BIOGAS PRODUCTION POTENTIAL OF DIFFERENT SUBSTRATE COMBINATIONS FROM KAITUI LOCATION, KERICHO COUNTY, KENYA

KIPNGETICH LANGAT

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Kipngetich Langat

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DECLARATION

This thesis is my original work and has not been submitted for the award of a degree in any other University.

Signature ……………… Date ……………………

Kipngetich Langat

This thesis has been submitted for examination with our approval as University supervisors.

Signature …..……………… Date...……………………

Dr. Paul Njogu

JKUAT, Kenya

Signature ………………… Date...……………………..

Prof. Joseph Kamau

JKUAT, Kenya

DEDICATION

I dedicate this thesis to my beloved mother Sarah, lovely wife Sharon and my entire family for their tireless support and inspiration.

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I wish to acknowledge the almighty God for the opportunity, the strength and the financial ability He graced me with during the entire exercise. Secondly I acknowledge and thank my able supervisors, Dr. Njogu and Prof. Kamau for their diligent supervision.

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LIST OF ACRONYMS & ABBREVIATIONS

AD	Anaerobic digestion
AP	Avocado pulp
A_T	Ambient temperature
CM	Cow manure
C/N	Carbon to nitrogen ratio
CGV	Cumulative gas volume
C_m	Specific heat capacity of the container
C_w	Specific heat capacity of water
DGV	Daily gas volume
DM	Dry matter
GHG	Greenhouse gases
GM	Goat manure
GOK	Government of Kenya
HHV	High heat value
HRT	Hydraulic retention time
IEA	International Energy Agency
IGAD	Inter- Government Authority on Development
IICA	Inter-American Institute for Cooperation on Agriculture
IIED	International Institute for Environment and Development
LPG	Liquefied petroleum gas
M_m	Mass of metallic container
MP	Methane potential
M_w	Mass of water
NEMA	National Environment Management Authority
OFMSW	Organic fraction of municipal solid waste
OLR	Organic Loading Rate
Q	Heat energy
RPR	Residue product ratio
S_T	Slurry temperature

TBP	Theoretical biogas potential
TS	Total solid
UNEP	United Nations Environment Programme
VFA	Volatile fatty acid
VS	Volatile solid
ΔT	Change in temperature

ABSTRACT

The over-dependence on fossil and wood fuels as primary energy source has led to multitudes of problems such as global climatic change, environmental degradation and various human health problems. Energy supplied from fossil fuels is not easily recycled and takes a long time to form, hence is exhaustible and not renewable. Renewable energy has remained one of the best alternatives for sustainable energy development. This study investigated the anaerobic digestion of biomass to convert energy stored in organic matter into useful biogas energy. The objectives were to study energy sources consumed per household, determine biogas production volumes from co-digestion of cow manure with goat manure, avocado pulp and bagasse and to derive wood fuel savings arising from adoption and use of biogas at the household level. The study was done within Kaitui location in Kericho County using interview schedule and empirical research method for data collection. Eight identical plastic bio-digesters of 15liters capacity were constructed and used to investigate the anaerobic digestion of the stated feedstocks. Cow dung was used as a control for the experiments and as an inoculum for other substrates. Feedstocks were collected and subjected to pre-anaerobic digestion treatments of pulverization, screening and mixing. The materials were blended at a ratio of 1:1 and mixed with water at a ratio of 1:2 then introduced to the bio-reactor as homogenized slurry after stirring. The data collected were tabulated then subjected to excel computer package for analysis. The high heat value of biogas was compared with the heat energy from other sources by performing experiments on quantity of heat. This helped in deriving the wood-fuel savings arising from the adoption of biogas technology at household level. The data collected revealed that firewood was mostly used (64.79%) while electricity was least used (2.81%). The other forms of fuel used by households in the study area were charcoal (16.9%) kerosene (7.05%) and liquefied petroleum gas (8.45%). Biogas energy had not been adopted (0%). The average energy use per household was 70MJ per week which is equivalent to 2m^3 of biogas. Co-digestion of feedstocks yielded more biogas compared to single substrate digestions. Co-digestion of cow manure with avocado pulp gave the greatest volume coefficient of 3 with a standard deviation of 3.69 and 113% increase in biogas production volume. The study found out that co-digestion of cow manure with avocado pulp has the highest biogas potential and upon its adoption, tonnes of woodfuel would be conserved and reflected on the effective forest cover.

CHAPTER ONE

INTRODUCTION

1.1 Background information

In Africa, access to energy is a major challenge; especially the rural poor who are seriously affected by the depletion of their energy resources, especially firewood. This has put pressure on women and children and further heightens their vulnerability to falls into attacks during firewood collection in woodlands. Energy is among the most important factors to global prosperity. The overdependence on carbon related fuels as primary energy source has led to global climate change, environmental pollution and degradation, thus leading to poor quality of life (Aremu and Agarry, 2012).

In Kenya, wood fuel accounts for 68% of the total primary energy consumption and is much higher in the rural areas where it is estimated to be 80% (UNEP, 2006). Wood harvesting leads to both regional and global environmental degradation. For instance, the gazetted forest cover in Kenya has declined from 12% in the 60s to 6% in 2011, substantially below the minimum recommended coverage of 10% (GOK, 2011). The demand for energy is expected to be commensurate with population growth, thereby exerting more pressure on already endangered forest cover (Kulundu, 2003). In addition, the livelihood of people in Kenya will continue to be significantly impaired by energy lapse.

Deforestation due to wood fuel poses a serious threat to environmental sustainability and is jeopardizing progress towards poverty and hunger eradication (UNDP, 2013). To meet these challenges, reducing dependence on oil and biomass has become one of the priority issues for most countries around the world. So far, biofuels such as biogas are the most rapidly expanding and widely used types of renewable household fuel, although they still accounted for only 1.5% of total global household fuel demand in 2006 (IEA, 2008).

Biogas as an alternative source of energy alleviates deforestation and is a better source of renewable. But petroleum is non-renewable and it has been confirmed that non-renewable source of energy could only last for over a given period of time. This uncertainty has created a lot of anxiety for industrialized and developing nations as they are now looking back to the past methods of using biomass as one of the most viable remedy with purpose of improving it and eventually making it an alternative to the current methods (Wante H., Wante S. and Galadima, 2014).

Biogas is an energy technology that has the potential to counteract many adverse social, economic, health and environmental impacts connected with traditional biomass energy use in Kenya. The use of biogas as energy source has proven itself to be an important strategy in solving the problems of energy usage in rural areas of developing countries (Aremu and Agarry, 2012).

Various types of feedstock can be used for the production of biogas: animal manure and slurries, crop residues, organic wastes from dairy production, food industries and agro-industries, wastewater sludge, organic fraction of municipal solid wastes, organic wastes from households and from catering business as well as energy crops. Biogas can also be collected, with special installations, from landfill sites.

One main advantage of biogas production is the ability to use "wet biomass" types as feedstock, all characterized by moisture content higher than 60–70% (e.g. sewage sludge, animal slurries, flotation sludge from food processing etc.) (Al Seadi, Rutz, Prassl, Köttner, Finsterwalder, Volk and Janssen, 2008).

By using existing substrates like dung and other waste products to produce biogas, single households and communities can become more self-sufficient in terms of energy and in the long run promotes sustainable livelihoods among the rural communities (NEMA, 2005).

1.2 Statement of the problem

Due to deforestation and scarcity of non-renewable petroleum and coal reserves, supply of fuel throughout the world is threatened and has led to research in different options to get access to renewable sources of energy. Solar energy, wind energy, different thermal and hydro sources and biogas energy are all renewable energy resources. However biogas is distinct and has an added advantage in that on top of provision of energy, the digestate can also be used as source of plant nutrient. It is also a method of cleaning the environment by exploiting organic waste matter. Biomass fuels are the main source of energy to most of the rural households (UNEP, 2006). However, problems relating to environmental degradation, deforestation, land clearance and population increase are placing more and more pressure on dwindling forest cover. Dependence on biomass fuel has led to wood fuel scarcity and increased costs due to the additional time spent collecting wood fuel (Mugo and Gathea, 2010). Modern fuels such as liquefied petroleum gas (LPG) and electricity are expensive and only affordable to few Kenyans, while the more friendly green energy such as wind-power, biogas and solar energy have not been sufficiently exploited (Karekezi and Kimani, 2004). Anaerobic digestion converts energy stored in organic matter into biogas energy. Biogas is distinct from other renewable energies because of its characteristics of producing, using, controlling and collecting organic wastes and at the same time producing fertilizer (Yimer and Sahu, 2014). Cow dung has high nitrogen content and due to pre-fermentation in the stomach of ruminant, is most suitable material for high yield of biogas (Rousan and Zyadin, 2014).Plant materials such as crop residues are more difficult to digest than animal wastes (dung) because of the difficulty in achieving hydrolysis of cellulosic and lignin constituents (Ukpai and Nnabuchi, 2012). The benefit of co-digestion of substrates usually outweighs that of single digestion because of synergistic effects. Co-digestion enhances microbial biodegradability and result in 25-32% higher specific methane production compared to single substrate digestion of cow manure (Chukwuma, Umeghalu, Orakwe and Bassey, 2013). It is necessary in the face of energy challenges facing developing countries to determine the optimum co-digestion mixing ratio.

This research intends to establish the peak biogas production from co-digestion of cow dung with goat manure, avocado pulp and bagasse keeping the mixing ratios constant.

