewable and sustainable if the amount utilised equals the amount that is naturally replenished. Primary biomass such as energy crops is cultivated with a specific purpose in mind, and the conversion technologies that use this biomass are dedicated conversion plants. For example sugarcane is grown for the purpose of producing sugar or ethanol and is therefore a primary source. The residues of sugarcane processing are biowaste and can be either processed separately or mixed up with other biowaste and therefore deemed a secondary source. Use of biowaste as a source of energy thus transforms a negative-value substance, namely waste; into saleable products such as energy and/or compost therefore it is useful in reducing waste, and providing fully renewable energy. Biowaste energy thus facilitates the closing of the biomass production cycle. Other advantages of biowaste energy emanate from the fact that the feedstock source is readily available and does not rely on additional land use or the development of specific cultivation technologies (International Energy Agency 2011). Furthermore, biowaste energy based on agricultural residues offers the opportunity for farmers to profit from biofuel production, which could positively affect rural development, especially in developing countries.

In the recent past a lot of research has emerged worldwide on the utilization of biomass for generation of energy (Kondili and Kaldellis 2007, Sanchez and Cardona 2008). Indeed, biomass in all its forms is researched to account for over 16% of the world’s final energy consumption by 2020 and almost 30% of the total global primary energy consumption in 2050 will be covered by regenerative energy sources (Deublein and Steinhauser 2008). Already in developing countries, biomass currently provides over 35% of the final energy consumption (Agency 2009) and its utilization is expected to increase as a strategy for carbon dioxide reduction. Indeed a lot of efforts have been expended in the studies of biofuel production leading to development of technologies with varying degrees of success. The main challenge has been on the production cost which is found to be higher than that of fossil fuels. In addition, the cultivation and use of energy crops for energy production may contravene the drive towards food security especially in most developing countries (Deublein and Steinhauser 2008). However, a substantial reduction in the cost of biofuel production can be achieved by addressing the problems associated with raw materials and the utilization of biowaste. Indeed the future of biofuels in most developing countries lies on the identification of non-food plants that can be grown in underutilized land and cascade utilization of the available biowaste such as plant residues. Nevertheless, plant residues are some of the most under exploited resources in most developing countries in spite of the fact that most of these countries’ economies are depended on agricultural production. As an example, agro biomass residues such as cotton and sisal waste theoretically have high energy potential primarily owing to their high cellulose content. Besides, there are several conversion options for transforming biomass or biowaste into solid, liquid or gaseous secondary energy carriers (Figure 3.1), these include thermo-chemical transformation via combustion, pyrolysis, liquefaction or gasification; physico-chemical transformation by compression, extraction, transesterification and biochemical transformation via alcoholic fermentation and anaerobic digestion.

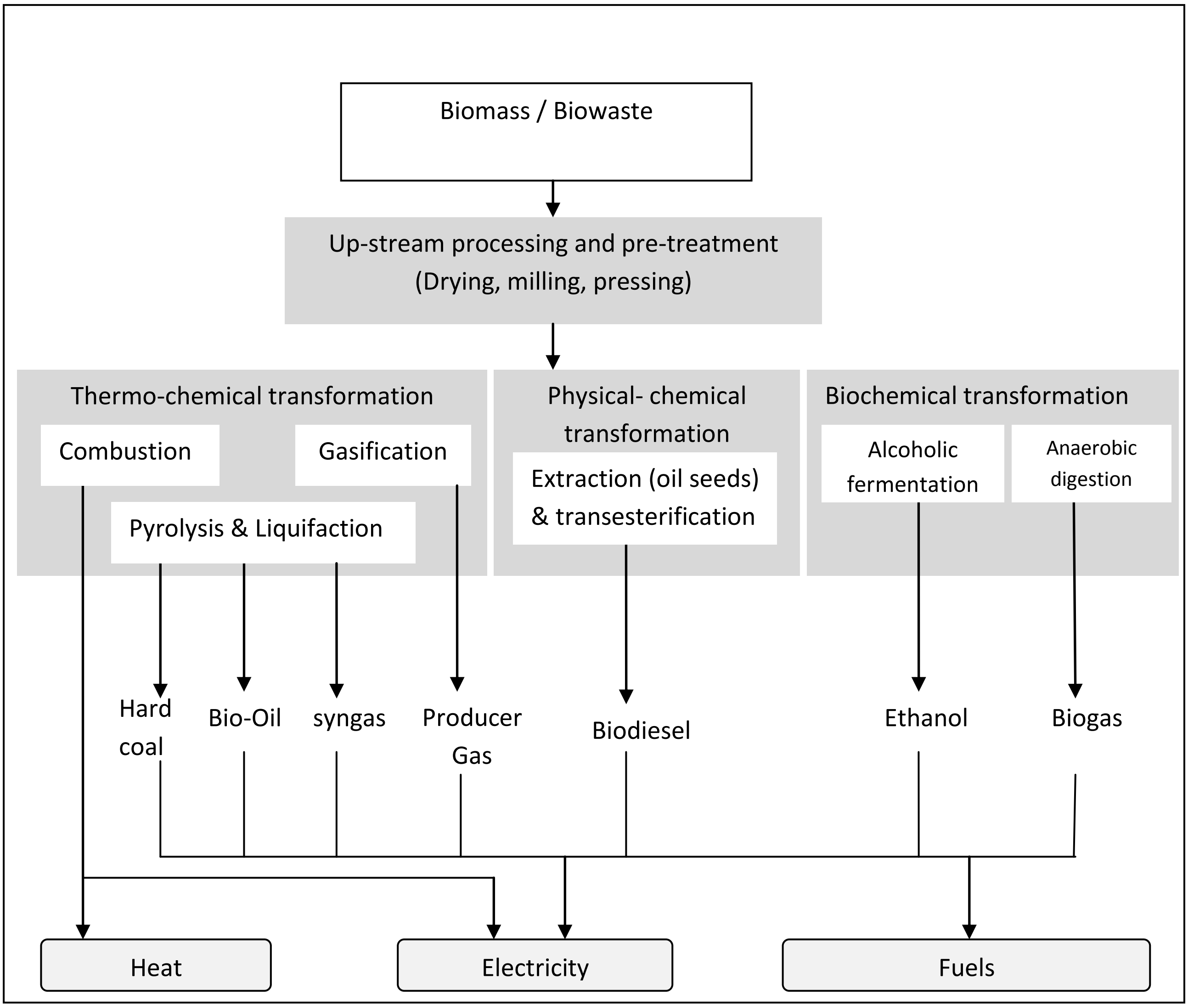

Figure 3.1 Technology options for transforming biomass/biowaste into secondary energy carriers. (Modified from Deublein **(Deublein and Steinhauser 2008)).**

3.2.1 Thermo chemical transformation

The energy stored in biowaste is released when this biomass is combusted. When the requirement is purely thermal, it can be met by using combustion systems and appropriately transferring heat to the required devices. The use of biowaste for energy production can be achieved commercially through boiler and steam turbines though this route is only efficient and economical at large power levels of the order of 5 MW or more. However due to the high capital investment required for large thermal power plants coupled with treatment costs in the range of 50 – 150 €`/tonne (Faaij 2006) and the low bulk density of most biowaste as well as the presence of agrochemical residues especially combustion may not be a viable option for certain biowaste such as cotton waste. Gasification of biomass on the other hand provides means for power generation at lower levels of cost per mega watt comparable to large thermal power plants. During gasification, the solid biomass residues are converted to a gaseous fuel called the producer gas. The producer gas thus generated can be used just like other gaseous fuels such as natural gas, besides, it can also be used for power generation in internal combustion engines or gas turbines. Pyrolysis converts biomass at temperatures around 500°C in the absence of oxygen to solid (hard coal), liquid (bio-oil) and gaseous fractions (Faaij 2006). Liquifaction is another way of converting biomass under high pressure into raw intermediate liquids (bio-oils). To date, pyrolysis and liquefaction are still quite expensive hence less well developed and the actual market implementation is so far negligible.

3.2.2 Physical-chemical transformation

Certain types of biowaste such as cotton gin waste and coffee berry residues contain oily seed fragments. When such biowaste is crushed and pressed, the resulting oil can be processed through transesterification to produce a high-quality biodiesel that can be used in a standard diesel car. The residue (press cake) can also be processed and used as biomass feedstock to power electricity plants or used as feedstock for biogas production while the resultant digestate can be used as fertilizer. Nevertheless, the biodiesel industry is largely depended on dedicated energy crops. For instance, biodiesel production in Europe is largely dependent on rapeseed even though the use of waste vegetable oil is gaining prominence. On the other hand, in Africa biodiesel production from non edible oil seeds such as jatropha curcas is gaining immense attention.

3.2.3 Biochemical transformation

Biochemical transformation via alcoholic fermentation and anaerobic digestion offers a very attractive route to utilize diverse categories of biomass and biowaste for meeting energy needs as well as contributing to resource and environmental conservation. Alcoholic fermentation and anaerobic digestion of biowaste into ethanol and biogas respectively can serve as a vital tool in closing the biomass value chain thus contributing to national development.

3.2.4 The role of biochemical transformation in a cascaded utilization of biomass .

Utilization of the potential presented by biomass and biowaste via a cascade system for biogas energy production and the subsequent use of the digestate as green manure can provide multiple environmental (Satyanarayan and Murkute 2008) and socio-economic benefits to the users and the community thus alleviating poverty. Indeed a simple yet all inclusive strategy for promoting the usage of biowaste might be the closed loop cascaded system (Figure 3.2). Bioconversion processes such as ethanol and biogas production can be employed as means of waste valorisation in energy production systems. The production of ethanol from biowaste can improve energy security and decrease pollution. Ethanol is an excellent transportation fuel and when blended with gasoline it leads to reduced gasoline use, thus lowering the need for fossil fuels. Besides the ethanol–gasoline blend has a better performance since ethanol provides oxygen for the fuel resulting in a more complete combustion with a low atmospheric photochemical reactivity. The ability of the biowaste derived glucose to be fermented by yeasts into bioethanol does not only address the issue of renewable energy but could also serve to control the accumulation and associated environmental problems due to biowaste.

Two main approaches i.e., phased and direct microbial conversion, have been examined for the hydrolysis of waste cellulose into glucose and the successive fermentation into bioethanol and other bioproducts (van Wyk 2001). The phased microbial conversion makes use of separate hydrolysis and fermentation processes whereby cellulase is added to pretreated biowaste resulting in the formation of glucose from the cellulose fraction after which yeast is added to ferment glucose into ethanol (Cardona and Sanchez 2007). With the direct microbial conversion, the microorganisms simultaneously produce cellulase, hydrolyze cellulose and ferment glucose into ethanol while at the same time, co-fermentation converts the hemicellulose sugars into bioethanol (Sanchez and Cardona 2008, Stenberg et al. 2000). Over the years there have been substantial advances in enzyme-based technology for ethanol production.

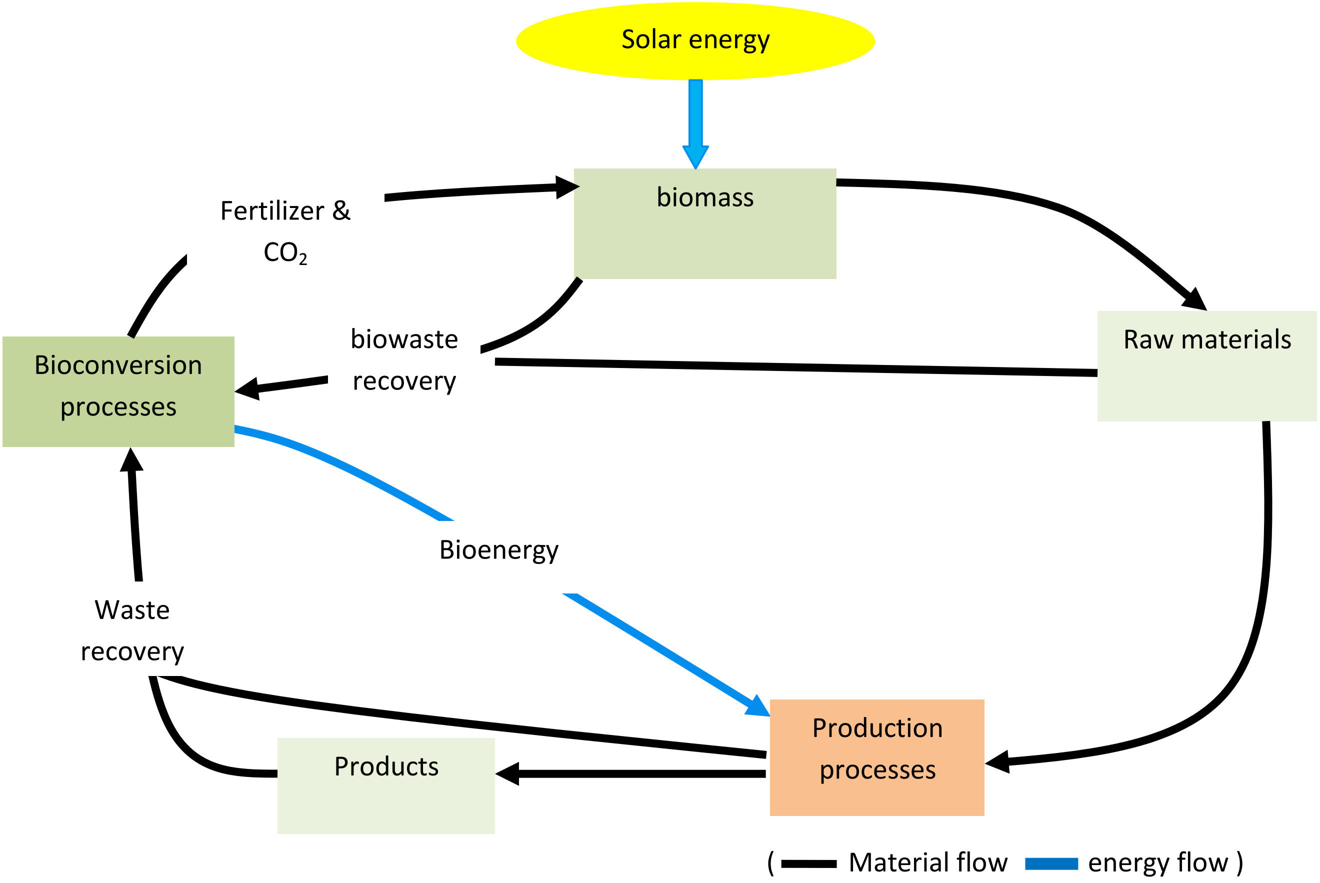

Figure 3.2: Cascaded system for the utilization biomass and biowaste, showing the role of bioconversion process in closing the loop.

Biogas on the other hand is produced through biomethanation process which is a biological transformation through which organic matter is degraded to methane and carbon dioxide. The biomethanation process consists of a series of discrete reactions catalysed by a consortium of metabolic groups of different bacterial species through which organic matter is converted to the main products of methane and carbon dioxide (Ranalli 2007, Yadvika et al. 2004). Indeed most biomass based upgrading and production processes release organic by-products and wastes thus biomethanation can be advantageously implemented into these technologies as a energy production, fertilizer recovery and waste stabilization process. In addition, biomethanation could eventually contribute a significant portion of the country's lighting requirements especially in the rural areas.

The bio-energy produced through biomethanation of agro-biowaste such as sisal and cotton can supplement the energy needs of the textile production processes while the energy savings can be used to enhance the profit of the farmers. Besides, the subsequent use of the digestate as green manure can provide multiple environmental and socio-economic benefits to the users and the community thus contributing to poverty alleviation. Moreover, realization of high-efficient bioconversion processes at places where the biowaste can be gathered and or translocated and where the 'green' products can be sold to a cluster of end users can be a vital key towards meeting the longer term policy goals in most developing countries.

3.3 The Sustainability Concept

Sustainability and sustainable development are broad concepts that have continued to attract increased attention within the public and private sector hence eliciting wide ranging discussions and debate over the last two decades. However, given their ubiquitous use and popularity, the lack of a concrete definition of 'sustainable' may appear rather surprising. Nevertheless, several definitions have been put forth (Heijungs et al. 2010, Simon and Morse 1999, Winterton 2003) including the most quoted definition after the sustainable development report of the World Commission on Environment and Development (World Commission on Environment and Development 1987), commonly referred to as the Brundtland report of 1987. "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". This definition is however open to various interpretations largely depending on how the needs of the present and future generations as well as the earth's carrying capacity to supply them are defined. Sustainable development is thus a very dominant theme in the global development interventions. The main catalyst for this dominance in recent years can be traced to the 1992 Rio de Janeiro Earth Summit that put forth a set of action points for sustainable development, collectively referred to as Agenda 21 (Simon and Morse 1999). In its broadest sense, the sustainable component of the sustainable development paradigm implies that whatever is done now should not harm future generations.

The sustainability concept has been explored further, and today, it is conceived as having three dimensions: the social-cultural, the economical and environmental dimension (Finkbeiner et al. 2010, Mauerhofer 2008). The social-cultural sustainability aims at preserving the stability of social and cultural systems whereas the economic view of sustainability aims at attaining maximum economic benefits at minimum cost while at least maintaining the assets on which the benefits are based. On the other hand, sustainability in the ecological sense means that the natural basis for life, that is the ecosystem, ought to be maintained therefore the ecosphere should not be exposed to an intolerable load. Nevertheless the conundrum is that the ecosystem, which is the basis of humanity's existence, needs to be maintained in order to fulfil its functions in the future. However, the conundrum presents a concise view of sustainability: ***sustainability is a technical balance between the present and future interests***. Sustainability can consequently be seen as the final target, that is, a balance of social and economic activities and the environment (Hofman and Li 2009) whereas sustainable development is the means of reaching the anticipated target. Therefore, to attain sustainable development in its entirety, all three dimensions of sustainability have to be taken into account. The interaction of the three dimensions and some of the preferred characteristics necessary to bring about sustainability is often viewed in terms of the "3 P's" of sustainable development: People, Profit and Planet as introduced by Elkington (Elkington 1997). This presentation underscores the need to integrate the sustainability dimensions and is presented in Figure 3.3. Coincidentally, the technicality behind and the result of, the integration of the three sustainability dimensions brings forth another aspect of sustainable development which has come to be referred to as the technical aspect (Wang et al. 2009). Nonetheless, concepts and evaluation techniques taking care of all the aspects simultaneously are not available.

Figure 3.3: The 3 P's (People, Planet and Profit) and preferred characteristics for sustainable development.

There are many factors that can contribute to achieving sustainable development. One of the most important within a society is the sustainable supply and an effective and efficient utilization of renewable energy resources (Dincer 2000). However, because renewable energy resources are stochastic and geographically diffuse, their ability to sustainably match demand is determined by adoption of either of the two approaches (Omer 2008): first, the utilization of a capture area not greater than that occupied by the community to be supplied and secondly, the reduction of the community's energy demands to a level commensurate with the locally available renewable resources. Sustainable development hence requires, among other things, the greater understanding of how renewable energy interrelates with the physical, natural and living world through studies of the chemistry and life cycle of substances, materials and organisms, their form, properties and behaviour as well as the interactions thereof. Such understanding is critical in solving the Trilemma (Nitta and Yoda 1995), that is, meeting the societal needs of a growing world population while minimising deleterious effects on the environment. Hence, for instance, a sustainable energy sector has a balance of energy production and consumption and has no, or minimal, negative impact on the environment, but presents a conducive opportunity for a country to employ its social and economic activities.

3.4 The multi-criteria sustainability framework

The multi criteria sustainability framework (MCSF) is a format for integrated sustainability evaluation that seeks to account for complex and evolving biophysical and socio-economic systems by addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multiple interests and perspectives. Compared to the conventional single criteria approach that seeks to identify the most efficient options at a low cost, the MCSF seeks to obtain an integrated result by employing multiple criteria or attributes. The MCSF for an energy system therefore ought to facilitate evaluation of the extend in which the system is deemed to be economically viable (economic sustainability), technically efficient (technical sustainability), environmentally bearable (environmental sustainability) and socially equitable (social sustainability). Hence, four main sustainability aspects do suffice namely economic, technical, environmental and social dimensions (Afgan et al. 2000, Finkbeiner et al. 2010, Mauerhofer 2008). Congruent to the sustainability dimensions are impact categories and the respective indicators.

Indicators have been widely employed by biologists for many years to gauge ecosystem health hence they are widely regarded as the core element in operationalizing sustainability. However, unlike most biological systems, sustainability incorporates many more dimensions (Mauerhofer 2008) thus a number of indicators are almost certainly required. Furthermore, due to the amount of sustainability criteria and indicators, their selection and prioritization is of main importance. The problem then becomes how many and which indicators to use? Clearly one cannot employ every sustainability indicator (SI) that may potentially be available hence an element of simplification while concurrently maximising unique and relevant information is essential. However, given the political character of sustainability definitions, building consensus on the selection, prioritisation and simplification of such indicators is a complex task. Nevertheless, the following principles do suffice and are generally obeyed (Simon and Morse 1999):

1. Systemic principle: The scope of the indicators should be relevant and should cover the diversity of issues (environmental, social and economic) with minimal overlap.
2. Consistency principle: The indicator should be consistent with the criteria objective, reliable and easy to contextualise without limiting the capacity to draw conclusions.
3. Measurability principle: The indicator should be measurable in quantitative value or qualitatively expressed.
4. Independency principle: The indicator should reflect the performance of alternatives from different aspects and should not have any inclusivity relationship at the same criteria level.

Other general requirements for indicator selection are reliability, relevance, completeness, non-redundant and independence of preferences.

Sustainability indicators have been a struggle of several public and private organisations with the focus being to produce a single definitive set of indicators (Dewulf and Van Langenhove 2005). However the adept aggregation of indicators is not only complex but suffers from the inherent disadvantage of loss of detail due to the loss of identity of the individual indicators in the final result. In this dissertation, the formulated MCSF departs from the classical approach by attempting to take into account the environmental, socio-economic and technical aspects of sustainability and retaining the identity of the indicators in the final integrated result. The framework proposes nine impact criteria categories and the respective indicators as presented in Figure 3.4. The choice of the indicators was guided by expert judgement and taking into account the “3 P’s “ of sustainable development (Elkington 1997) as well as in accordance to the principles for indicator selection as stipulated by Simon and Morse (1999). Acknowledging that there are potentially many other indicators that could possibly have been selected based on the foregoing indicator requirements, an additional qualification was imposed for the indicator selection, that is, usefulness to the Kenyan situation as outlined in the methodology presented later in **Chapter 6**. Nevertheless, the multi criteria sustainability assessment framework was designed to be relevant to Kenya as well as the neighbouring region and a wider setting where environmental, technical and socio-economic considerations are required devoid of human subjectivity. Moreover, the calculation details and the use of commonly used units were intended to enable readers to adjust the assessment framework to reflect on their own priorities. Hence the assessment scheme can be applied internationally especially to compare different alternatives within the same technology. However, while the criteria chosen are applicable to a wider setting where environmental, technical and socio-economic considerations are required, the corresponding indicators and units have been defined with specific focus to biogas production systems.

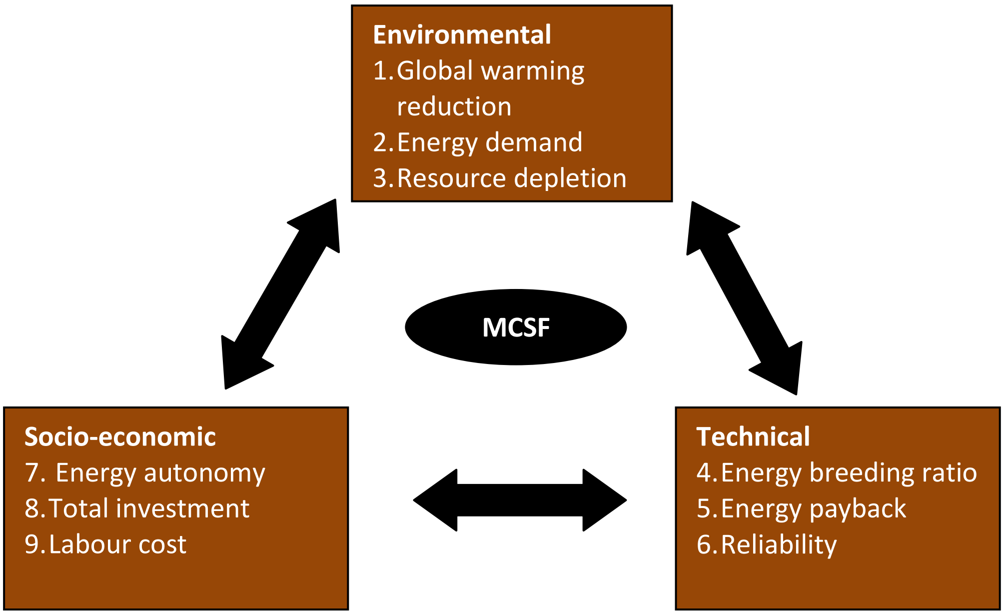

Figure 3.4: Sustainability dimensions and criteria applied in the MCSF

In Table 3.4, the framework is further elaborated showing the operationalization as progressively defined by the objectives and the proposed impact criteria indicators and the corresponding indicator units. The following sections summarise the MCSF methodology with regard to the environmental aspect, the technical aspect and the socio-economic aspect.

3.4.1 Environmental sustainability aspect

The main objective with regard to the environmental sustainability aspect is the maximisation of environmental performance. When biogas systems are compared to other bio energy systems such as biodiesel and bioethanol production systems, they are normally found to lead to environmental improvements in terms of lower emissions to soil and water and the potential recovery of nutrients (Berglund and Borjesson 2006). However, when different biogas systems are compared together factoring in different infrastructures of production, the environmental impact of the background processes suffice. The direct implication of extending the system beyond the biogas production facility is that the requirement to account for emissions of the background processes such as the production, handling and transport of (bulk) raw materials. Sources of GHG emissions in the background processes are mainly from the use of fossil fuels, fertilizers and land use change. In this framework, three specific objectives pertaining to minimisation of environmental pollution, energy demand and resource depletion are defined (Table 3.4). The assessment of the environmental performance is done by means of the Life Cycle Sustainability Assessment (LCSA) which represents the state of the art in science and application based on the ISO 14040 and 14044 environmental standards (Arvanitoyannis 2008).

3.4.2 Technical sustainability aspect

The main objective with regard to the technical sustainability aspect was to maximise technical viability while the specific objectives related to maximisation of useful energy and performance and minimisation of the period needed to recoup the invested energy. Comparison of different biogas systems has shown that there exist differences in energy efficiency for different installations thereby causing differences in performance (Börjesson and Berglund 2007). In this regard, the objective on maximising useful energy seeks to determine the energy balance for the different biogas systems considering the respective output and the input energy. The objective pertaining to energy payback seeks to establish the time span over which the invested energy is recouped for the different biogas systems. On the other hand, the objective on maximising performance seeks to compare the different biogas systems in terms of their respective reliability.

3.4.3 Socio-economic sustainability aspect

Technology is arguably one of the key drivers of socio-economic advancement since people are the creators and key beneficiaries of the ensuing benefits. The improvement of living conditions and the enhancement of socio-economic structures are key goals for biogas initiatives (Nzila et al. 2010). The main objective pertaining to the socio-economic aspect was therefore to maximise socio-economic benefits whereas the specific objectives are chosen with a view to maximise savings, economic viability and labour productivity. The characterisation of the different socio-economic impact categories for the different biogas systems seeks to quantify the savings arising due to the replacement of fossil fuel with biogas, as well as the valorisation of capital and determination of labour productivity.

Table 3.4: Definition of sustainability objectives and impact criteria indicators applied in the MCSF for the assessment of biogas production

Sustainability Aspect/dimension	Objective	Specific objectives	Impact criteria category	Indicator	Definition	Indicator Units
Environmental	Maximise environmental performance	Minimise environmental pollution	Global warming reduction	GHG balance	Green House Gas emission saving as a result of replacing fossil fuel (kerosene) with biogas.	$kgCO_2eq/Nm^3$
		Minimise energy demand	Energy demand	Cumulative energy demand	The amount of energy consumed to produce a unit volume of biogas	MJ/Nm^3
		Minimise resource loses and depletion	Resource depletion	Exergy equivalent	The amount of energy that is available to be used per unit of production	MJ_{ex}/Nm^3
Technical	Maximise technical viability	Maximise useful energy	Energy breeding	Energy balance	The ratio of output energy to the input energy	MJ_{out}/ MJ_{in}
		Minimise the period needed to recoup invested energy	Energy payback	Energy payback period	A measure of the time period over which the energy generated equals the expended energy	Years or months
		Maximise performance	Reliability	Operational reliability	Capacity of the system to perform as designed without need for extensive refurbishment	%
Socio-economic	Maximise socio-economic benefits	Maximise savings	Energy autonomy	Fossil energy replacement saving	A measure of savings arising from the substituted of fossil energy resources per unit of production	$\$/Nm^3$
		Maximise economic viability	Total investment	Total capital investment cost	A measure of the valorisation of investment per unit of production	$\$/Nm^3$
		Maximise labour productivity	Labour	Direct labour cost	A measure of the cost of labour per unit of production	$\$/Nm^3$

3.5 Operationalizing the MCSF for biogas production

The operationalization of the MCSF to compare different alternatives for biogas production is graphically illustrated in Figure 3.5 and demonstrated in chapter 6 of this work. The inventory data, commonly in distinct measurements but usually presented per functional unit, is processed for each indicator in accordance with the LCSA approach and chosen characterisation factors to yield the corresponding impact category scores. The three impact category scores for each sustainability dimension are presented separately and comparison for the different alternatives under investigation is performed for each dimension. The three dimensional scores are then dimensionally normalised so as to be presented in a radial unit spider-gram for an integrated comparison of the three alternatives for biogas production.

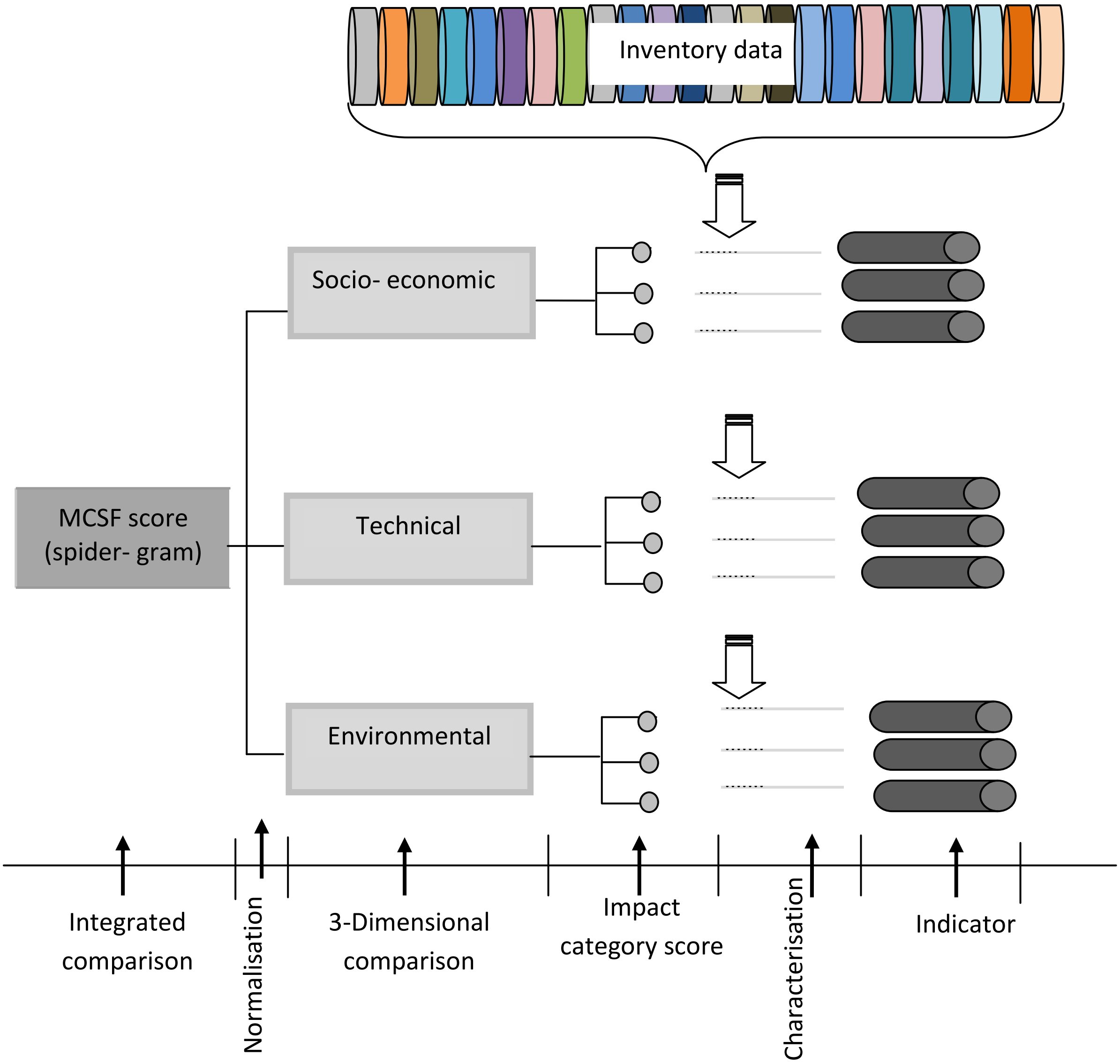

Figure 3.5: MCSF evaluation scheme addressing the characterisation of impacts and comparison at each dimension level as well as normalisation and the eventual integrated comparison.

All the impact criteria in the spider-gram are given equal prominence and scaled with increasing level of suitability from zero to one. The total spider-gram area occupied by the different alternatives denotes their suitability with respect to the impact criteria under consideration. Characterisation of the impact criteria categories were all based on LCA and are summarised in Table 3.5. The selection

Table 3.5: Characterisation factors for operationalising the MCSF

Indicator	Characterisation factor	Units
GHG balance	$GHG\ balance = GHG_{replaced\ fossil} - GHG_{biogas\ prod.}$	kg CO_2 eq/Nm^3
Cumulative energy demand	$CEENE_j = \sum_{i=1}^{184}(X_i * a_{ij})$	MJ_{ex}/Nm^3
Exergy equivalent	$CED = \sum_j X_j * n_j$	MJ/Nm^3
Energy balance	$Energy_{out} / Energy_{in}$	MJ/Nm^3
Energy payback period	$\frac{\sum Energy_{in}\ (MJ)}{Energy_{out/yr}\ (MJ/yr)}$	Years
Operational reliability	$\frac{\sum Digesters_{faultless}}{\sum Digesters} x100\%$	%
Fossil energy replacement saving	$\left\{\frac{Energy_{biogas}\ (MJ/m^3)}{Energy_{fossil}\ (MJ/kg)} - Q_{fossil}\ (kg/Nm^3)\right\} * P_{fossil}\ (\$/kg)$	\$/ Nm^3
Total capital investment cost	$Cost_{invest}\ (\$) / V_{biogas}\ (Nm^3)$	\$/ Nm^3
Direct labour cost	$Cost_{labour}\ (\$) / V_{biogas}\ (Nm^3)$	\$/ Nm^3

3.6 Operationalizing the environmental sustainability dimension to assess the impact of biowaste valorisation to the environmental profile of the African *Kitenge*

The environmental criterion in the sustainability framework is built upon the recognition of two philosophies pertaining to the way people interact with their natural environment. First, is the fact that natural resources are finite therefore they need to be used wisely. Second, is the notion that the use of resources by humans can pose negative consequences to the environment such as pollution which ought to be avoided or at least mitigated. Following these two notions and pursuant to the conclusion from the second law of thermodynamics (Atkins 1984, Winterton 2003) that there is no such a thing as a waste-less process, the objective of maximising environmental performance in the textile sector is structured considering the added value of biowaste valorisation to the environmental profile of the African *Kitenge*. This is further elaborated in chapter 7 of this dissertation.