1.3 Justification of the study

Majority of the people in the rural areas depend on wood fuel (charcoal or firewood) for their energy needs. A small section of the population uses fossil fuel (kerosene and LPG) because it is expensive as compared to wood fuel. However, with the increasing population, too much overdependence on wood fuel has resulted in deforestation and environmental destruction due to land clearance whereas increased use of fossil fuel results in higher level of greenhouse gases (GHG) emission. Burning biogas produces energy like natural gas and much more than wood fuel. Furthermore, the energy produced using biogas is renewable and relatively cost effective with high calorific value of 6kWh/m^3 (Itodo, Agyo, and Yusufu, 2007).

It is regarded as a clean energy source as it reduces the emission of greenhouse gases to the environment. Stabilized organic wastes from a digester, known as digestate, contain less odour than the unstable waste, yet retain almost all the nutrients from the feed material (Jorgensen, 2009).

There is a need to establish the best type of substrates that can be co-digested with cow dung to realize better degradation via synergies produced by mixing feedstocks and achieve peak biogas production level within a shorter retention time.

1.4 Research objectives

1.4.1 Main objective

To assess biogas energy potential from substrate co-digestion in kaitui location, Kericho county, Kenya.

1.4.2 Specific objectives

i) To study energy sources used in Kaitui location, Kericho County.
ii) To compare biogas production volumes from co-digestion of cow dung with goat manure, avocado pulp and bagasse.
iii) To derive energy savings arising from the adoption and use of biogas at the household level.

1.5 Scope of the study

The research on biogas energy potential was done within Kaitui location where data was collected to ascertain the availability of different feed-stocks (substrates) to the residents. Several experiments were thereafter conducted to determine the heating value of the commonly used energy source and biogas production through single substrate digestions and co-digestions using the available substrates.

1.6 Study limitation

The experiments were carried out during a rainy season which affected greatly the production of biogas; increase in temperature increases the rate of biogas generation. Indoor experiments were opted to realize mesophilic temperature. The gas jar used in gas collection had an accurate scale calibration range of 5 milliliter (ml), which meant it was not possible to read a scale below it. This range was therefore sub-divided to a 1 ml scale to increase the accuracy of the reading.

1.7 Theoretical & Conceptual Framework

In Kenya, wood fuel accounts for 68% of the total primary energy consumption and it is much higher in the rural areas where it accounts for 90% of the households that use wood fuel as their main cooking energy (G.o.K, 2011). The demand for energy is expected to grow with population growth thus posting a serious gap on the energy source.

Anaerobic digestion results in the production of biogas energy and the pathogen free digestate. Applying the digestate to cropland will replace commercial fertilizers and leads to crop nutrition thus better livelihood (Jorgensen, 2009).

Decaying plants and animal manure from agricultural activities contributes to the accumulation of greenhouse gases (GHG) in the environment. Though the full environmental impact of GHG-emissions is not known, it is widely recognized that there is a link between GHG-emissions and a rising global temperature. This implies that GHGs cause damage to the environment resulting in a cost for society. These emissions will be minimized by a great margin through biogas energy use, which eventually translates to a better livelihood. The adoption of biogas energy leads to reduced wood and fossil fuel use which paves way to forest conservation.

To generate sufficient and reliable biogas energy, research has to be done from different feedstocks to ascertain the best substrate co-digestion that yields peak volume within a short retention time under normal conditions. Cow manure is suitable for use as "carrier" substrate because of; its high water content, which act as solvent for dry waste materials, its high buffering capacity that regulate the optimum pH in the reactor, and the high level of nutrient, a requirement for optimal bacteria growth (Angelidaki and Ellegaard, 2003).

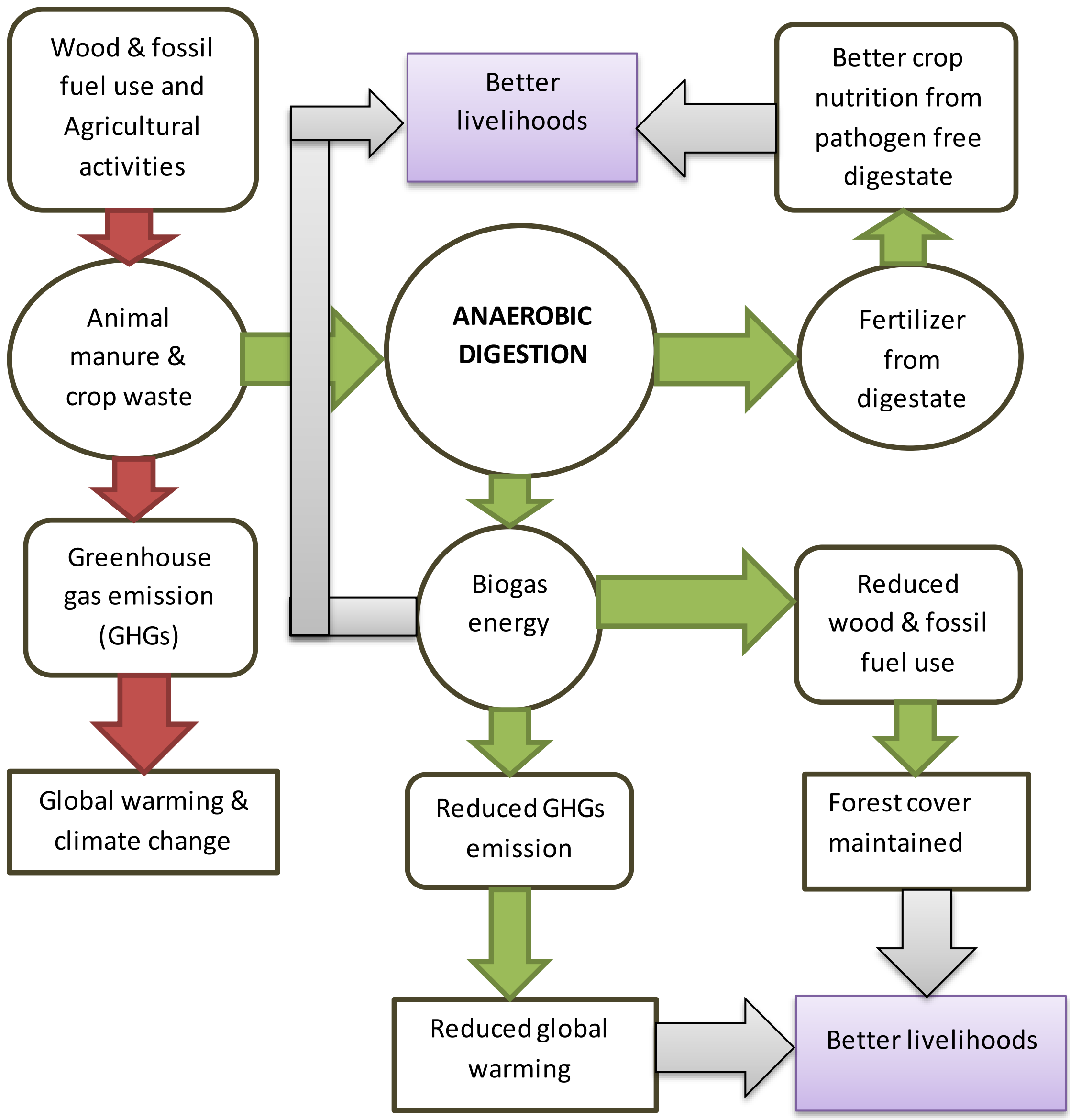

Figure 1.1: Conceptual frameworks.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

A great challenge in the 21st Century is that of implementing sustainable development and meeting the energy needs of the ever increasing world's population. According to the International Energy Agency (IEA), about 2.4 billion people, (that is around a quarter of the world's population) have no access to electricity and rely heavily on unsustainable biomass energy to meet their energy needs (IEA, 2008). Moreover, under today's energy policies and investment trends in energy infrastructure, projections show that as many as 1.4 billion people will still rely on biomass by 2030 (IGAD, 2007).

The biomass demand in Kenya is estimated at 40.5 million tonnes against a sustainable supply of 16 million tonnes (Kamfor, 2002). Biomass energy (mainly firewood and charcoal) constitutes 70 per cent of national energy supply, 90 per cent of which is consumed by households (UNEP, 2006).

To date, firewood and charcoal are still the most significant energy resources in Kenya and will be in the foreseeable future. Firewood is mainly a rural fuel with more than 90% of the population using it for cooking and heating. Charcoal is predominantly an urban fuel with 72% of the urban population as users. Due to decreased wood availability, some parts of the countries are opting for agricultural residue and animal dung as energy for cooking (Kamfor, 2002).

Climate change, together with an increasing demand for energy, volatile oil prices, and energy poverty has led to a search for alternative sources of energy that would be economically efficient, socially equitable, and environmentally sound. Cleaner energy systems are needed to address all of these effects and to contribute to environmental sustainability (NEMA, 2009).

2.2 General information on biogas

2.2.1 History of Biogas utilization

It has been known from several centuries that combustible gas is generated when organic wastes are allowed to rot in huge piles. For example in the seventeenth century, Van Helmont recorded that decaying organic material produce flammable gases. In 1776, Volta resolved that there was a direct connection showing how much organic material was used and how much gas the material produced (Energypedia, 2014).

Biogas use was introduced in Kenya in 1957 by Tim Hutchinson who had built a biogas digester for his personal use (Shell foundation, 2007).

Biogas is a clean-burning methane-rich gas produced through anaerobic digestion (bacterial action in the absence of air) of organic feed stocks (crop residues or animal dung). 28.3 m^3 of processed biogas is equivalent to 16.99 m^3 of natural gas, 0.031 m^3 of butane, 0.024 m^3 of gasoline, or 0.021 m^3 of diesel oil. For cooking and lighting, a family of four would consume 4.25 m^3 of biogas per day, an amount that is easily generated from the family's night dung of three cows (Shell foundation, 2007).

Biogas is a versatile, renewable fuel that can be used for production of heat, electricity and/or vehicle fuel. It can be combusted in gas boilers to produce heat or in gas turbines to produce electricity. It can also be upgraded to vehicle fuel quality by increasing the methane content through removal of most of the other compounds present (Luostarinen, Normak and Edström 2011).

2.2.2 Composition of Biogas

Biogas is produced by the biological breakdown of organic matter in the absence of oxygen. The composition and quantity of the biogas is largely determined by the feedstock and its loading rate. Biogas produced in an anaerobic digester is typically composed of 50-70% methane (CH_4) and 30-40% carbon dioxide (CO_2). Depending on the feedstock, biogas can also contain significant amounts of hydrogen sulphide (H_2S), water (H_2O) and traces of other chemical products (Hassan and Haddad, 2004).

Table 2.1: Typical composition of biogas from normally digesters

Compound	Chemical symbol	Range %
Methane	CH_4	50-70%
Carbon (IV) oxide	CO_2	30-40%
Nitrogen	N_2	1-2%
Hydrogen	H_2	5-10%
Water vapor	H_2O	0.3%
Hydrogen sulphide	H_2S	Traces
Ammonia	NH_3	0.01-2.5mg/m^3

Source: (Hassan, 2004).

2.2.3 Calorific value

Biogas is about 20% lighter than air and has an ignition temperature in the range of 650°-750° C. It is an oduorless and colourless gas that burns with clear blue flame similar to that of LPG gas. The calorific value of biogas is about 6kWh/m^3 (20 mega joule) - this corresponds to about half a litre of diesel oil. The net calorific value depends on the efficiency of the burners or other user appliances; a conventional biogas stove has an efficiency of 50-60 %. Methane is the valuable component under the aspect of using biogas as a fuel (Itodo, Agyo and Yusufu, 2007).

Table 2.2: Biogas compared with other fuels

Fuel	Unit (U)	Calorific value kWh/U	Application	Efficiency %	U/m^3 biogas
Cow dung	Kg	2.5	Cooking	12	11.11
Wood	Kg	5.0	Cooking	12	5.56
Charcoal	Kg	8.0	Cooking	25	1.64
Hard coal	Kg	9.0	Cooking	25	1.45
Butane	Kg	13.6	Cooking	60	0.40

Propane	Kg	12.0	Cooking	60	0.39
Diesel	Kg	12.0	Engine	30	0.55
Electricity	kWh	10.0	Motor	80	1.79
Biogas	m^3	6.0	Cooking	55	1

(Source: Itodo et al., 2007).

2.3 Feedstocks for biogas production

Biogas is produced through anaerobic fermentation of organic substances. In theory, all biodegradable materials with reasonable lignin content (i.e. not wood) are suitable raw materials for biogas processes. In agriculture, manure and most plant biomass can be directed to biogas plants, while from municipalities, food waste and sewage sludge are the most important material flows to biogas processes. Moreover, different industries produce biodegradable by-products which can be used in biogas plants.

Different raw materials will produce different amounts of biogas and methane depending on their content of carbohydrates, fats and proteins as indicated in table 2.3 (Luostarinen et al., 2011).

Table 2.3: Theoretical production of biogas and methane

Substrate	Biogas (m^3/t)	Methane (m^3/t)	Methane content%
Carbohydrates	830	415	50.0
Fats	1444	1014	70.2
Proteins	793	504	63.6

(Source: Luostarinen et al., 2011).

2.3.1 Biogas potential from animal manure

Basically all manure forms can be directed to biogas plants and produce biogas, but depending on their quantities, characteristics and the plant design. The methane production potential of manures differs between the manure types (Table 2.4) and also case-specifically depending on e.g. animal feeding and housing solutions, manure total solid (TS) content and the bedding material used (Rousan and Zyadin, 2014). Manure is a good base material for biogas plants as: It is continuously produced and available, contains all the nutrients required by the anaerobic bacteria and has high buffering capacity.

Table 2.4: Biogas potential from selected livestock manure.

Animal	Total manure (kg/head/day)	Total solid(TS) (kg/head/day)	Biogas yield (m^{3}/kg dry matter)	Carbon/Nitrogen ratio (C/N)	Volatile solids (VS) % fresh manure
Cow	20	4.0	0.20 - 0.50	18 – 25	13
Buffalo	25	4.5	0.15 - 0.32	18 – 25	-
Pigs	1 – 5	0.6	0.56 - 0.65	13	12
Sheep	1.8	0.6	0.37 - 0.61	29	-
Poultry	0.1	0.03	0.31 - 0.54	-	17
Horses	24	7.1	0.20 - 0.30	24 – 25	-
Rabbits	0.2	0.1	0.36	-	-

(Source: Rousan and Zyadin, 2014).

2.3.1.1 Composition of cow manure

Cow manure is composed of several components of different percentage (Table 2.5).The manure characteristics also establish the percentage of carbon dioxide and methane in the biogas produced. Cow manure biogas will typically be composed of 55 to 65% methane and 35 to 45% carbon dioxide. Traces of hydrogen sulfide and nitrogen will also be present in the final biogas (Burke, 2001).

Table 2.5: Cow manure composition.

Component	% Dry of Matter
Volatile solids	83.0
Ether Extract	2.6
Cellulose	31.0

Hemicellulose	12.0
Lignin	12.2
Starch	12.5
Crude Protein	12.5
Ammonia	0.5
Acids	0.1

(Source: Burke, 2001).

2.3.2 Biogas potential from energy crops and crop residue

Residues from the agricultural sector such as spent straw, hay, cane trash, corn, plant stubble, and bagasse needs to be shredded in order to facilitate their flow into the digester reactor as well as to increase the efficiency of bacterial action (Shane, Gheewala and Kasali, 2015).

Table 2.6: Theoretical biogas potential from crop residues

Crop Name	Product (10^6kg)	RPR	Residue (10^6kg)	TS (%)	VS (%)	MP (m^3/kg VS)	TBP ($TJyr^{-1}$)
Sugarcane bagasse	2,798	0.33	923.34	24	87	0.45	3,332
Sugarcane top/leaves		0.05	139.90	90	98	0.33	1,564
Maize Stalk	1,780	2	3,559.15	74	82	0.28	23,227
Maize Cob		0.3	533.87	30	94	0.6	3,470
Wheat stalk	154	1	153.60	94	87	0.26	1,254
Cassava Peels	1,115	0.15	167.31	35	97	0.377	823
Groundnut shell	108	1	108.01	94	93	0.3	1,088

(Source: Shane et al., 2015).

2.3.3 Municipal and industrial materials

Several municipal and industrial wastes and by-products are suitable substrates for biogas plants. The characteristics of these materials may vary in many ways. For example, the characteristics of the organic fraction of municipal solid waste (OFMSW) vary depending on collection method (source-or mechanically sorted), collection site (restaurant, school, hospital, residential area etc.) and time of year (e.g. amount of gardening waste). Also, sewage sludge from municipal and industrial wastewater treatment plants may be directed to biogas processes (Luostarinen et al., 2011).

2.3.4 Co-digestion

Co-digestion is the digestion of two or more substrates within the same digester in order to increase biogas production, overcome inhibition by dilution with co-substrates and improve degradation via synergies produced by mixing different materials. Co-digestion improves biogas production because complex material is likely to have most of the components required for microbial growth (Muzenda, 2014).

Animal manure provides a relatively small amount of biogas per 0.5 kg of material when compared to other potential feed-stocks like industrial wastes and energy crops. Nonetheless, animal waste has continually been used in digesters because of its widespread availability and handling/management issues. However, digesting organic materials with higher biogas potential than animal manure, or even combining such waste with animal manure, would greatly increase biogas production.

There are three main advantages of using animal manure for co-digestion. First; it is a source for nutrients like trace metals, vitamins and other compounds necessary for microbial growth. Second; it plays a role in lowering pH. Third; the high water content in manure helps dilute the concentrated organic wastes, which would be inhibitory and difficult to treat separately (Angelidaki and Ellegaard, 2005).

2.4 Anaerobic digestion (AD)

Anaerobic digestion is a process of controlled decomposition of biodegradable materials under managed conditions where free oxygen is absent, at temperatures suitable for naturally occurring mesophilic or thermophilic anaerobic and facultative bacteria and archaea species, that convert the inputs to biogas. If the substrate for AD is a homogenous mixture of two or more feedstock types (e.g. animal slurries and organic wastes from food industries), the process is called “co– digestion” and is common to most biogas applications (Al Seadi et al., 2008).

The anaerobic digestion process is dependent on the growth of microorganisms. Thus, there is a necessity to supply nutrients in sufficient amounts and at right proportions to sustain an optimal growth of the bacteria and archaea to obtain an efficient biogas.

The carbohydrates and lipids of an organic substrate mostly provide carbon, oxygen and hydrogen, while nitrogen and sulfur are supplied via proteins and phosphorus from e.g. nucleic acids phospholipids. Together with these elements, most organic substrates provide potassium, sodium, magnesium, calcium and iron and to some extent trace metals (micro-nutrients). The proportions and availability of the nutrients in a given substrate will to a certain extent be reflected in the microbial community and also determine the growth rate (Karlsson, Björn, Yekta and Svensson, 2014).