3.7 Biowaste-based biogas energy specific sustainability issues

Biowaste-based biogas energy (BBE) has various unique features that can significantly reduce some of the sustainability problems faced by many terrestrial biofuel sources. For example no direct/indirect land use changes or competition for agricultural land, besides, BBE offers an opportunity for fertilizer production instead of consumption. Nevertheless, integrating the full potential of all these benefits influences other choices within the BBE concept. In addition, choosing the most environmentally, economically and socially sustainable approach is quite complex. Nonetheless, some important risks and opportunities to be considered are discussed below.

3.7.1 Land use: opportunities and risks

Direct land use changes (LUC) are caused when new areas or virgin land such as forest areas or degraded land are taken into production to directly cover the additional energy feedstock demand. On the other hand an indirect land use change (ILUC) is caused when existing agricultural land is used to cover the feedstock demand of additional bio fuel production. This will indirectly cause an expansion of the land use for biomass production to the new areas when the previous users of the feedstock, such as food markets, do not scale down their feedstock demand. Both LUC and ILUC can have positive and negative consequences on aspects such as biodiversity, carbon stocks and livelihoods (Simon and Morse 1999). Nevertheless, since BBE relies on residues such as agro based residues, it therefore follows that BBE systems do not have stringent land quality requirements. Technically all the land under agricultural production can be deemed to be available for BBE production. Consequently there is an enormous amount of land suitable for BBE production that does not compete with agricultural land and avoids conversion of land with high carbon stocks. Generally since biowaste energy relies on biowaste such as agro residues, it suffices to say that there are no inherent land use risks specific to BBE production.

3.7.2 Resource cascading: opportunities and risks

Resource cascading, which implies the sequential exploitation of the full potential of a resource during its use (Clift 1995), is one of the key ways of improving efficient utilization of raw materials. Biomass cascading for instance via BBE production is thus an important concept to consider when striving for efficient biomass utilization. BBE thus offers one of the possibilities for exploiting valuable biowaste characteristics. Indeed current conditions of residue availability and the associated environmental nuisances, as well as the demands from the climate change agenda and the global transition towards a biobased economy are triggering new opportunities and frontiers for BBE (Nzila et al. 2010, Verstraete et al. 2005). The flexibility and simplicity of BBE thus renders it to be able to increase its contribution to economical and environmental sustainability of the entire biomass chain through waste reduction and production of extra energy and bio fertilizer for soil amendment in a closed loop biomass resource cascade configuration (Figure 3.4).

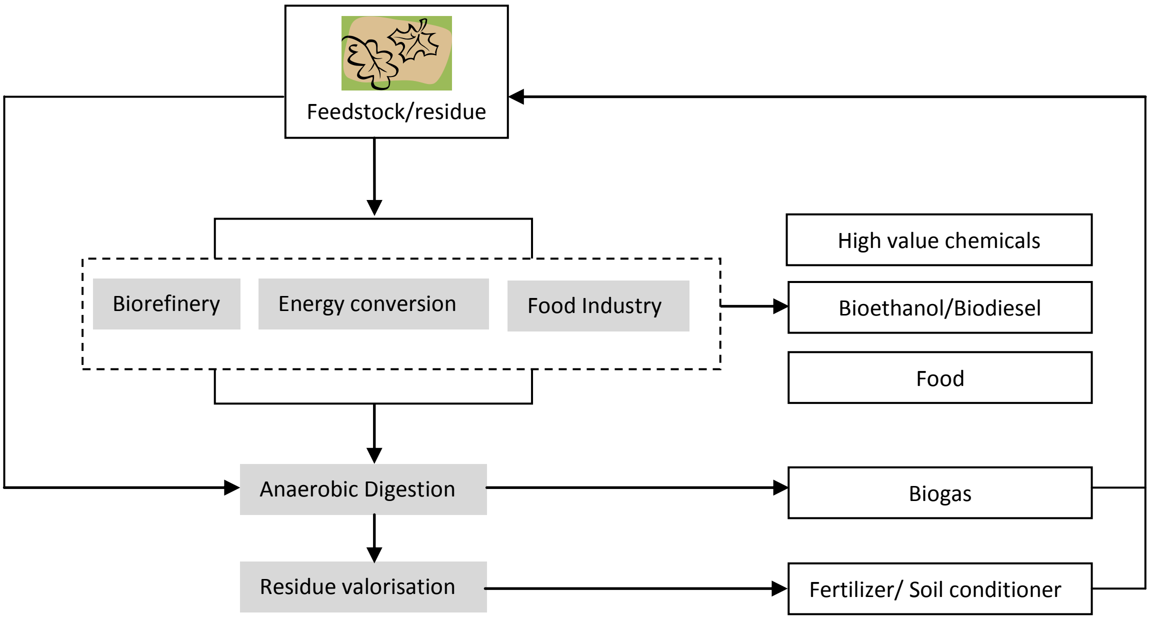

Figure 3.4: Possibilities for closed loop biomass resource cascade configurations having anaerobic digestion as a key element for BBE.

Several examples demonstrating the contribution of BBE to biomass cascades have been shown. Van Haandel (van Haandel 2005) demonstrated the digestion of vinasse and bagasse resulting from the production of ethanol from sugarcane in Brazil where 8,750 kW are produced in addition to the 5,000 litres ethanol produced from the original 65 – 75 ton wet sugarcane. Similarly in another study (Clarke et al. 2008) it was demonstrated that there are no technical barriers to cascading the utilization of banana biomass at a commercial scale in Australia. In this study it was shown that 1 ton of banana waste per day can generate 7.5 kW of electricity, enough to supply six to eight houses. Moreover, the added value of BBE to a grass biorefinery concept has also been demonstrated in Switzerland (Baier and Delavy 2005). In this particular case BBE adds value to the biomass chain by generating 500 kWh per ton grass in addition to the 0.4 ton fibres and 0.12 ton proteins originally produced from the initial ton of biomass. A similar study in Kenya (Nzila Charles et al. 2009) obtained that if 50% of the sisal and cotton residue can be harnessed for bioconversion into energy, about 94,000 MW of electricity and 141,000 MW of thermal energy can be generated.

Most technological research in the field of bioenergy focuses mostly on one stage of the process and the inner system possibilities for optimization of the process efficiency. However research is needed for the optimization of the full chain considering demands of the expanded boundary of the outer system as outlined in **chapter 2**. Hence the question that suffices is how to tackle any potential risks as well as how the expanded boundaries and resource cascade conditions influence the role that BBE can play in the different biomass chains.

One of the possible problems of BBE production is associated with humus formation from the agro residues. For instance when the BBE production systems are centralised, it then necessitates transportation of the BBE feedstock from the agricultural fields to the BBE facilities. Consequently concerns are that such translocation of biowaste may have a negative effect on soil quality, especially on soil organic carbon stocks (Brandão et al. 2010). Indeed if the digestate slurry is not transported back to the fields then the soils could be deprived of the vital constituents for humus formation.

3.8 Kenya as a case study area and biogas as a case study bio energy carrier

The possibility of creating energy and other products in a competitive way out of biomass as well as biowaste might improve the economic conditions of vast population in developed and developing countries (Nielsen et al. 2004). Tropical developing countries especially in Africa are perceived as having good bioenergy production potential (Nzila et al. 2010) as they possess large tracts of land, good agricultural production conditions in terms of sun hours, rainfall, low temperature fluctuations and cheaper production costs as compared to Europe (Faaij 2006). However concerns are in place as pertains to the low utilization of biowaste for energy production.

Kenya can be regarded as a country exemplifying such a panorama, having a wide range of opportunities for the utilization of biomass and biowaste besides emerging concerns due to the rapid global developments in bioenergy production. Agriculture is a key sector of Kenya’s economy, contributing about 25% of the Gross Domestic Product (GDP) and providing employment to an estimated 70% of the labour force. According to the Kenya Integrated Household Budget Survey

(KIHBS) report of 2007, 68.8% of all households in Kenya are engaged in crop farming activities. In the rural areas, this proportion stands at 85.4%. Farming is practiced on an estimated 5 million hectares out of a total area of about 59 million hectares. However, irrigation farming is practiced only in 6% of all agricultural parcels. Furthermore, 66.0% of the households keep at least one type of livestock with poultry and cattle being the predominant livestock. 67% of the households rear chicken while 64% of the households rear cattle. Other livestock types reared include goats, sheep, pigs, camel and donkeys. Nationally, the country's energy matrix show that 68.3% of all households use firewood as cooking fuel and over 80% of rural households rely on firewood for cooking compared to 10% of the households in urban areas. The percentage of households using electricity for cooking was reported to be 0.6% whereas the usage of biogas was insignificant, recorded at below 0.1% (Table 3.8). On the other hand, kerosene is the major source of lighting fuel in majority of households (76.4%). One of the most important constraints facing biogas technology dissemination in the country is inadequate feedstock for biogas production (Nzila et al. 2010). The incorporation of BBE into Kenya's energy matrix could thus deliver various benefits like the delivery of valuable biogas for farmers to use in different applications such as cooking, heating and lighting. The reincorporation of nutrients and residual carbon into the land is another additional benefit. The Kenya case can serve as a model case that can further be extrapolated and applied to other East African countries.

Table 3.8: Energy use (%) for cooking and lighting in Rural and urban areas of Kenya

Source of energy	Rural		Urban		National	
	Cooking	Lighting	Cooking	Lighting	Cooking	Lighting
Electricity	0.2	3.9	1.8	51	0.6	15.6
Kerosene	2.7	86.4	44.6	46.3	13.2	76.4
Fuelwood	87.7	5.8	10	0.5	68.3	4.5
Charcoal	7.7	-	30.2	-	13.3	-
Solar	0.0	2.0	0.0	0.7	0.0	1.6
LPG	0.7	0.2	11.9	0.2	3.5	0.2
Biogas	0.0	0.0	0.1	0.0	0.0	0.0

Source: Kenya Integrated Household Budget Survey, 2007 (Nassiuma 2007)

3.9 Appendix 3.1: Calculations in the Multi Criteria Sustainability Assessment framework

1. **$CEENE_j = \sum_{i=1}^{184}(X_i * a_{ij})$** (eq 1)

   Where:

   $CEENE_j$ = cumulative exergy extracted from the natural environment for a product *j* (MJ_{ex})

   X_i = characterisation factor of the i^{th} reference flow (MJ_{ex}/kg, MJ_{ex}/MJ, MJ_{ex}/Nm^3, MJ_{ex}/m^2.a)

   a_{ij} = amount from reference flow *i* (kg, MJ, Nm^3, m^2.a) necessary to obtain product *j*.

2. **CED = $\sum_j X_j * a_j$** (eq 2)

   Where:

   CED = cumulative energy demand (MJ)

   X_j = characterisation factor of resource *j* (MJeq/kg, MJeq/m^3, MJeq /m^2a),

   a_j =amount of resource *j* (kg, Nm^3, m^2.a per functional unit)

3. **GHG saving =** $GHG_{\text{replaced fossil}}$ (kg $CO_{2\,eq}/m^3$) − $GHG_{\text{biogas prod}}$ (kg $CO_{2\,eq}/m^3$) (eq 3)

   Where:

   $GHG_{\text{replaced fossil}}$ = CDE_{fossil} (kg $CO_{2\,eq}$ /kg_{fossil}) * FER (kg/m^3)

   $GHG_{\text{biogas prod.}}$ = $\sum_j X_j * m_j$

   $GHG_{\text{replaced fossil}}$ = Green house gas potential for the fossil fuel replaced by biogas (kg CO_2eq/$Nm^3{}_{\text{biogas}}$)

   $GHG_{\text{biogas prod}}$ = Green house gas emitted due to biogas production (kg CO_2eq/$Nm^3{}_{\text{biogas}}$)

   CDE_{fossil} = carbon dioxide equivalent for fossil fuel (kg CO_2eq/kg_{fossil})

   X_j =characterisation factor of emission *j* (kg CO_2 eq/kg)

   m_j =mass of emission *j* (kg/ $Nm^3{}_{\text{biogas}}$)

4. **EBR** = $\frac{output\ energy\ (MJ/m3)}{input\ energy\ (MJ/m3)}$ (eq 4)

Where:

- EBR = Energy breeding ratio
- output energy is the energy content of biogas per unit volume
- Input energy is the energy expended to produce the biogas (cumulative energy demand) per unit volume.

5. **EPP**= $\frac{total\ energy\ input\ (MJ)}{annual\ energy\ output\ (MJ/yr)}$ (eq 5)

Where:

- EPP (years) = Energy payback period

- Total energy input (MJ) = energy demand (MJ/m^3) * total volume of biogas produced (m^3)
- annual energy output $\left(\frac{\text{MJ}}{\text{yr}}\right) = \frac{\text{total biogas output } (\text{m}^3) * \text{biogas energy content } (MJ/\text{m}^3)}{20\ yrs}$

6. **Reliability** $(\%) = \frac{\sum digesters\ without\ need\ for\ extensive\ refurbishment}{\sum digesters} * 100\%$ (eq 6)

7. **Total investment cost** = $\frac{construction\ cost\ (\$) + direct\ labour\ cost\ (\$)}{total\ biogas\ production\ (m3)}$ (eq 7)

Where:

- Construction cost = cost incurred ($) in the construction of the respective digester
- Direct labour cost = labour input (man days) * minimum daily wage ($/day)

8. **FERS** ($/ Nm^3) = $\left\{\frac{E_{biogas}\ (MJ/\text{m}^3)}{E_{fossil}\ (MJ/\text{kg})} - Q_{fossil}\ (\text{kg/Nm}^3)\right\} * P_{fossil}\ (\$/\text{kg})$ (eq 8)

Where:

FERS = Fossil energy replacement savings ($/ Nm^3)

E_{biogas} = Biogas energy content (MJ/Nm^3) = 35.8 MJ/Nm^3 (or 9.845 MJ/Nm^3 considering 50% CH_4 and 55% standard biogas stove efficiency)

E_{fossil} = Fossil resource energy content (MJ/kg)

Q_{fossil} = fossil resource used during biogas production (kg/Nm^3)

= CED non ren. (MJ/m^3) $x \frac{\delta_{fossil}\ (kg/L)}{G_{fossil}\ (MJ/L)}$

δ_{fossil} =density of fossil fuel (density of kerosene = 0.81kg/l)

G_{fossil} = energy content of fossil fuel (LHV of kerosene) = 37.7 MJ/l (or 18.85 MJ/L considering 50% standard kerosene stove efficiency)

P_{fossil} = Price of fossil resource ($/kg)

9. **Labour cost** $(\$/\text{m}^3) = \frac{\text{Direct labour demand (man-days) x daily wage (\$/man-day)}}{total\ biogas\ production\ (\text{m}^3)}$ (eq 9)

Where:

The daily wage is based on the average minimum wage consideration in the country

Chapter 4

Characterisation of agricultural residues and segregated textile mill effluents for biogas and nutrient recovery

ABSTRACT

In the modern energy-demanding lifestyle there is an overwhelming need for exploring and exploiting new sources of energy which are renewable as well as eco-friendly. In Kenya, typical to many developing countries, various industrial waste streams and residual biomass that have a good potential to cater for the energy demand are available in plenty though rarely utilised efficiently. Bioconversion of selected residual waste streams for energy production is a promising option for exploiting the huge potential offered by the underutilised residues in many developing countries. Biogas technology offers a very attractive route to valorise various categories of biowaste and offers multiple benefits to the users and community besides meeting the energy needs, resource conservation and environmental protection. However sustainable application of biogas technology demands a sound understanding of the feedstock characteristics. Hence it is imperative to screen the substrates so as to evaluate their suitability for biogas energy production. In this study three different textile mill effluents and four agricultural residues were characterised in terms of proximate analysis, bio methane potential assay, biogas quality and digestate analysis. The results demonstrate that coffee pulp residues, sisal brushing residues and sisal plume tow are quite suitable for biogas production whereas all the substrates are very promising for nutrient recovery.

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4.1 Introduction

The modern energy-demanding lifestyle presents an overwhelming need for exploring and exploiting new sources of energy which are renewable as well as eco-friendly. In the resent past a lot of research interest has emerged worldwide on the utilisation of biomass for generation of energy (Dincer 2000; Sims 2004; Demirbas 2007; Fischer 2007; Parawira 2008; Prochnow, Heiermann et al. 2009; Moriarty and Honnery 2011; Popp, Hascic et al. 2011; Saidur, Hossain et al. 2011; Singh and Olsen 2011; Wiley, Campbell et al. 2011). Indeed, biomass in all its forms is researched to account for over 16 % (over 1097 million tonnes of oil equivalent (TOE) of the world's total energy consumption by 2020 (Parikka 2004). Already in developing countries, biomass currently provides over 35% of the total energy consumption. In USA biomass contributes about 70 million TOE whereas in the European Union, biomass contributes around 40 million TOE (International Energy Agency 2011). Biomass utilization is expected to increase as a strategy for CO_2 reduction since it is considered to be a CO_2 neutral fuel. The consideration of biomass as a green fuel is further attributed to its extensive geographical distribution. Belgium and most of EU states have aggressively embarked on biofuel production in the last ten years whereas biofuel research in Kenya and many other developing countries is still at its infancy. However, biofuel production from non-food crops and agricultural residues in Kenya has the potential of putting underutilized resources into optimal use and this can lead to national development as well as alleviation of poverty. In Kenya, typical to many developing countries, various industrial waste streams and residual biomass that have a good potential to cater for the energy demand are available in plenty but largely remain under utilised. However bioconversion of selected residual waste streams for energy production is a promising option for exploiting the huge potential offered by the underutilised residues in many developing countries (Sims 2004).

The most common bioconversion routes are alcoholic fermentation and anaerobic digestion to yield bio-ethanol and biogas, respectively. Nevertheless, the present study is confined to biogas production but for a general overview of the former, the reader is referred to Nzila (2009) and Sanchez (2008). Biogas is produced through biomethanation process which is a biological transformation through which organic matter is degraded through anaerobic digestion. The biomethanation process consists of a series of discrete reactions catalysed by a consortium of metabolic groups of different bacterial species through which organic matter is converted to the main products of methane, carbon dioxide and digestate (Yadvika 2004; Ranalli 2007). Biomethanation can therefore be advantageously implemented, as energy as well as fertilizer recovery and waste stabilization process, into most biomass based upgrading and production processes which release organic by-products and wastes. In addition, the biogas from biomethanation could eventually contribute a significant portion of the lighting requirements especially in the rural areas (Sims 2004). Besides, the subsequent use of the digestate as green manure can provide a multiple environmental and socio-economic benefits to the users and the community thus contributing to poverty alleviation.

Biogas technology is therefore one of the widely employed bioconversion techniques that offers a very attractive route to utilize various categories of biowaste and offers multiple benefits to the users and community besides meeting the energy needs, resource conservation and environmental protection. However sustainable application of biogas technology demands a sound understanding of the feedstock characteristics. Indeed biogas production is strongly influenced by feedstock restrictions such as substrate complexity, quality and quantity as well as year-round cost-effective availability. Consequently in a typical biogas value chain (BVC), biogas production depends for the most part on the biodegradability and hydrolysis rate of the substrate (Fernandes 2009). Substrate availability and adequate digestibility is thus a principal requirement in biogas production systems. Nevertheless large quantities of potential biogas substrates remain under utilized due to knowledge gaps especially with respect to their suitability as biogas substrates (Yu 2008; Nzila 2010). Indeed in many developing regions, the abundant supply of readily available biogas feedstock has largely remained underutilized while the need for secure, affordable, reliable, clean and sustainable energy supply continues to escalate. Hence it is imperative to screen and indeed map the substrates so as to evaluate their suitability for biogas energy production. Besides, claims of the beneficial impacts of the digestate are of no significance if the recoverable nutrients are not substantiated.

The aim of this paper is therefore to employ simple yet effective procedures to screen and characterise different types of agricultural residues and segregated textile mill effluents so as to evaluate their suitability for biogas and validate the nutrients recovered.

4.2 Materials and methods

4.2.1 Biowaste material

The test substrates consisted of agricultural biowaste and textile effluents. The agricultural biowaste material species were derived from an evaluation conducted as part of the REDSEA Kenya project, taking into account selected features such as their availability, ease of collection and multipurpose use. The agricultural biowaste included coffee pulp residue, sugarcane leaves, banana stalks, sisal plume tow and brushing residue. The textile effluents included cold bleach, wash off and scouring effluents. The agricultural biowaste were collected from different farms in Kenya whereas the textile mill effluents were collected from a textile factory in Kenya (Rivatex East Africa Limited). The agricultural biowaste were air- dried at ambient conditions to an average equilibrium moisture content of 10.0% (±1.5), grinded and sieved to pass through a 0.2 mm mesh so as to avoid the interference of particle size in Biochemical Methane Potential (BMP) assays as previously reported (Moller, Sommer et al. 2004). The parameters analysed during the course of screening the different biowaste for energy production and nutrient recovery included dry matter (DM), ash content at 500°C, volatile solids (VS), total COD, crude protein, crude fibre, volatile fatty acids (VFA), methane (CH_4), hydrogen sulphide (H_2S), total ammonia nitrogen (NH_4^+-N), orthophosphates (PO_4^{3-}-P) and Potassium (K^+).

4.2.2 BMP assay

The experimental set up for the BMP assay consisted of 1 L glass BMP bottles with side ports. Each test was carried out in duplicate. After putting the required amount of substrate and inoculum in each reactor, tap water was added to a volume of 200ml. The inoculum/substrate ratio, in terms of VS, was maintained at an average of 1.5 and each reactor contained on average 15g VS/l solution. In addition, 1.2 ml of macro nutrients and 0.1 ml of micronutrients (Kleerebezem, Pol et al. 1999) were dosed in each reactor vessel and the pH was buffered using a 10 mM phosphate buffer (Field 1988; Cho, Park et al. 1995). The reactors were then flushed with nitrogen gas for about five minutes to purge out oxygen after which the top of each reactor was sealed with a Polytetrafluoroethylene (PTFE) lined screw cap. The reactors were then incubated for 5 weeks at 30(±1) °C in a shaker (New Brunswick Scientific). Duplicate blank reactors were used to correct for the gas production by the inoculum mix while a similar batch flask containing the same amount of only water was used to correct for temperature variations.

The parameters analysed prior to the commencement of the BMP assay included DM, VS, ash content, crude protein and crude fibre content. The parameters monitored during the course of the BMP assay included gas pressure and composition, pH and VFA concentration. The gas pressure in each reactor was measured daily using a digital pressure meter model GMH 3150 (Greisinger, Germany) whereas the pH, VFA and composition in terms of CH_4, CO_2 and H_2S content were measured weekly.

4.2.3 Analytical methods

The characterisation of the substrates in terms of DM, ash, VS and total COD analysis were performed according to standard methods (Lenore 1998). Nitrogen analysis was performed according to modified Kjeldahl method in which the sample is digested using H_2SO_4 and H_2O_2 and $CuSO_4$ as catalyst (Harold Egan, Ronald S. Kirk et al. 1981). All nitrogen is converted to $(NH_4)_2SO_4$, which is later determined by adding an excess of NaOH and by distilling the liberated NH_3. This free NH_3 is collected in H_3BO_3 solution and titrated with HCl solution. The crude protein content was calculated by multiplying the nitrogen content estimated via the Kjeldahl method by 6.25 g protein per g N (Stringer, Stapleton et al. 1994). The crude dietary fibre was analysed by means of a combination of enzymatic and gravimetric methods according to (Prosky et al. 1992).The analysis of nutrient parameters in terms of NH_4^+-N, PO_4^{3-}-P and K^+ was performed using a photometer *NANOCOLOR* 500D (Filter Service NV, Belgium) (Macherey-Nagel, 2011). The determination of NH4-N is based on the reaction basis whereby at a pH value of about 12.6, ammonium ions react with hypochlorite and salicylate in the presence of sodium nitroprussiate as catalyst to form a blue indophenol from which the concentration of NH4-N (mg/l) is obtained photometrically. Similarly, the determination of PO4-P is based on the reaction basis whereby ortho-phosphate ions react with molybdate/vanadate to form a yellow phosphate-molybdate-vanadate complex from which the concentration of PO4-P (mg/l) is obtained photometrically. Determination of potassium on the other hand is based on the reaction basis whereby potassium reacts with sodium tetraphenylburate to form an insoluble compound which can be photometrically measured as turbidity. Prior to the nutrient analysis, the digestate was centrifuged at 10,000 rpm for 10 minutes to eliminate any turbidity interference.

During the course of the experiments, liquid samples were analysed for pH. Gas composition was determined with a *Fisons Instruments GC* 8000 series equipped with two columns connected to a thermal conductivity detector that is a *Molsieve* column (30m X 0.53 mm X 10 μm) for measuring O_2, N_2 and CH_4 and a *Parabond Q* column (25m X 0.53mm X 10μm) for measuring CO_2. Helium was used as the carrier gas. The temperatures of the oven, injection port and flame ionization detector were 40°C , 110°C and 99°C respectively. The H_2S content was analysed using *Antek Instruments GC 7000* series equipped with sulphur chemiluminescence detector. The oven and back inlet temperatures were 120 and 150°C respectively. All analyses were performed in duplicate.

4.2.4 Inoculum material

The inoculum used was a sludge mixture consisting of active suspended digested cow dung and anaerobic granular sludge. The digested cow dung with 5.0 % DM and 67.0 % VS in DM was obtained from a mesophilic cow dung-based biogas digester whereas the granular sludge with 15.4 % DM and 70.8 % VS in DM originated from a mesophilic up-flow anaerobic sludge blanket (UASB) reactor treating paper mill effluents. The Substrate to Inoculum ratio (S/I ratio) on VS basis was kept at 0.6 to guarantee adequate presence of hydrolytic and methanogenic microbial populations.

4.3 Results and discussions

4.3.1 Physico-chemical characterisation of biowaste

The physico-chemical characterisation of the different biowaste is presented by means of proximate analysis (Table 4.1) in terms of DM, VS, ash, crude protein and crude fibre. The solid biowaste had a relatively high ash content ranging from 4.63% (coffee pulp residues) to 33.77% (banana stalks). In comparison to woody biomass ash (<1% for softwoods and 1–3% for hardwoods) these ash contents are extremely high, but they are not uncharacteristic for agro-industrial residues since ash contents in the range from 5 to 22 wt% for wheat straw, corn stover and cotton gin waste have been reported (Agblevor et al. 2006). Nevertheless, the high ash content values can be attributed to the incorporation of inorganic materials in the residues and effluents. The VS content ranged from 44.06% (scouring effluent) to as high as 94.21% (coffee pulp residues). Volatile solids are generally one of the common indicators for biogas production potential hence in this aspect and with respect to the solid substrates, coffee pulp residues would be expected to yield the highest amount of biogas whereas banana stalks would be expected to yield the lowest amount of biogas. Using the same analogy for the liquid effluents, the wash off effluent would be expected to yield the highest amount of biogas whereas the scouring effluent would be expected to yield the lowest amount of biogas. Of course this proposition presupposes long term conditions (over three months) since in the short term (around 30 days) the anaerobic digestibility of the residue and the absence of toxic intermediates is much more important (Ranalli 2007).

The crude protein and fibre content of the residues were generally comparable. However sugarcane leaves and banana stalks were an exception with significantly low crude protein content of 1.41% and 0.08%. On the other hand the crude fibre content for all the solid residues was quite comparable apart from coffee pulp residues which had a significantly lower crude fibre content of 21%. The crude protein and fibre content of sisal and coffee pulp residue render them suitable for use as animal feed, however the hard crusty appearance of coffee pulp residue coupled with bitter taste make it unattractive to animals. Generally the proximate analysis results of the current study as presented in Table 4.1 show a consistency with experience elsewhere in terms of characterisation of digestate and plant biomass of different fibre contents (Klimiuk et al., 2010; Nzila et al., 2010; Fantozzi 2009). The crude protein of sugarcane leaves and banana stalks however represent significantly low N-content which appears uncharacteristic of the other plant materials considered in the analysis. However the elemental composition of plant biomass has been observed to vary significantly depending on many factors such as plant type, origin, farming system, climatic conditions, time of harvest etc. N-content of sugarcane leaves and banana residues has been reported bearing values as low as 0.09 and 0.02 (wt %) respectively (ECN Phyllis 2011, Clarke 2008) thus the low crude protein content of sugarcane leaves and banana stalks are not exceptional. Nevertheless the implication of such low crude protein content is that there is a very high likelihood of nitrogen insufficiency during anaerobic digestion. Hence there is need to supplement the N-content during biogas production from such substrates by for instance co-digestion with substrates with higher crude protein content.

Table 4.1
Proximate analysis of the biowaste

	Proximate analysis (Standard dev, n=2, in brackets)				
Substrate	**%DM**	**% ASH ***	**%VS ***	**Crude Protein ***	**Crude Fibre ***
Coffee pulp residues	92 (4)	5 (1)	94 (2)	12.21 (1.12)	21.09 (1.96)
Sugarcane leaves	20 (0)	29 (4)	71 (4)	1.41 (*0.10)*	80.26 *(1.28)*
Sisal Plume tow	94 (0)	18 (2)	82 (2)	12.31 (*0.10)*	71.47 *(2.10)*
Sisal brushing residue	94 (0)	14 (0)	86 (0)	12.16 *(0.08)*	80.00 *(2.70)*
Banana stalks	10 (0)	34 (1)	66 (1)	0.08 *(0.00)*	85.13 (2.98)
Cold bleach effluent	3 (0)	54 (2)	46 (2)	12.15 (*1.40)*	30.57 *(2.47)*
Wash off effluent	0 (0)	45 (3)	55 (3)	28.41 *(4.82)*	17.34 *(12.79)*
Scouring effluent	0 (0)	56 (7)	44 (7)	26.92 *(4.79)*	11.76 (*7.19)*

***Expressed in terms of %DM; values for DM, ASH and VS have been rounded off.**

On the other hand, the low protein content of sugarcane leaves and banana stalks render them unsuitable for use as animal feed. Moreover since the crude protein content of most plant-based substrates has a strong influence on the biogas potential (Lubken, Gronauer et al. 2007) then it can be postulated that the biogas yield from both sugarcane leaves and banana stalks would be probably lower as compared to the other residues.

4.3.2 BMP assay and gas quality

The net results (after correction for blanks) of the BMP assay and gas quality of the different substrates is presented in Table 4.2. The BMP assay of the solid residues showed a range from as low as 0.091 m^3 CH_4/kg VS (sugarcane leaves) to as high as 0.309 m^3 CH4/kg VS (banana stalks). On the other hand the methane yield ranged from as low as 12.68 m^3 CH_4/ton (sugarcane leaves) to as high as 214.47 m^3 CH_4/ton (coffee residues). Similarly the BMP assay of the liquid effluent showed a rather comparable range from as low as 0.228 m^3 CH_4/m^3 (cold bleach effluent) to as high as 0.314 m^3 CH_4/m^3 (wash off effluent). On the other hand the methane yield ranged from 0.45 CH_4/m^3 (scouring effluent) to 3.10 m^3 CH_4/m^3 (cold bleach effluent). However for the liquid effluents the methane yield in terms of m^3 CH_4/ton-COD removed correspond to 219, 302 and 483 for cold bleach, wash off and scouring effluents respectively. Values in the range of 96 to 277 m^3 CH_4/ton-COD removed have been reported in the literature for mixed textile effluents (Kuai, Vandevivere et al. 1998; Nzila 2008). The methane yields from the segregated effluents therefore present a remarkable improvement from the figures reported in literature. From the foregoing, it is also apparent that high BMP value does not necessarily correspond to high methane yield per ton substrate primarily due to the differences in VS, digestibility and methane content of the substrates.

Generally the methane yield for both sugarcane leaves and banana stalks (respectively 12.7 and 20.8 m^3 CH_4/ton substrate) are significantly lower as compared to the yield from sisal and coffee residues which are in the range of 124 to 214 m^3 CH_4/ton substrate. This occurrence implies that the anaerobic digestion and hence mineralisation of both sugarcane leaves and banana stalks is quite different from that of coffee and sisal residues. There is possibly a wide array of physical, chemical and biological factors behind such an occurrence. Nevertheless, from Table 4.1 it is apparent that the relatively lower VS content coupled with significantly higher ash content in both sugarcane leaves and banana stalks possibly has a direct bearing on the low biogas yield from the two residues. These findings are in agreement with previous studies showing that anaerobic mineralisation of some COD does not necessarily end up with more biogas (Ranali 2007; Nzila et al 2008).

Table 4.2
BMP assay and gas quality from the different biowaste substrates

BMP Assay & Gas Quality Analysis (Standard dev, n=2, in brackets)		
Substrate	**BMP** **(m^3 CH_4/kg VS)**	**Methane Yield** **(m^3 CH_4/ton $_{substrate}$)**
Coffee pulp residues	0.257 (0.002)	214.47
Sugarcane leaves	0.091 (0.001)	12.68
Sisal Plume tow	0.163 (0.011)	124.84
Sisal brushing residue	0.214 (0.008)	172.29
Banana stalks	0.309 (0.001)	20.77
Cold bleach effluent*	0.228 (0.045)	3.10
Wash off effluent*	0.314 (0.001)	0.65
Scouring effluent*	0.303 (0.044)	0.45

**** Methane yield values in m^3 CH_4 / m^3 $_{Substrate}$***

The biogas H_2S content (ppmv) for all the substrates (Figure 4.1) ranged from as low as 100 (sisal plume tow) to 4600 (cold bleach effluent) whereas the CH_4 content varied from 39.5% (sugar cane leaves) to 73% (cold bleach effluent). Generally, one of the major contaminants of biogas is H_2S commonly ranging from 2000 – 20000 ppmv depending on the pH value and sulphate concentration of the substrate (Schieder, Quicker et al. 2003). Generally, the presence of H_2S in the biogas renders it “sour” that is malodorous and corrosive besides causing SO_2 emissions during combustion. Consequently for domestic applications such as in lighting and combustion in burners and boilers, the H_2S content is required not to be more than 0.1% or 1000 ppmv (Ranalli 2007; Amrit, Jagan et al. 2009). Removal of H_2S (desulphurisation) from the biogas as previously discussed in chapter 2 eg., by means of dry oxidation (for instance using activated carbon) or liquid phase oxidation (for instance using bio trickling filters) is required so as to render the gas suitable as a fuel (Jensen and Webb 1995). In this regard, the biogas from sugarcane leaves as well as from all the liquid effluents apart from the wash off effluent is deemed to be way above the upper limit for domestic applications and hence might require desulphurisation prior to any combustion. On the other hand the biogas from coffee, sisal residues and banana stalks can be regarded to be suitable for direct domestic application since it is within the required limit for H_2S content.

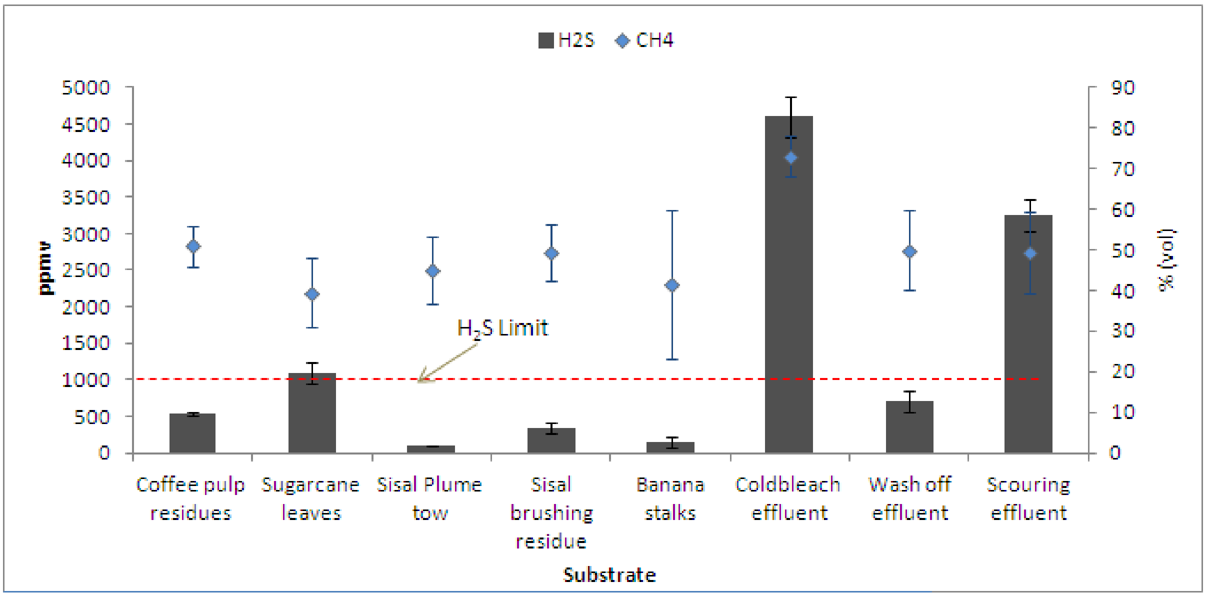

Figure 4.1: Biogas CH_4 content (%, vol.) and H_2S content (ppmv) from the different substrates showing the range of substrates whose biogas falls within the H_2S limit of 1000 ppmv. (Error bars are included with standard deviation, n=7)

4.3.3 Fertilizing properties and value of the digestate

Anaerobic digestion generally favours mineralisation hence the availability of nutrients such as NPK which are regarded as the three most important elements in plant nutrition. The digestate slurry thus presents a potential source of NPK nutrients thus knowledge of the fertilizing properties is essential for any meaningful integrated crop sustenance scheme. Our results (Figure 4.2) show that the digestate slurry from all the substrates contains appreciable quantities of the NH_4^+-N, K^+ and PO_4^{3-}-P inorganic nutrients. The N content (mg/l) of the different digestate ranged from 355 to 545 whereas the P content (mg/l) ranged from 232 to 431. On the other hand the K content (mg/l) ranged from 1500 to 3000. On average for all the different digestate the potassium content was about five times more than the nitrogen content. However most soils in Kenya are rich in potassium hence it is not of primary importance in the country as a soil nutrient (Mathenge 2009).

The relatively large nutrient content in sugarcane leaves digestate in relation to the low biogas (CH_4) production implies that anaerobic digestion of the sugarcane leaves favours bio-mineralisation to biomethanation. Indeed it has been reported that sulphate reducers as well as nitrate reducing bacteria compete successfully for the hydrogen normally used for CO_2 reduction to CH_4 (Ranali 2007). Substrates with high sulphur content may therefore cause less CH_4 formation and considerable H_2S formation. The relatively lower CH_4 production from sugarcane leaves coupled with higher H_2S content in the resultant biogas is therefore not surprising. However further work is required to bring out more insight with a view to finding ways of optimising the biogas production from both sugarcane leaves and banana stalks.

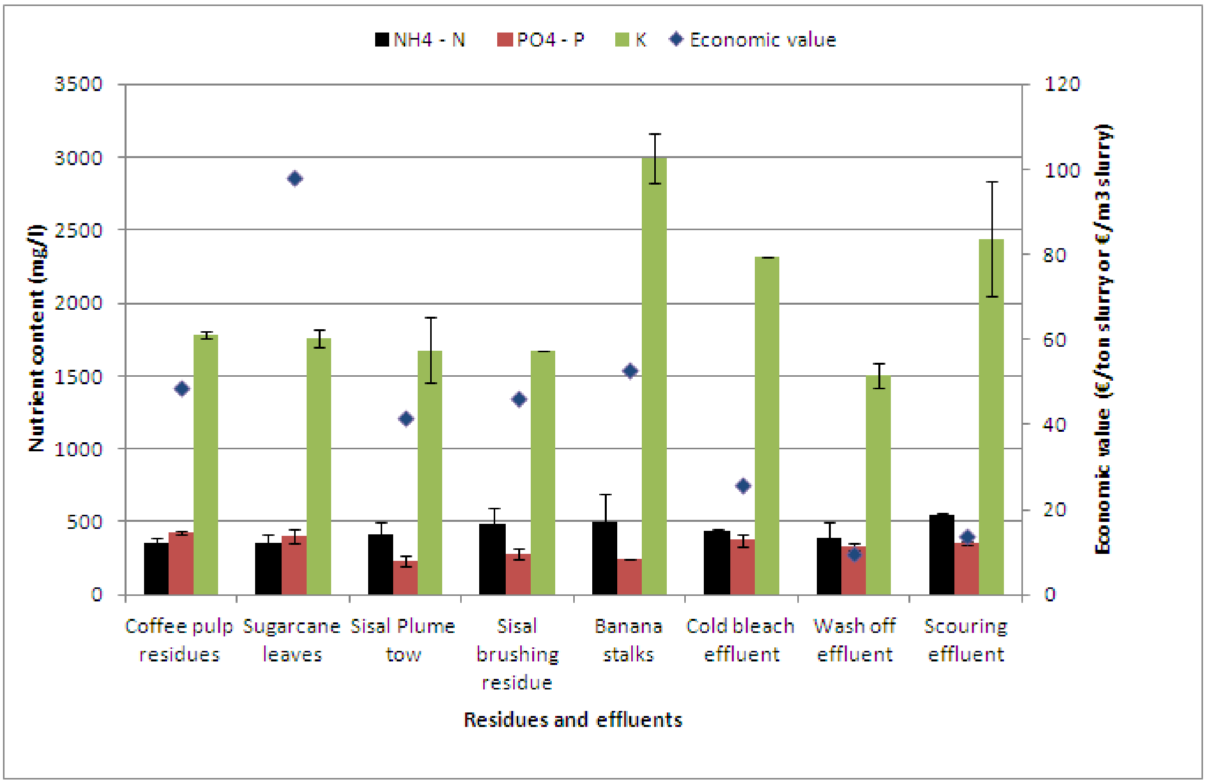

Figure 4.2: The digestate nutrient content (mg/l) and corresponding aggregate economic value (€) of mineral fertilizer that can be replaced by a tonne or m^3 of digestate from different agricultural residues and textile effluents (Error bars are included with standard deviation, n=2)

The economic value of mineral fertilizer that can be replaced by the digestate can be discerned by considering the cost of the active ingredients in three standard straight fertilizers that is CAN, TSP and KCl as sources of nitrogen, phosphate and potassium respectively (Table 4.3). Generally it suffices to say that nitrogen is the highest value nutrient followed by phosphate and potash. The economic value of the different digestate is quite comparable however one tonne of sugarcane leaves digestate appears to be quite outstanding since it can possibly replace mineral fertilizer having an economic value of 98.3 €. Several fertilizers have been used to meet the NPK requirements of different crops in Kenya (Table 4.4) as well as in the vast Sub-Saharan Africa (SSA). Nevertheless in spite of persistent low crop production in most of SSA, the use of commercial fertilizers is economically constrained thus about 9 kg of fertilizer nutrients per Ha of cultivable land are used compared to 100 in South Asia and 73 in Latin America (Mathenge 2009). The application of the digestate to complement fertilizers in the vast SSA thus suffices as a viable option for mitigating the low fertilizer usage.

Table 4.3
Fertiliser prices in Kenya

Fertiliser	NPK ratio (%)	Price per 50 kg bag (€)	Cost of active ingredient (€/kg)
CAN	26:0:0	20	1.53
TSP	0:46:0	29	1.26
KCl	0:0:60	20	0.67

Source: Ministry of agriculture, Government of Kenya (2011)

Table 4.4
Typical fertilizers used in Kenya

Type of fertilizer	NPK ratio (%)	Field of application
NPK	8:16:24	Tobacco farming
	16:16:16 or 17:17:17 or 20:10:10	Coffee farming
	20:20:0 or 23:23:0	General planting
	22:21:17 or 25:5:5 or 22:6:12+5S	Tea farming
TSP	0:46:0	General planting
MAP	11:44:0	
DAP	18:46:0	
Urea	46:0:0	Top-dressing
CAN	26:0:0	
KCL	0:0:60	General planting
Fowl manure	2.1:1.6:1	General application
Cow manure	1.0:0.4:0.5	

Source: Ministry of agriculture, Farm Inputs Division (2011)

4.4 Conclusions

The results of this study demonstrate that coffee pulp residues, sisal brushing residues and sisal plume tow are most suitable for biogas production with corresponding methane yields (m^3 CH_4/ton substrate) of 214, 172 and 124, respectively. On the other hand the methane yields from banana stalks and sugarcane leaves (20 and 12 m^3 CH_4/ton substrate respectively) are significantly much lower however the methane yield from all the textile effluents are even lower. Nevertheless, for the textile effluents, the cold bleach effluent presents a higher methane yield (3 m^3 CH_4/m^3 substrate) than the other two textile effluents. Hence selective segregation of textile effluent can be vital when harnessing biogas energy from the textile waste stream. Pertaining to biogas quality in terms of H_2S content, the biogas from sugarcane leaves as well as from all the liquid effluents apart from the wash off effluent is deemed to be above 1000 ppmv which is the upper limit for domestic applications, hence it might require desulphurisation prior to any combustion. On the other hand the biogas from coffee, sisal residues and banana stalks is regarded to be suitable for direct domestic application since it is within the required threshold of H_2S content. Furthermore, the digestate slurry from all the substrates screened presents a potential source of NPK nutrients with an economic value (€/m^3 digestate slurry) ranging from 9.81 to 98.30. Nevertheless, the economic value of the different digestate is quite comparable however the sugarcane leaves digestate with an economic value of 98.3 €/ton slurry appears to be quite outstanding.

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Chapter 5

Biowaste energy potential in Kenya

ABSTRACT

Energy affects all aspects of national development. Hence the current global energy crisis demands greater attention to new initiatives on alternative energy sources that are renewable, economically feasible and sustainable. The agriculture-dependent developing countries in Africa can mitigate the energy crisis through innovative use of the available but underutilised biowaste such as organic residues from maize, barley, cotton, tea and sugarcane. Biogas technology is assumed to have the capacity to economically and sustainably convert these vast amounts of biowaste into renewable energy, thereby replacing the unsustainable fossil energy sources, and reducing dependency on fossil fuels. However, the total energy potential of biogas production from crop residues available in Kenya has never been evaluated and quantified. To this end, we selected five different types of residues (maize, barley, cotton, tea and sugarcane) from Kenya and evaluated their energy potential through biomethane potential analysis at 30° C and a test time of 30 days.

The specific methane yields for maize, barley, cotton, tea and sugarcane residues obtained under batch conditions were respectively 363, 271, 365, 67 and 177 m^3 per tonne volatile solids. In terms of energy potential, maize, cotton and barley residues were found to be better substrates for methane production than tea and sugarcane residues and could be considered as potential substrates or supplements for methane production without compromising food security in the country. The evaluated residues have a combined national annual maximum potential of about 1,313 million cubic meters of methane which represent about 3916 Gigawatt hour (GWh) of electricity and 5887 GWh of thermal energy. The combined electrical potential is equivalent to 73% of the country's annual power production of 5307 GWh. Utilization of the residues that are readily available on a 'free on site' basis for energy production could substitute the fossil fuels that account for a third of the country's total electricity generation. Besides, exploitation of the potential presented by the biowaste residues can spur an energy revolution in the country resulting in a major economic impact in the region.

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5.1 Introduction

To date there is a global energy crisis as a consequence of declining quantity of fossil fuels coupled with the unprecedented rising crude oil prices. The crisis demands greater attention to alternative energy sources and revision of existing technologies. Hence it is critical now not only to focus on sustained economic use of the existing limited resources but to identify new technologies and renewable resources that have the potential to cater for the increasing energy demand in addition to possessing other positive attributes such as being sustainable, globally available, easy to exploit as well as having the capacity to positively contribute towards actualization of the United Nations millennium development goals, MDG (Biogas-Africa 2008; UN 2008).

Biomass could play a phenomenal role for future energy supply mainly through thermochemical, physicochemical, and biochemical transformations as well as conventional combustion. Suffice to say that biogas, biodiesel and bioethanol are some of the candidate alternative fuels from biochemical transformations that have continued to receive wide attention owing to their inherent 'green' potential. However, in terms of technological and social economic considerations, biogas technology is more preferred due to its economical feasibility (Deublein 2008) and sustainability potential (Satyanarayan and Murkute 2008) as well as its ability to meet all the MDGs (Biogas-Africa 2008). Besides, biogas technology is mature and offers a very attractive route to utilize diverse categories of biomass (Yadvika 2004) and the inherent biowaste for meeting energy needs as well as contributing to resource and environmental conservation. Biogas is particularly suited for meeting small scale energy needs, can contribute to environmental sanitation (Nzila 2008) and biogas technology is simple enough to avoid production limitations. Overall, the energy balance is particularly favourable for biogas when considering the ratio of energy yield (output) versus all the energy invested (input), excluding the energy content of the biomass but including all process efficiencies as shown in Table 5.1.

Table5.1

Energy balance for different final energy carriers (Deublein 2008; US-NREL 2008)

Source	**Energy carrier**	**Energy balance (Output/Input)**
Corn, sugar beet, wheat, sorghum	Ethanol	1.6 - 5.0
Rapeseeds, sunflower, soybean, jatropha seeds	Biodiesel	3.2 – 15
Rice husks, bagasse and woody biomass	Electricity and heat (from combustion)	8.5 - 20.4
Excrement, crop residues and whole crops (straws, corn, miscanthus)	Biogas	5.0 - 28.8

5.2 The potential of biogas technology

Biogas technology has not been successfully adopted for both energy and economic strategies within the African continent(Biogas-Africa 2008). A case point is East Africa where the technology has continued to lag behind since 1950 when the first biogas plant was introduced in the region. It is still at its infancy due to economical factors as well as inadequate knowledge and hence overreliance on animal dung as the principle digester feedstock. Indeed recent initiatives to revamp the biogas technology in the region have been solely modelled on livestock dung on the premise that animal manure is the only viable biogas digester feedstock. Basing the overall biogas potential on livestock numbers alone does not present the true potential of a given region since various other substrates such as grass, abattoir residues, market waste, potato waste and food leftovers (Ranalli 2007) have been shown to have a better biogas potential than animal manure with its reported biogas potential of only 2-45 m^3 per tonne(Reith 2003). Undeniably, as evidenced in other parts of the world (Reith 2003), the sustainability and future prospects of bioenergy in Africa calls for a paradigm shift hence the development of multi feedstock and multi product bio-refineries.

The multi-feedstock biorefinery approach has been under investigation in several developed countries (Sims 2004) where it has been reported to exhibit tremendous potential especially when based on energy crops (Kaparaju, Luostarinen et al. 2001; Heiermann 2002; Amon T 2003; Ranalli 2007). Indeed a steady technical development of energy crop digestion plants has been observed within the last decade in countries such as Germany, Austria and Sweden (Weiland 2002; Weiland 2005). The rising demand for energy crops is thought to be behind the “third scramble for Africa” by large multi-national firms eager to capitalise on the global energy crisis. However, the cultivation of energy crops and the use of whole crops for energy generation are seen to contravene the drive towards food security in most developing countries (FAO 2008). Nevertheless, it is possible to mitigate the global energy crisis in a sustainable way through innovative use of the available but underutilised resources such as agricultural residues.

Kenya being an agricultural based economy produces huge amounts of residues such as corn stalks, rice and wheat straws, tea and coffee waste, bagasse, barley residues, sisal and cotton wastes. The energy potential presented by these biowaste residues is yet to be exploited in spite of a growing interest in biogas production as evidenced by the local launch of the Biogas for Better life – An African Initiative that targets a better life for two million households in Africa through implementation of domestic biogas plants (Biogas-Africa 2008). Unfortunately, the focus of the Biogas-Africa initiative project is biogas production from animal dung only without any reference to other sources of biogas such as crop residues. Consequently, most agricultural residues are wasted in the farms through burning or uncontrolled decay thus leading to nitrogen leakage and eutrophication in the surrounding water bodies (Lehtomäki, Viinikainen et al. 2008) as well as contributing to odour and green house gas (GHG) emission through release of volatile (Keppler, Hamilton et al. 2006) and unburnt hydrocarbons. However, biogas technology has the capacity to economically and sustainably convert the vast amounts of biowaste in Kenya to renewable energy thus substituting (especially in the rural sector) the unsustainable conventional sources of energy. Besides, the digestate is a valuable soil amendment.

The objective of this study was to screen and evaluate the biogas potential of selected biowaste from Kenya. More specifically, the study screened and evaluated the biogas potential of maize, barley, cotton, tea and sugarcane residues. The biowaste materials were screened by means of chemical and biochemical characterization and their energy potential was determined by means of biomethane potential (BMP) analysis. Based on the results, the potential of the biowaste to spur an energy revolution in Kenya and the region was evaluated.

5.3 Materials and methods

5.3.1 Substrates

All substrates used in the analysis were residues obtained from western Kenya. The maize residue was collected from a farm whereas the barley, cotton, tea and sugarcane residues were collected from waste stockpiles of a brewery plant, ginnery, tea factory and sugar factory, respectively. About 6 kg of each sample were collected from the respective stock piles by means of the grab technique. Thereafter, the samples were air-dried at ambient conditions in a laboratory at Moi University to average equilibrium moisture content of 10% (±1.5). Subsequently, the samples were transported to the laboratory of Lettinga Associates Foundation (LeAF) in Wageningen, The Netherlands for analysis. The substrates for BMP analysis were used without any further preparation apart from the maize and sugarcane residues which were chopped into 1cm long pieces. The substrates studied in this work were characterised in terms of composition according to the American Society of Materials and Testing (ASTM) standard testing methodologies. For the chemical analysis, all the substrates, apart from tea residues, were homogenised by means of a domestic blender. The parameters analyzed were dry matter, volatile solids, ash, crude protein, lipids and fibre content.

5.3.2 Inoculum

The inoculum used was a mixed culture of active anaerobic granular sludge and digested cow dung. The specifications of the inoculum in terms of per cent dry matter (DM) and per cent volatile solids (VS) in DM were 15.4 and 70.8 for the granular sludge and 5.0 and 67.0 for the cow dung. The granular sludge was obtained from a paper mill Upflow Anaerobic Sludge Blanket (UASB) reactor in Eerbeek, the Netherlands, whereas the cow dung digestate was obtained from a local cow dung biogas digester.

5.3.3 Experimental set up.

The BMP test flasks were 1L glass bottles with side ports for sampling. Each test was carried out in duplicate. After putting the required amount of substrate and inoculum in each reactor, tap water was added to a volume of 200ml. The inoculum/substrate ratio, in terms of VS, was maintained at an average of 1.5 and each reactor contained on average 1.5g VS/100ml solution. In addition, 1.2 ml of macro nutrients and 0.1 ml of micronutrients (Kleerebezem, Pol et al. 1999) were dosed in each reactor vessel and the pH was buffered using a 10 mM phosphate buffer (Field 1988; Cho, Park et al. 1995). The reactors were then flushed with nitrogen gas for about five minutes to purge out oxygen after which the top of each reactor was sealed with a Polytetrafluoroethylene (PTFE) lined screw cap. The reactors were then incubated at 30(±1) °C in a shaker (*New Brunswick Scientific*). Duplicate blank reactors were used to correct for the gas production by the inoculum mix while a similar batch flask containing the same amount of only water was used to correct for temperature variations. The parameters monitored during the course of the BMP assay were pH, volatile fatty acids (VFA) concentration, gas pressure and composition. The gas pressure in each reactor was measured regularly with a digital pressure meter model *GMH 3150*, (*Greisinger-Germany*) while the pH, VFA and gas composition were measured weekly except in the first week when the pH and VFA measurements were carried out every two days.

5.3.4 Analysis

For the VFA analysis liquid samples were collected in 2 ml vials and centrifuged at 10,000 rpm for 10 min. The supernatant liquors were diluted with 3 % formic acid at a ratio of 1:1 and subsequently transferred into 1.5 ml vials and stored at 4 °C until further analysis. The VFAs in the aqueous samples were determined by means of a gas chromatograph (GC) analysis according to a method described earlier by Pabon-Pereira *et al* .The VFA-COD (mg/l) was computed by the summation of the products of the respective measured VFA concentrations multiplied by their COD equivalents as shown in Table 5.2.

Table 5.2

Short-chain VFAs and COD – equivalents

VFA	COD-equivalent (g COD/gVFA)
Acetic acid	1.07
Propionic acid	1.51
n-butyric acid or iso-butyric acid	1.82
n-valeric acid or iso-valeric acid	2.04
n-capronic acid or iso-capronic acid	2.20

The biogas composition was analysed by injecting 100 µL of the gas into a gas chromatograph (*GC 8000* series, *Fisons Instruments*) equipped with two different columns to separate the gasses namely a Molsieve column (30mbij 0.53 mm bij 10 µm) and a Porabond Q (25m by 0.53 mm by 10 µm) connected to a thermal conductivity detector (TCD). Helium was used as a carried gas. The temperature of the injector, oven and detector were 110, 40 and 99°C respectively. The chromatograms are analyzed using Chromeleon software version 6.80.

The biogas volume (V_{biogas}) in litres was determined using the following equation:

$$V_{biogas} = \frac{\Delta P . V_h}{R . T} . V_{mol} \text{ .... } (1)$$

Where

ΔP = change of pressure in the reactor (kPa) after correcting for temperature changes

V_h = reactor headspace volume (L)

V_{mol} = molar gas volume at 303K (L/mol)

R = universal gas constant (8.31kPa.L/mol.K)

T = temperature (303K)

The pressure correction for temperature change was done by subtracting the pressure difference in the water reactor (ΔP_w) from the pressure difference in the substrate reactor (ΔP_s) using the following equation

$$\Delta P = \Delta P_s - \Delta P_w \text{ .... } (2)$$

The methane volume (V_{CH4}) per gram volatile solids (VS) was determined using the following equation

$$V_{CH4} = \eta_{CH4} . \frac{V' biogas - V'' biogas}{VS} \text{ .... } (3)$$

Where

η_{CH4} = fraction of CH_4 in the biogas

V'_{biogas} = biogas volume produced by the substrate (L)

V''_{biogas} = biogas volume in the blank reactor (L)

5.3.5 Biomass residue quantities and methane potential determination

The residue quantities were computed using the country's production data from the FAOSTAT database (FAO 2008). The maximum residue output potential (RO_{max}) in tonnes of dry matter per year for the respective types of residues was determined using the following equation:

$$RO_{max} = Q . \beta . DM \text{ .... } (4)$$

Where

Q = average annual produce of a given crop (tonnes per yr)

β = residue to crop produce ratio

DM = dry matter ratio

The realizable residue potential (RO_{real}) was computed from the RO_{max} and the approximate residue use factor (δ) using the equation:

$$RO_{real} = \delta RO_{max} \text{ .... } (5)$$

The residue maximum methane potential (RO_{CH4max}) and the realizable residue methane yield ($RO_{CH4real}$) were computed from the RO_{max} and RO_{real} respectively and the experimental biomethane production (V_{CH4}) of the biomass in m^3CH_4/tonne using the equations:

$$RO_{CH4max} = V_{CH4} . RO_{max} \text{ .... } (6)$$

$$RO_{CH4real} = V_{CH4} . RO_{real} \text{ .... } (7)$$

In the calculations, a conservative δ estimate of 50% for each biomass category was used (Fischer 2007).

5.4 Results & Discussion

5.4.1 General properties of the substrates

The proximate analysis demonstrated the similarities and differences among the substrates in terms of their chemical properties (Table 5.3). The results for each substrate emanate from a thoroughly mixed batch from which three different sub-samples were taken. A key characteristic feature of the substrates was their high volatile solids content that was quite comparable and ranged from 84 % in barley residues to 96 % in maize residues. On the contrary, the crude protein, fat and carbohydrates content in the residues varied a lot.

Table 5.3

Characteristic values and standard deviations (in parenthesis, n=3) of the substrates

Particulars	BR	MR	TR	SR	CR
DM (%)	89 *(1)*	93 *(0)*	91 *(0)*	94 *(1)*	91 *(1)*
VS (%DM)	84 *(1)*	95 *(0)*	87 *(0)*	90 *(1)*	88 *(1)*
Ash (%DM)	5 *(0)*	5 *(0)*	5 *(0)*	4 *(1)*	4 *(0)*
Crude protein (%DM)	2.59 *(0.04)*	10.86 *(0.31)*	19.49 *(1.36)*	1.17 *(0.20)*	15.56 *(3.94)*
Crude lipids (%DM)	3.46 *(0.45)*	2.86 *(0.26)*	0.88 *(0.10)*	0.28 *(0.06)*	17.36 *(0.04)*
Crude fibre (%DM)	66.54 *(0.50)*	80.84 *(0.75)*	74.87 *(1.16)*	94.49 *(0.76)*	63.41 *(4.02)*

BR = Barley residue; MR = maize residue; TR = tea residue; SR = sugarcane residue; CR = cotton residue; DM = dry matter

The crude protein content varied from around 1 % in sugarcane residues to 24 % in barley residues. The crude fat content varied from less than 0.3 % in sugarcane residues to 17 % in the cotton residues. Similarly, the crude fibre content varied significantly from 63 % in cotton residues to 94 % in sugarcane residues.

The volatile solids compared to the amount of material give an indication of the proportion of organic matter present in a given substrate from which biogas is subsequently produced. Hence in this respect barley residue, due to its comparatively lower volatile solids content, is expected to produce the least amount of biogas. However, this assumption completely ignores the effect of substrate composition and biodegradability. Organic matter composition in terms of non-recalcitrant Chemical Oxygen Demand (COD) , crude protein, lipids and carbohydrates (Ranalli 2007) has a strong influence on the biogas potential and CH_4 yield as shown in Table 5.4.

Table 5.4

Theoretical polymer COD equivalent, biogas yield and composition (Ranalli 2007)

Polymer	Structural formula	COD equivalent	Biogas yield (L/g)	% CH_4	%CO_2
1g Carbohydrates	$C_6H_{12}O_6$	1.07g COD	0.75	50	50
1g Lipids	RCO_2H	2.91g COD	1.25	68	32
1g Proteins	$(C_4H_{1.6}O_{1.2})x$	1.5g COD	0.70	71	29

Consequently, based on the proportions of the crude proteins, lipids and carbohydrates (Table 3) and the corresponding conversion factors (Table 5.4), the theoretical BMP for the respective substrates is computable as presented in Table 5.5. The theoretical BMP computation in this case regards the crude fibre content of the substrates in Table 3 to represent the carbohydrates content.

Table 5.5

Theoretical BMP of barley residues (BR), maize residues (MR), tea residues (TR), sugar residues (SR), and cotton residues (CR)

Crop residue	BR	MR	TR	SR	CR
BMP (m^3/tonne VS)	401	381	385	363	463

These results show that theoretical BMP for the residues analysed range from 363 m^3/tonne VS for sugarcane residue to 463 m^3/tonne VS for cotton residues. It is clear that in addition to VS content, other chemical properties of biowaste influence the BMP. Substrate characterisation is thus deemed to be paramount in the interpretation of biowaste BMP studies as evidenced by the calculations in Table 5.5, which shows that the BMP of barley residues is only second to that of cotton residues, whereas the VS amount suggested a very low BMP.

5.4.2 Relationship between substrates and pH

The pH during anaerobic digestion plays an important role in methane fermentation since it influences every running reaction (Suidan, Strubler et al. 1983). Apart from the control reactors, all the reactors showed a pH drop between 0.4 and 0.6 pH unit in spite of the presence of a phosphate pH buffer in the setup. However, the reactors pH window of between pH 6.6 and 7.3 (Figure 5.1) was within the generally accepted optimum methane fermentation pH range of approximately 6.5-8.2 (Nzila 2008).

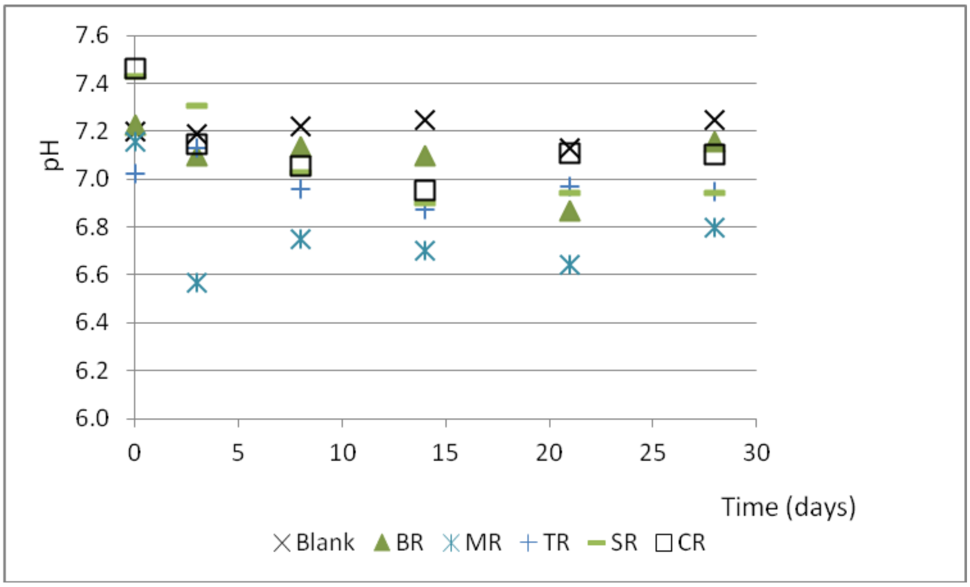

Figure 5.1. Reactor pH profiles for barley residue (BR), maize residue (MR), tea residue (TR), sugarcane residue (SR) and cotton residue (CR) during the course of the BMP analysis

With respect to the blank test, all the substrates demonstrated a significant pH drop during the course of the experiment. Maize residues produced the highest pH drop of about six tenths units hence in full scale application rapid reactor acidification can be expected with noticeable reduced methane production rates in the absence of a pH buffer. Compared to the other substrates, barley residues had a steady pH during most of the experiment period thus their co-digestion with the other residues can be expected to improve the pH buffering capacity of the system. Moreover, cow dung has been shown to possess good pH buffering characteristics (Kaparaju, Luostarinen et al. 2001) thus co-digestion of the residues can be expected to yield good buffering in the reactors. However, in spite of incorporation of a good buffer in this study, it is noteworthy that the maize residues showed a significant pH drop.

5.4.3 VFA-COD profiles during the course of the experiment and substrate digestibility

At the onset of the experiment, all the substrates were found to contain varying amounts of VFAs. Acetic and propionic acids were the predominant VFAs detected in all the substrates during the course of the experiment. Both cotton and tea residues had the highest amounts of initial VFAs with respective VFA-COD equivalent of 130 and 89 mg/L (Figure 5.2). Acetic acid is considered to be the major precursor of methane hence its higher presence in cotton and tea residues at the initiation of the experiment shows that the substrates had better initial digestion properties than barley, sugarcane and maize residues.

During the course of the experiment, acetic acid and propionic acid remained the predominant VFAs detected in all the substrates fermentation products though insignificant traces of butyric acid, and valeric acid were noticed in the cotton waste fermentation products between day 3 and day 14. Towards the end of the experimental period there was a build up of only acetic acid in all the reactors albeit at a reduced rate. This shows that the higher intermediates were being converted to acetic acid as the digestion progressed. Similar results have been reported in literature (Odinyo A. 1999; Lata, Rajeshwari et al. 2002). Generally, the VFA-COD in all the substrates tested was less than 10 mg/L (Figure 5.2) towards the end of the experiment implying that the intermediate fermentation products had been converted to biogas.

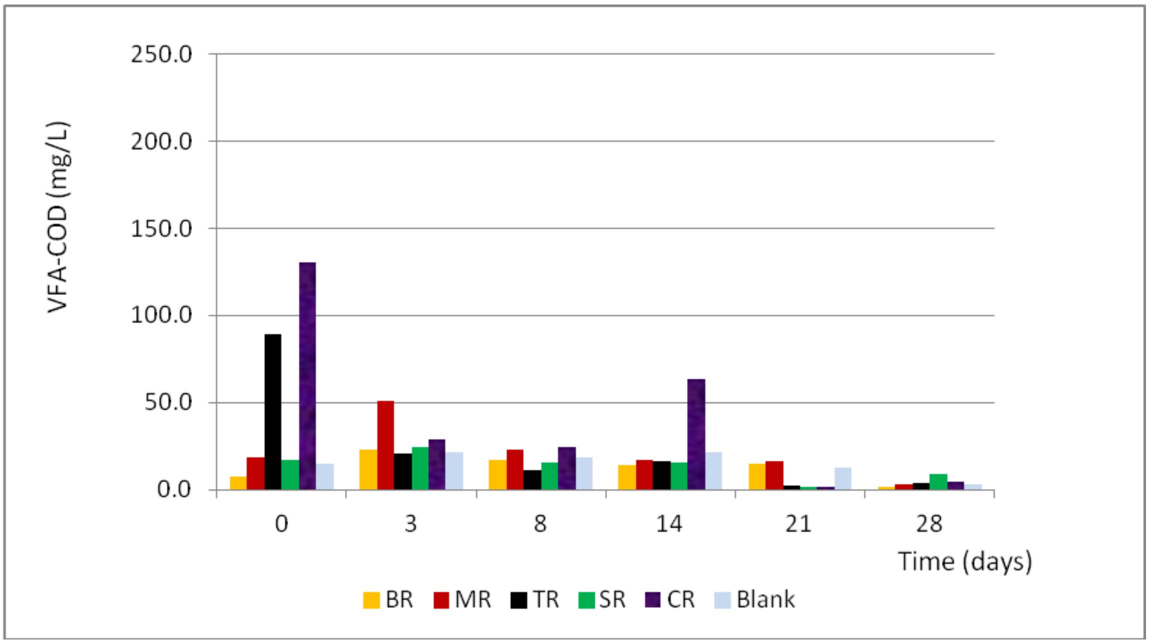

Figure 5.2. VFA-COD concentrations in the residues of barley (BR), maize (MR), tea (TR), sugarcane (SR) and cotton (CR) on different days during the course of the experiment,

5.4.4 Relationship between substrates and methane production

Methane production from the residues of barley, maize, tea, and cotton commenced within a day after the onset of the experiment (Figure 5.3) however methane was only noticed from the sugarcane residues after four days (Figure 5.3b). The methane production rate generally remained high for maize, barley and cotton residues while sugarcane and tea residues showed a constrained methane production rate. At the experiment HRT of 30 days, maize, barley and cotton residues yielded BMP (ml CH_4/g VS) of 359, 271 and 365, respectively, whereas sugarcane and tea residues yielded 177 and 67, respectively.

Since it was shown that sugarcane residue contains methane precursors (Figure 5.2), the delayed production of methane from their reactors shows an element of methane inhibition which the methanogenic consortia appear to have managed to overcome to some extend after four days. However methane production from sugarcane residues further appeared to be constrained throughout the duration of the experiment as demonstrated by the corresponding almost constant methane production rate.