2.4.1 Biochemical process of AD

Biological decomposition of organic matter to methane (CH_4), carbon dioxide (CO_2) and small traces of other gases under oxygen depleted system is an interactive process. It is an interaction of different types of bacteria with diverse functions in the entire anaerobic process. What may be a waste product from some bacteria could be a substrate (or food) for others, and in this way the bacteria are interdependent (Jørgensen, 2009).

Micro-organisms derive energy and grow by metabolizing organic material in an oxygen-free environment resulting in the production of CH_4. The anaerobic digestion process can be subdivided into the following four phases, each requiring its own characteristic group of micro-organisms namely hydrolysis, acidogenesis, acetogenesis and methanogenesis (Al Seadi et al., 2008).

2.4.1.1 Hydrolysis

Hydrolysis is theoretically the first step of AD, during which the complex organic matter (polymers) is decomposed into smaller units (mono- and oligomers).During hydrolysis, polymers like carbohydrates, lipids, nucleic acids and proteins are converted into glucose, glycerol, purines and pyridines. Hydrolytic microorganisms excrete hydrolytic enzymes, converting biopolymers into simpler and soluble compounds as it is shown below:

Lipids $\longrightarrow$ fatty acids + glycerol

Polysaccharide $\longrightarrow$ monosaccharide

Protein $\longrightarrow$ amino acids

2.4.1.2 Acidogenesis

During acidogenesis, the products of hydrolysis are converted by acidogenic (fermentative) bacteria into methanogenic substrates. Simple sugars, amino acids and fatty acids are degraded into acetate, carbon dioxide and hydrogen (70%) as well as into volatile fatty acids (VFA) and alcohols (30%) (Angelidaki et al., 2002).

2.4.1.3 Acetogenesis

Products from acidogenesis, which cannot be directly converted to methane by methanogenic bacteria, are converted into methanogenic substrates during acetogenesis. VFA and alcohols are oxidised into methanogenic substrates like acetate, hydrogen and carbon dioxide. Acetogenesis and methanogenesis usually run concurrently, as symbiotic of two groups of organisms (Angelidaki et al., 2002).

2.4.1.4 Methanogenesis

The production of methane and carbon dioxide from intermediate products is carried out by methanogenic bacteria. 70% of the formed methane originates from acetate, while the remaining 30% is produced from conversion of hydrogen (H_2) and CO_2 (Dobre et al., 2014), according to the equations:

Acetic acid $\longrightarrow$ methane + carbon dioxide

Hydrogen + carbon dioxide $\longrightarrow$ methane + water

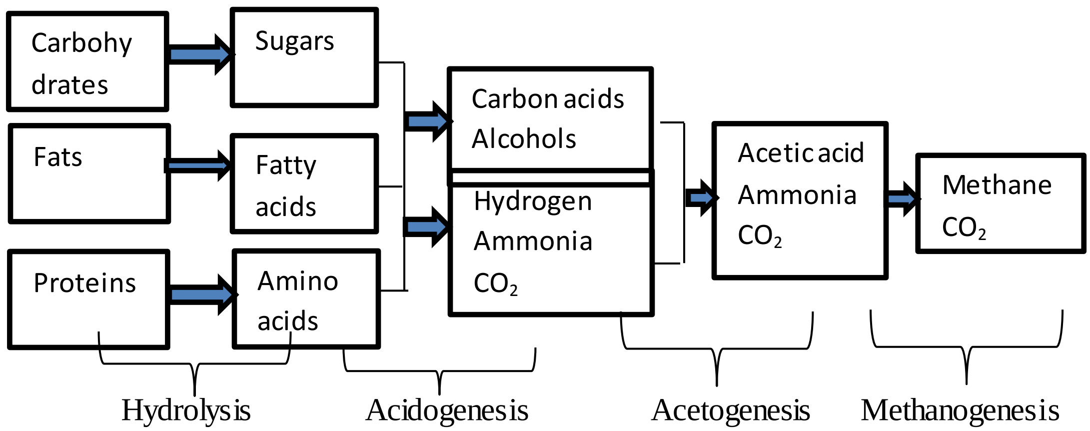

Figure 2. 1: **Schematic diagram of AD** (Dobre et al., 2014).

2.5 Factors affecting AD

The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the AD efficiency. The temperature, retention time, pH, carbon nitrogen ratio(C: N) total solid content, organic loading rate and mixing (Monnet, 2003).

2.5.1 Temperature

The AD process can take place at different temperatures: psychrophilic (below 20°C), mesophilic (30°C–42°C), and thermophilic (43°C -55°C). There is a direct relation between the process temperature and the retention time (RT) (Table 2.7).

Table 2.7: Thermal stage and typical retention times

Thermal stage	Process temperatures	Minimum retention time
Psychrophilic	< 20 °C	70 to 80 days
Mesophilic	30 to 42 °C	30 to 40 days
Thermophilic	43 to 55 °C	15 to 20 days

(Source: Al Seadi et al., 2008).

In practice, the operation temperature is chosen with consideration to the feedstock used and the necessary process temperature is usually provided by floor or wall heating systems, inside the digester. Many modern biogas plants operate at thermophilic process temperatures as it provides many advantages, compared to mesophilic and psychrophilic processes. They include: effective destruction of pathogens, higher growth rate of methanogenic bacteria at higher temperature, reduced retention time, making the process faster and more efficient, improved digestibility, better degradation of solid substrates and better substrate utilization.

Operation temperature influences the toxicity of ammonia. Ammonia toxicity increases with increasing temperature and can be relieved by decreasing the process temperature. However, when decreasing the temperature to 50°C or below, the growth rate of the thermophilic microorganisms will drop drastically, and a risk of washout of the microbial population can occur, due to a growth rate lower than the actual HRT (Angelidaki, 2004).

This means that a well-functioning thermophilic digester can be loaded to a higher degree or operated at a lower HRT (Figure 2.2).

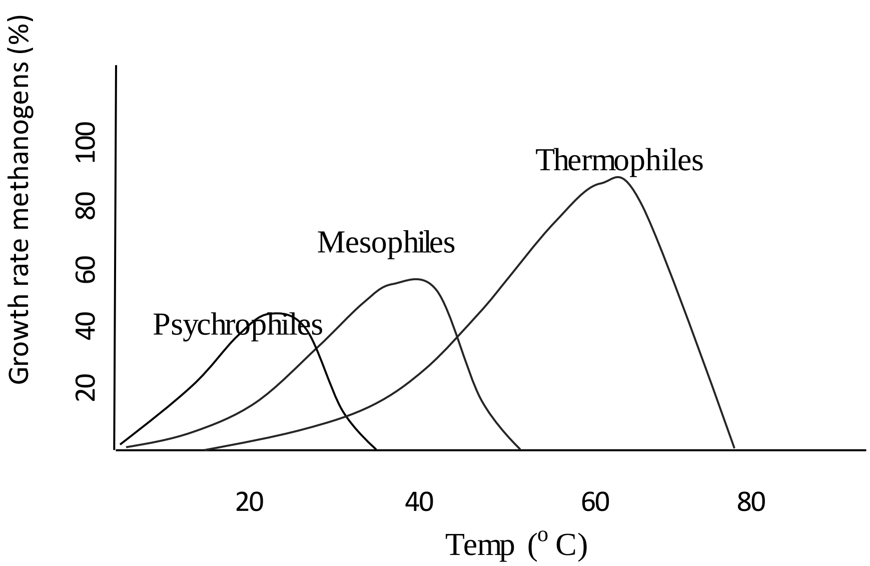

Figure 2.2: **Relative growth rates of methanogens** (Mőnkäre, 2015).

Thermophilic operation temperature results in faster chemical reaction rates, thus better efficiency of methane production, higher solubility and lower viscosity. The growth rate of methanogenic micro-organisms is known to be faster at higher temperatures and the most comparative continuous studies with biowaste have found higher methane yield from thermophilic AD compared to mesophilic (Mőnkäre, 2015).

2.5.2 pH

Anaerobic bacteria, particularly the methanogens, are sensitive to pH within the digester and their growth can be inhibited. Acid solutions have a pH less than 7 while alkaline solutions are at a pH above 7-14. Optimum pH value for AD lies between 5.5 and 8.5. During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestate affects the pH value and in a batch reactor acetogenesis occurs at a rapid pace. Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5. Excessive generation of acid can inhibit methanogens, due to their sensitivity to acidic conditions (Fang, Angelidaki and Boe, 2010).

The suitable pH value can be controlled by the addition of lime or recycled filtrate obtained during residue treatment. In fact, the use of recycled filtrate can even eliminate the lime requirement. As digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8. Once methane production is stabilized, the pH level stays between 7.2 and 8.2 (Fang, Angelidaki and Boe, 2010).

2.5.3 Carbon to Nitrogen (C/N) ratio

For efficient biogas plant operation, the C/N ratio of the input substrate should be kept within the desired range since the nutrient composition has an impact on the optimal growth and activity of micro-organisms. Optimum C: N ratios in anaerobic digesters are between 20 and 30. A high C:N ration is an indication of rapid consumption of nitrogen by the methanogens and results in a lower gas production. On the other hand a lower C: N ratio causes ammonia accumulation and the pH value exceeds 8.5, which is toxic to methanogenic bacteria (Nijaguna, 2002).