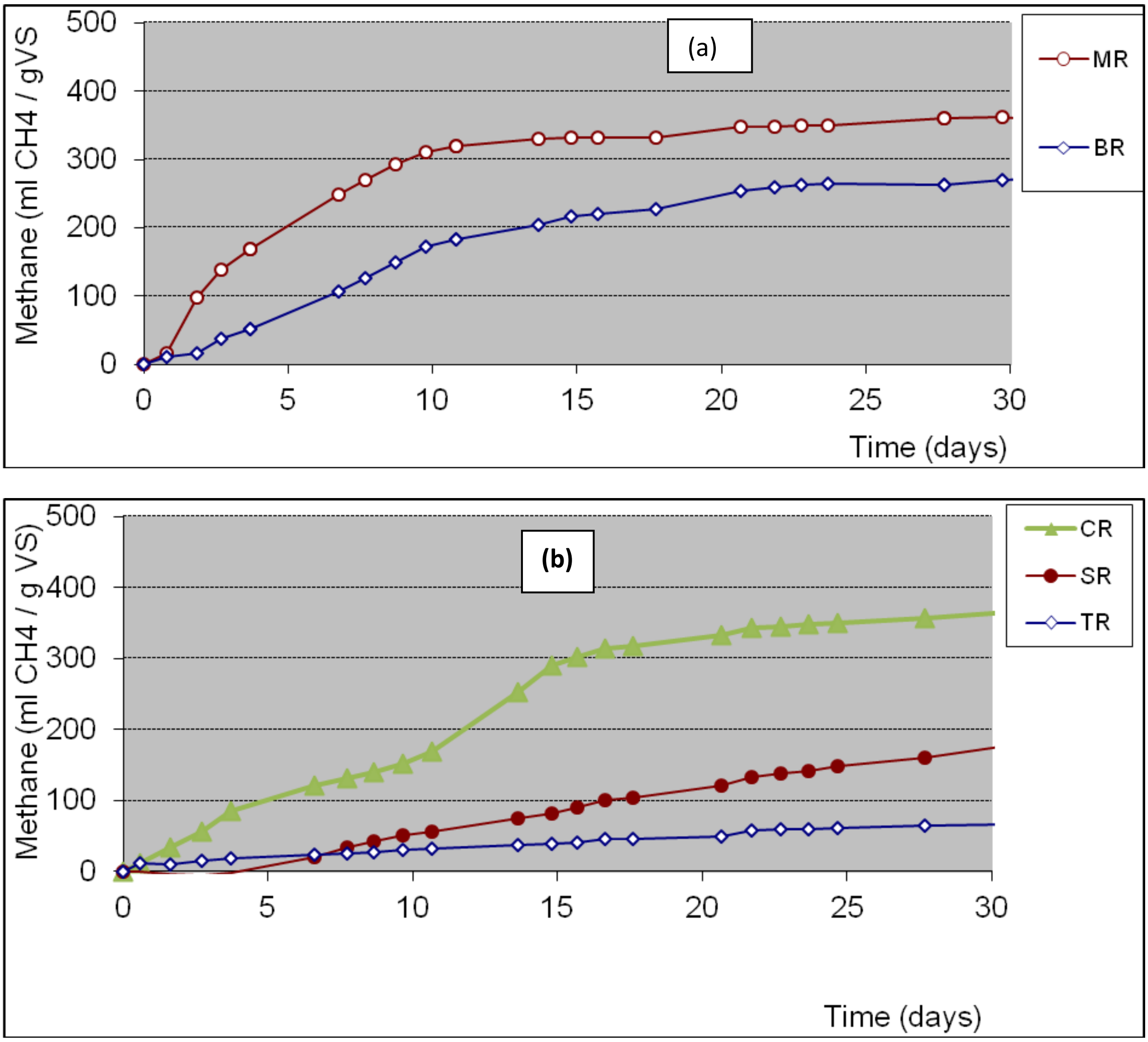

Figure 5.3. Cumulative methane production in (a) barley residue (BR) and maize residue (MR) and (b) tea residue (TR), Sugarcane residue (SR) and cotton residue (CR)

The methane yield from tea residues on the other hand, was not as earlier anticipated. In spite of the tea residues having higher initial VFA than barley, maize and sugar cane residues (Table 5.3), the methane yield was lower. Moreover, up to day 14, the VFA in the tea residue fermentation products were comparable with those of the barley residue fermentation products (Figure 5.2) yet the methane yield from the barley residues was five times higher than the yield from the tea residues (Figure 5.3). Indeed, the methane production from tea residues appears to have been quite constrained throughout the time course of the experiment. It has been reported in literature (Lata, Rajeshwari et al. 2002) that although tea waste yields a better digestible leachate than vegetable market wastes the latter has higher methane potential. It is clear from our findings that the choice of substrates for methane production should not be based singularly on the presence of digestible leachate since methanogenesis inhibition can suffice later on. Moreover, from our studies it appears that tea residues possibly contain methanogenesis inhibiting factors such as tannins (Field 1988), which makes their digestible leachate not to correspond with the expected methane production. The possibility of inhibition is further evidenced by the existence of a lag phase which appears to have lasted for about two weeks. The tea residue cumulative methane production of 170 ml/g VS (Figure 5.3b) with an average biogas methane of less than 45% (Figure 5.4) shows that tea residue are less competitive for energetic methane production as compared to the other residues investigated in this study. However, substrates with slow biogas and methane release during anaerobic digestion have found use in the remediation of metal-contaminated soils (Utomo and Hunter 2006; Amarasinghe and Williams 2007; Wasewar et al. 2008).

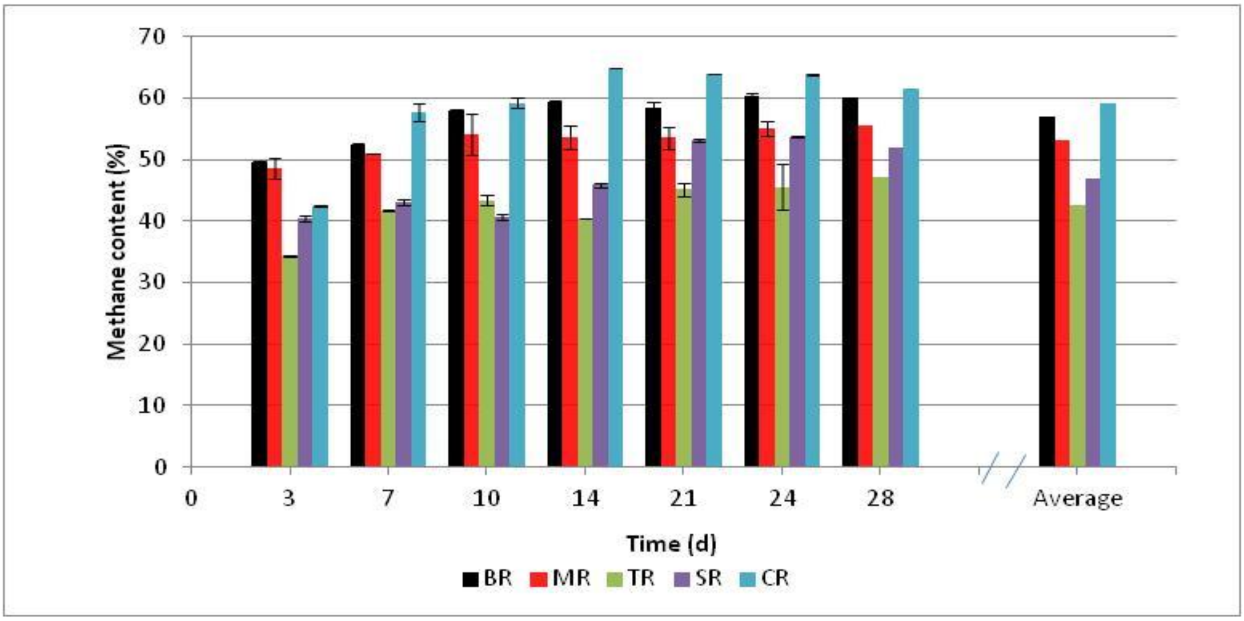

Figure 5.4. Time course and average biogas methane content for barley residue (BR), maize residue (MR), tea residue (TR), sugarcane residue (SR) and cotton residue (CR) including error bars with standard error (n=12).

The BMP values for the residues of barley, maize, tea, sugarcane and cotton reported in this study (Table 5.6) correspond to respectively 68%, 95%, 17%, 49% and 79% of the theoretically calculated BMP (Table 5.5). Moreover the BMP values for the residues of barley, maize, sugarcane and cotton are quite comparable to the BMP range of 179 – 658 $m^3 tonne^{-1} VS$ for some selected commercially produced energy crops reported in literature (Heiermann 2002; Weiland 2002; Ranalli 2007). Hence the residues from Kenya can be suitably utilised in energy production without compromising the core (food crop) function of the respective crops.

It is important to distinguish the laboratory generated BMP values in Table 5.6 from the theoretical BMP values in Table 5.5. The theoretical BMP values as earlier espoused in section 5.4.1 are calculated based on specific theoretical conversion factors and incorporate various assumptions such as completely digestible substrate and thus streamlined anaerobic digestion but this is rarely experienced in practice. Hence theoretical BMP computation is generally prone to over estimation. However when the proximate content of substrates is the only available data and in the absence of laboratory BMP analysis then the theoretical computation of BMP suffices especially for the initial pre-screening purposes.

Table 5.6

Comparison of the BMP from the residues with results obtained from selected energy crops

	Biomass	BMP (m^3.tonne^{-1}VS)	HRT (days)	Reference
Residues	Barley	271	30	This work
	Maize	363		
	Tea	67		
	Sugar cane	177		
	Cotton	365		
Whole crop	Barley	353-658	>30	(Heiermann 2002)
	Maize	205-450		(Ranalli 2007)
	Sugar beet	236-381		(Ranalli 2007)
	Potatoes	276-400		(Weiland 2002)
	Miscanthus	179-218		(Ranalli 2007)
	Oilseed rape	240-340		(Weiland 2002)

5.4.5 Residue energy and economic potential

The economic value of 1m^3 of biowaste generated methane when used in a Combined Heat and Power (CHP) system in the country can be evaluated as shown in Figure 5.5 and Table 5.7. The reference system was a small scale CHP with a capacity in the range of 5kW to 1.5 MW. The CHP system's overall efficiency (conservative values) was taken as 75% with a respective 30% and 45% conversion efficiency to electricity and thermal energy (US-EPA 2008). The rates for electrical and thermal power were the average unit rates obtained from the Independent Power Producers (IPPs) in Kenya (personal communication, November 2008). It can be noted that 1m^3 of the biowaste generated methane (≥95% CH$_4$, energy value 35.8 MJ/m^3) has a combined gross economic value of €0.77

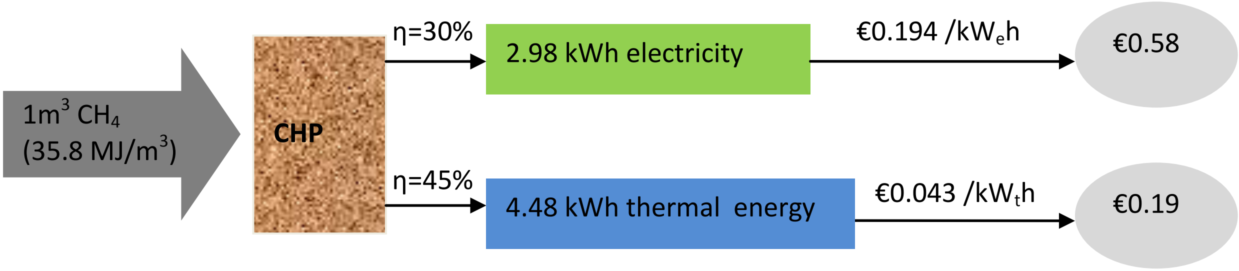

Figure 5.5. Economic value of 1 m^3 CH$_4$ as applied to a CHP system

The methane generation and electricity gains computed in gross and realizable values according to equations 6 and 7 as well as Figure 5.5 are presented in Table 5.7. The gross values were computed taking into account the experimental conversion efficiency in terms of biomethane production

(BMP) of the agricultural residues (m^3 CH_4 / tonne) whereas the realizable values were computed by factoring the residue-use-factor (δ) into the gross values.

Table 5.7
Total annual residue output (RO_{max}) and methane potential (RO_{CH4max}) with corresponding electrical and thermal energy potential and economic values for the selected substrates.

Residues	**RO_{max} ($x10^3$tonnes/yr)**	**RO_{CH4max} ($x10^6m^3$/yr)**	**Electrical energy potential**		**Thermal energy potential**	
			(GWh/yr)	**Value($x10^6$€)**	**(GWh/yr)**	**Value($x10^6$€)**
Barley	54	11	33	6	49	2
maize	4,185	1,134	3,379	656	5,080	218
Tea	436	22	66	13	99	4
Sugar cane	1,045	138	411	80	618	27
Seedcotton	32	9	27	5	40	2
Total (gross)	5,752	1,313	3,916	760	5,887	253
Total (realizable)	2,876	657	1,958	380	2,944	127

The annual total electrical energy generation in the country stands at 5307 GWh, a third of which is produced from fossil fuels by independent power producers. Hence the combined gross and real annual electrical energy potential of the selected biowaste residues of 3916 GWh and 1958 GWh respectively is equivalent to about 73% of the overall annual electricity generation in the country. The electrical energy potential presented by the residues considered in this study translates to a combined gross asset value of € 760 million and €253 million from CHP generated electricity and thermal energy respectively. When a residue use factor of 50% is considered (Fischer 2007), the realizable annual electrical energy potential of the selected biowaste residues amounts to 1.96 TWh. This realizable potential is way above the country's independent power producers total annual electricity generation capacity of 1.77 TWh. In addition, there is heat demand in Kenya especially in the manufacturing sector such as in food, textile and alcohol brewing industry where steam is an essential resource input. The establishment of a biogas based CHP system in any of these industries can complement or substitute steam generation from fossil fuels. Utilization of the residues for energy production could therefore impact positively in the country's economy through income generation, job creation and alleviation of poverty. Besides, the methane derived electricity could replace the fossil fuel based electricity hence contributing to the preservation of the environment. In this connection, integration of the realizable BMP within a geospatial framework is presented for the Rift Valley province of Kenya in terms of biowaste-based biogas energy potential from five different crops (Figures 5.7 – 5.11). The geospatial representation allows a preliminary examination of different locations for biogas production from the different biowastes. Generally, the central Rift Valley region is observed to have a higher potential for biogas production from the different biowastes investigated. Nevertheless in spite of the quite promising residue energy and economic potential as presented in this work, there are logistical and attendant economic challenges which have to be surmounted prior to actualisation of any of the potential. Further feasibility studies are therefore essential.

5.5 Conclusions

The results presented here demonstrate the potential of energy production from selected biowaste in Kenya. It is clear that in addition to VS content, other chemical properties of biowaste influence the BMP. Substrate characterisation is thus deemed to be paramount in the interpretation of biowaste BMP studies as evidenced by our results which show that the BMP of barley residues is only second to that of cotton residues, whereas the VS amount suggested a very low BMP. Besides, it is clear from our findings that the choice of substrates for methane production should not be based singularly on the presence of digestible leachate since methanogenesis inhibition can suffice later on.

Biowaste from maize, cotton, barley, sugarcane and tea residues exhibited varying capabilities of bio-methane potential ranging from 9 to 1,134 million m^3 of CH_4. Moreover, residues from maize, cotton and barley showed better digestibility qualities than sugarcane and tea residues as depicted from the VFAs in the respective digestate. These residues can be used to substitute or supplement livestock dung in biogas reactors especially in the country's intensive agricultural regions. Indeed, the combined gross annual electrical energy potential of the selected biowaste residues of 3.92 TWh is equivalent to 73% of the total annual electricity generation in the country. Besides, even half of this potential still exceeds the combined country's current fossil fuel dominated independent power producers (IPPs) annual generation capacity of 1.77 TWh. The biowaste energy potential highlighted by this study is encouraging and can be used in the country's energy decision support system. These research findings are promising and warrant a broader consideration of other locally available biowaste residues for energy potential analysis.

Acknowledgements

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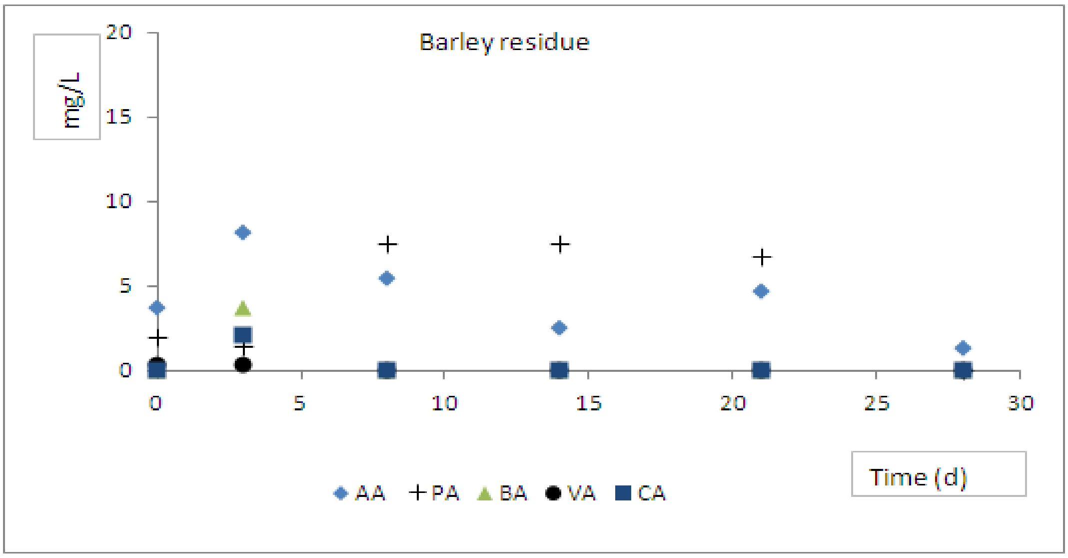
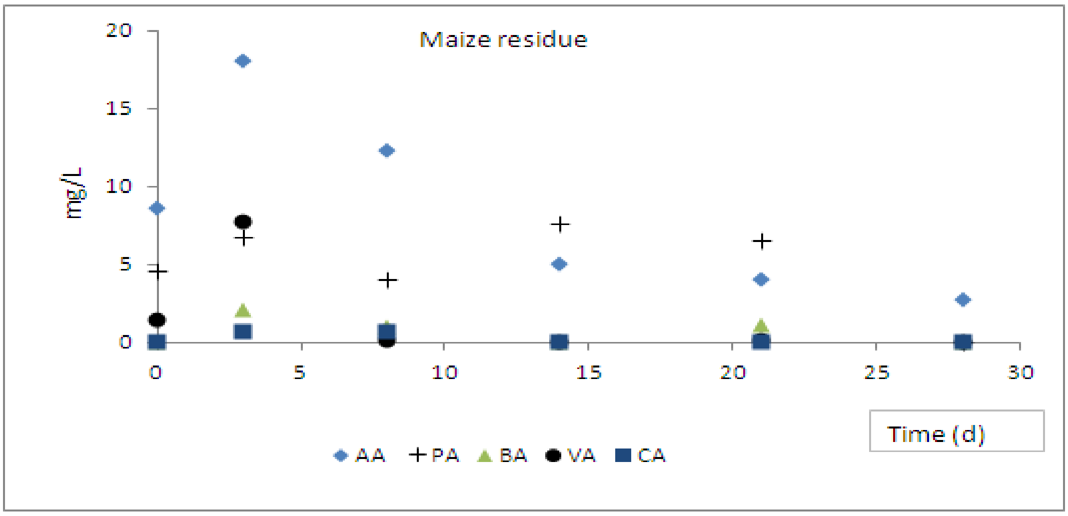
5.6 Additional information

5.6.1 Time course acetic acid (AA), propionic acid (PA), butyric acid (BA), valeric acid (VA) and capronic acid (CA) profiles for barley, maize, tea, sugarcane and cotton residues.





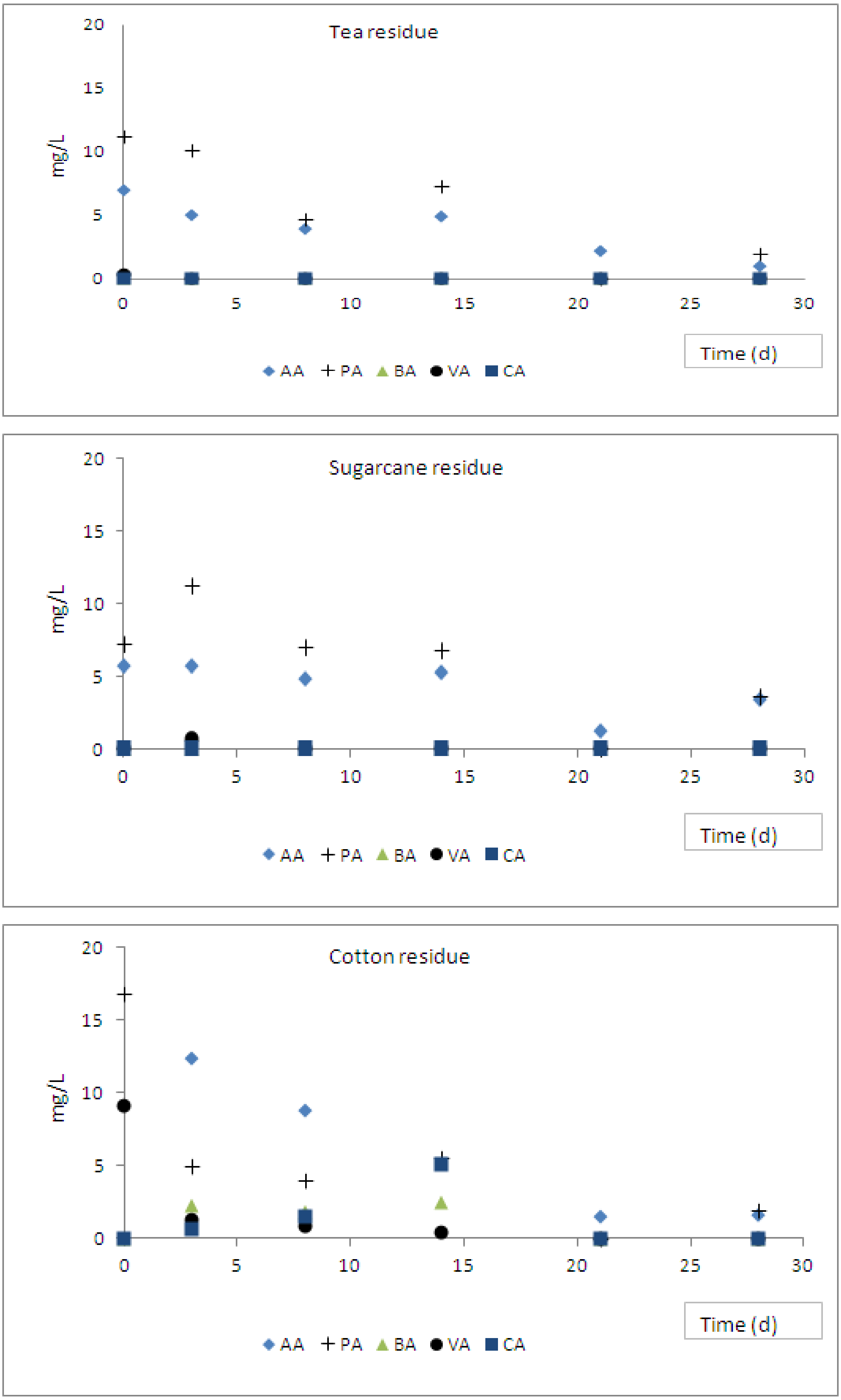


Figure 5.6. Time course VFA profiles for barley, maize, tea, sugarcane and cotton residues

5.6.2 Integration of realizable BMP within geospatial framework

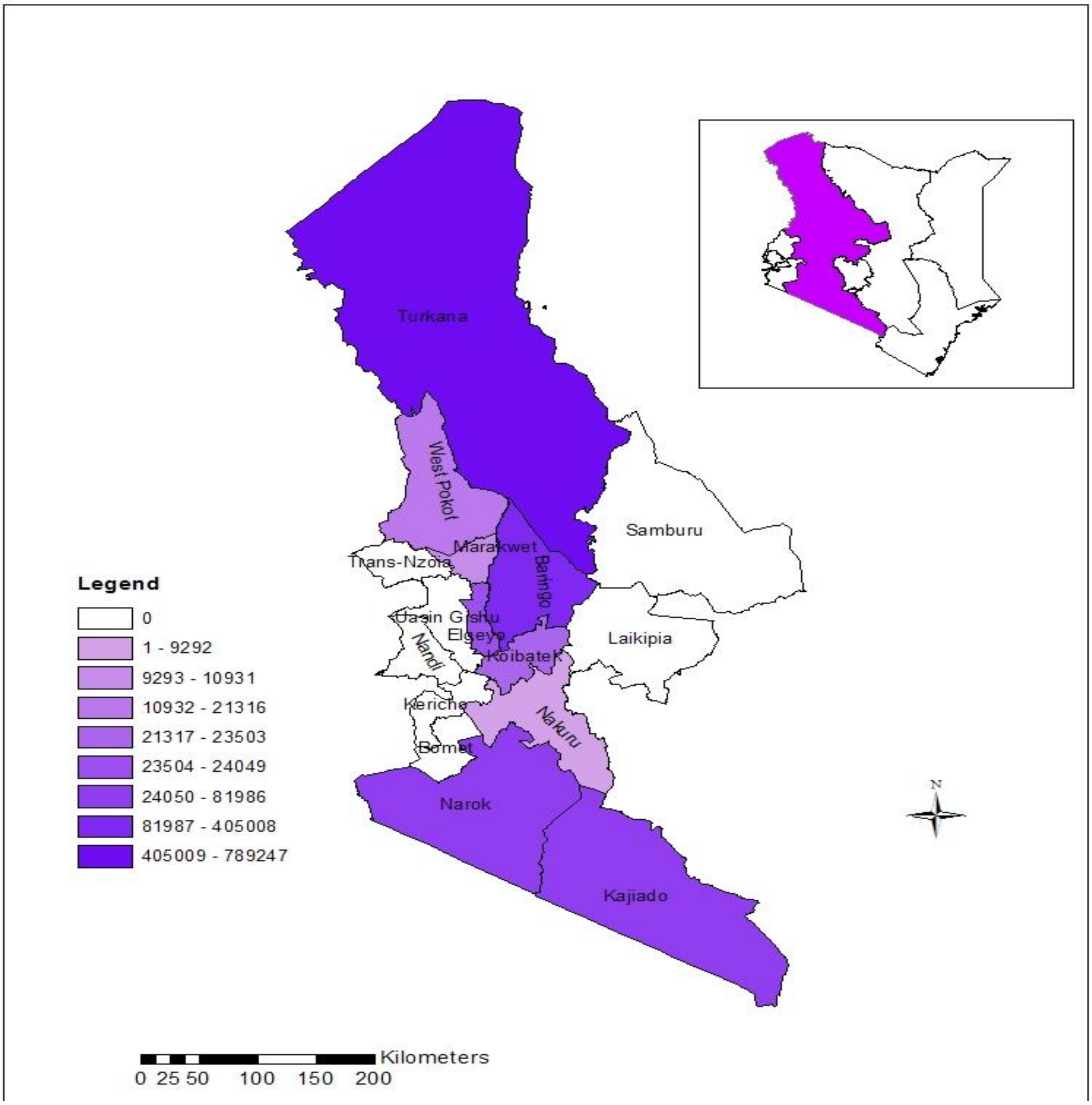


Figure 5.7 Cotton biowaste-based biogas energy potential (m^3 CH_4/yr) in Rift Valley Counties

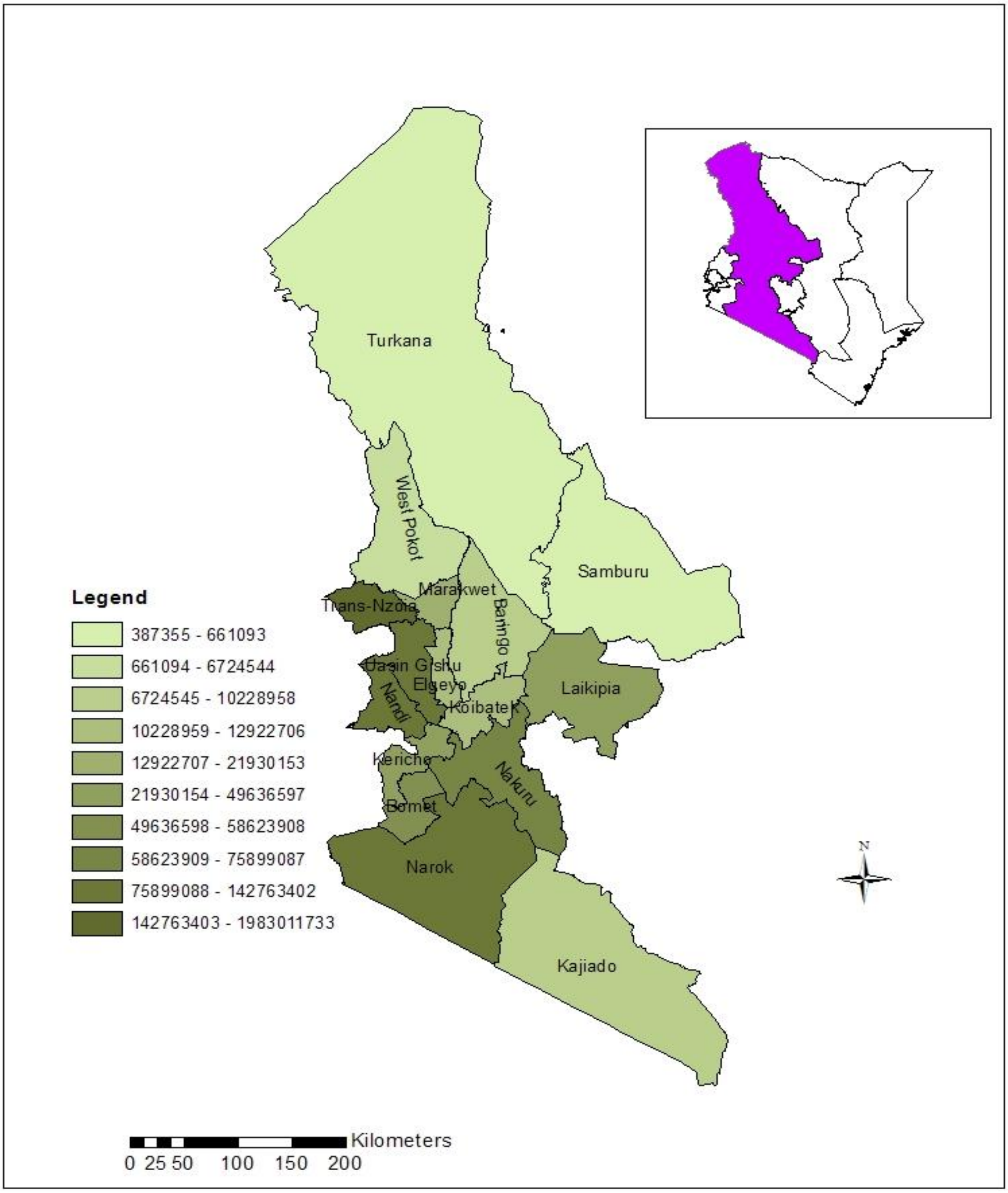


Figure 5.8 Maize biowaste-based biogas energy potential (m^3 CH$_4$/yr) in Rift Valley Counties

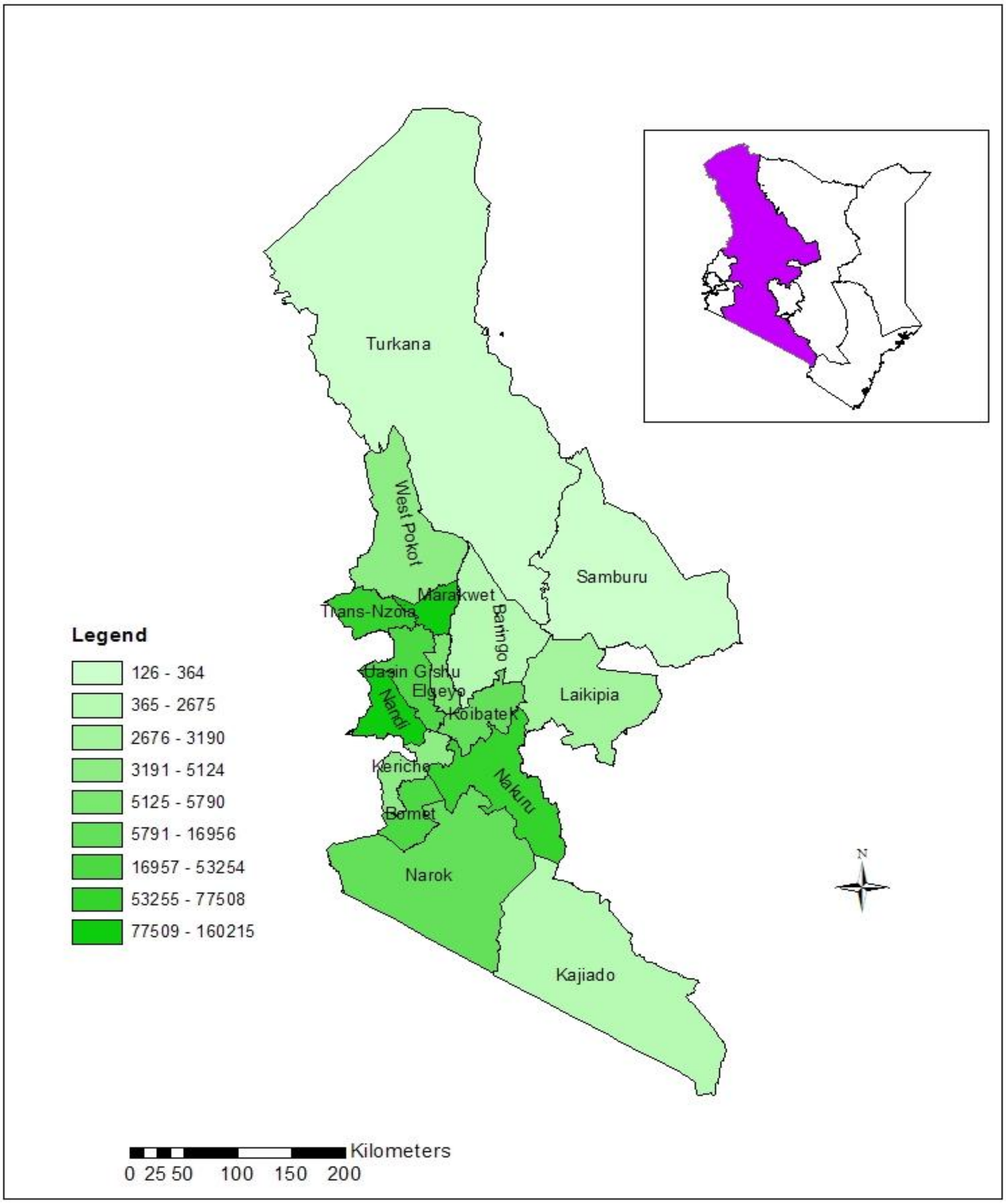


Figure 5.9 Banana biowaste-based biogas energy potential (m^3 CH_4/yr) in Rift Valley Counties

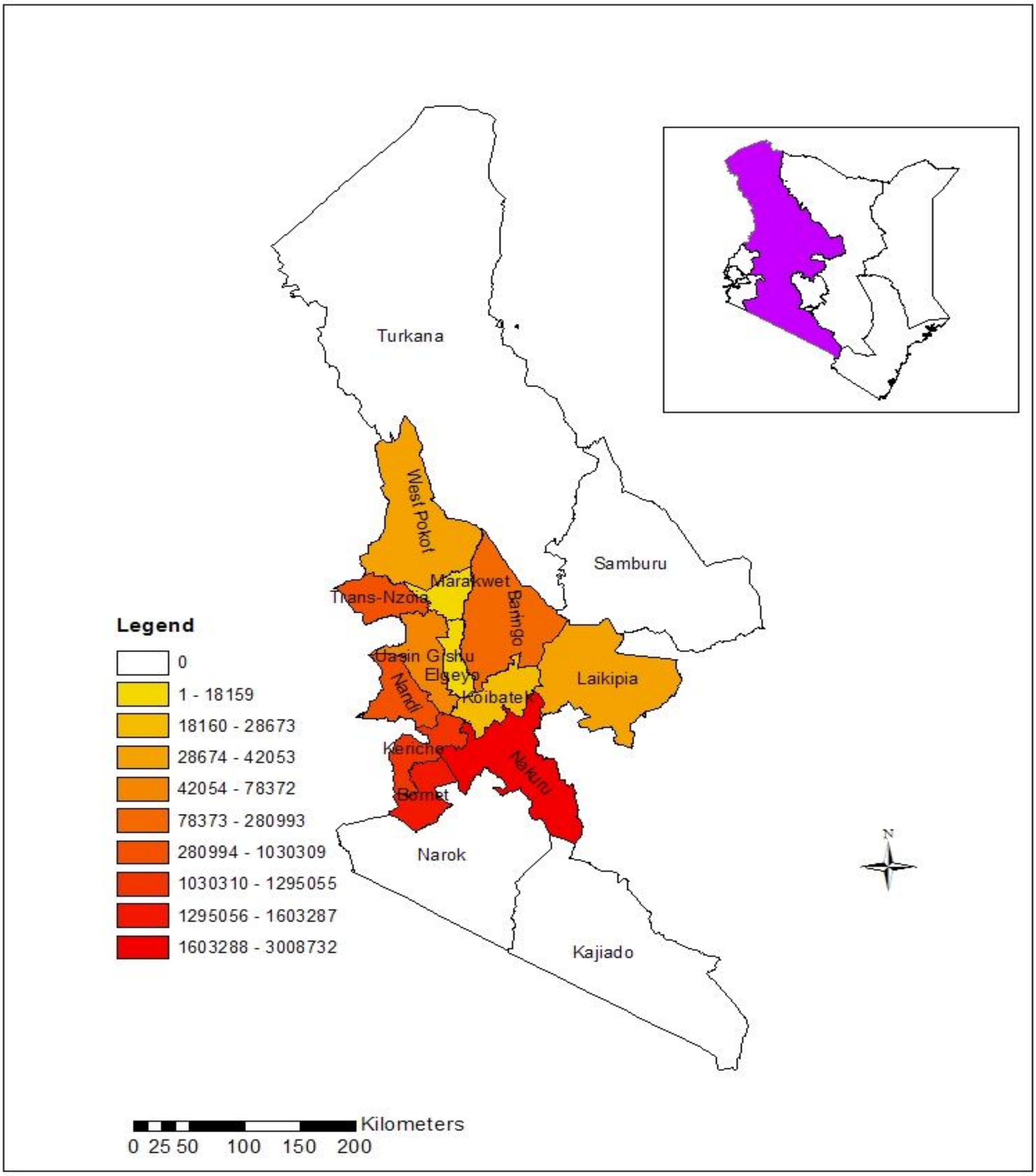


Figure 5.10 Coffee biowaste-based biogas energy potential (m^3 CH_4/yr) in Rift Valley Counties

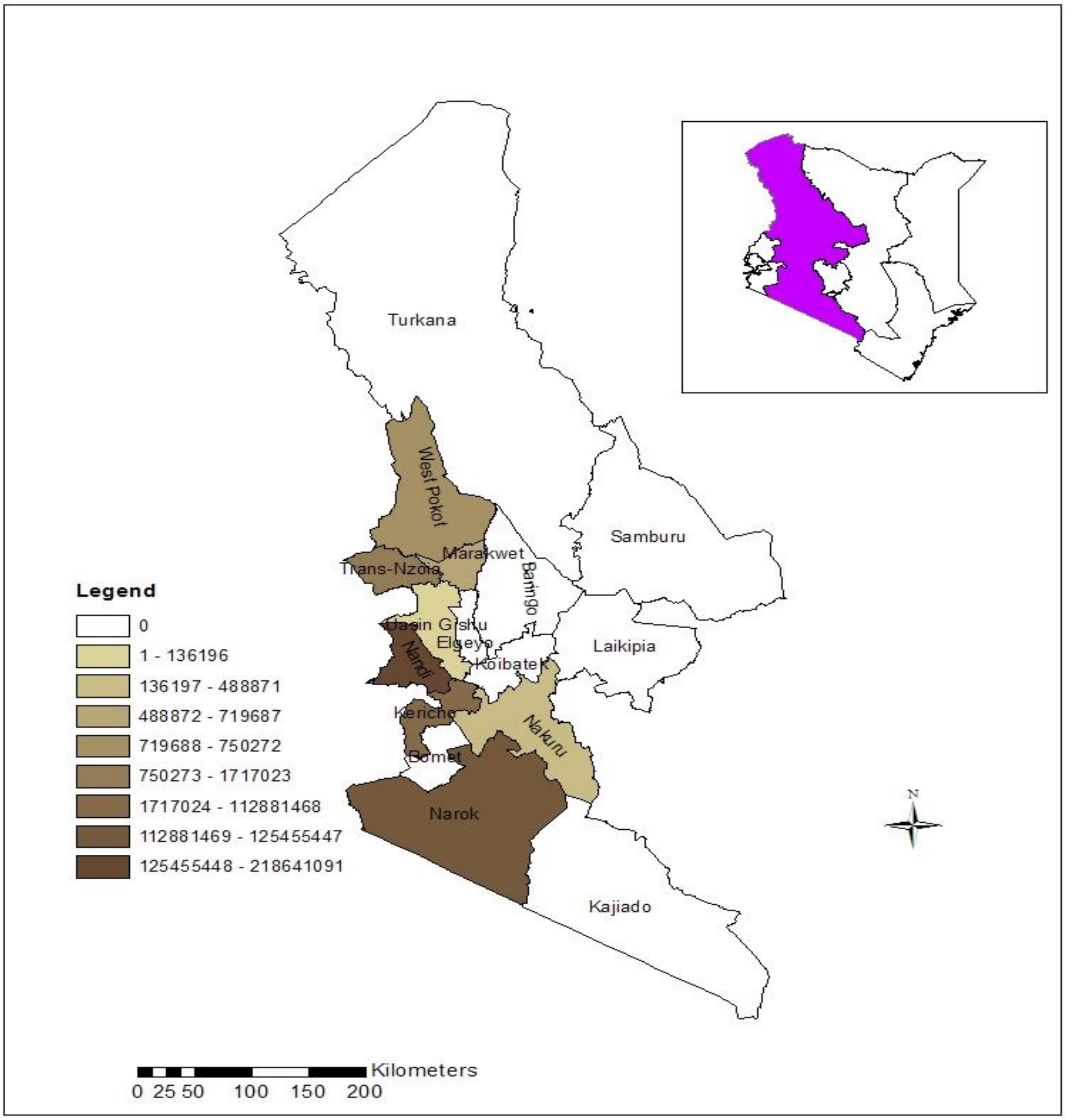


Figure 5.11 Sugarcane biowaste-based biogas energy potential (m^3 CH_4/yr) in Rift Valley Counties

Chapter 6

Multi criteria sustainability assessment of Biogas production in Kenya

ABSTRACT

Energy poverty is a global threat to sustainable development and improved livelihoods hence the availability of clean, affordable, reliable and sustainable energy is a central issue to Kenya's national development objectives. Biogas technology in Kenya has been earmarked as one of the main drivers towards the elimination of energy poverty in majority of rural households and to this end different biogas digester models are actively promoted. Consequently, assessing the sustainability of the biogas systems in Kenya is one of the topical issues driving the discussion on biogas development. Hence developing an assessment technique capable of reliably screening the different alternatives and highlighting the sustainability hot spots is of critical essence in decision making for all biogas stake holders in the country. This paper comparatively analyses the common biogas production systems in Kenya by linking the biogas energy with infrastructures of production. A multi criteria perspective is employed for the analysis focusing on technical, socio-economic and environmental sustainability dimensions. The evaluation in the work follows the life cycle sustainability assessment (LCSA) methodology based on the ISO 14040 and 14044 environmental management principles. It is observed that the tubular and the fixed dome digesters with respective cumulative multi criteria sustainability scores of 70% and 57% are the most sustainable with respect to animal manure as the predominant feedstock. The biogas multi-criteria sustainability assessment approach as presented in this work might be a very vital tool for interventions in the biogas energy sector such as biogas policy formulation in Kenya, the neighbouring region as well as a wide range of developing countries.

Redrafted from: Charles Nzila, Jo Dewulf, Henri Spanjers, David Tuigong, Henry Kiriamiti, Herman van Langenhove. Multi Criteria Sustainability Assessment of Biogas Production in Kenya. *Applied Energy, 2011 (In Press)*

6.1 Introduction

6.1.1 Biogas and the elimination of energy poverty

Biogas technology offers multifaceted benefits to the users hence in Kenya it has been earmarked as one of the main drivers towards the elimination of energy poverty in majority of rural households (BiogasAfrica 2010, Brown 2006, Parawira 2009, WorldBank 2010). To this end, different biogas programmes have been initiated. Nevertheless, based on the mode of construction, the three main types of tested biogas plants that have gained widespread acceptance and are actively promoted in Kenya include the floating drum, fixed dome, and the inflatable tubular reactors. However, the selection of the most appropriate biogas plant design in the country is still a matter of conjecture, largely being determined by the conventional trial and error approach due to scarcity of information. Typical design criteria include space, existing structures, cost, substrate availability and the energy needs of the plant owner. Moreover owing to the fragmented manner in which the scarce information on biogas systems in the country has been presented in the past (Nzila et al. 2010) and the apparent lack of clear benchmarks, it has neither been possible to broadly agree on for instance the most appropriate biogas system to implement in the country nor to ascertain the sustainability of the same.

All the same, financial assistance by way of biogas programme subsidies like for instance in the Nakuru County (Mwirigi et al. 2009) indicate that tubular reactors on average attracted a higher subsidy grant (84%) compared to 50% and nil for the fixed dome and floating drum reactors. However on the national front, the two main biogas support programmes under the auspices of both the Energy and Agriculture Ministries do not consider the tubular biogas reactors for subsidy allocation. Indeed in both programmes it appears that the basis for subsidy allocation is solely the digester volume (fixed dome digester) without taking into account other pertinent parameters such as environmental, technical and economic factors. Consequently because of the existing diversity in biogas systems and digester design considerations, it is imperative that the relative merits and demerits of each system be widely and readily available, and presented in a structured, transparent and uniform manner so that stake holders and decision makers can make informed decision on which system to implement based on both sustainability as well as their needs (Demirbas 2007, Ramesohl et al. 2006). An opportunity thus exists for establishing the most sustainable or eco-efficient biogas system to implement in the country in spite of the complexities in the different biogas production systems.

6.1.2 Sustainability assessment of biogas production

Biogas technology is quite mature however sustainability assessment of biogas production is a topic that has not been well documented. This prognosis was given credence by a search of published literature in the web of science over the last decade which returned only five articles as compared to the more than 3230 articles on general “sustainability assessment“ of other products and services. Nevertheless the overall concept of sustainability (Heijungs et al. 2010) has continued to attract increased attention over the last two decades after the sustainable development report of the World Commission on Environment and Development, commonly referred to as the Brundtland report of 1987 (World Commission on Environment and Development 1987). The sustainability assessment concept is albeit quite unexplored in most of the southern countries as demonstrated in the study on sustainability of cane sugar production (Contreras et al. 2009). Conversely, sustainability assessment has been operational in the north for, among others, assessment of: corporate contributions to sustainability (Figge and Hahn 2004), forest sustainability (Mendoza and Prabhu 2000), bio-ethanol and biodiesel sustainability (DeWulf et al. 2005, Halog and Manik 2011, Sheehan et al. 2003, Thamsiriroj and Murphy 2011), technology sustainability (Dewulf and Van Langenhove 2002, 2005, Heijungs et al. 2010) and biogas production (Poschl et al. 2010, Prochnow et al. 2009). While all the previous studies mentioned do not deal with biogas, the latter two studies respectively deal with sustainability of biogas production from grass (review) and energy efficiency of biogas systems.

Frequently, it appears that most sustainability studies on biogas as well as other renewable energy systems fail to link the infrastructure developments to the energy system thus focusing more on limited aspects such as feedstock sustainability or energy efficiency. However since most renewable energy systems such as the biogas technology offers multifaceted benefits to the users it naturally follows that any sustainability assessment of the renewable energy system ought to adopt a multi criteria methodology. Hence, sustainability assessment of renewable energy technologies such as biogas is thus better illustrated from an expanded approach that considers the dimensions of environmental, economic, social (Finkbeiner et al. 2010, Finnveden et al. 2009, Halog and Manik 2011, Mauerhofer 2008) and technical sustainability (Wang Jiang-Jiang, Jing, You-Yin et al. 2009). On all four aspects, a life cycle perspective is necessary to avoid problem shifting in the product system. Integration of the different dimensions of sustainability is thus feasible through multi criteria sustainability assessment (MCSA). However in contrast to the environmental, technical and economic aspects of sustainability assessment, the social aspect still lacks a broad consensus on adequate indicators or a standardised method (Halog and Manik 2011). Nevertheless, this paper focuses on a MCSA study of biogas technology based on the environmental, technical and economic dimensions. In the MCSA study, the appropriate criteria categories are identified, quantified and the attributed impacts are quantitatively explained without weighting and aggregation of the indicators (Berglund and Borjesson 2006, Chevalier and Meunier 2005, Finkbeiner et al. 2010, Mauerhofer 2008, Wang Jiang-Jiang, Jing, You-Yin et al. 2009)

The objective of this study is to develop and apply an assessment technique for comparatively and reliably screening different alternatives of biogas production when linking biogas energy with infrastructures of production. Specifically the study couples integrated life cycle concepts to comparatively analyse from a multi criteria perspective the technical, economic and environmental performance of three different biogas systems commonly promoted in Kenya. The work is structured to highlight the biogas energy and the multi criteria sustainability assessment concept and thereafter provides a review of the biogas technologies in Kenya that are to be subjected to the assessment. Subsequently the development and application of the multi criteria assessment methodology is presented considering three sustainability dimensions. Finally the results of the multi criteria assessment are presented while comparing the three different biogas systems.

6.2 Domestic biogas technologies in Kenya

6.2.1 Floating drum digester

The floating drum biogas plant (Figure 6.1) consists of masonry cylindrical or dome-shaped digester with a cylindrical top and a movable, floating gas-holder or drum (ETC Group. 2007). The digester is usually made of brick, concrete or quarry-stone masonry with plaster while the gas holder is normally made of metal. Typically the gas-holder normally consists of 2.5 mm steel sheets for the sides and 2mm sheets for the top. Braces can be welded into the drum as a means of breaking up the scum when the drum rotates. The drum is normally coated with oil paints, synthetic paints or bitumen paints to protect it against corrosion, besides thorough de-rusting and de-soiling are essential. Correct priming is vital hence there must be at least two preliminary coats and one top coat of plastic or bituminous paint. The cover coats should be reapplied annually. A well-kept metal gas-holder can be expected to last between 3 and 5 years in humid, salty air or 8-12 years in a dry climate. Materials regarded as suitable alternatives to standard grades of steel are galvanized sheet metal, plastics (glass-fibre reinforced plastic, plastic sheeting) and ferro-cement with a gas-tight lining.

The gasholder drum floats either directly on the fermenting slurry or in a separate water jacket, depending on the pressure of gas in the digester. Water-jacket drums are usually clean and easy to maintain besides the drum cannot get stuck in a scum layer even if the substrate has a high solids content. The gas-holders of water-jacket plants have a longer average service life, particularly when a film of used oil is poured on the water seal to provide impregnation. The drum has an internal and / or external guide frame that provides stability and keeps it upright. As gas production proceeds, the drum is pushed up, indicating a rise in the amount of gas. When the gas is used up, the drum sinks back. The drum level thus provides a useful visual indicator of the quantity of gas available. Fabrication and installation costs of the floating drum digester vary significantly among the dealers and obviously depend upon the size and model. According to the 2009 partial biogas digester survey, there were over 284 floating drum biogas digesters in different parts of the country with a cumulative installed capacity of over 4424 m^3 (Ministry of Energy 2009).

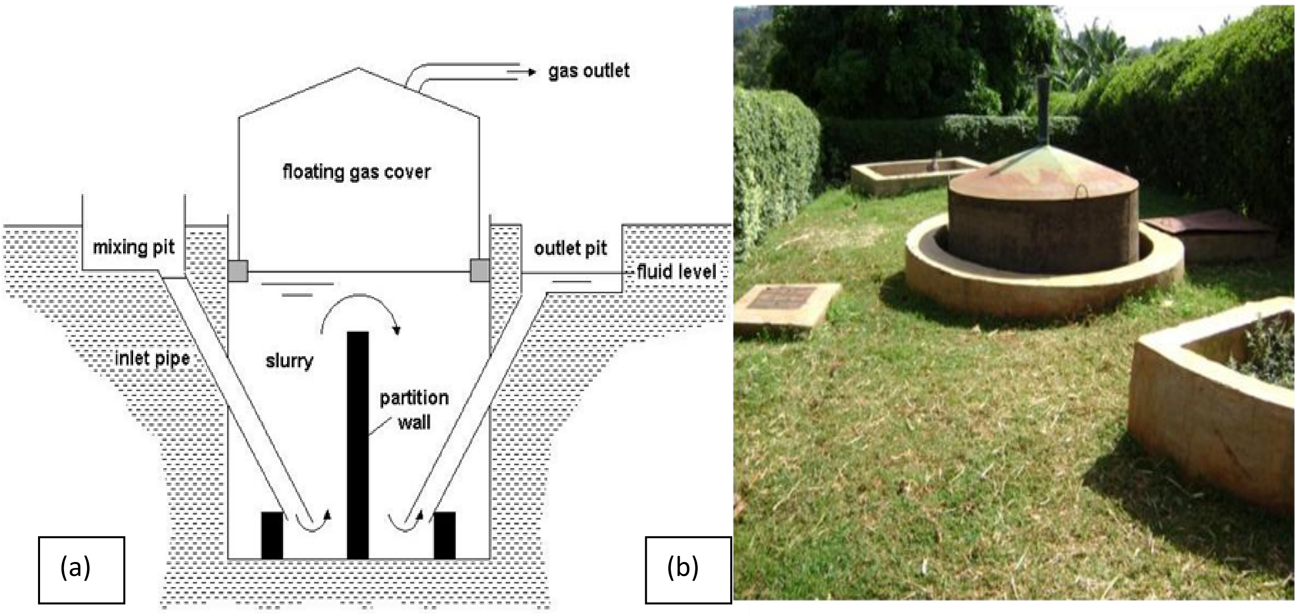


Figure 6.1: Floating drum biogas digester: (a) general scheme and (b) typical plant in Kenya (Ministry of Energy 2009)

Floating drum digesters are easy to understand, install and operate. They provide gas at relatively constant pressure (about 0.1 bar) and the stored gas volume is immediately recognisable via the drum's position. However the steel drum is relatively expensive and maintenance-intensive. De-rusting and painting has to be carried out regularly, usually annually. Besides if fibrous feedstock is used, the drum shows tendency to get stuck in the resultant floating scum hence it has to be freed regularly. The life-time of the drum is relatively short (about 5 years) whereas the lifespan of the digester is up to 15 years.

6.2.2 Fixed dome digester

The fixed dome digester (Figure 6.2a) comprises of a closed, dome-shaped masonry construction, usually built under the ground level with an immovable, rigid gas space (gas holder) and a feedstock inlet and digestate outlet that also serves as a displacement pit or a compensation tank (ETC Group. 2007). The gas space is usually airtight and since concrete, masonry and cement rendering are not gas-tight, the gas space must therefore be painted with a gas-tight layer such as water-proofer, Latex or synthetic paints. A latrine can be coupled to the digester (Figure 6.2b) to provide additional steady supply of digester feedstock. When gas production commences, the slurry gets displaced into the compensation tank whereas the biogas is stored in the upper part of the digester. When the gas is extracted, a proportional amount of slurry flows back into the digester. The gas pressure therefore does not remain constant since it increases with the amount of stored gas as well as depending on the height difference between the two slurry levels.

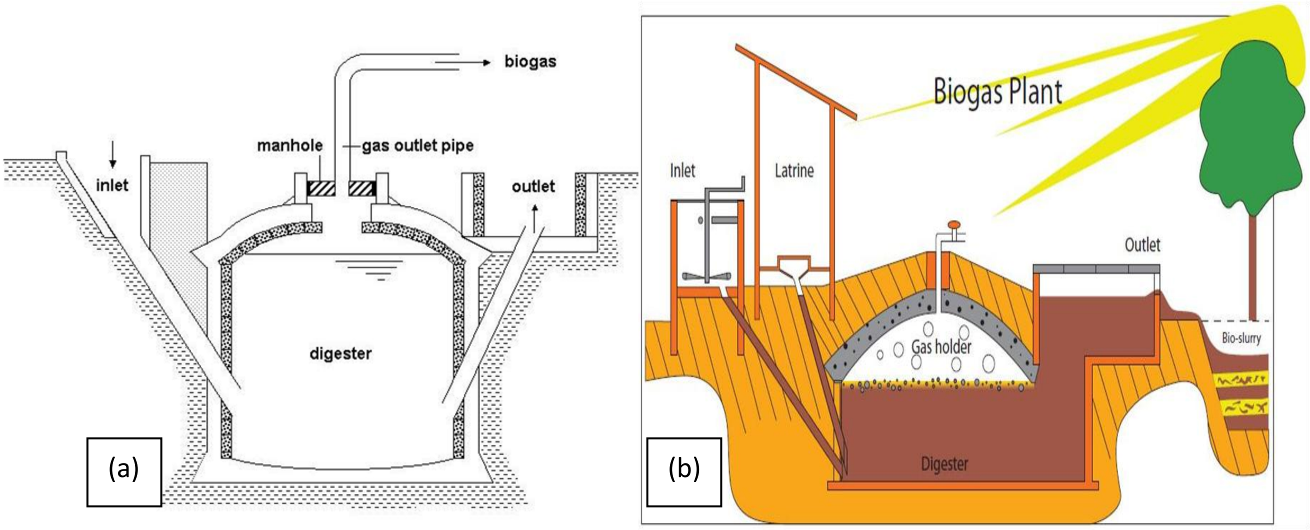
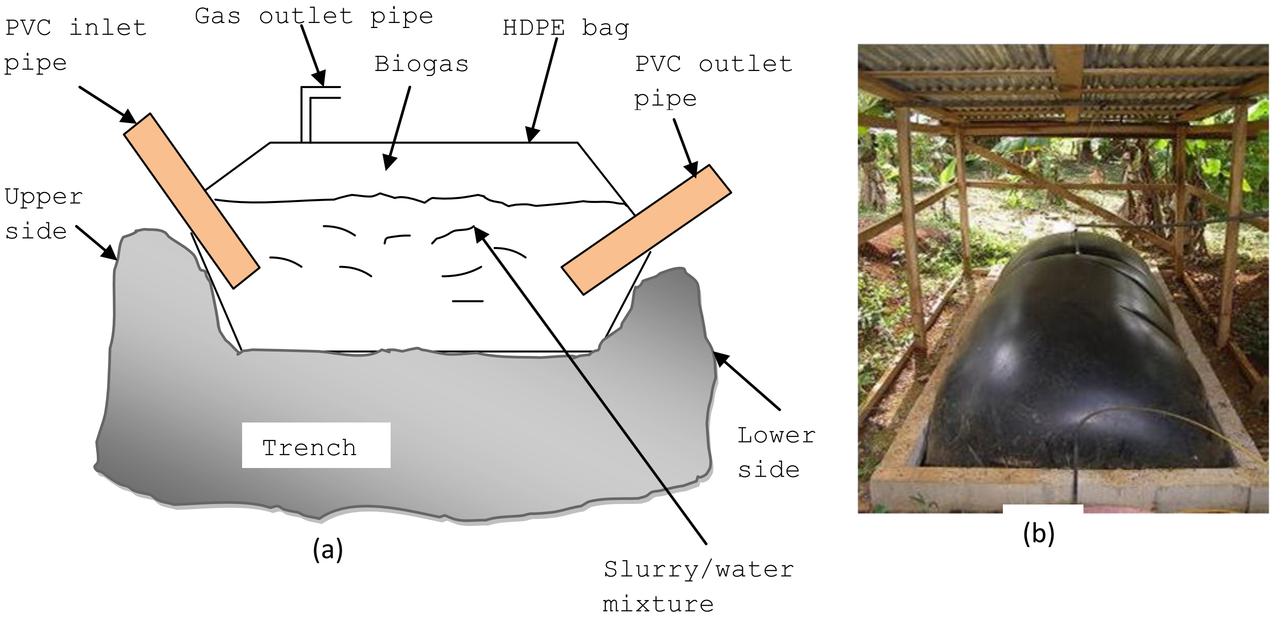


Figure 6.2: Fixed dome biogas digester: (a) General scheme of a fixed dome biogas digester and (b) Fixed dome digester with a coupled latrine (DBFZ 2009)

Fixed dome plants can handle fibrous substances in conjunction with animal manure, since the motion of the substrate breaks up the scum each day. Generally the plant is operated on a continuous feed mode, but if the displacement pit is large enough it can accept several days' worth of substrate at a time. The construction of fixed dome plants is labour intensive and requires skilled supervision. Besides the plants must be covered with earth up to the top of the gas-filled space to serve as insulation as well as to counteract the internal pressure (normally 0.1 – 0.15 bar). There are several designs of the fixed dome digester such as the Chinese fixed dome plant, the Indian *Deebandhu*, the *Akut* and the CAMARTEC model with each having the hemispherical dome shell structure as the central feature (Ministry of Energy 2009). However the *Akut* and CAMARTEC models are the most common type of fixed dome digesters in Kenya. Generally fixed dome plants are characterised by modest initial cost and a long operational life (about 15-20 years), since no moving or rusting parts are involved. Nevertheless, the masonry is prone to porosity and cracks thus it is not normally gastight hence requires the use of special sealants. Cracking often causes irreparable leaks. Moreover the fluctuating gas pressure complicates gas utilization.

6.2.3 Inflatable tubular (plug flow) digesters

The inflatable tubular digesters (Figure 6.3) consist of a weather resistant, heat sealed and usually reinforced HDPE plastic or rubber bag (balloon) equipped with inlet and outlet units (ETC Group. 2007). The top and bottom parts of the digester serve as the gas holder and digester respectively. The requisite gas pressure is occasionally achieved by placing weights on the bag.



(a)

(b)

Figure 6.3: Inflatable tubular digester (a) general scheme and (b) typical plant in Kenya

These digesters normally benefit from standardized prefabrication at low cost besides the shallow installation makes them suitable for use in areas with a high ground water table. However the plastic balloon is rather fragile, besides it is susceptible to mechanical damage and has a relatively short operational life, typically 2-5 years. Besides, the digester is prone to suffer from effects of variable temperature. Extreme exposure to low temperature can curtail biogas production whereas there is likelihood that possible exposure to excess heat can catalyse the production of other volatile gases in the digester besides the methane. The digester therefore requires some form of protection, and possibly insulation against the extreme weather however this increases the costs of installation. The resource inputs for the inflatable tubular digester are generally less than those for the floating drum and fixed dome digesters (Table 6.1), besides the digester offers sufficient flow of the slurry feedstock resulting in more biogas.

Table 6.1
Comparison of three biogas plant designs

Design: Criteria:	Floating-drum	Fixed dome	Tubular type
Design principle	continuous-feed, mixed digester	continuous-feed, mixed digester with slurry store	continuous-feed, fermentation channel
Main components digester/gasholder	masonry digester, floating metal gasholder	masonry with displacement pit	integrated digester/gasholder made of plastic sheeting
Preferred substrates	Fibrous and non fibrous feedstock eg., animal excrements, and or vegetable waste	Fibrous and non fibrous feedstock eg., animal excrements, and or vegetable waste	Non fibrous feedstock eg., animal excrements
Lifespan (yrs) [a]	12-15	15-20	2-5
Range of digester volume (V)	5 m^3 - 70 m^3 (domestic) 100 m^3 - 248 m^3 (industrial)	6 m^3 - 91 m^3 (domestic) 124 m^3 - 740 m^3 (industrial)	5 m^3 - 20 m^3 (domestic)
Advantages	easy construction and operation, uniform gas pressure, mature technology	low cost of construction, long useful life, well-insulated	Prefabricated construction, easy operation
Drawbacks [b]	metal gasholder can rust	sealing of gasholder, fluctuating gas pressure	in-site processing and short useful life (2-5 years) of plastic material, low gas pressure
Operation and maintenance	simple and easy; regular painting of metal gasholder	easy after careful familiarization	easy; regular control of gas-pressure weights
Daily gas-output [c] **(m^3 biogas/m^3 Vd)**	0.3-0.6	0.2-0.5	0.3-0.8
Cost elements	metal gasholder, digester	combined digester/ gasholder, Excavation	HDPE plastic sheeting
Remarks	fully developed, reliable family size system	inexpensive equipment, good for agro residue, extensive building experience required	Suitable for fast solutions, offers possibility for recycling of plastic waste.
Installed capacity [d]	> 4000 m^3	> 4000 m^3	< 1000 m^3

[a] estimated useful life
[b] All biogas plants require careful, regular inspection/monitoring of the gas-containing components
[c] depends on substrate composition; given values are for cattle dung
[d] based on 2009 accounted cumulative installed capacity of 8733 m^3 (Ministry of Energy 2009)

6.3 Methodology

6.3.1 Multi criteria sustainability assessment characterisation

A multi-criteria sustainability assessment of an energy system ought to facilitate the evaluation of the extend in which the system is deemed to be efficient, bearable, viable and equitable hence four main sustainability aspects do suffice, namely; technical (resource valorisation), environmental, economic and social aspects (Afgan et al. 2000, Finkbeiner et al. 2010, Mauerhofer 2008). The multi-criteria sustainability assessment approach applied in this study however focuses on three main sustainability aspects that constitute the three dimensional multi-criteria sustainability assessment involving the environmental, technical and socio-economic dimensions. The three-dimensional sustainability assessment was subsequently applied to characterise the sustainability of biogas production in Kenya. The identification of impact criteria categories for the different sustainability dimensions was based on literature study (Afgan et al. 2000, Bauer et al. 2010, DeWulf et al. 2005, Doukas et al. 2007, Figge and Hahn 2004, Finkbeiner et al. 2010, Halog and Manik 2011, Mauerhofer 2008, Mendoza and Prabhu 2000, Simon and Morse 1999, Wang Jiang-Jiang, Jing, You-Yin et al. 2009, Williams et al. 2009) as well as informal stake holder discussions.

The general requirements for selection of impact criteria were reliability, measurability and relevance / usefulness to the Kenyan situation. Additional requirements included completeness, non-redundant, avoidance of double accounting and independence of preferences. Consequently three impact criteria categories were identified for each of the three sustainability dimensions as summarised in the Multi criteria sustainability assessment scheme (Table 6.2). The impact criteria categories were characterised, using the respective estimation methods, in terms of three different indicators. The usefulness of the criteria applied was assured by the availability of well considered sets of criteria for sustainability assessment (Afgan et al. 2000, Bauer et al. 2010, Heijungs et al. 2010, Mauerhofer 2008, Monteiro et al. 2009, Williams et al. 2009). Measurability of the criteria presupposed adequate definition of the criteria in addition to the identification of an unambiguous indicator suitable for a reliable and valid quantitative judgement. In line with the respective impact categories, corresponding sustainability indicators were therefore computed according to the calculation methodology introduced in **chapter 3** (table 3.5 and section 3.9). The computation results were employed in the sustainability assessment for bench-marking purposes besides aiding in comparing the different biogas production systems.

Table 6.2
Multi criteria sustainability assessment scheme.

Dimension / Impact criteria category	Indicator	Units	Estimation method	References
Environmental				
• **Resource depletion**	Exergy equivalent	MJ / Nm^3 biogas	LCA (CEENE)	(DeWulf et al. 2005)
• **Global warming reduction**	Green House Gas (GHG) saving	kg CO_2eq/ Nm^3 biogas	LCA (IPCC 2007)	(IPCC Intergovenmental Panel on Climate Change 2007, Thamsiriroj and Murphy 2011)
• **Energy demand**	Cumulative energy demand	MJ / Nm^3 biogas	LCA (CED)	
Technical				
• **Energy breeding ratio**	Energy balance	MJ_{out} / MJ_{in}	Energy balancing	(DeWulf et al. 2005, Nzila et al. 2010)
• **Energy payback**	Energy payback period	Months	Energy accounting	(Doukas et al. 2007, Mwirigi et al. 2009, Wang J. J. et al. 2008)
• **Reliability**	operational reliability	%	Non-failure rate	(Wang Jiang-Jiang, Jing, You-Yin et al. 2009)
Socio-Economic				
• **Total investment**	Total capital investment cost	$ Cents/ Nm^3 biogas	Cost estimation	(Wang Jiang-Jiang, Jing, You-Yin et al. 2009)
• **Energy autonomy**	Fossil energy replacement saving	$ Cents / Nm^3 biogas	Energy accounting	(Sheehan et al. 2003)
• **labour cost**	Direct labour (Technology specific labour)	$ Cents / Nm^3 biogas	Direct labour accounting	(Ministry of Energy 2009, Mwirigi et al. 2009)

6.3.2 Characterisation of impacts

6.3.2.1 Environmental sustainability impact criteria categories and indicators

The impact criteria categories, indicators and estimation methods for the environmental sustainability dimension were all based on LCA. The selection of the impact criteria categories of resource depletion, global warming, and energy demand was intended to cover the main environmental burdens (resource consumption and cumulative energy demand) of the life cycle of biogas production against the environmental benefits (global warming reduction) in terms of GHG saving versus the alternative scenario whereby kerosene (2.713 CO_2eq/kg) is used instead of biogas.

Energy demand was used to denote the total energy expenditure due to construction and operation of the different biogas systems. The total energy embodied in the bulk construction materials was factored in the assessment. The labour service attributable to the different digester systems was also accounted for in the energy demand computation by equating one man day (8 hours) to 15.68 MJ(Ransom and Sutch 2001, Yilmaz et al. 2005).

(i) Environmental impact estimation

The environmental sustainability dimension impact estimation was done by means of Life Cycle Analysis (LCA) based on the ISO 14040 and 14044 environmental standards (Arvanitoyannis 2008) pertaining to the goal, scope, system description and boundary definition, inventory analysis, impact assessment and interpretation. The LCA was performed using the SimaPro software and the Ecoinvent 2.2 database (Swiss Centre for Life Cycle Inventories 2010) while the quantification of the respective impacts was done using field data from Kenya. The following subsections describe the LCA methodology according to the scheme provided by the ISO standards.

(a) Goal and Scope

The goal of the study on environmental impact estimation was to employ integrated life cycle concepts to compare the environmental performance of three different biogas digester designs namely floating drum, fixed dome and tubular digester with a view to identifying the best option in terms of resource and energy consumption while simultaneously evaluating the environmental benefits in terms of GHG reduction.

(b) System description and boundary

The initial system boundary (Figure 6.4) for each design consists of bulk raw material extraction, processing, transport and construction of a 16 m^3 biogas reactor, biogas production and its subsequent disposal at the end of the useful life. The operation of the biogas reactor included in the system boundary is based on cattle dung as the sole feedstock.

(c) Functional Unit

The functional unit for the comparison was the production of 1 m^3 of biogas (60% CH_4). The analysis took into account the entire life cycle of biogas production. The modelling for the three different biogas production systems considered a 16 m^3 biogas digester operating uninterruptedly for 340 days per year for a period of 20 years which is the highest estimated useful life of the digesters (Table 6.1).

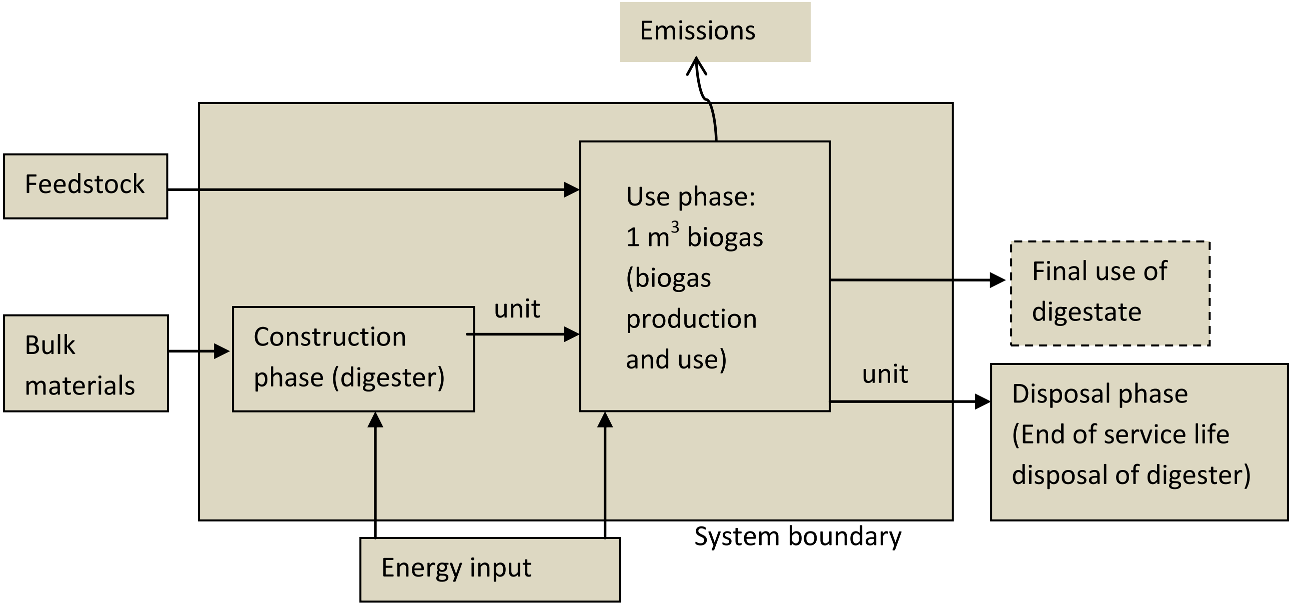


Figure 6.4: Simplified scheme for MCSA of biogas production in Kenya.