Co-digestion with different substrate materials can improve the biogas production since a single substrate can be limiting due to its nutrient content. Optimum C: N ratio of the feedstock materials can be achieved by mixing waste of low and high C: N ratio, such as organic solid waste mixed with sewage or animal manure (Monnet, 2003).

In anaerobic digestion, the carbon utilization by micro-organisms is 25-30 times higher than nitrogen. Thus, for optimum functioning microbes usually need 25-30:1 ratio of C:N with the largest part of the carbon being easily degradable. Any deviation from this ration gives a less efficient process. In China, as a means to balance C/N ratio, it is customary to load straw at the bottom of the digester upon which latrine waste will be discharged (Lam and Heegde, 2010).

Table 2.8: C/N ratio of some of the commonly used materials.

Raw Materials	C/N Ratio	Raw Materials	C/N Ratio
Duck dung	8	Buffalo dung	24
Human excreta	8	Water hyacinth	25
Chicken dung	10	Elephant dung	43
Goat dung	12	Straw (maize)	60
Pig dung	18	Straw (rice)	70
Sheep dung	19	Straw (wheat)	90
Cow dung	24	Saw dust	above 200

(Source: Lam and Heegde, 2010).

2.5.4 Hydraulic retention time (HRT)

It is the average time interval when the substrate is kept inside the digester tank. HRT is correlated to the digester volume and the volume of substrate fed per time unit, according to the following equation:

$$HRT = \frac{V_d}{V_s} \quad \text{..........} \quad 1$$

HRT- hydraulic retention time [days]

V_d -digester volume [m³]

V_s -volume of substrate fed per time unit [m³/d]

Increasing the organic load reduces the HRT. The retention time must be sufficiently long to ensure that the amount of microorganisms removed with the effluent (digestate) is not higher than the amount of reproduced microorganisms. The duplication rate of anaerobic bacteria is usually 10 days or more. A short HRT provides a good substrate flow rate, but a lower gas yield. It is therefore important to adapt the HRT to the specific decomposition rate of the used substrates. Knowing the targeted HRT, the daily feedstock input and the decomposition rate of the substrate, it is possible to calculate the necessary digester volume (Al Seadi et al., 2008).

2.5.5 Influent Total Solids (TS)

The total solids content of the influent waste determines the amount of organic matter to be digested. At any given waste retention time, the total solids content of the waste influent is limited by the processing capacity of the bacteria involved in anaerobic digestion. The presence of too much organic material can, if hydraulic retention times are too short, lead to the production of volatile fatty acids at rates that exceed the ability of the acetogenic and methanogenic bacterial populations to remove them. This results in depressed rates of anaerobic digestion or even outright digester failure.

The level of influent solids also determines the level of dilution of the waste in the reactor. By adding water to the organic part of the waste, dilution acts to increase the volume of the waste, thereby increasing the size of the reactor vessel and its costs (Ciborowski, 2001).

2.5.6 Organic Loading Rate (OLR)

Organic loading rate is the rate of volatile solids feed to a reactor per unit of reactor volume. The organic loading rate is set to realize a desired digester hydraulic retention time, given an influent waste of some known total solids content (Karlsson et al., 2014).

2.5.7 Mixing

Mixing within the digester, improves the contact between the micro-organisms and substrate thus improves the bacterial population's ability to obtain nutrients. It ensures efficient transfer of organic material and nutrients to the active microbial biomass, an even distribution of temperature and buffering alkalinity, to release gas bubbles trapped in the reactor fluid and to prevent sedimentation of particulate material (Karlsson et al., 2014).

Mixing also prevents the formation of scum and the development of temperature gradients within the digester. However excessive mixing can disrupt the micro-organisms and therefore a slow mixing is preferred. For the case of co-digestion, the different feed stocks should be mixed before introduction into the digester to ensure a sufficient homogeneity (Monnet, 2003).

2.5.8 Particle size

The production of biogas is also affected by particle size of the substrate. Too big particle size is problematic for microbes to digest and it can also result in blockage in the digester. Small particle size gives a large surface area for substrate interaction and thus allows the increased microbial activity resulting to the increase in gas production (Yadvika, Santosh, Sreekrishnan, Kohli and Rana, 2004).

2.6 Inhibition of the biogas Process

Inhibition means that a substance has a negative effect on bacteria without directly killing them. The process can be inhibited in two ways normally endogenous and exogenous inhibition. Endogenous inhibition is due to conditions or material created during the process itself that under certain circumstances may inhibit the process, and exogenous inhibition is due to external conditions (Jørgensen, 2009).

2.6.1 Nitrogen inhibition

One of the most significant endogenous inhibitors is ammonia (NH_3). Ammonia is created during the bacterial degradation of nitrogen-containing substances such as proteins. Nitrogen is essential for bacterial growth and ammonia is an important source of nitrogen. But ammonia at high concentrations is highly toxic to the bacteria (Jørgensen, 2009).

In an aqueous solution ammonia is always found in equilibrium with ammonium ion (NH_4^+). This equilibrium is determined by the acidity, pH and temperature of the environment.

$$NH_4^+ \rightleftharpoons NH_3 + H^+ \qquad \text{...2}$$

At a high pH, the equilibrium is shifted to the right, and the environment becomes more toxic to bacteria. Higher temperatures will also shift this equilibrium to the right. This is why a thermophilic biogas process (all other things being equal) is more sensitive than a mesophilic process to ammonia inhibition (Jørgensen, 2009).

2.6.2 Acidification

An organic acid formed during the process also contributes to endogenous inhibition. If these are not removed as soon as they are formed – which can happen during an overload – it leads to an acidification of the process (Jørgensen, 2009).

2.6.3 Antibiotics

Among the exogenous causes, antibiotics and disinfection agents are obvious inhibitors of the process. This is because they kill microorganisms. Both substances are used in livestock production to treat sick animals as well as to keep animal houses and milking parlous clean. They can therefore also be found in the slurry, but apparently only at concentrations so low to have a negative impact on the biogas plant (Jørgensen, 2009).

2.7 Types of digesters

Digesters are classified into three: batch digesters, semi-batch digesters and continuous digesters.

2.7.1 Batch digesters

Batch digesters are filled and then emptied completely after a fixed retention time when biogas production is weakened. Each design and each fermentation material is suitable for batch filling, but batch digesters require high labor input. The digester is opened, digestate is removed to be used as bio-fertilizer and the new batch replaces the digestate. The tank is then resealed and ready for operation. As a major disadvantage, their gas output is not steady (Al Seadi et al., 2008).

2.7.2 Continuous digesters

Continuous digesters are fed and emptied continuously. They empty automatically through the overflow whenever new material is filled in. The substrate must be fluid and homogeneous. They are suitable for rural households as the necessary work fits well into daily routine. Gas production is constant and higher than in batch digesters.

Continuous digesters can be vertical, horizontal or multiple tank systems. Depending on the solution chosen for stirring the substrate, continuous digesters can be completely mixed digesters and plug flow digesters. Completely mixed digesters are typically vertical digesters while plug-flow digesters are horizontal (Energypedia, 2014).

2.7.3 Semi-batch digesters

These digesters are suitable for the co-digestion process. If straw and dung are to be digested together, then the biogas digester can be operated on semi-batch basis. The slowly digested straw-type material is fed in twice a year while the dung is added and removed regularly **(**Al Seadi et al., 2008)**.**

2.8 Household Bio-digester designs

The bio-digester is a physical structure, commonly known as the biogas plant. Since various chemical and microbiological reactions take place in the bio-digester, it is also known as bioreactor or anaerobic reactor. The main function of this structure is to provide an anaerobic condition within it. As a chamber, it should be air and water tight. It can be made of various construction materials and in different shapes and sizes (Lam and Heegde, 2010).

The commonly used household digesters include: fixed dome digester, floating drum digester, plug flow digester, Polyethylene tube digester and plastic tank digester. Others are Balloon plant, horizontal plants, earth pit plants and Ferro cement plants.

2.8.1 Fixed dome digester

The fixed dome also known as Chinese model biogas plant was developed and built in China as early as 1936. It consists of an underground brick masonry compartment (fermentation chamber) with a dome on the top for gas storage. In this design, the fermentation chamber and gas holder are combined as one unit. This design eliminates the use of expensive mild steel gas holder which is susceptible to corrosion (Lam and Heegde, 2010).

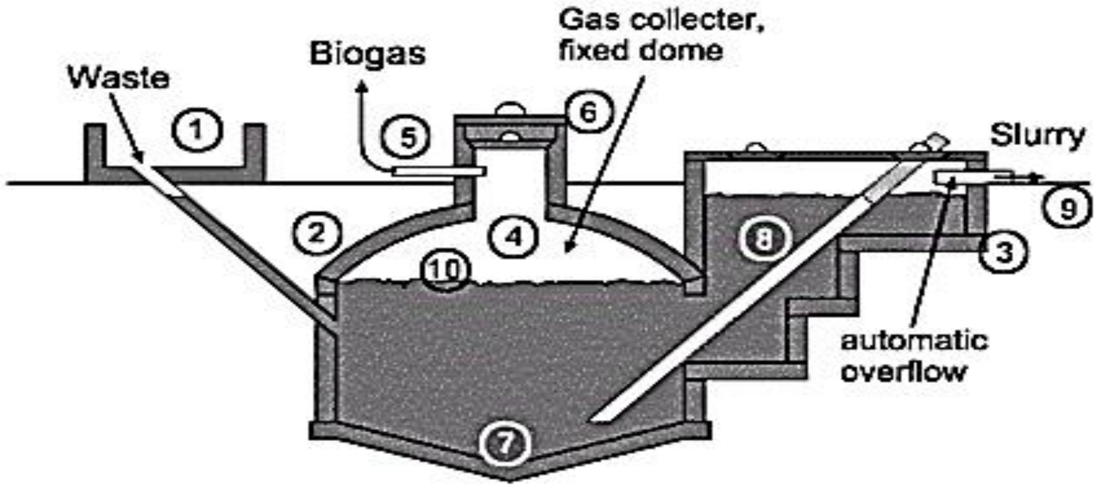

Figure 2. 3: **Fixed dome digester** (Kossmann et al., 1999).

1. Mixing tank with inlet pipe and sand trap **2**.digester **3.**compensation and removal tank. **4.** gas holder **5.**gas pipe **6.**entry hatch with gastight seal **7.**accumulation of thick sludge **8.**outlet pipe **9.**reference level **10.**supernatant scum

This digester is usually built underground. Its size depends on the location, number of households, and the amount of substrate available (Kossmann et al., 1999).

2.8.2 Floating drum digester

The floating drum digester model developed in 1962 by Khadi and Village Industries Commission (KVIC). Even though the model is pretty old, it is one of the most widely accepted and used designs for household purposes in India.

The design includes a movable inverted drum placed on a well-shaped digester. An inverted steel drum that acts as a storage tank is placed on the digester, which can move up and down depending on the amount of accumulated gas at the top of the digester. The weight of this inverted drum applies the pressure needed for the gas flow through the pipeline for use (Rajendran, Aslanzadeh and Taherzadeh, 2012).

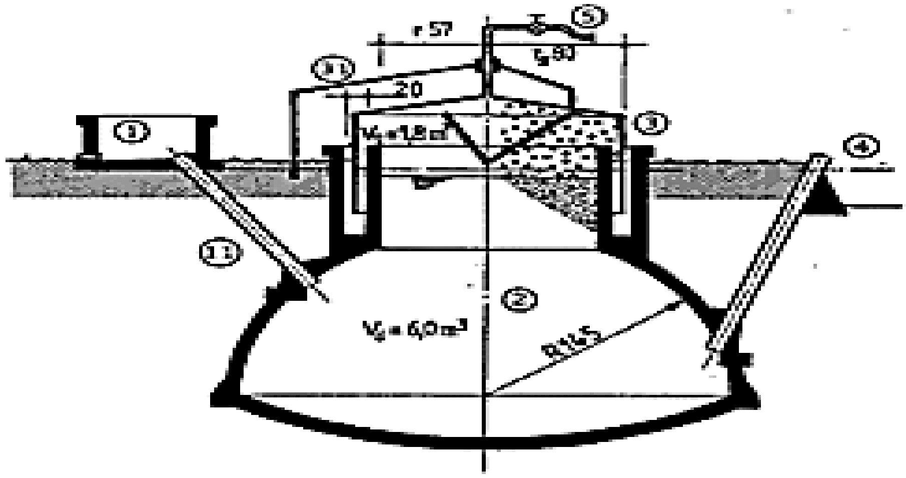

Figure 2.4: Floating drum digester (Kossmann et al., 1999).

1. Mixing pit **2**.digester **3**.gasholder **4**.slurry store **5**.gas pipe

From the position of the drum, the amount of biogas accumulated under the drum is easily detectable. However, the floating drum needs to be coated with paint in a constant interval to avoid rust. Additionally, fibrous materials will block the movement of digester. Hence, their accumulation should be avoided if possible. Such designs have been widely used in the past but are considered as obsolete nowadays, compared to fixed dome models due to a shorter lifespan and more maintenance requirements (Rakotojana, 2013).

2.8.3 Polyethylene tube Digester

A polyethylene bio-digester unit is a sealed tubular structure made of polyethylene “plastic” bags that has an inlet for organic material (manure) and an outlet for expelling decomposed material (effluent). The fermentation unit is one open area consisting of two parts; a liquid and a gas phase. The liquid phase is a mixture of water and manure at a ratio of 4:1 respectively. The domestic use of biogas can be improved by filtering it through lime water to eliminate the carbon dioxide, and through iron fillings such as a “pot washer” to remove the corrosive effect of the hydrogen sulfide (IICA, 2009).

As the fresh substrate is added from the inlet, the digestate flows towards the outlet at the other end of the tank. The inclined position makes it possible to separate acidogenesis and methanogenesis longitudinally, thus producing a two-phase system. The disadvantage with the fixed dome and floating drum models is, once installed they are difficult to move while this digester is portable.

Plug flow tube digesters have a constant volume, but produce biogas at a variable pressure. The size of such digesters varies from 2.4 to 7.5 m^3. In order to avoid temperature fluctuations during the night and maintain the process temperature, a gable or shed roof is placed on top of the digester to cover it, which acts as an insulation both during day and night. The usefulness of these digesters includes easy installation, easy handling, and adaptation to extreme conditions at high altitudes with low temperatures (Lüer, 2010).

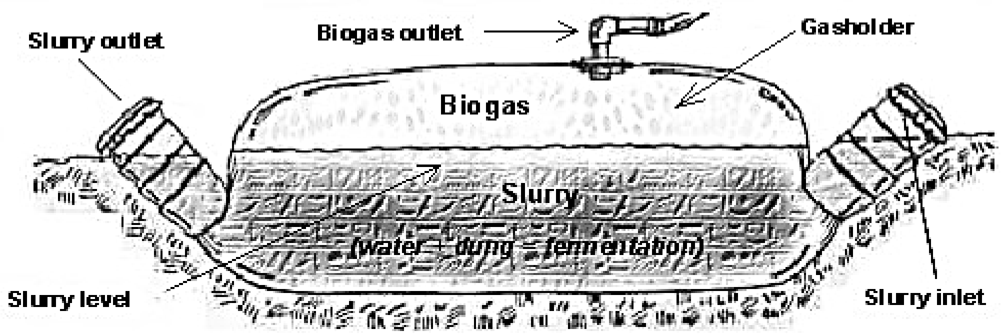

Figure 2.5: Polyethylene tube digester (Lüer, 2010).

2.8.4 Plastic tank digester

This technology is mainly composed of two pre-built rigid plastic tanks: a first tank for the digestion of organic materials, and a second tank for the storage of the biogas that is produced. It is thus rather easy to install (Rajendran et al., 2012).

This digester is derived from water tank technologies and has a typical volume of 1.8 m^3 for the digester tank and 1.5 m^3 for the gas storage tank. A lifespan of 20 years can consequently be expected by analogy with water tanks. However, it must be noted that the number of plastic tanks digesters installed is very low (Rakotojaona, 2013).

Figure 2.6: Plastic tank digester (Rakotojaona, 2013)

2.9 Merits and demerits of the digesters

Table 2.9: Pros and cons of different types of domestic biogas plants

Technology	Pros	Cons
Plastic tube digester	-Inexpensive technology: Between € 100 and € 150 (USD 130-200) -Ease of transportation - Low construction sophistication	-Prone damage -Short lifespan: 4 years max -Relatively few successful installations. -Not easy to operate dismantling and recycling of the unit
Plastic tank digester	-Easy installation. -Quick biogas production start-up after installation (3-4 days) - Small digester tank volume, therefore appropriate for limited livestock	-Expensive technology Approximately € 740 (USD 960) for the 1.8 m^3 model. - Potentially damageable - Small digester volume available, hence low biogas production
Fixed dome digester	- Long lifespan: more than 20 years. - Not damageable (underground) -Easy to operate -No moving or rusting parts involved	- Expensive technology Between € 670 and € 1150 (USD 870-1500) -Potentially long durations before the start-up of the biogas production -Requires high technical skills for

	- Compact basic design -Low maintenance	gas-tight construction -Difficult to repair in case of leakage - Requires heavy construction materials
Floating drum digester	-Provides constant gas pressure at outlet. -Visual indication of the amount of available gas – -Simple and easy to understand operation Constant gas pressure	-Very expensive compared to fixed dome digesters. - Steel drum (gasholder) is subject to corrosion. - Lower lifespan -High maintenance because of regular painting of drum

(Source: Cheng et al, 2014).

2.10 Pre-treatments

Different pre-treatments may be used prior to the actual biogas reactor (Angelidaki and Ahring, 2000). It is done in order to: improve the degradation of the raw materials (higher VS removal), increase biogas production, ensure the hygienic quality of the digestate, facilitate technical functions (e.g. prevent blockages), ensure homogenous feed, remove potentially inhibitive compounds and enable process intensification (higher OLR, shorter HRT, smaller reactor size). Many of the pre-treatments used facilitate more than one of the benefits above. They include maceration and grit separation.

2.10.1 Maceration

Maceration is the simplest physical treatment available. It incorporates physically chopping, grinding, or blending manure. The ultimate goal of maceration is to trim down the particle size and to separate lignin from the degradable biomass portion. Particle size reduction increases the surface area of fibers which allows a greater microbial access to the substrate (Angelidaki and Ahring, 2000).

Many raw materials for biogas processes are macerated (food waste, industrial by-products) or chopped (plant biomass) before feeding into the digester in order to decrease the particle size. Of the different manure types, usually only solid manures with larger particles from bedding material may require maceration/chopping, while liquid manure is usually just pre-mixed to ensure homogeneousness prior to feeding (Luostarinen et al., 2011).