(ii) Method and assumptions

All the resource flows into the different biogas systems were identified, summarised and quantified from a life cycle perspective and compared with the biogas yield over the life span of the respective system from an eco-efficiency perspective. The excavation, bulk raw materials, transportation, energy input for fabrication and end of service life disposal of the respective biogas digesters were included in the system boundary. General fittings to the digesters as well as the production of the digester feedstock were not considered in the analysis. All calculations were based on bill of quantities from existing digesters in the country. Hence the analysis focuses on resource flows and biogas systems in Kenya however the results could be valid within the East Africa region as well as other regions with similar conditions. Calculations of energy inputs were based on primary energy inputs i.e., from the perspective of unconverted and untransformed natural resources. The energy output was calculated based on the net energy content in the biogas produced over a period of 20 years. It was assumed that the digesters would operate at their designed maximum capacity for the entire period of operation. The construction costs for 16m^3 floating drum, fixed dome and tubular plug flow digesters were taken as KShs. 120,000 ($ 1,410), KShs. 122,000 ($1,435) and KShs. 90,000 ($ 1,060) respectively (Ministry of Energy 2009).

6.3.2.2 Technical sustainability impact criteria categories and indicators

The technical sustainability dimension impact criteria categories included directly quantifiable technical aspects such as energy breeding ratio, energy payback and reliability. The impact quantification methods were respectively energy balancing, energy accounting and non-failure rate computation.

(i) Energy breeding ratio estimation

Energy breeding ratio (EBR) was used to denote how much useful energy was obtained from the different biogas systems against the overall energy expenditure for each system. The indicator for EBR was the energy balance which was calculated as the ratio of the output energy to the input energy of the respective biogas systems. EBR can be viewed as one of the pillars of a sustainable energy policy (Wang Jiang-Jiang et al. 2009) whereby higher energy balance values signify higher sustainability potential.

(ii) Energy Payback

Energy Payback was estimated from the Energy Payback Period (EPP) which in itself is typically a technical extension of the economic payback period. In this study, the EPP was basically a measure of the period of time over which the energy generated by the respective biogas system equalled the amount of energy expended in the biogas system. The concept of energy payback in biogas production thus intuitively measures how long the biogas system takes to recoup the invested energy. In the short term, biogas investors would obviously prefer shorter EPPs as opposed to longer payback periods (Doukas et al. 2007, Wang J. J. et al. 2008).

(iii) Reliability estimation

Reliability of a system basically refers to the capacity of the system to perform as designed without failure. Operational reliability of the different biogas systems was therefore a measure of the digesters that operated flawlessly in supplying biogas without need for extensive refurbishment. The results were expressed as a percentage of the digesters in the respective category.

6.3.2.3 Socio-economic sustainability impact criteria categories and indicators

The socio-economic sustainability dimension impact criteria categories included aspects directly and indirectly quantifiable in monetary terms such as respectively total investment energy autonomy and labour cost. The USA dollar (exchange rate 1$ = 85 KShs) was used as the currency unit for global comparison purposes. Computations for the economic dimension impact criteria were done using data obtained from interviews with biogas plant owners, contractors, biogas programme coordinators as well as the Kenya Biogas Survey of 2009 (unpublished) which considered a total of 494 biogas plants spread across the country with a combined installed capacity of 8733 m^3.

(i) Total investment cost

Biogas investment cost is composed of all costs relating to construction and installation of biogas digesters. The total capital investment cost indicator was therefore aimed to obtain valorisation of the investment ($ cents) per unit biogas produced. The site preparation, bulky construction materials and biogas accessories were included in the capital investment cost. General operation and maintenance costs were excluded in the total investment cost. The total investment cost for the respective digesters was aggregated for the base period of 20 years. Investment cost is widely used by investors and stakeholders of energy projects to evaluate the energy systems.

(ii) Energy autonomy

The energy autonomy consisted of a measure of the saving arising from the quantity of foreign energy resources substituted by the biogas. The indicator of energy autonomy was the fossil energy replacement saving (FERS) computed with adaptations from (Mwirigi et al. 2009, Sheehan et al. 2003) using the prevailing price of kerosene of $ 0.88/L). The FERS indicator for energy autonomy was expressed in terms of $ Cents per unit volume of biogas produced.

(iii) Labour cost

The labour impact criteria based on direct labour wages and expressed in terms of $Cents per unit volume of biogas produced over the entire lifetime of the digester provided a measure of the labour cost of biogas production. Generally the lower the labour costs per unit volume of biogas produced the more sustainable the biogas system under consideration.

6.4 Results and discussion

6.4.1 Data inventory

The data inventory for the different types of biogas digesters is listed from a life cycle perspective in Tables 6.3 – 6.5 in terms of phase inventory summaries and their corresponding impacting categories for 16 m^3 fixed dome, floating drum and tubular biogas digesters. The data was collected from biogas reports (Biogas Africa 2010; Ministry of Energy 2009) as well as from personal communication with biogas contractors and Biogas Africa Program personnel. The life cycle stages for the different biogas systems can be summarised in terms of construction, use and disposal phases. The construction phase corresponds to extraction and utilization of bulk raw materials in the construction of the respective biogas digester hence resulting to depletion of resources and capital expenditure. The use phase corresponds to the operation of the digesters and utilization of the biogas and digestate for cooking and bio fertilizer purposes respectively with concomitant environmental, technical and socio-economic impacts. The disposal phase corresponds to the end of life scenario with attendant impacts for the respective digesters. The inventory data was processed according to the respective impact estimation methodology and the impacts were characterised accordingly as shown in the subsequent sections.

Table 6.3

Fixed dome digester phase inventory summaries and impacting categories

Phase	Particulars			Impacting category		
	Resource Item	**Units**	**Quantity**	**Environment**	**Technical**	**Economic**
Construction	**INPUTS**					
	Bricks (20x10x6.5 cm)	kg	5024	X		X
	Cement	kg	1510	X		X
	Lime	kg	200	X		X
	Sand	kg	10000	X		X
	Gravel (¾”, ½”)	kg	7000	X		X
	Water	L	6040	X		X
	PVC pipe (4”)	kg	5.89	X		X
	Chicken Wire	kg	4	X		X
	Galvanised pipe (¾”)	kg	79	X		X
	Galvanised pipe (½”)	kg	32	X		X
	Plastic pipe (PU),(¾”)	kg	11.25	X		X
	Excavation, Construction & Piping work	man days	62	X		X
	Supervision work (man days)	man days	18	X		X
	Land area required	m^2a		X		X
	OUTPUTS					
	Fixed dome digester	Unit	1			
Use	**INPUTS**					
	Fixed dome digester	Unit	1		X	
	Labour	man days	1700			X
	Feedstock slurry	kg	768000	X	X	
	OUTPUT					
	Biogas	m^3	38080	X	X	X
Disposal	Digester	Unit	1	X		
	Land	m^2a	16	X		X
	Labour	man days	1			X

Table 6.4

Floating drum biogas digester phase inventory summaries and impacting categories

Phase	Particulars			Impacting category		
	Resource Item	**Units**	**Quantity**	**Environment**	**Technical**	**Economic**
Construction	INPUTS					
	Bricks (20x10x6.5 cm)	kg	5263	X		X
	Cement	kg	1610	X		X
	Lime	kg	200	X		X
	Sand	kg	10500	X		X
	Gravel (¾”, ½”)	kg	7000	X		X
	Stones	kg	7000	X		X
	Gas holder drum (2.5 / 2.0 mm Steel)	kg	261	X		X
	PVC pipe (4”)	kg	5.89	X		X
	Chicken Wire	kg	4	X		X
	Galvanised pipe (¾”)	kg	79	X		X
	Galvanised pipe (½”)	kg	32	X		X
	Plastic pipe (PU), (¾”)	kg	11.25	X		X
	Excavation, Construction & Piping work	man days	62	X		X
	Supervision work	man days	18	X		X
	Water	L	6440	X		X
	Timber	m^3	0.021	X		X
	Land area required	m^2a	16	X		X
	OUTPUTS					
	Floating drum digester	unit	1			
Use	INPUTS					
	Floating drum digester	Unit	1		X	
	Labour	man days	1700			X
	Feedstock slurry	kg	768000	X	X	
	OUTPUTS					
	Biogas	m^3	48960	X	X	X
Disposal	Digester	Unit	1	X		
	Land	m^2a	16	X		X
	Labour	man days	1			X

Table 6.5

Tubular biogas digester phase inventory summaries and impacting categories

Phase	Particulars			Impacting category		
	Resource Item	**Units**	**Quantity**	**Environment**	**Technical**	**Economic**
Construction	**INPUTS**					
	Bricks (20x10x6.5 cm)	kg	240	X		X
	Cement	kg	50	X		X
	Sand	kg	300	X		X
	Water	L	200	X		X
	Precast and reinforced plastic bag (HDPE)	kg	13.8	X		X
	PVC pipe (4”)	kg	5.89	X		X
	Timber	m^3	0.516	X		X
	Galvanised pipe (¾”)	kg	79	X		X
	Galvanised pipe (½”)	kg	32	X		X
	Plastic pipe (PU), (¾”)	kg	11.25	X		X
	Excavation, Construction & Piping work	man days	3	X		X
	Supervision work	man days	2	X		X
	Land area required	m^2a	16	X		X
	OUTPUTS					
	Tubular digester	Unit	1			
Use	**INPUT**					
	Tubular digester	Unit	1		X	
	Labour	man days	1700			X
	Water	L		X		
	Feedstock slurry	kg	768000	X	X	
	OUTPUT					
	Biogas	m^3	59840	X	X	X
Disposal	Digester	Unit	1	X		
	Land	m^2a	16	X		X
	Labour	man days	1			X

The data on biogas production as presented in Tables 6.3 - 6.5 show that biogas output from the different digesters follows the pattern fixed dome < floating drum < tubular digester. While there could be many reasons that can explain such an occurrence, the general configuration of the digesters as presented in Figures 6.1 – 6.3 shows potential differences in the manner in which the substrates mix or flow through the digesters as well as the likelihood of short channelling within the respective digesters. It is thus apparently clear that the substrate in the fixed dome digester has the least chance for streamlined plug flow coupled with the highest chance for short channelling whereas the substrate in the tubular digester has the highest chance for streamlined plug flow. On the other hand the substrate in the floating drum digester has the highest chance for mixing within the digester. It has been reported that the nature of substrate flow and mixing within the digester has a direct bearing on biogas production (Ranali 2007). Consequently the low output in biogas production from the fixed dome digester as compared to the other two digesters is therefore not surprising.

6.4.2 Characterization

6.4.2.1 Environmental Sustainability

The environmental impacts of the three digesters in terms of resource depletion, energy demand and contribution to the reduction of global warming are comparatively shown in Figure 6.5. On average the floating drum digester biogas life cycle consumes the highest amount of resources and energy (1.92 and 1.89 MJ) to produce 1 m^3 of biogas. Moreover the floating drum digester biogas life cycle yields the lowest reduction in global warming (0.96 kg CO_2 eq) per unit of biogas produced. It is worthwhile to note that in both cases the resource and energy consumption does not include the energy embodied in the biowaste (animal manure) which is regarded as waste of no economic value. Methane leakage from the digestate has not been taken into account. It is however important to note that the methane leakage from the digestate should be quite insignificant as compared to the possible methane released when the animal manure is left in pits in the fields without any prior treatment in an anaerobic digester. However it is possible for the reduction in global warming for all the three digesters to be more than the maximum computed value of 1.092 kg CO_2 eq (for tubular digester biogas life cycle) if the methane released when the animal manure are left in the fields without any prior treatment in an anaerobic digester is factored. This aspect thus deserves further studies. Nevertheless, it is evident that the tubular digester biogas life cycle as well as the fixed dome digester biogas life cycle offer better environmental performance as compared to the floating drum digester biogas life cycle.

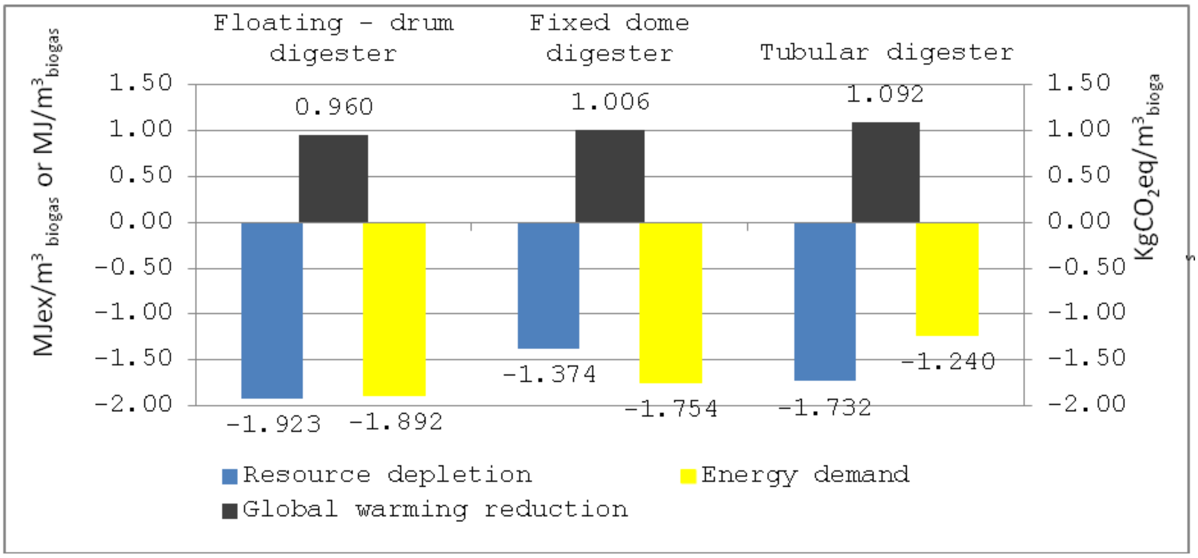


Figure 6.5: Environmental impacts of biogas production in Kenya comparing resource depletion (MJex/m^3 $_{biogas}$), energy demand (MJ/m^3 $_{biogas}$) and resultant global warming reduction (kg CO$_2$eq/m^3 $_{biogas}$). The negative sign denotes depletion of resource/energy.

6.4.2.2 Technical Sustainability

Figure 6.6 presents the technical impacts of biogas production. The energy breeding factor in terms of energy balance (MJ $_{out}$/ MJ $_{in}$) for the three digesters is observed to range from 9.5 for floating drum digester to 14.4 for the tubular digester. It can therefore be argued that biogas production from the three digesters yields significantly more energy than the initially invested energy. Besides, these values are in agreement with other writers (Nzila et al. 2010) who reported that the energy balance for biogas (excluding the inherent energy content of the biomass but including all process efficiencies) ranges from 5.0 to 28.8. In terms of energy payback, the payback period is observed to range from 16.6 months (tubular digester) to 25.4 months (floating drum digester). It is therefore apparent that the biogas life cycle for the three digesters has an inherent energy deficit that can only be overcome by operating the digesters for a period of at least 17, 24 and 26 months for tubular, fixed dome and floating drum digesters respectively. The operational reliability of the three digesters, on the other hand, is observed to vary from 40% (tubular digesters) to 95% (fixed dome digesters). If reliable feeding of the digesters is assumed, their operational reliability will then depend to a large extend on the workmanship and operational diligence however the tubular digesters are more prone to damage especially due to falling objects. Nevertheless it could be argued that while the different technical sustainability criteria have different significance, the energy payback is of critical importance.

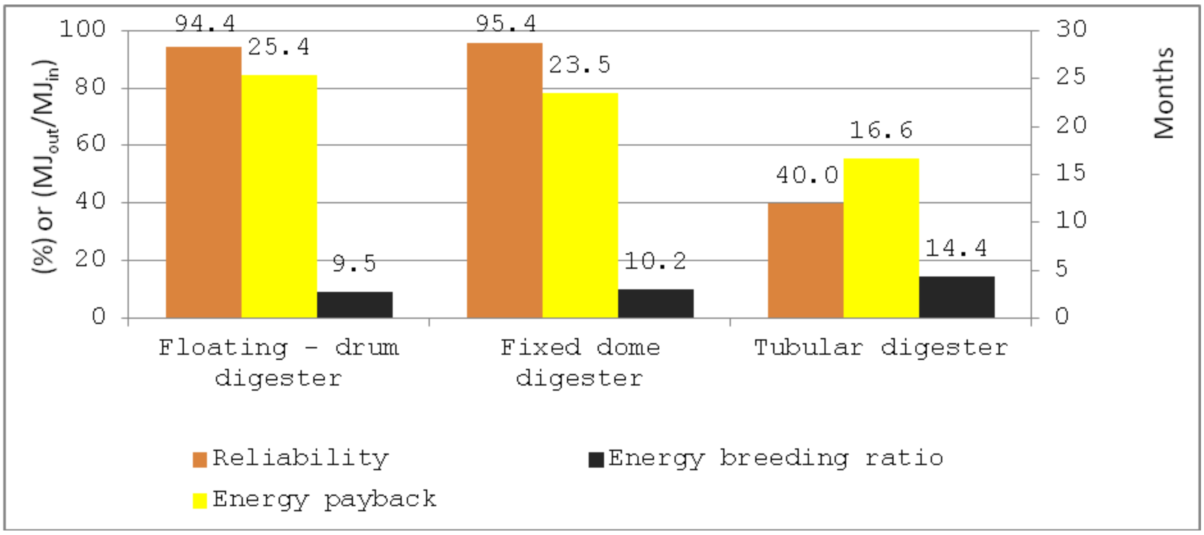


Figure 6.6: Technical impacts of biogas production in Kenya comparing reliability (%), energy payback (months) and energy breeding factor (MJ$_{out}$/MJ$_{in}$).

6.4.2.3 Socio-economic Sustainability

From a socio-economic point of view (Figure 6.7) it is shown that the floating drum, fixed dome and tubular digesters offer energy autonomy to the users with respective fossil energy replacement saving ranging from 42.18 to 44.79 $Cents/m^3 of biogas. On the other hand, the average investment ($ cents) per unit of biogas produced is observed to lie between 1.8 and 3.8. However the tubular digester offers the highest energy autonomy (fossil energy replacement) per unit of investment. Apparently, the tubular digester has the lowest labour cost (5.7 $Cents /m$^3_{biogas}$) as compared to both the floating drum digester and fixed dome digester (7.27and 9.35 $Cents /m$^3_{biogas}$ respectively). Generally, the fixed dome digester is shown to have the highest total costs per unit of biogas produced. When the investment and labour cost components are combined and subtracted from the energy autonomy, the resultant net energy autonomy ($Cents /m$^3_{biogas}$) becomes 32.03, 30.13 and 37.32 respectively for floating drum, fixed dome and tubular digester implying that the three biogas systems offer a significant return for investment.

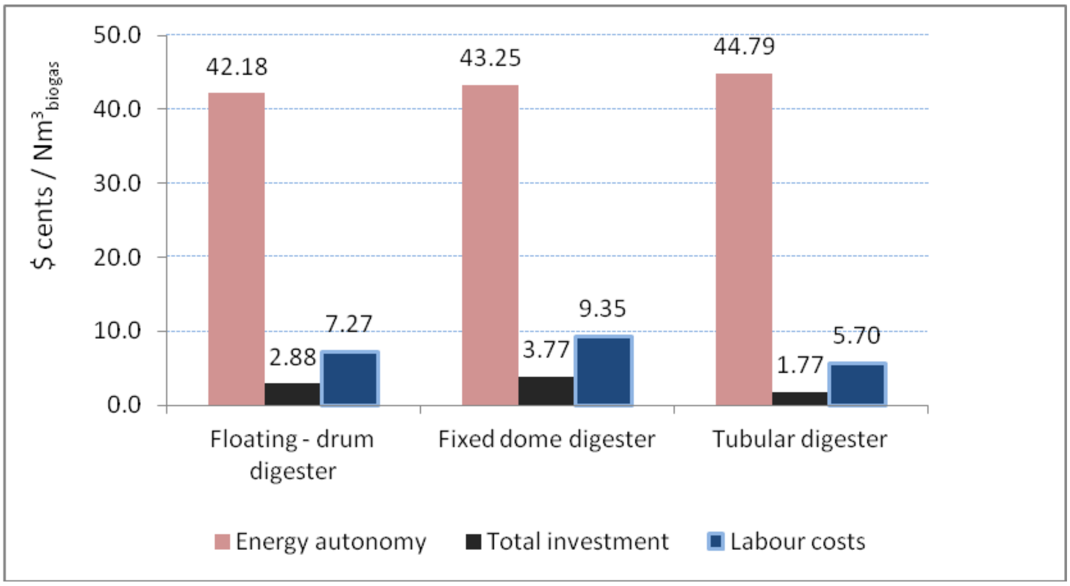


Figure 6.7: Socio-economic impacts of biogas production in Kenya ($ cents/m$^3_{biogas}$) comparing energy autonomy, total investment and labour costs.

6.4.3 Multi criteria analysis

A general overview of the multi criteria comparative analysis is presented in a radial spider-gram (Figure 6.8) whereby all the sustainability criteria are given equal prominence and scaled from zero to one with the interval denoting increasing level of suitability. The total node lengths occupied by the respective digesters indicates their respective suitability with respect to the multi criteria assessment. It is therefore shown that the floating drum, fixed dome and tubular digester biogas production have respective spider-gram cumulative node lengths (MCSA score) that are 77 %, 79 % and 91% of the cumulative spider - gram node lengths of 9 length units. Moreover the floating drum digester and the fixed dome digester -biogas production have respective spider-gram cumulative node lengths that are respectively 16 % and 14 % less than the cumulative spider-gram node lengths of the tubular digester biogas production indicating that the tubular digester scores are better in most categories of the sustainability spider-gram with an exception of the reliability and employment categories where it scores dismally.

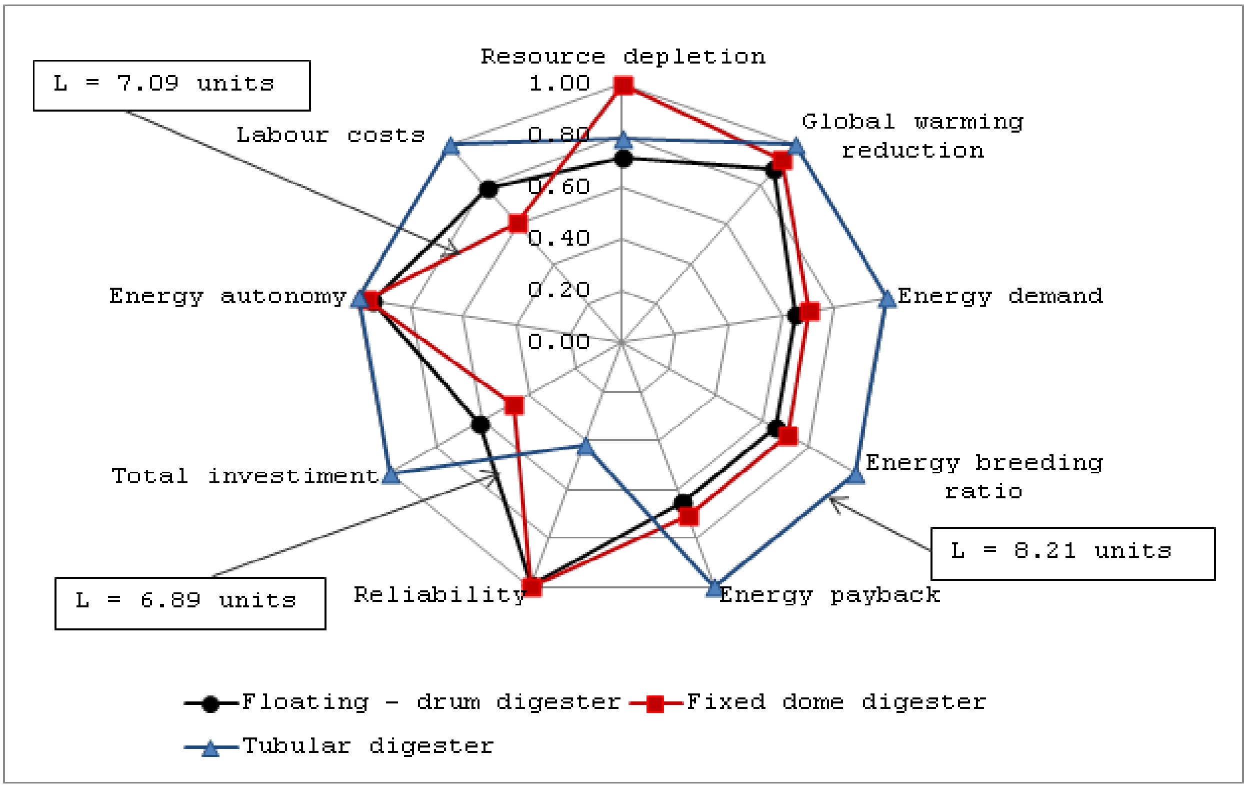


Figure 6.8: Multi criteria sustainability assessment spider - gram of biogas production in Kenya comparing the performance with respect to the total node lengths (L) occupied by the three biogas production systems as a result of respective environmental impacts (resource depletion, global warming reduction and energy demand), technical impacts (energy breeding ratio, energy payback and reliability) and socio-economic impacts (total investment, energy autonomy and labour costs). The bigger the area occupied the more sustainable the energy system.

Therefore from these results, it is clearly apparent that for predominantly non fibrous feedstock, such as cow dung, the tubular digester biogas production is the most sustainable of the three digesters. However it is paramount to further investigate possible mitigation measures for ameliorating the low reliability of the tubular biogas digesters.

6.5 Conclusions

Biogas technology offers multifaceted benefits to the users hence sustainability assessment of the technology requires a multi criteria methodology that is structured taking into account different sustainability dimensions. This study has therefore build on the existing informational gap and presented an integrative approach for multi criteria sustainability assessment of biogas production in Kenya.

Results from the study show that apart from the feedstock utilization, biogas production is also associated with environmental resource depletion ranging from 1.37 to 1.92 MJ ex/m^3_{biogas}, whereas the associated energy demand ranges from 1.24 to 1.89 MJ/m^3_{biogas}. Under the same conditions, the associated global warming reduction, when kerosene is taken as the replaced fuel, is seen to vary from 0.96 to 1.09 kg CO_2 eq/m^3_{biogas} which could be a pointer to the environmental sustainability of the three biogas systems investigated. With respect to technical sustainability it is shown that the biogas life cycle for the three digesters has an inherent energy deficit that can only be overcome by operating the digesters, at least, for a period of between 17 and 26 months, however the overall energy breeding ratio for the three biogas digesters is quite promising. Moreover, from a socio-economic perspective, the study shows that biogas production from the three digesters offers significant energy autonomy to the users with respective fossil energy replacement saving ranging from 30 to 37 \$Cents/m^3_{biogas} suggesting a rather significant return for investment.

Hence from the results presented in the work in terms of the selected environmental, technical and economic sustainability criteria, it can be concluded that the three biogas lifecycles demonstrate significantly different sustainability behaviours. The tubular digester biogas production is deemed to be more sustainable as compared to the fixed dome and floating drum digester biogas production. However the issue of low reliability (40%) of the tubular digesters is of prime concern and requires further insight. In addition, further work should endeavour to rank the different criteria categories highlighted in this work with a view to gaining deeper insight on the rather controversial sustainability issue. It is noted that the integrative approach for multi criteria sustainability assessment as presented in this work can constitute a vital tool for possible interventions in complex sectors such as the biogas sector.

6.6 Perspectives

The work presented in this study was carried out from a Kenyan setting hence the resource quantities are specific to Kenya. However, the multi criteria sustainability assessment scheme formulated and presented in this work is relevant to the neighbouring region and a wider setting where environmental, technical and economic considerations are required devoid of human subjectivity. Moreover, the calculation details and the expression of results in commonly used units enable readers to adjust them to reflect on their own priorities. Hence the assessment scheme can be applied internationally especially to compare different alternatives within the same technology. It is therefore possible to use the scheme not only to compare different alternatives for biogas production but also to compare different options for other biofuels such as biodiesel or bioethanol production. Furthermore, since this work integrates the infrastructures of production with the produced biogas, therefore the results present a suitable basis for computing Carbon Abatement Revenue under the Clean Development Mechanism when kerosene is considered as the replaced fuel

Acknowledgements

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6.7 Supplementary information

6.7.1 Formulae employed in the Multi Criteria Sustainability Assessment framework.

1. $CEENE_j = \sum_{i=1}(X_i * a_{ij})$ (eq. 1)

where:

$CEENE_j$ = cumulative exergy extracted from the natural environment for a product *j* (MJ_{ex})

X_i = characterisation factor of the *i*th reference flow (MJ_{ex}/kg, MJ_{ex}/MJ, MJ_{ex}/Nm^3, MJ_{ex}/m^2.a)

a_{ij} = amount from reference flow *i* (kg, MJ, Nm^3, m^2.a) necessary to obtain product *j*.

2. $CED = \sum_j X_j * n_j$ (eq. 2)

where:

CED = cumulative energy demand (MJ)

X_j = characterisation factor of resource *j* (MJeq/kg, MJeq/m^3, MJeq /m^2a),

n_j =amount of resource *j* (kg, Nm^3, m^2.a per functional unit)

3. **GHG saving =** $GHG_{replaced\ fossil}\ (kg\ CO_{2\ eq}/m^3) - GHG_{biogas\ prod}\ (kg\ CO_{2\ eq}/m^3)$ (eq. 3)

where:

$GHG_{replaced\ fossil}$ = $CDE_{fossil}\ (kg\ CO_{2\ eq}/kg_{fossil}) * FER\ (kg/m^3)$

$GHG_{biogas\ prod.}$ = $\sum_j X_j * m_j$

$GHG_{replaced\ fossil}$ = Green house gas potential for the fossil fuel replaced by biogas (kg CO_2eq/$Nm^3{}_{biogas}$)

$GHG_{biogas\ prod}$ = Green house gas emitted due to biogas production (kg CO_2eq/$Nm^3{}_{biogas}$)

CDE_{fossil} = carbon dioxide equivalent for fossil fuel (kg CO_2eq/kg_{fossil})

X_j = characterisation factor of emission *j* (kg CO_2 eq/kg)

m_j = mass of emission *j* (kg/ $Nm^3{}_{biogas}$)

4. **EBR** = $\frac{output\ energy\ (MJ/m3)}{input\ energy\ (MJ/m3)}$ (eq 4)

where:

- EBR = Energy breeding ratio
- output energy is the energy content of biogas per unit volume

- Input energy is the energy expended to produce a unit volume the biogas.

5. **EPP**= $\frac{total\ energy\ input\ (MJ)}{annual\ energy\ output\ (MJ/yr)}$ (eq 5)

where:

- EPP = Energy payback period (years)
- Total energy input (MJ) = energy demand (MJ/m^3) * total volume of biogas produced (m^3)
- $\text{annual energy output}\ \left(\frac{\text{MJ}}{\text{yr}}\right) = \frac{\text{total biogas output}\ (\text{m}^3) * \text{biogas energy content}\ (MJ/\text{m}^3)}{20\ yrs}$

6. **Reliability** $= \frac{\sum digesters\ without\ need\ for\ extensive\ refurbishment}{\sum digesters} * 100\%$ (eq. 6)

7. **Total investment cost** = $\frac{construction\ cost\ (\$) + direct\ labour\ cost\ (\$)}{total\ biogas\ production\ (m3)}$ (eq. 7)

where:

- Construction cost = cost incurred ($) in the construction of the respective digester
- Direct labour cost = labour input (man days) * minimum daily wage ($/day)

8. **FERS** (\$/ Nm^3) = $\left\{\frac{E_{biogas}\ (MJ/\text{m}^3)}{E_{fossil}\ (MJ/\text{kg})} - Q_{fossil}\ (\text{kg/Nm}^3)\right\} * P_{fossil}\ (\$/\text{kg})$ (eq. 8)

where:

- FERS = Fossil energy replacement savings (\$/ Nm^3)
- E_{biogas} = Biogas energy content (MJ/Nm^3) = 35.8 MJ/Nm^3 (or 9.845 MJ/Nm^3 considering 50% CH_4 and 55% standard biogas stove efficiency)
- E_{fossil} = Fossil resource energy content (MJ/kg)
- Q_{fossil} = fossil resource used during biogas production (kg/Nm^3)

  $= \text{CED non ren.}\ (\text{MJ}/\text{m}^3)\ x \frac{\delta_{fossil}\ (kg/L)}{G_{fossil}\ (MJ/L)}$
- δ_{fossil} =density of fossil fuel (density of kerosene = 0.81kg/l)
- G_{fossil} = energy content of fossil fuel (LHV of kerosene) = 37.7 MJ/l (or 18.85 MJ/L considering 50% standard kerosene stove efficiency)
- P_{fossil} = Price of fossil resource (\$/kg)

9. **Labour cost** $(\$/\text{m}^3) = \frac{\text{Direct labour demand (man-days) x daily wage (\$/man-day)}}{total\ biogas\ production\ (\text{m}^3)}$ (eq. 9)

where:

- The daily wage is based on the average minimum wage consideration in the country

6.7.2 Reliability details of fixed dome, floating drum and tubular biogas digesters.

Table 6.6

Specific and total operational reliability details for different biogas digesters

Digester type	Total No. of digesters	Digesters operating without need for extensive of refurbishment	Operational reliability (%)
Fixed Dome	197	188	95.4
Floating drum	284	268	94.4
Tubular	5	2	40.0
Total	486	458	94.2

Source: biogas digester census (Ministry of Energy 2009).

The operational reliability is an aggregate measure of flawless operation of the different digesters in the country.

Chapter 7

The added value of biowaste valorisation to the environmental profile of the African *Kitenge*

Abstract

The African *Kitenge* is a resource intensive textile product having profound popularity and widespread use, especially in the vast sub Saharan Africa. *Kitenge* is made of 100% cotton and for every kilogram of *Kitenge* produced in a textile factory, 3.96 kilograms of cotton have to be produced at the farm level with concomitant generation of about 10.33 kilograms of biowaste. The generation of such an amount of biowaste demands closer attention owing to the inherent adverse potential consequences to the environment. In the present study, an assessment of the added value of biowaste valorisation to the environmental profile of the African *Kitenge* is carried out considering three alternatives in which biogas and nutrient rich digestate are produced and used to replace different proportions of fossil fuels and mineral fertilizers in the *Kitenge* production chain. The analysis used the current practice as the reference scenario. The assessment is performed using the life cycle sustainability assessment methodology based on the ISO 14040 and 14044 principles. The environmental assessment metrics employed in the study include the Intergovernmental Panel on Climate Change with a timeframe of 100 years and the cumulative energy demand. It is observed that valorisation of about 50% of the biowaste from *Kitenge* production has the capacity to offset the *Kitenge's* carbon footprint and cumulative energy demand by up to 45% and 37% respectively. These results unveil interesting insight for sustainable management and branding of the African *Kitenge*.

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Charles Nzila, Jo Dewulf, Henri Spanjers, David Tuigong, Jerry Rawlings, Henry Kiriamiti, Herman van Langenhove. Life Cycle Environmental Sustainability Assessment of the African *Kitenge*. *MU_K* – VLIR_UOS International Symposium, February 2011, Kisumu, Kenya.