2.10.2 Grit separation

A great variety of pre-treatment processes are available and the selection is done based on the nature of the feedstock used. Pre-treatment process for manure is mostly limited to grit removal or mixing with other organic wastes. Grit is composed of heavy mineral matter such as sand and gravel which may accumulate in the bottom of the digester (Monnet, 2003).

2.11 Construction of household digester

A household digester is basically composed of: Reception tank, Digester or fermenter, Gas holder and Overflow tank.

2.11.1 Sizing a household digester

The amount of manure fed into a digester each day has an important effect on its operation. This is measured by volume added in relation to the volume of the digester, but the actual quantity fed to the digester also depends on the temperature at which the digester is maintained.

The size of the digester, i.e. the digester volume V_d, is determined on the basis of the chosen retention time RT and the daily substrate input quantity Sd.

$$V_d = S_d \times RT \quad \ldots\ldots 3$$

$$[M^3 = M^3/\text{day} \times \text{number of days}]$$

The retention time, in turn, is determined by the chosen/given digesting temperature. For an unheated biogas plant, the temperature prevailing in the digester can be assumed as 1-2

Kelvin above the soil temperature. Seasonal variation must be given due consideration, however, i.e. the digester must be sized for the least favorable season of the year. The substrate input depends on how much water has to be added to the substrate in order to arrive at a solids content of 4-8% (Kossmann et al., 1999).

Substrate input (Sd) = biomass (B) + water (W) [M^3/d]

$$S_d = B + W \quad \ldots\ldots 4$$

In most agricultural biogas plants, the mixing ratio for dung (cattle and / or pigs) and Water (B:W) amounts to between 1:3 and 2:1(Kossmann et al., 1999).

2.11.2 Sizing the gasholder

The size of the gasholder, i.e. the gasholder volume Vg, depends on the relative rates of gas generation and gas consumption. The gasholder must be designed to: cover the peak consumption rate gc_{max} (>Vg1) and hold the gas produced during the longest zero-consumption period tz_{max} (>Vg2)

$$V_g 1 = gc_{max} \times tc_{max} = vc_{max} \text{ and } V_g 2 = G_h \times tz_{max} \quad \ldots\ldots 5$$

gc_{max} = maximum hourly gas consumption [m^3/h

tc_{max} = time of maximum consumption [h]

$Vcmax$ = maximum gas consumption [m^3]

Gh = hourly gas production [m^3/h] = G ÷ 24 h/d

tz_{max} = maximum zero-consumption time [h]

The larger *Vg*-value (*Vg1 or Vg2*) determines the size of the gasholder. A safety margin of 10-20% should be added:

$$V_g = 1.15(\pm 0.5) \times \max(\left(V_g 1, V_g 2\right) \quad \ldots\ldots 6$$

The ratio $V_d \div V_g$ is a major factor with regard to the basic design of the biogas plant. For a typical agricultural biogas plant, the Vd/Vg-ratio amounts to somewhere between 3:1 and 10:1, with 5:1-6:1 occurring most frequently (Kossmann et al, 1999).

Gas holder capacity, C =Gas holder volume, Vg/Daily gas production, D

$$C = \frac{V_g}{D} \quad \ldots\ldots 7$$

2.11.3 Digester loading

The digester loading L_d is calculated from the daily total solids input *TS/d* or the daily volatile solids input *VS/d* and the digester volume V_d (Kossmann et al., 1999).

$$Ld_T = \frac{\mathrm{TS}}{\mathrm{d}} \div Vd(kg/m^3 d) \quad \ldots\ldots 8$$

$$Ld_v = \frac{\mathrm{TS}}{\mathrm{d}} \div Vd(kg/m^3 d) \quad \ldots\ldots 9$$

2.12 Operational and maintenance problems

There are several operational and maintenance activities that have to be addressed. They include water, dung collection, scum formation, sediment formation and condense formation (Lam and Heegde, 2010).

2.12.1 Water

The substrate of most digesters needs to be mixed with an equal amount of water. During the dry season in semi-arid places this can lead to an additional burden for the plant operator. Therefore it is not recommendable to build a digester with a large volume if the nearest permanent water source is more than 30 minutes away (Lam and Heegde, 2010).

2.12.2 Dung

In many places cattle are not kept in stales and are, at least for a part of the day, free roaming. Dung collection will not be simple with families who keep free roaming cattle as this new activity might be seen as an inconvenience.

2.12.3 Condense formation

Relative humidity inside the reactor is 100%. If the temperature of the gas drops, i.e. during the passage through an underground pipeline, the (absolute) humidity decreases and water condenses. This water may eventually obstruct the gas flow inside the gas pipeline. Therefore, it is necessary to drain condensed water. A special device, a water trap, for collecting the condensed water needs to be implanted at the lowest point in gas pipe line. This gadget needs to be placed with care especially so that the gas flow will not be hampered.

2.12.4 Scum formation

Scum formation and/or floating layers on top of the substrate in the digester, can be a serious maintenance problem for biogas plants which are fed with a substrate that contains straw-like material. No problems have been reported with common use of dung. However when others especially lighter materials like husks are used, scum formation may take place readily. Also poultry droppings and protein-containing wastes (like slaughtering wastes and wastewater) also have a bad reputation in this respect.

Scum formed inside the reactor may eventually even clog the gas pipeline, and/or the outlet of the digester. When a relative big portion of gas is escaping from the outlet, a scum layer will be the problem. The only solution is then to open up the digester from above and take out the scum with a bucket or a stick (Lam and Heegde, 2010).

2.12.5 Sediment formation

Collection of dung from stales with a non-paved floor and from farmyards can lead to pollution of the dung with gravel and soil. These heavy parts will accumulate at the bottom of the digester as sediment that needs to be removed when it takes up too much volume.

2.13 Social - Economic and Ecological benefits of Biogas Technology

Although it is regarded a capital intensive project, biogas technology has several socio-economic and environmental benefits. Biogas technology plays an important role in providing a clean source of energy that is free from smoke and soot. The use of raw biomass and dung as fuel is common phenomena in the lives of the rural community especially the poor.

Integrating biogas technologies among the dairy farmers could help reduce indoor air pollution, thus reduced incidences of respiratory diseases. A quantitative study carried out in Nepal revealed that households that used biogas energy for their cooking had their respiratory diseases, eye infection and headaches decreased by approximately 40% for women and 20% for male respondents (Katuwal and Bohata, 2009).

The main advantage of anaerobic digestion technology is that it produces renewable energy while stabilizing waste organic matter. This renewable energy can be a part of solving some issues such as climate change and high energy costs. This system reduces odour and the risk of groundwater contamination originating from intensive livestock operations.

2.13.1 Greenhouse gas reduction

Methane emissions in agricultural systems primarily come from three sources: livestock feed fermentation, livestock manure waste, and crop cultivation. Biogas systems can be used to capture methane that would escape into the atmosphere and contribute to climate change, and use it to create energy instead. The 239 livestock biogas systems operating in the United States (U.S) reduce methane emissions by approximately 2 million metric tons of carbon dioxide equivalent annually. These projects provide enough renewable energy to power the equivalent of almost 70,000 average American homes.

Anaerobic digestion of livestock manure has been adopted by the State of California as an eligible project type for the generation of offsets under its statewide cap-and-trade program. This means that there is a developing market demand for offsets from dairy and swine manure digester projects (USDA, 2014).

2.13.2 Protection of the Environment

In addition to reducing methane emissions, some of the many environmental benefits of biogas systems include: Stabilization of nutrients, including substantial reduction of pathogens in manures and food wastes, Nutrient recovery and recycling, Reduction of odors during storage and decomposition, Providing a natural waste treatment process, Reduced volume of waste for transport and land application and Efficient organic decomposition (USDA, 2014).

In the past, agriculture, livestock husbandry and energy were three independent sectors. Reasons to develop manure-biogas digestate system are due to positive environmental impact from reduction of industrial fertilizer use from agricultural perspective, substitution of fossil energy fuel from energy perspective and improvement of manure management system. The GHG emission from manure-biogas-digestate and relation between each of them are shown in Figure 4 (Guo, 2010).

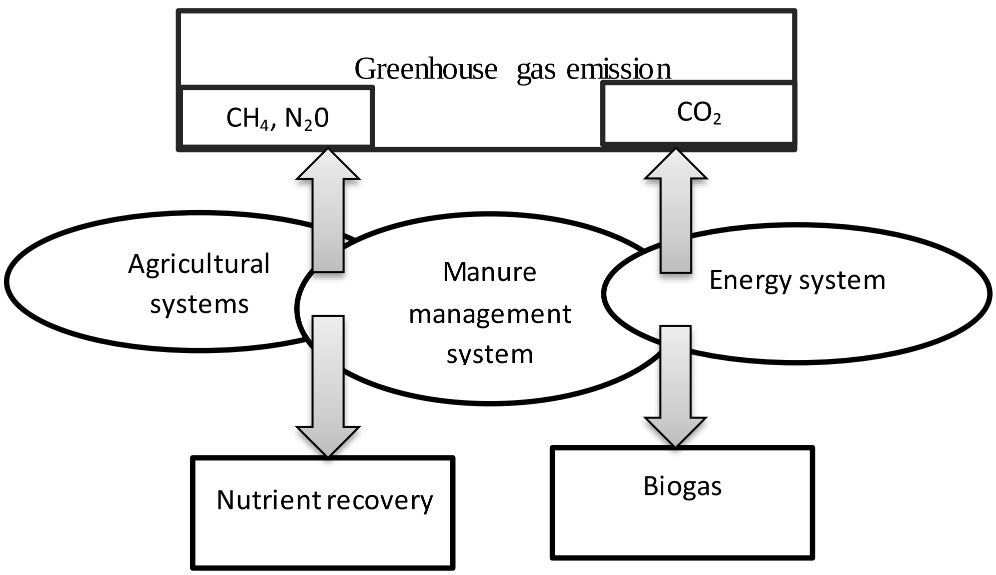

Figure 2.7: Environmental benefits from manure-biogas-digestate system

2.13.3 Enhance Resilient Communities

Biogas systems can support sustainable communities by reducing energy costs and generating revenue. They can also play a vital role in helping communities adapt and become more resilient to the effects of climate change. For example, the distributed nature of the biogas systems can increase the reliability of critical services – food, energy, waste management, wastewater treatment, and transportation – during and after disasters (USDA, 2014).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Research Design

Both descriptive survey and empirical research methods were used in assessing the potential of biogas energy from the feedstocks that were easily available to the residents.