7.1 Introduction

In Africa, wax prints are referred as *Kitenge*, an ever in vogue textile product popular in almost all the African countries. The African *Kitenge* is a high ethnic value - multicoloured wax print that represents various moods, culture and tradition of the native African people. Besides, *Kitenge* is an effective communicative clothing that differs from other communication gadgets in that it does not have to integrate a number of different technical elements such as control interfaces, sensors, data processing devices, etc (Gupta 2009) but instead makes use of simple artwork and or poetry as a means of communication between the wearer and the surrounding people. The *Kitenge* garment is typically unisex by nature and it is worn by either simply wrapping it over the body or by tailoring it into a custom designed dress. Being made from 100% cotton, the garment is effective against perspiration and suits the hot environment of Africa besides keeping alive the traditional sentiments in the minds of the African people. Owing to the diversity of the processes preceding the finished *Kitenge* as well as its profound popularity and widespread use, the sustainability assessment of the African *Kitenge* is therefore warranted so as to identify any potential sustainability hot spots besides informing its prudent management. The present study is carried out from a case study perspective with consideration on *Kitenge* production in Kenya. The *Kitenge* production is a component of the cotton value chain in Kenya (Figure 7.1) that is broadly composed of cotton farming, ginning and transformation (spinning, weaving and refining) in a textile factory.

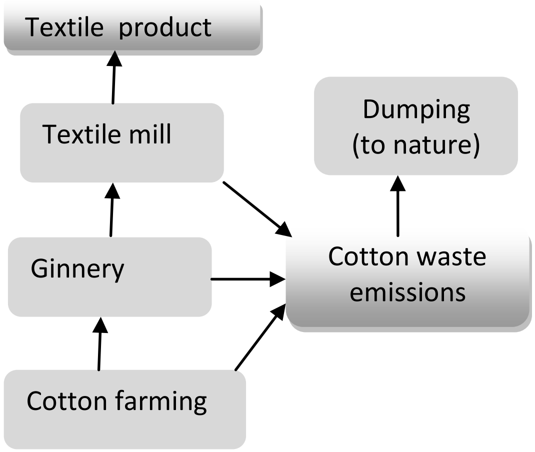


Figure 7.1: The cotton system in Kenya showing the existing scenario with material and energy flows for textile product and concomitant damping of waste emissions to nature.

Cotton farming in Kenya is predominantly carried out in the country's coast, eastern and western regions by small holder farmers whose farms mostly range from 0.2 to 2 hectares. Generally, the estimated potential land for cotton farming is over 400,000 hectares capable of producing over

270,000 bales of cotton lint per annum through rain-fed cotton production. The harvested cotton is transported by road to the ginnery where it is mechanically processed to get rid of trash (cotton gin waste) and to separate the cotton lint from the seed. The ginned cotton is transported by road to the textile factory where it is subsequently spun into yarn and then woven prior to being subjected to various refining processes before it is finally deemed to be a finished *Kitenge*. Waste management is a significant problem facing the cotton industry, for example, at the ginning stage, about 40 –147 kg of cotton gin waste is produced per bale of cotton (227 kg) (Agblevor et al. 2006). Furthermore the entire cotton transformation process in a textile factory is associated with substantial material and energy consumption (Nzila et al. 2008). Hence it is prudent besides being a worthwhile Corporate Social Strategy for *Kitenge* producers to track its impacts on the environment. However the impact tracking ought to be through suitable indexes that can be easily interpreted by different stakeholders (Global Reporting Initiave 2011). With this regard, substantial in-depth sustainability assessment is warranted. However such investigation can be of greater value if an effort is put first, to integrate the entire cotton value chain, that is from cotton farming to the finished fabric such as *Kitenge*, so as to present comparable and comprehensive results, and secondly, to strive to maximise the utilization of the entire biomass and resultant biowaste encompassed in the *Kitenge* chain. Generally biowaste valorisation in many agricultural residues has been carried out in the past (Afgan et al. 2000, Agblevor et al. 2006, Alonso-Pippo et al. 2009, Cherubini et al. 2008, Cleary 2009, Gerin et al. 2008, Lansing et al. 2008, Neves et al. 2006, Parawira et al. 2008, Zheng et al. 2009) however the cotton production chain has been paid relatively little attention. In this connection there is a need to evaluate the added value of biowaste valorisation to the cotton chain.

The objective of this study is therefore to evaluate the implications of cotton biowaste valorisation to the environmental profile of the African *Kitenge*. The study is based on a cradle to gate case study of a typical *Kitenge* production chain (Figure 7.2) in Kenya that consists of cotton farming, ginning, spinning, weaving and refining to produce a finished *Kitenge*. The assessment is undertaken in line with the Life Cycle Sustainability Assessment (LCSA) methodology based on the ISO 14040 and 14044 principles (Arvanitoyannis 2008, UNEP SETAC 2010). The production of *Kitenge* is associated with various emissions to air, soil and water.

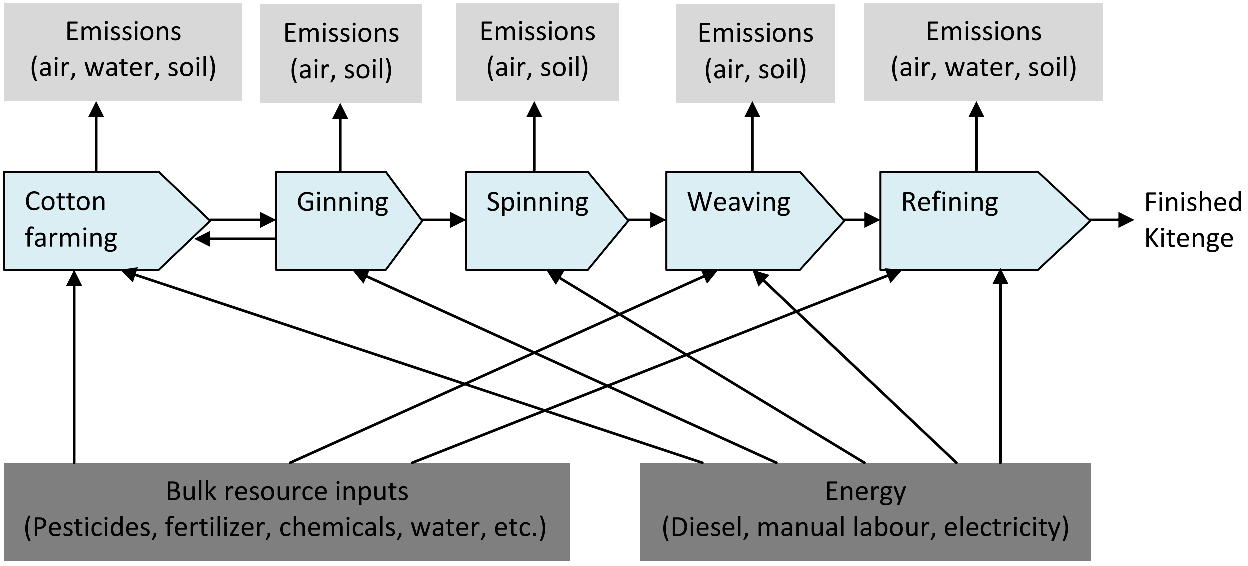


Figure 7.2: Resource flows and emissions in the *Kitenge* production chain system

7.2 Materials and Methods

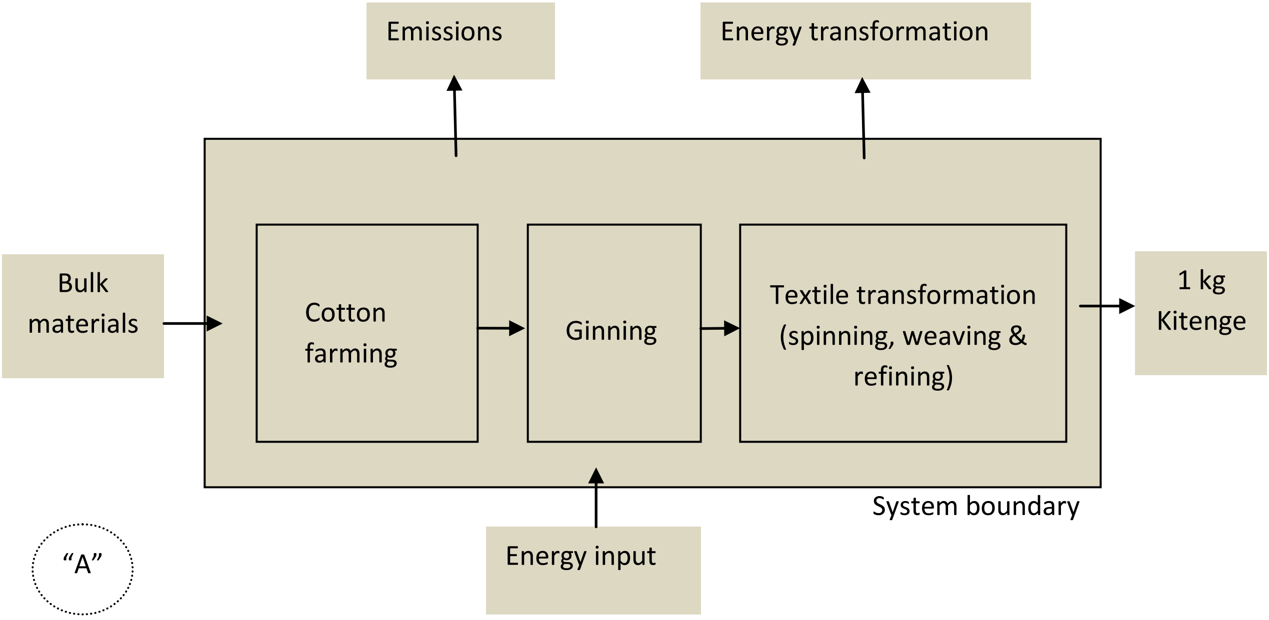
7.2.1 Methodology

The present study emanates from data collected between 2009 and 2011. Generally in the *Kitenge* production chain, sophistication and hence process reproducibility tend to increase along the chain due to increased automation and process controls. Consequently, the data collection exercise was structured to address the variability in the bottom segment (farming level) of the *Kitenge* production chain. A total of 92 farms in Western, Coast and Eastern regions of Kenya that practised the best available techniques of cotton farming were deemed to be among the model representation for the cotton farming step of the *Kitenge* production chain. Moreover, the model farms employed mechanised tillage and followed a strict regime of pesticide and fertilizer application. However, at the ginning stage there were only 6 ginneries operating in the country during the period of study. With respect to the textile refining stage, there were only two textile factories having *Kitenge* as a niche product at the time of the study. Consequently for proprietary logistical reasons data was collected from one farm, one ginnery and one of the textile factories. Generally, data collection was by means of face to face interview.

The environmental profiling was done by means of Life Cycle Analysis (LCA) based on the ISO 14040 and 14044 environmental management standards (Arvanitoyannis 2008) pertaining to the goal and scope definition, inventory analysis, impact assessment and interpretation). The LCA was carried out using SimaPro software and the Ecoinvent 2.2 database (PRe Consultants 2010, Swiss Centre for Life Cycle Inventories 2010).

7.2.2 Goal and scope definition

The goal of the study was to evaluate by means of LCA concepts, the environmental implications of biowaste valorisation in the production of African *Kitenge* based on a typical case study of *Kitenge* production in Kenya. The simplified system boundary for the *Kitenge* LCA study (Figure 7.3) consisted of “cradle to gate” which entailed bulk raw material extraction, cotton farming, ginning and textile transformation (spinning, weaving and refining) to produce the finished *Kitenge*. The functional unit for the study was therefore the production of one metric kilogram of *Kitenge*. The marketing, sales, usage and end of life scenarios of the *Kitenge* were excluded from the system boundary.



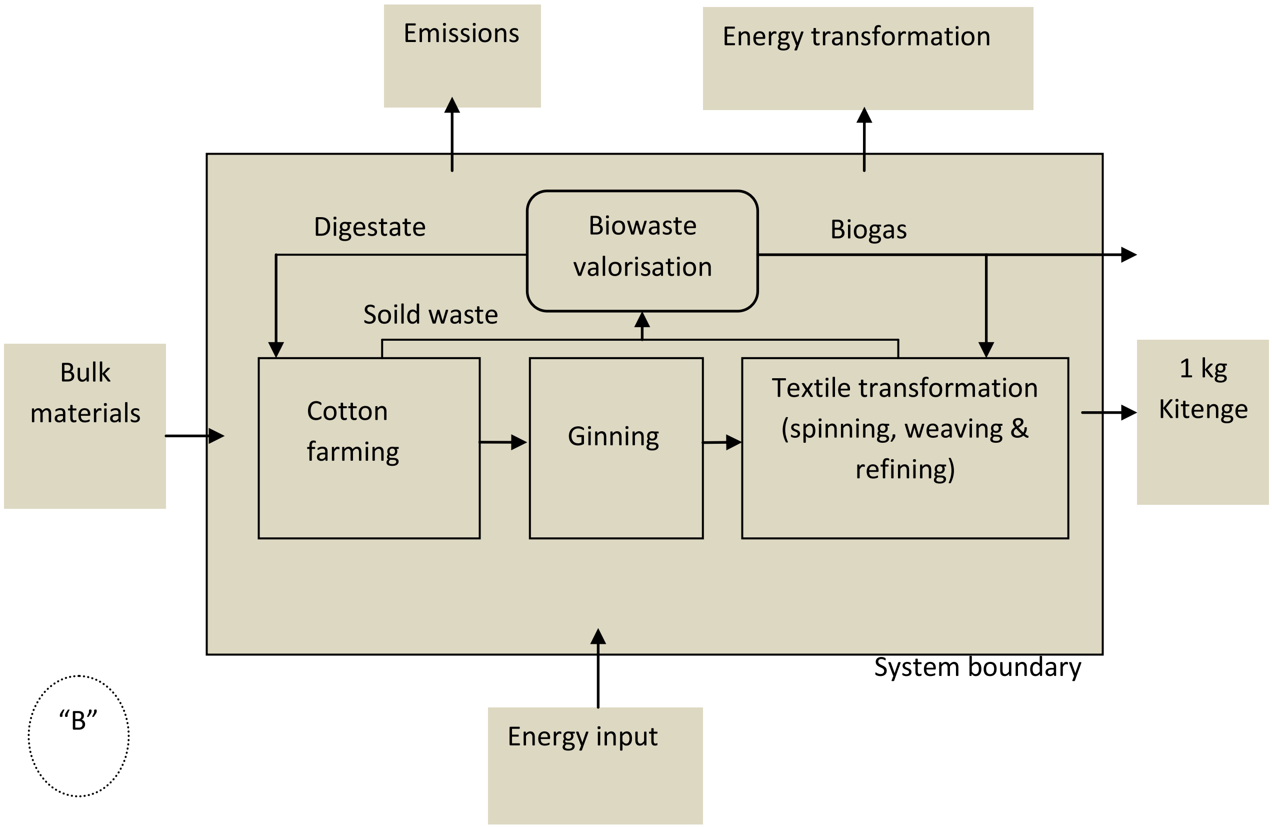


Figure 7.3: Simplified system boundary for the production of 1kg African *Kitenge* showing present scenario "A" and alternative scenario(s) "B" with expanded system boundary to incorporate biowaste valorisation through biogas and nutrient rich digestate production.

7.2.3 Inventory analysis

All the resource and emission flows (Table7.1) into the system boundary were identified and quantified for each unit process of the *Kitenge* production chain. The inventory was therefore carried out in a manner that reflects the typical situation for *Kitenge* production in Kenya. Data gaps especially for air emissions were however modelled from the corresponding resource inputs using secondary data gathered from literature (Swiss Centre for Life Cycle Inventories 2010). Nevertheless, for every woven and refined part of Kitenge, correspondingly 1.01, 1.27 and 3.96 parts were respectively required to be produced at spinning, ginning and farming stages with concomitant generation of about 10.33 kilograms of biowaste.

Table 7.1

***Kitenge* life cycle inventory analysis**

Unit Process	Unit Process Exchanges	Details	Units	Quantity	Source of data
FARMING	**Reference Product**				
	cotton fibres (farm gate)	seed cotton	kg	1	*
	From Nature (RESOURCES)				
	Resource/Land	occupation arable	ha a	7.73E-04	*
	Resource/in water	rain	m^3	1.39E-01	*
	From Technosphere (RESOURCES)				
	Pesticides	Bulldock (Beta-Cyfluthrin)	kg	4.42E-04	*
	Mineral fertilizer	DAP	kg	1.28E-01	*
		CAN	kg	1.28E-01	*
	Diesel fuel	ploughing / tillage, harrowing	kg	4.34E-02	*
	Planting seeds	Cotton seeds	kg	2.57E-02	*
	To Nature (EMISSIONS)				
	Soil	Biowaste	kg	7.37E+00	*
	air/low population density	Heat	MJ	1.96E+00	**
		Dinitrogen monoxide	kg	5.12E-03	**
		Ammonia	kg	2.07E-02	**
		Nitrogen oxides	kg	1.08E-03	**
	Water/river	Phosphate	kg	3.87E-04	**
		Phosphorus	kg	3.92E-04	**
	Water/Ground	Phosphate	kg	1.24E-04	**
		Nitrate	kg	8.84E-02	**
	Soil/agricultural	Cadmium	kg	1.35E-06	**
		Chromium	kg	9.26E-05	**
		Copper	kg	-4.46E-08	**
		Mercury	kg	-6.23E-08	**
		Nickel	kg	3.07E-06	**
		Lead	kg	3.00E-06	**
		Zinc	kg	2.88E-06	**
		Cyfluthrin	kg	8.29E-05	**
GINNING	**Reference Product**				
	cotton fibres	Ginned Lint	kg	1	*
	From Technosphere (RESOURCES)				
	Transport systems (road)	3.5-16t lorry	tkm	2.43E-01	*
	Electricity production mix	Electricity, low voltage, KEN	kWh	5.43E-01	*
	To Nature (EMISSIONS)				
	Air/unspecified	Heat, waste	KJ	1.96E+00	**
	Soil	Biowaste	kg	2.71E+00	*

SPINNING	**Reference Product**				
	Spinning, cotton	Spun Yarn	kg	1	*
	From Technosphere (RESOURCES)				
	Electricity production mix	Electricity, low voltage, KEN	kWh	4.77E-01	*
	Transport systems (road)	3.5-16t lorry	tkm	2.43E-01	*
	To Nature (EMISSIONS)				
	Soil	Biowaste	kg	2.57E-01	*
	Air/unspecified	Heat, waste	KJ	1.96E+00	**
WEAVING	**Reference Product**				
	Weaving, cotton	Woven *Kitenge*	kg	1	
	From Technosphere (RESOURCES)				
	Electricity production mix	Electricity, low voltage, KEN	kWh	1.07E-01	*
	To Nature (EMISSIONS)				
	Soil	Biowaste	kg	1.00E-01	*
	Air/unspecified	Heat, waste	KJ	36.4	**
REFINEMENT (FINISHING)	**Reference Product**				
	refining, *Kitenge*	Refined *Kitenge*	kg	1	
	From Technosphere (RESOURCES)				
	Electricity production mix	Electricity, low voltage, KEN	kWh	4.73E-02	*
	Oil/heating systems	Light fuel oil	MJ	3.05E+01	*
		Wood fuel	kg	1.16E+01	*
	Transport systems (road)	3.5-16t lorry	tkm	1.16E+00	*
	Water supply	tap water at user	kg	24	*
	Chemicals/inorganics	Sodium chloride powder	kg	9.69E-04	*
		Hydrogen peroxide	kg	3.04E-02	*
		Caustic soda	kg	0.19487	*
		(Sodium) Silicate	kg	1.38E-03	*
		Tristearin	kg	1.45E-03	*
		Sulphonic acid	kg	2.18E-03	*
		Acrylic polymer (Thickener)	kg	9.69E-05	*
		Urea	kg	2.91E-02	*
		Amine-Cobalt PhthaloCyanine	kg	9.69E-03	*
		Hemi -Zinc chloride (Black K salt)	kg	4.84E-03	*
	Chemicals/organics				
	Washing agents	Acetic acid		4.84E-04	*
	Wastewater treatment	wastewater	m3	24	*
	To Nature (EMISSIONS)				
	Air/unspecified	Heat, waste	MJ	3.993	**

Key: * - Primary data; ** – Secondary data from Ecoinvent database

7.2.4 Impact assessment

The effects of resource use and emissions generated were grouped and quantified from a LCA perspective using the SimaPro 7.2 software and the Ecoinvent 2.2 database (PRe Consultants 2010, Swiss Centre for Life Cycle Inventories 2010). The modelling took cognisance of the impacts of major background processes in *Kitenge* production such as the production of fertilizers, electricity and fuel oil using secondary data from Ecoinvent. The impact quantification was done using two environmental assessment metrics (Table 7.2) namely; Cumulative Energy Demand (CED) and the carbon footprint estimation according to Intergovernmental Panel on Climate Change with a timeframe of 100 years (IPCC 100a) (Dewulf et al. 2007, IPCC Intergovenmental Panel on Climate Change 2007, Swiss Centre for Life Cycle Inventories 2010).

Table 7.2
***Kitenge* production impact quantification categories and indicators**

Impact category	Indicator	Units	Estimation method	References
Global warming	CO_2 equivalent	kg CO_2 eq/ kg	LCA (IPCC 2007, 100a)	(IPCC Intergovenmental Panel on Climate Change 2007)
Energy demand	Energy equivalent	MJ / kg	LCA (CED)	(Swiss Centre for Life Cycle Inventories 2010)

7.2.5 Biowaste valorisation scenario formulation and assumptions

The cotton biowaste valorisation scenarios in the modified cotton production and conversion chain (Figure 7.4 and Table 7.3) entailed biogas and digestate production and use at the textile factory and the farm level. The valorisation scenarios were categorised into three different alternatives with reference to the current practice:

B1 – biogas produced and used for domestic purposes at the farm level while the digestate is used to replace 10% of mineral fertilizers.

B2 – biogas produced at the textile factory level where the biogas is used to replace 50 % of fuel oil consumption while the digestate is transported to the farms where it is used to replace 50% of mineral fertilizers. The remaining 50% of biogas produced is set aside to generate electricity but since electricity in Kenya is predominantly from renewable sources, the effect of this portion of biogas potential to Kitenge sustainability impact will be mainly economical and it is not considered in the present study.

B3 – biogas produced at the textile factory level where the biogas is used to replace 100 % of fuel oil consumption while the digestate is transported to the farms where it is used to replace 10% of mineral fertilizers.

In scenario B1, the savings of fossil fuel at the farm level have not been taken into account in the Kitenge life cycle however these savings have been comprehensively analysed from a broad perspective in Chapter 6 of this work. Under scenario B2 and B3, it is assumed that the digestate produced at the textile factory would be allowed to dry after which it is transported to the cotton collection points where farmers can pick it after delivering their cotton. Under such an arrangement, the otherwise idle capacity of the return trip for both parties is fully utilised. The biowaste valorisation was structured to reflect mesophilic biogas production and nutrient recovery from digestate as determined in **chapter 4** and **5** of this work. Generally the cotton waste emanating from the cotton production chain was subjected to biochemical methane potential analysis at 30°C and the methane production and nutrient recovery were profiled. Consequently, in the scenario analysis (Table 7.3) biowaste methane and nutrient recovery were taken into account to reflect a BMP of 0.365 m^3 CH_4/kg VS, 91% DM, 88% VS in DM as well as nutrient NPK content (as % of DM) of 0.509%, 0.257% and 0.715% respectively.

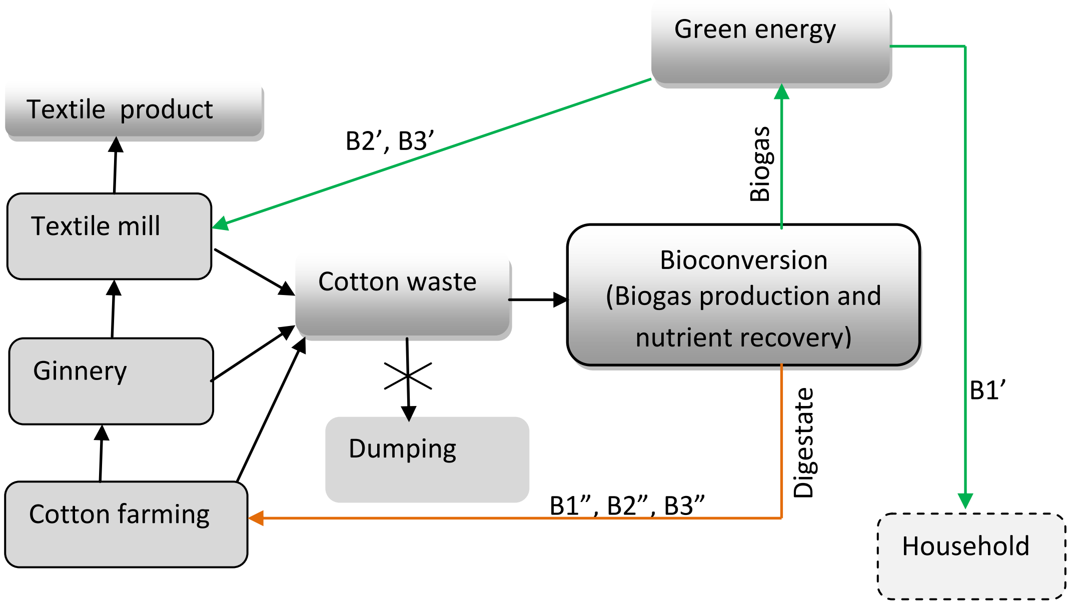


Figure 7.4: The modified cotton system (B -scenario) showing elimination of dumping of biowaste to nature and incorporation of additional flows for biowaste valorisation in:

(a) Scenario B1: biogas energy (B1') and digestate (B1") produced and used at household and farm level respectively,

(b) Scenario B2 and B3: respective biogas energy (B2’ & B3’) produced and different proportions used at textile factory while the digestate produced (B2” & B3”) is used at farm level.

The savings of fossil fuel at the household level as a result of use of biogas within the household under scenario B1 has not been factored in the present study.

Table 7.3
The biowaste parameters considered during the impact quantification in *Kitenge* production

Parameter	Scenario			
	Reference scenario	B1	B2	B3
Biowaste generation from farming to refining (kg/ kg *Kitenge*)	10.330	10.33	10.33	10.33
Biowaste available (kg/ kg *Kitenge*) assuming 25% and 50% waste recovery at farming and ginning to refining respectively.	3.32	3.32	3.32	3.32
Methane content in the available cotton biowaste per kg *Kitenge* (m^3 CH_4/ kg *Kitenge*))	0.967	0.967	0.967	0.967
Methane recovered (m^3 CH_4/ kg *Kitenge*)	0.00	0.967	0.967	0.967
Energy equivalent of available methane (MJeq/kg *Kitenge*)	34.61	34.61	34.61	34.61
Energy recovered at textile factory per kg *Kitenge* (MJeq/kg)	**0.00**	**0.00**	**34.61**[ѣ]	**34.61**
Fertilizer application (kg NPK/kg *Kitenge*) *	0.256	0.2307	0.117	0.2307
Nutrient content of digestate (kg NPK/kg *Kitenge) **	0.0253	0.0253	0.139[#]	0.0253
Digestate nutrients recovered for farming (kg NPK/kg *Kitenge) **	0.00	0.0253	0.139[#]	0.0253
Mineral fertilizer replaced by digestate (%)**	**0**	**10**	**50**	**10**

* NPK nutrient content by mass based on Nitrogen + Phosphorus + Potassium.

[#] Projected NPK nutrient content of the total biowaste assuming 100% biowaste recovery.

[ѣ] 50% of recovered energy is reserved for electricity generation.

The study took into account 25% biowaste recovery at the farming level and 50% biowaste recovery from ginning to the refining levels. The assigned lower biowaste recovery at the farming level was attributed to the presence of higher proportion (about 50%) of woody matter in the cotton farm waste which is deemed to present biomethanation challenges during anaerobic digestion due to the presence of recalcitrant lignin. The LCA study in this work focuses on resource and emission flows of *Kitenge* production in Kenya however it is assumed that the results could be valid in the larger East Africa and other African regions with *Kitenge* production conditions similar to Kenya.

7.2.6 Interpretation of impacts

The results emanating from the impact assessment were analysed and interpreted, based on which conclusions and recommendations were drawn for the possible improvement in the management of the African *Kitenge*. Pertaining to energy demand, generally the magnitude of energy demand (MJ) expresses the minimum external work needed to be done on the environment to obviate the depletion of energy hence the more energy demand a resource use carries, the more it deviates from the natural environment. The life cycle of *Kitenge* involves the consumption of an array of resources however the energy indicator raises a unified thermodynamic metric for objectively evaluating resources and environment. On global warming, the carbon footprint embodied in the various *Kitenge* production emissions offers a fairly reliable measure of the potential for environmental harm and represents the ecological status of the *Kitenge* production chain. Hence the two metric, Cumulative Energy Demand and the Carbon footprint, were used to assess the environmental impact of *Kitenge* production.

7.3 Results and Discussions

7.3.1 Global warming

Results from the analysis for global warming are presented in Figures 7.5 and 7.6. Figure 7.5 presents the carbon footprint of *Kitenge* production comparing the reference scenario with the alternative scenarios. On the other hand, Figure 7.6 presents the unit process contribution to the carbon footprint of *Kitenge* production for the reference scenario at 4.25% node cut-off implying that unit processes with a contribution less than 4.25% are not shown in the figure.

As shown in Figure 7.5, the current practice (reference scenario) of *Kitenge* production is associated with an emission of 15.58 kg CO_2 eq/kg product over the cradle to gate production chain of which fibre farming and refining contribute about 73% and 22% respectively (Figure 7.6). The carbon footprint of the Kitenge can be equated to the environmental impact of driving an average car for 63 Km in a highway or the total carbon sequestered by three healthy trees per year (IPPC

Intergovernmental Panel on Climate Change 2000, Wackernagel and Rees 1996) implying that enhancing forest cover could provide a good counter footprint for *Kitenge* production. The main background processes at 4.25% node cut-off (Figure 7.6) behind the carbon footprint of *Kitenge* due to farming are the manufacture of the mineral fertilizers diammonium phosphate as P_2O_5 and ammonium nitrate both of which have a combined contribution of about 33%. On the other hand the main background processes behind the carbon footprint of *Kitenge* due to refining process are production of electricity and light fuel oil both of which have a combined contribution of about 22 %.

Valorisation of the cotton biowaste for biogas and digestate production at farm level and at textile factory is observed to have different positive implications for the *Kitenge* production chain. When the biogas is produced and used at the farm level and digestate is applied in the cotton farms to replace 10 % of the mineral fertilizers (scenario **B1**), the carbon footprint of *Kitenge* production is seen to decline by 7 % (from 15.58 to 14.45 kg CO_2 eq/kg *Kitenge*). The observed decline in the carbon footprint of *Kitenge* is principally due to the decline of the carbon footprint of the farming process which declines from that of the reference scenario by 10 % owing to the 10 % less fertilizer usage. This observation implies that usage of digestate at the cotton farms has a positive influence on the environmental profile of the *Kitenge* chain. On the other hand, when the biogas is produced and used at the textile factory to replace 50 % of fuel oil while the digestate is transported to the cotton farms where it replaces 50 % of mineral fertilizers (scenario **B2**), the carbon footprint of *Kitenge* production is seen to decline from the reference scenario by 45 % (from 15.58 to 8.59 kg CO_2 eq/kg *Kitenge*). Another important feature of scenario **B2** is the decline of the carbon footprint due to refining which declines from that of the reference scenario by 41% (from 3.35 to 1.99 kg CO_2 eq/kg *Kitenge*). Finally, when the biogas is produced and used at the textile factory to replace fuel oil (100 % replacement) while the digestate is transported to the cotton farms where it replaces 10 % of mineral fertilizers (scenario **B3**), the total carbon footprint of *Kitenge* production is seen to decline from the reference scenario by 25 % (from 15.58 to 11.73 kg CO_2 eq/kg *Kitenge*). Another key feature of scenario **B3** is the decline of the carbon footprint due to refining which declines from that of the reference scenario by 81 % (from 3.35 to 0.62 kg CO_2 eq/kg *Kitenge*).

From the foregoing discourse, it can be surmised that possible ways to diminish the net impact of *Kitenge* production to the environment include enhancement of the counter footprint through investment in natural capital protection (increasing forest cover, pasture land, marine reserve, etc.) or cascading the utilization of cotton biomass to incorporate valorisation of the biowaste. Whereas the benefits of natural capital protection cannot be gainsaid (Wackernagel and Rees 1996), it is also clearly demonstrated from these results that cascading the usage of cotton biomass to incorporate the valorisation of cotton biowaste for biogas and digestate production could potentially improve the environmental profile of *Kitenge*.

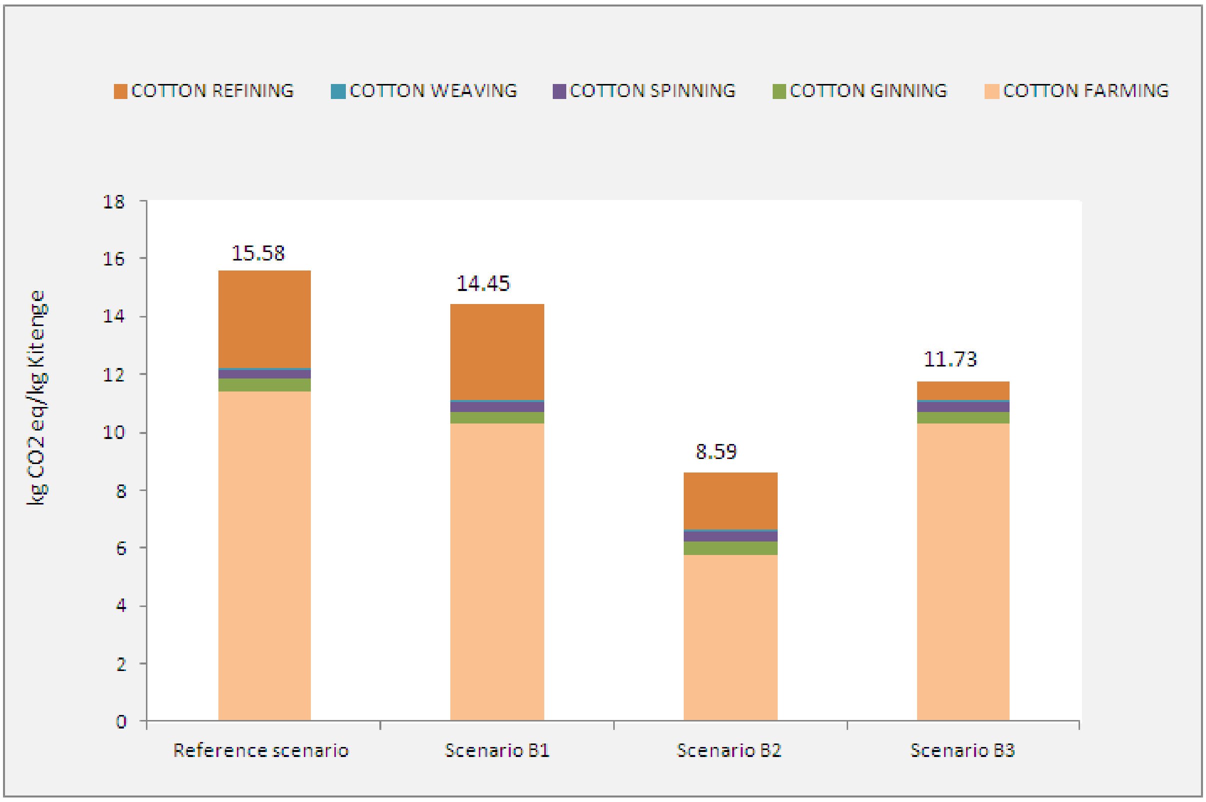


Figure 7.5: Carbon footprint (Kg CO_2 eq/kg *Kitenge*) in *Kitenge* production comparing the alternative scenarios B1, B2 and B3 (for different configurations of biowaste valorisation) with reference scenario (current status).

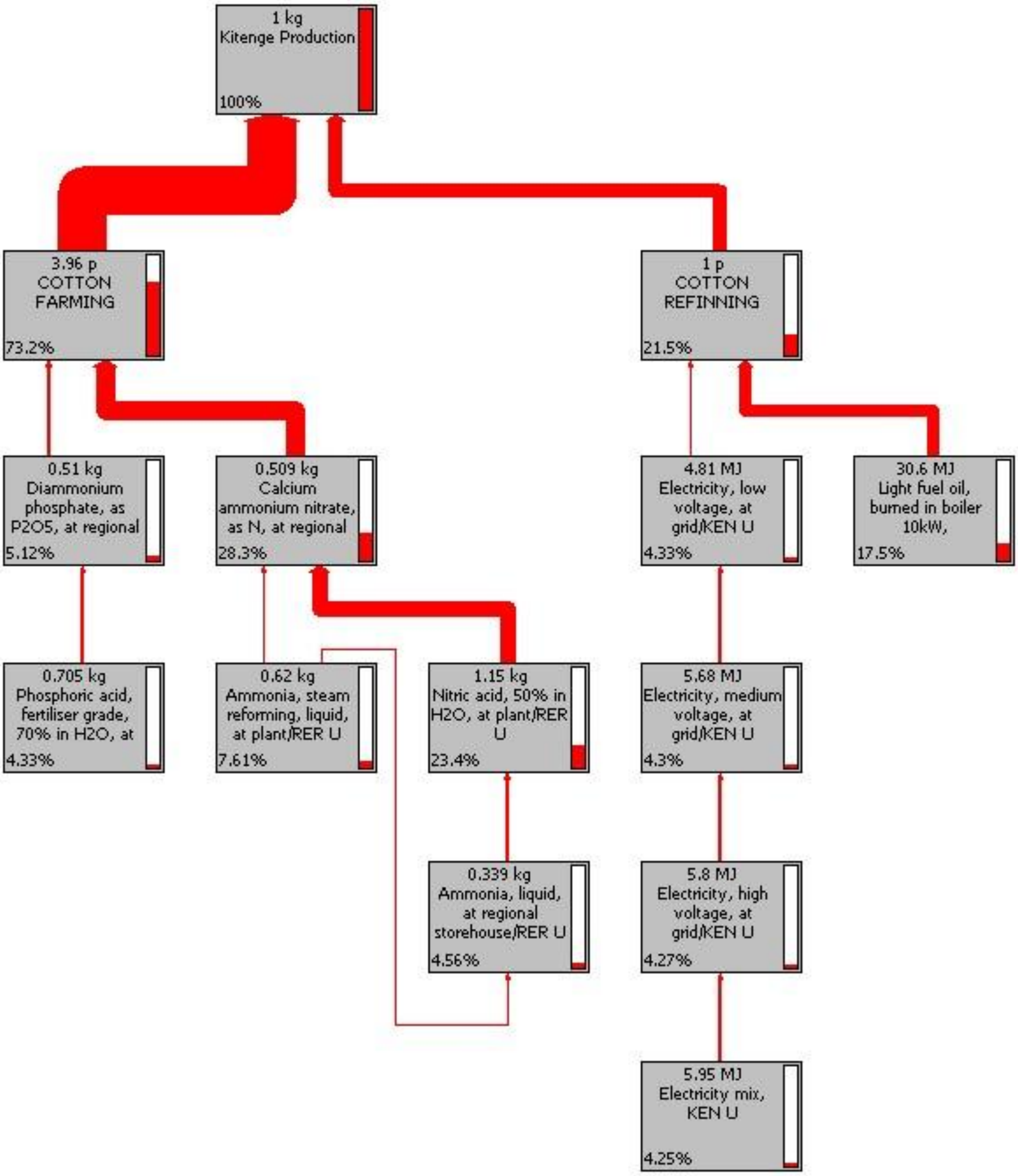


Figure 7.6: Unit process contribution to the carbon footprint of *Kitenge* production in the reference scenario depicting 4.25% node cut-off.

7.3.2 Energy demand

The energy demand in *Kitenge* production is presented in Figure 7.7 while the unit process contribution to energy demand for the reference scenario is presented in Figure 7.8. The cumulative energy demand in the *Kitenge* production chain (in the reference scenario) is estimated at 120.5 MJeq/kg *Kitenge* (Figure 7.7). Noticeably, the contribution of farming and refining processes to the cumulative energy demand are respectively 46 % and 43 % thus underpinning the energy intensiveness of the two processes. The energy demand at the farming level translates to 13.98 MJeq/kg of cotton produced. Other researchers (Yilmaz et al. 2005) have reported comparable values (16.67 MJeq/kg) of energy use in cotton production. However it is also reported that the net return per kilogram of cotton produced is insufficient to cover costs of production hence underscoring the need for exploring other options for valorising the cotton biomass. The main background processes impacting heavily on the energy demand in *Kitenge* production (Figure 7.8) are seen to be the production of calcium ammonium nitrate fertilizer and light fuel oil both of with a combined contribution of 60 % (26 % and 34 % respectively). It is therefore envisaged that substitution of fertilizer and the fuel oil by less energy demanding substitutes such as digestate and biogas should have a positive influence in the energy demand profile of *Kitenge* production.

The valorisation of biowaste for biogas production and use at the farm level while concomitantly the digestate is used to replace 10 % of fertilizers (scenario B1) is observed to reduce the cumulative energy demand of the *Kitenge* production chain by about 4 % (from 120.57 to 116.29 MJeq/kg *Kitenge*). Noticeably under scenario B1, it is also observed that the energy demand at farming level declines by 8 % from the reference scenario (from 55.38 to 51.11 MJeq/kg *Kitenge*). Such a reduction in energy demand could potentially translate to energy savings by the farmers. Besides, there are other benefits that accrue to farmers owing to the usage of biogas such as cleaner fuel, reduced expenditure on fuel costs and reduction on deforestation owing to reduced usage of wood fuel.

When the biogas is produced and used at the textile factory while the digestate is transported to the cotton farms under scenario **B2** and **B3** substantial reduction in the cumulative energy demand is observed. Under scenario **B2**, the cumulative energy demand is observed to drop by 35 % (from 120.57 to 78.79 MJeq/kg *Kitenge*). Moreover in this scenario, the energy demand at the cotton refining process is noticeably seen to drop by 40 % (from 51.65 to 31.23 MJeq/kg *Kitenge*). On the other hand, under scenario **B3**, the highest drop in the overall cumulative energy demand is observed, that is by 37 % (from 120.57 to 75.45 MJeq/kg *Kitenge*) while specifically for the cotton refining process the drop in cumulative energy demand is as much as 79 % (from 51.65 to 10.81 MJeq/kg *Kitenge*). The observed drop in cumulative energy demand in scenario **B2** and **B3** can be attributed to the differentiated effect of replacing mineral fertilizer with digestate and light fuel oil with biogas. These results therefore show that valorisation of cotton biowaste for biogas and digestate production could potentially improve the environmental profile of the *Kitenge*.

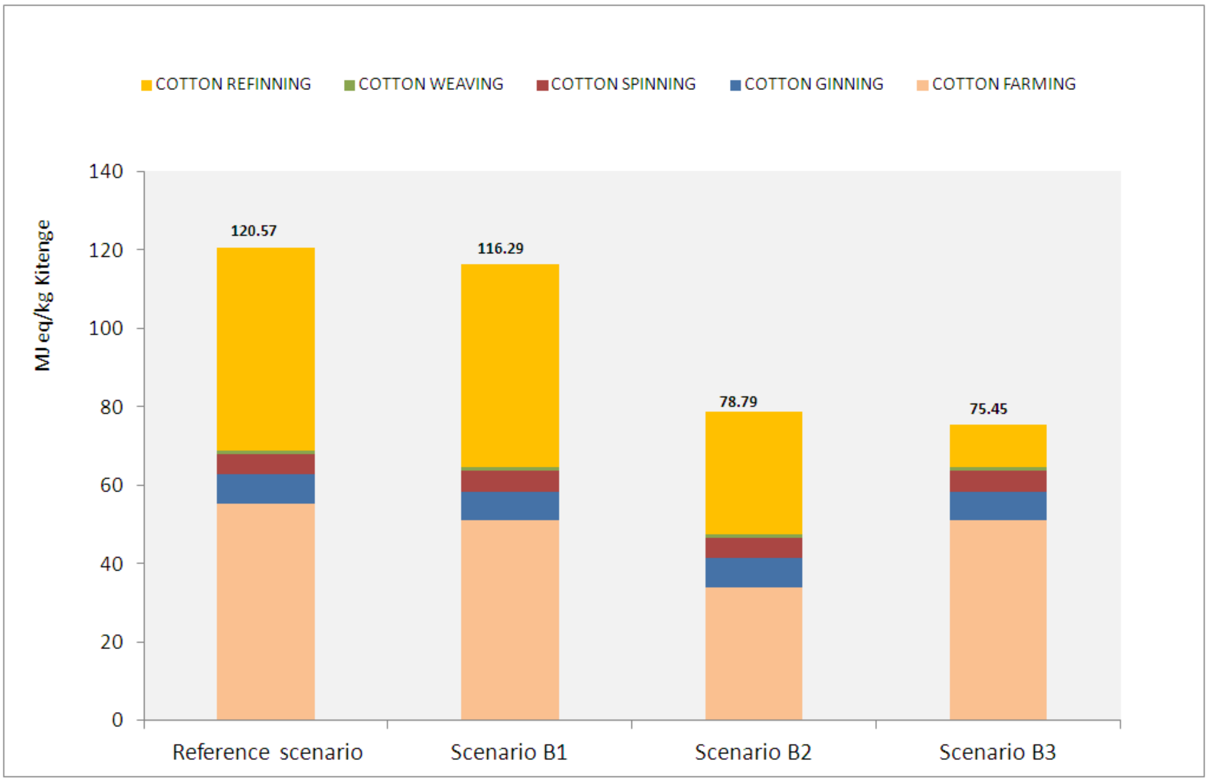


Figure 7.7: Energy demand (MJ eq/kg *Kitenge*) in *Kitenge* production chain comparing the alternative scenarios B1, B2 and B3 (for different configurations of biowaste valorisation) with reference scenario (current status).

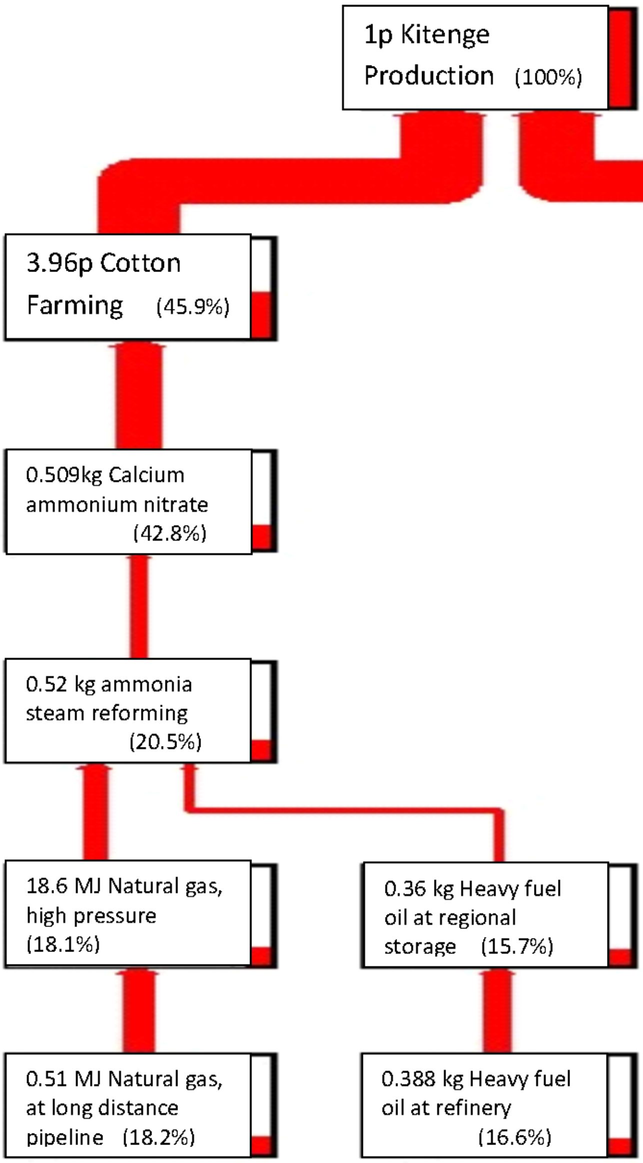


Figure 7.8: Unit process contribution to the cumulative energy demand in *Kitenge* production in the reference scenario.

7.4 Conclusions and Recommendations

This study has considered the implication of biowaste valorisation to the environmental profile of the African *Kitenge*. The current practice (reference scenario) of *Kitenge* production is associated with a carbon footprint of 15.58 kgCO_2eq/kg product and a corresponding cumulative energy demand of 120.5 MJ eq/kg product. The major background processes impacting heavily on the environmental profile of *Kitenge* are found to be the production of mineral fertilizers and light fuel oil hence it can be concluded that intervention measures targeted at the two background processes could be of immediate benefit to the environmental profile of *Kitenge*. The incorporation of biowaste valorisation in the *Kitenge* production chain to yield biogas and digestate under the three alternative scenarios (B1, B2 and B3) is noted to yield overall improvements of up to 25% and 37 % for carbon foot print and cumulative energy demand respectively. It can therefore be further concluded that incorporation of biowaste valorisation in the *Kitenge* production chain can improve the environmental profile of *Kitenge*. In addition, since the usage of the digestate at the cotton farms could lead to other economic benefits not tackled in the present study, further work should endeavour to evaluate the economic consequences of biowaste valorisation to the *Kitenge* production chain.

Acknowledgements

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Chapter 8

General discussion, scientific significance and perspectives

8.1 Discussion

This dissertation has investigated the potential of biogas production from biowaste and its contribution to environmental sustainability. The work is divided into seven chapters. **Chapter 1** provides a general introduction detailing the motivation, scope and organization of the study. In **chapter 2**, an analysis of the biogas value chain (BVC) is provided whereas **chapter 3** presents an overview and development of the sustainability assessment framework for biowaste energy production. Chapter 4 and 5 provide different aspects of biowaste valorisation. **Chapter 4** presents characterisation of biowaste material for biogas and nutrient recovery whereas in **chapter 5** an elucidation of biowaste energy potential from preselected feedstock is the main subject. **Chapter 6** provides an operationalization of the multi criteria sustainability assessment framework comparing different biogas systems. **Chapter 7** presents a case study on biowaste valorisation and therefore provides an assessment of the added value of biowaste valorisation to the environmental profile of the African *Kitenge*. This chapter gives a general discussion of the dissertation.

In this dissertation a comprehensive analysis of the BVC from a sustainability viewpoint has been carried out. While previous studies attempted to analyse fragmented segments of the BVC (Lei et al. 2007, Sahlstrom 2003, Yadvika et al. 2004) in this study a critical analysis of the recent advances in the integrated BVC was selected as the focal point and the analysis was executed from the life cycle sustainability analysis “cradle to cradle” perspective (**chapter 2**). This study shows that while research advances and diversity decrease along the BVC, the chain ends up in a wide variety of end-use applications with respect to waste stabilization, energy and nutrient recovery. In addition, while a huge diversity exists in biomass pre-treatment for digestion, technological factors such as energy balance, CO_2 emission and requirements for downstream processing need to be factored when selecting pre-treatment techniques. Besides, it is highlighted that the readily available biomass in southern countries is a secure, reliable and sustainable source for biogas however there exist knowledge gaps pertaining to BVC potential, sustainability and choice of key technology options for harnessing the BVC as well as the integration of BVC into the mainstream industrial setups.

After presenting the BVC in a broader perspective and in cognisance to the existence of the inherent knowledge gaps, effort was put to first characterise biowaste for biogas and nutrient recovery (**chapter 4**) and secondly establish biowaste energy potential in Kenya (**chapter 5**). In total, biowaste from eight agricultural crops and three different effluents from a textile factory were examined. The focus on agricultural residues was motivated by the need to sustainably maximise the benefits from agricultural production which is the backbone of Kenya’s economy. On the other hand the focus on textile effluents was to lay the groundwork for subsequent sustainability assessment of a cotton-based textile product when integrating biowaste valorisation through biogas and nutrient recovery.

The characterisation of the different biowaste demonstrates that the agricultural residues are generally better suited than the textile effluents for both biogas and nutrient recovery. In the study BMP values (m^3 CH_4/ton VS) of between 67 and 365 were observed and corresponding electrical energy potential (GWh/yr) of up to 3379 were computed. In addition, it was noted that theoretical BMP values based on proximate analysis do not necessarily tally with laboratory generated BMP values. The foregoing can be explained from the BMP results which show that the biomethanation of residues from maize, barley, cotton and sisal follows first-order kinetics and hence can be explained with a high level of certainty however the biomethanation of the other residues necessitates rather longer term tests. The latter observation is apparent from the existence of a lag phase within the first week of the experiments possibly implying a necessity for longer term adaptation. Indeed for the case of tea residues the biogas production appeared to be quite constrained throughout the time course of the experiment, and moreover the average methane content was less than 45%. Nevertheless these findings show that tea and sugarcane residues are less competitive for energetic methane production as compared to the other residues investigated in the study. However since adaptation in anaerobic reactors can last long (over 5 years), long term continuous tests are needed to conclusively reveal if tea and/or sugarcane residue are less competitive for methane production.

Theoretical values are often used to design and estimate the energy output during sustainability studies (Cherubini and Ulgiati 2010, Simon and Morse 1999). However, for biogas systems, the reality is that these values are only indicative since when comparing theoretical values with laboratory values differences can be observed, which can be attributed to the biomethanation dynamics and unforeseen biodegradation characteristics of the feedstock. Consequently, theoretical energy output values can be quite misleading especially due to overestimation and when they are brought into the context of a highly contentious issue such as sustainability assessment, they only aggravate the controversy. In this study, laboratory BMP values corresponded to between 17 and 95 % of theoretical values which puts credence to the foregoing.

In **chapter 3** of this dissertation, the multi criteria sustainability assessment framework for the assessment of biogas has been developed and proposed based on the sustainable development concept. The framework proposes environmental, technical and socio-economic objectives, criteria and indicators for assessing three different domestic biogas systems from a comprehensive LCA perspective. Three innovative features of the framework suffice. First, the indicators are developed from a modest fitness for purpose perspective that is using different indicator sets for different purposes. Secondly, the choice and integrated approach in which the indicators are defined enable them to seamlessly link the environmental, technical and socio-economic dimensions of sustainability. Lastly, the methodological approach confers the multi-dimensionality character to the indicators. Consequently, during the comparison of the three biogas systems, the assessment framework presents the ability to aggregate the different indicator sets and present the results without obscuring the different indicators in the aggregated result. Different aspects of the developed framework are applied in **chapters 6** and **7** of this dissertation.

Operationalization of the multi criteria sustainability assessment framework as availed in **chapter 6** focuses on comparing the three different biogas production systems from an expanded boundary approach when biogas is integrated into the infrastructures of production. The focus of the multi criteria sustainability methodology as presented in this work was from a comparative perspective with a view of establishing which of the three biogas systems is more sustainable. The results show that while all the biogas systems studied can be regarded as sustainable, the tubular digester biogas system is seen to be more sustainable than the other two biogas systems. The tubular biogas system returns the best results in seven out of the nine indicators considered. However, owing to the dismal performance of the tubular digester biogas system with respect to the reliability indicator, technical improvements are needed so as to enhance its reliability prior to increased implementation of the biogas system. On the other hand, the results for the floating drum biogas system are quite similar to the fixed dome biogas system. This observation is however at variance with the priorities of most biogas support programs in most developing countries such as Kenya which normally only support the fixed dome digester biogas system. The apparent lack of interest in the alternative biogas systems could be attributed to possible existence of knowledge gaps thus resulting in subjective decisions among most biogas programs. The results of this dissertation therefore present a need for a paradigm shift with a view to paying closer attention to the alternative biogas systems.

After studying the sustainability of biowaste based biogas energy, effort was put to position biowaste valorisation in a larger context. In industrial ecology, biowaste valorisation presents a clean technology opportunity for extending the focus from the benefit of a product to the possibility of delivering the benefit in another way with less environmental impact (Clift 1995). Consequently, the environmental aspect of the multi criteria sustainability assessment was implemented in evaluating the added value of biowaste valorisation to the environmental profile of the African *Kitenge* (**chapter 7**). In this research, reduction of *Kitenge's* carbon footprint and energy demand of up to 24.7 and 37.4% respectively is demonstrated upon valorisation of cotton biowaste for energy and nutrient recovery. The implications of the results from this study are twofold. First, from an expanded boundary perspective, implementation of biowaste recovery at the farm level has a concomitant effect to the finished product at the industry level as evidenced by the reduction in carbon footprint and energy demand of *Kitenge* by 7.25 and 3.55%, respectively. Secondly, while the added value of biowaste valorisation in the *Kitenge* environmental profile cannot be gainsaid the textile industry stands to gain even more from an energy point of view by implementing biowaste valorisation hence contributing to better environmental sustainability.

8.2 Scientific significance

The growing interest in renewable energy technologies such as anaerobic digestion often presents the energy producers with challenges in the selection of alternative and sustainable energy systems. However stating which alternative technologies are more sustainable has to be argued by metrics (Dewulf and Van Langenhove 2005). The innovative framework presented in this study for comparing different biogas systems from a multi criteria perspective that covers the technical, socio-economic and environmental concern is therefore valuable to the sustainability concept. While appreciating that the effect of technology is generally a complex phenomenon, understanding the impacts of alternative technologies from a multi criteria perspective can help us predict more sustainable technologies. Moreover, innovative aspects of the proposed framework render it versatile hence it can be employed in different renewable energy alternatives.

Agricultural and industrial biowastes are often insufficiently exploited in developing countries despite being a potential feedstock for value-added products with local applications such as biogas and bio fertilizer (Nzila et al. 2010). At the same time these biowastes can cause problems for human and animal health and the environment. This research has brought biowaste energy and nutrient potential into perspective. Knowledge of the potential presented by different biowaste can help us to design and implement the appropriate technology options to sustainably harness the prospects presented by biowaste. Indeed biowaste has the potential to mitigate significantly the current global energy crisis that is acknowledged to demand greater attention to new initiatives on alternative energy sources that are renewable, economically feasible and sustainable. The agriculture dependent developing countries especially in Africa can mitigate the energy crisis through innovative use of the available but underutilised biowaste such as agro residues. Accordingly, the application of anaerobic digestion technology is expected to continue growing worldwide because of its multi-faceted socio-economic and environmental benefits.

A consequence of the increasing implementation of anaerobic digestion will be the necessity to characterise and determine the ultimate biogas potential for several solid substrates. In fact this is a key parameter for assessing design, economic and managing issues for the full scale implementation of anaerobic digestion (Angelidaki et al. 2009). The importance of characterising biowaste for the selection of biomass material suitable for anaerobic digestion has therefore been affirmed. At the same time, results from BMP tests if properly obtained and of good quality can be used to obtain further information on the substrate studied such as the hydrolysis rate provided that hydrolysis is limiting the anaerobic conversion process. The hydrolysis rate constant is characteristic of a given substrate and gives information about the time required to generate a given ratio of the ultimate methane potential. On the other hand, integration of BMP data within a geospatial framework presents an interesting phenomenon of delivering the rather complex scientific information to the wider society thus aiding in decision making. Besides, the spatial biowaste BMP data allows a preliminary examination of the suitability of locations for biowaste-based technology implementation.

8.3 Perspectives

The current research provides insight into the potential of biogas production from biowaste energy and its contribution to environmental sustainability however it also highlighted new questions that could be investigated. Some suggestions for further research are presented below.

The BMP profile for three of the substrates analysed showed a lag phase that on average lasted for about two weeks. This phenomenon was not witnessed in the other substrates tested and since the incubation temperature was controlled whilst the pH profile remained stable then it can be postulated that the hydrolysis of the concerned substrates suffered from inhibition. Further work is therefore needed to establish the cause of the initial hydrolysis inhibition with a view to formulating suitable mitigation measures. However any attempts on the advancement of hydrolysis ought to consider the overall sustainability of the BVC.

The increasing implementation of anaerobic digestion technology especially for biogas production has necessitated the determination of the ultimate BMP for several solid substrates. Different assays have been used in the past to determine BMP of various substrates thus generating different results that are generally not comparable. However a protocol has since been defined that unifies and standardises assays in order to gain comparable results. There is therefore a need to re-examine BMP values of solid substrates in the wake of the standardised protocol besides having the results posted in a suitable database so as to serve as an initial screening step for further anaerobic digestion studies.

The multi criteria sustainability assessment framework presented in this research proposes a set of nine environmental, socio-economic and technical indicators for the assessment of different alternatives of biogas systems. However the applicability of the assessment framework for other renewable energy production pathways is recommended. More attention should also be given to designing a suitable algorithm based on mathematical definitions of the different indicators. Besides, the assessment framework can find an application under the Clean Development Mechanism (CDM) (Unfccc 2011) to compute Certified Emission Reduction (CER) credits. It is noteworthy that several biogas program activities in most developing countries such as Kenya have not been registered under CDM principally due to the absence of an appropriate methodology under which small scale biogas projects can claim carbon abatement for avoiding use of unsustainable fossil fuels. However, the multi criteria framework presented in this dissertation for the assessment of biogas production could serve to fill this void. The option for computing GHG reduction in this methodology can be applied to implement a small scale biogas based emission reduction projects relying on the various installed small scale biogas digesters. Such an approach can earn saleable CER credits which can be counted towards meeting the Kyoto targets.

Biowaste valorisation was observed to improve the environmental profile of cotton based textile product. However further research is needed to evaluate changes in cotton productivity and fibre quality when different proportions of mineral fertilizers are replaced by the digestate. Besides, this study has considered valorisation of cotton biowaste from anaerobic digestion perspective however further work can be carried out from a biodiesel and bio ethanol perspective. Such studies could yield data which might be helpful for further enhancement of the environmental profile of cotton products.

One of the main challenges in implementing biogas support programmes in temporary set-ups such as nomadic setting is the migration character of the people. Both the floating drum and fixed dome biogas systems are designed as long term fixed investments with a lifespan of over 15 years. However, for a nomadic or semi-nomadic community the viability of these biogas systems is therefore not foreseen. Nevertheless, it suffices to say that for a nomadic setting, a biogas program has a better chance of success if it is adoptive to the people's way of life. A mobile biogas system can therefore present a viable option for such communities. In this study, it has been shown that the tubular biogas system is more sustainable than the other two biogas systems. The implications of these results are twofold. First, policy development and biogas support programs ought to reconsider the apparent lack of support towards the tubular biogas systems. Moreover unlike the fixed dome digester biogas system, the tubular biogas system can be turned into a mobile biogas system thereby fitting into the way of life of migratory communities. Secondly, there is need for further research on the functionality of biogas systems under mobile or semi-mobile conditions with a view of diversifying the reach of biogas technology to diverse communities.

Summary

The inspiration of utilising biowaste to provide a sustainable alternative energy source was the motivation behind this work. The evaluation of biowaste energy potential and the development of a simple methodology to assess its sustainability were the main challenges undertaken as part of this research. In this work objectives were therefore set to gain insight in the biogas value chain from the perspective of biowaste energy. The research also sought to formulate and operationalize a sustainability assessment framework for biowaste energy production. In addition, the research analysed the potential contribution of biowaste-based biogas energy to environmental sustainability from a case study perspective.

Pursuance to the research objectives, in **chapters 1** and **2** an introduction and analysis of the biogas value chain is given. **Chapter 1** presents the motivation of the study and the scope of the work whereas **chapter 2** focuses on the biogas value chain (BVC) integrating the BVC production oriented advances with targeted valorisation from the life cycle analysis perspective. Three different categories of advances and system wide challenges and opportunities are evaluated. It is shown that while the BVC system presents virtually unlimited opportunities for the valorisation of biowaste it suffers from apparent disconnect in most of the advances. Consequently it is observed that substantial sustainability insight of the BVC is eminent for it to incontrovertibly remain competitively vital to the sustainable energy matrix.

An overview and development of the sustainability assessment framework for the assessment of biowaste-based biogas energy is given in **chapter 3**. Innovative aspects of the proposed framework are the development of a multi dimensional assessment system with a typology of multi criteria indicators relevant for biogas energy. In addition two main sustainability issues that could potentially undermine the sustainability of Biowaste-based Biogas Energy (BBE) and hence the assessment framework are defined highlighting the associated opportunities and risks. First land use, opportunities and risks are to be taken into account. However since BBE relies on residues such as agro based residues, it therefore follows that BBE systems do not have stringent land quality requirements. This implies that technically all the land under agricultural production can be deemed to be available for BBE production. Consequently it can be accentuated that BBE production does not compete with agricultural land and avoids conversion of land with high carbon stocks. In

addition since biowaste energy relies on biowaste such as agro residues, it suffices to say that there are no inherent land use risks specific to BBE production. The second sustainability issue of major concern is resource use, opportunities and risks. While BBE offers possibilities for improving efficient utilization of raw materials, there are concerns on how to tackle potential risks such as soil organic carbon stocks. Nevertheless, the possibilities for closed loop biomass resource cascade configurations are deemed to sufficiently address the forgoing concerns.

In **chapters 4** - **7** of this thesis, different aspects of the sustainability framework are expounded further. In **chapter 4**, two main features related to sustainable application of biowaste in biogas production are defined and tackled by means of characterisation in terms of biogas quality and the key plant nutrients. The results demonstrate the suitability of agricultural residues and segregated textile effluents for biogas and nutrient recovery. Since the valorisation of biogas as a sustainable energy carrier especially for domestic applications precludes the need for specialised biogas cleaning, the results further corroborate the need to explore increased use of the feedstock devoid of gas contaminant precursors as highlighted earlier in chapter 2.

Chapter 5 elucidates on biowaste energy potential in Kenya and concomitant electricity gains which amount to about 73% of the country's annual power production of 5307 GWh. The evaluation is executed for agricultural residues from five of the major crops produced in the country and takes cognisance of other competing uses of the residues. The results demonstrate that the exploitation of the potential presented by the biowaste residues in biogas production can have a major economic impact in the country. Building on the framework introduced in **chapter 3**, in **chapter 6**, a multi criteria sustainability assessment method is developed and applied to screen three different alternatives of biogas production when linking biogas energy with infrastructures of production. The assessment couples integrated life cycle concepts to comparatively analyse the technical, economic and environmental performance of the floating drum, fixed dome and tubular biogas digester systems commonly promoted in Kenya. From the study, it is shown that the three different biogas production systems demonstrate significantly different sustainability behaviours. Furthermore, it is shown that to produce biogas from waste in Kenya, energy inputs are limited to 1.89 $\mathrm{MJ/m^3}_{\mathrm{biogas}}$ while the total energy invested in biogas production for 20 years can be recouped within 26 months of digester operation. In addition, replacement of kerosene by biogas from waste is observed to yield direct global warming reduction of up to 1.09 kg $\mathrm{CO_2}$ eq/$\mathrm{m^3}_{\mathrm{biogas}}$. On the other hand, the energy autonomy due to biogas production yields a fossil energy replacement saving ranging from 30 to 37 \$Cents/$\mathrm{m^3}$ biogas. In general, the tubular biogas digester life cycle scores significantly better in six of the nine impact criteria considered. In **chapter 7**, a case study is presented on the added value of biowaste valorisation to the environmental profile of the African *Kitenge*. The environmental profile of the production of 1kg *Kitenge* is evaluated comparing the scenario without biowaste valorisation to the scenario where biowaste is valorised in biogas production and nutrient recovery. The case study employs some of the principles presented in chapter 5 and 6. This study revealed that the production of *Kitenge* is currently associated with a carbon footprint of 15.58 kg CO_2 eq/kg and a corresponding energy demand of 120.5 MJ eq/kg. However it was observed that biowaste valorisation, especially for biogas and nutrient recovery, could yield up to 25% and 37% reduction in carbon foot print and energy demand respectively. These findings underscore the added value of biowaste valorisation to the environmental sustainability of the African *Kitenge*.

Chapter 8 is a general discussion of this dissertation while positioning it in the scientific literature and outlining the perspectives.

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2008 – 2011 **PhD studies - Ghent University**, Belgium.

"Biogas production from biowaste in Kenya and its contribution to environmental sustainability"

2009 (Sept. – Oct) Lettinga Associates Foundation, Wageningen, The Netherlands, Guest researcher

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2001 – 2003 **MSc studies - Ghent University**, Belgium.

Qualification: Obtained MSc degree (with Great Distinction) in Environmental Sanitation.

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1993 – 1998 **Bachelor of Technology studies – Moi University**, Kenya.

Qualification: Obtained Bachelor of Technology (Honours) in Textile Engineering

Work experience

2007 – To date: Lecturer, School of Engineering, Moi University, Kenya.

2000 – 2006: Assistant Lecturer, School of Engineering, Moi University, Kenya

1998 – 1999: Assistant Operations Manager, ACI Ltd. Mombasa, Kenya.

Recent Publications

1. **Charles Nzila**, Jo Dewulf, Henri Spanjers, Henry Kiriamiti and Herman van Langenhove. **Biowaste Energy Potential in Kenya.** Renewable Energy, **35** (2010) 2698 – 2704.

2. **C. Nzila**, P. Wambua, J. Githaiga, D. Tuigong, et al., **The Potential of a Low Cost EPAD System in the treatment of Textile mill effluents**. The Kenya Journal of Mech. Engineering, 2008, **4**.

3. **Charles Nzila**, Jo Dewulf, Henri Spanjers, Henry Kiriamiti, David Tuigong, Simon Too and Herman van Langenhove. **Multi criteria sustainability assessment of biogas production in Kenya.** Applied Energy *(in Press)*

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6. H. K. KIRIAMITI**,** S. S. CHEMJOR, S. L. KIAMBI, A. OCHIENG, **C. NZILA**. **Water hyacinth as raw material for the production of pulp, lignin and pentose sugars**. *East Africa Journal of pure and applied science* (*under review*)

7. M'Arimi M., Kiprop A., Chirchir A., and **Nzila C**. **Dichlorodiphenyl Trichloroethane (DDT) and it's Observed Effects on Body Functions in Vertebrates.** East African Journal of Public Health (*Under review*).

Scientific contributions at international conferences

1. **Charles Nzila**, Jo Dewulf, Henri Spanjers, David Tuigong, Jerry Rawlings, Henry Kiriamiti, Herman van Langenhove. **Life Cycle Environmental Sustainability Assessment of the African *Kitenge***. MU_K – VLIR_UOS International Symposium, February 2011, Kisumu, Kenya.

2. **Charles Nzila**, Jo Dewulf, Henri Spanjers, Henry Kiriamiti, David Tuigong and Herman van Langenhove. **Characterization of selected textile and agricultural residues for energy production in Kenya** *(6th International Annual Conference, Moi University: September 2010)*

3. **Charles Nzila**, Jo Dewulf, Henri Spanjers, Henry Kiriamiti, David Tuigong and Herman van Langenhove. **Advances in feedstock processing for biogas production** *(6th International Annual Conference, Moi University: September 2010).*

4. **Charles Nzila**, Jo Dewulf, Henri Spanjers, Sheila Odhiambo and Henry Kiriamiti. **Valorisation of textile residues for energy production in Kenya** *(5th International Annual Conference, Moi University: August 2009).*

5. Paul Wambua, James Njuguna, Kirimi Kiriamiti, Occhieng Aoyi and **Charles Nzila. Industrialization and poverty eradication through manufacturing and application of composite materials**, *IEK International Conference 2009, 22 –24th April, 2009, Nairobi, Kenya*

6. H.K. Kiriamiti, **C. Nzila**, S. Kiambi. **Enhancing mobility and poverty eradication through use of biodiesel from *Jatropha Curcus***. *(1st National Conference and Exhibition for Dissemination of Research Results and Review of Innovations, KICC, Nairobi: April 2008)*

7. D. Tuigong, **C. Nzila**, J. Githaiga, **Exploitation of Silk production as a renewable and sustainable rural micro-enterprise for poverty alleviation**. *(3rd International Annual Conference, Moi University: August 2007)*.

8. E. Ataro**,** A. Muumbo, **C. Nzila. The Use of ICT in Enhancing Quality, a Case Study- Moi University**. *(3rd Annual International Conference, Moi University, Eldoret Kenya: July 2007).*

9. Henry K Kiriamiti, **Charles Nzila,** & Samuel Sarmat. **Fractionation of crude pyrethrum extracts using supercritical carbon dioxide.** 1st international conference on Advances in Engineering and Technology, 16th -19th July 2006 (ISBN 13:978-0-08-045312-5 and ISBN- 10-08-045312-0, pgs 339-346).

Other activities

2009 – 2011 Responsible for students' tasks, Life Cycle Assessment MSc. Course

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