3.2 Study area

Kaitui location is located in Soliat ward, Soin/Sigowet constituency, Kericho County.

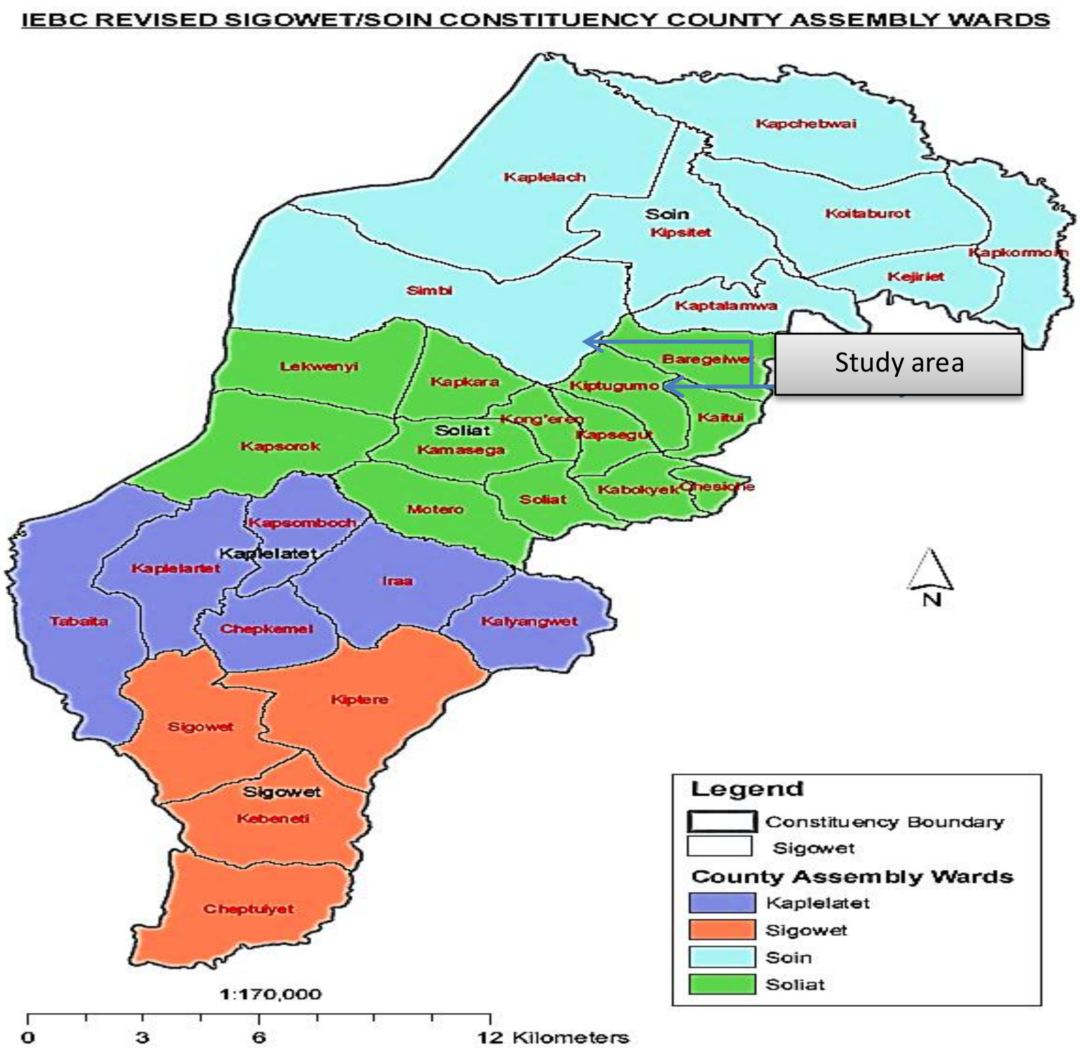

Figure 3.1: Site map (CBS, 1999)

It consists of Kaitui, Kiptugumo, Sombicho and Chemutian sub-locations with an average population of 4,700 people and 602 households. The respondents sampled from the entire area of study composed of small scale farmers, employed cum farmers and the employed.

3.3 Sample Size determination

The study adopted a probability sampling design in which each item in the target population was accorded equal chances of being included in final sample. This was realized by making random samples per sub-location and adding up to represent the entire location. According to Mugenda and Mugenda (2003) 10% to 30% of the total population is appropriate for the study. The respondents were selected from residents using random sampling technique involving cluster sampling method. It was conducted in the four sub-locations each being accorded equal chance of participation.

Sample size determination for the residents was done using the Fisher formula as recommended by Mugenda & Mugenda, (1999). When the population is more than 10,000 individuals, 384 of them are recommended as the desired sample. There were 602 households in the study area. This population was used to derive the sample size as indicated below:

$$nf = \frac{n}{1+\frac{n}{N}} \quad \ldots\ldots 10$$

nf= desired sample size when the population is less than 10,000,
n= desired sample when the population is more than 10,000,

N= estimate of the population size.
Using the above formula, sample size will be:

$$nf = \frac{384}{1+\frac{384}{602}}$$

= 234 households

3.4 Sample procedure

Proportional random samples of the households were selected from each sub-location. Table 3.1 shows sample households within the entire location.

Table 3.1: Sample households

Sub-location	Number of households N	Sample households	Random sample(30% sample household),n
Kaitui	180	69	21
Kiptugumo	111	50	15
Sombicho	144	55	17
Chemutian	167	60	18
Total	602	234	71

3.5 Data collection techniques

Data collection was done through interviews and empirical research method (experimental method) depending on the specific objective.

3.5.1 Interviews

The chosen sample of respondents was interviewed within Kaitui location (Table 3.1). In-depth structural interviews were carried out to determine the number of animals they rear (cows and goats) thereafter; the average animal manure calculated as per Table 2.4, availability of bagasse and avocados to ascertain the option of adopting biogas energy technology (Table 4.2).

They were asked to state and quantify the energy source used in their day to day cooking and heating purposes giving the approximate duration it takes when used continuously. Firewood consumption was recorded on the basis of mass of backloads, and bundles

(Table 4.1). The respondents were interrogated on the know-how of the biogas technology and how they gauge its viability (Appendix 1).

3.5.2 Experiments

Several experiments on quantity of heat and anaerobic digestion of different feedstocks (single substrate digestion for the control experiments and co-digestion) were conducted. For all the digestion experiments, eight replicate plastic bio-reactors each of volume 15L were designed and used to allow simultaneous operations with similar experimental conditions. Thermometers (-10^{o} C-100^{o}C), electrical balance and gas jars were used to measure temperature (slurry and ambient), mass of substrates and gas volume respectively. The hydraulic retention time was 30 days.

3.6 Source of substrates

Animal manure (cow dung and goat manure) and avocados were collected from the farmers within the study area. The bagasse was obtained from chewed sugarcane which is the major cash crop in Kaitui location.

3.7 Heating value of wood fuel energy

The requirements were: water, a small aluminium container of a known specific heat capacity, thermometer, firewood and electrical balance.

3.7.1 Determination of heating value of firewood

1000 g of water was poured into the aluminium calorimeter and its initial temperature recorded (T_1). A mass of a reasonable bundle of firewood was measured with the initial mass (M_1). It was used to heat water to a final temperature (T_2) then heating stopped and the remaining mass of firewood measured (M_2).The energy supplied by firewood was depicted from equations below.

The mass of firewood used, $\Delta M = M_1 - M_2$

Temperature change, $\Delta T = T_2 - T_1$

Heat energy supplied by firewood Q= Heat energy gained by calorimeter $(M_c C_c \Delta T)$ + Heat energy gained by water ($M_wC_w\Delta T$).

$$Q = M_C C_C \Delta T + M_W C_W \Delta T \quad \ldots\ldots 11$$

Q-Heat energy, M_c-Mass of calorimeter, C_c-Specific heat capacity of the container, M_w – Mass of water, C_W-Specific heat capacity of water, ΔT-Change in temperature (Oyelami and Bolaji, 2016).

3.7.2 High heating value of biogas compared to firewood

The HHV of biogas was calculated and compared to the heating value of firewood to ascertain the energy difference. This difference was used to derive energy savings arising from adoption and use of biogas energy at the household level.

3.8 Biogas production from avocado pulp, bagasse, cow and goat manure

There were four single substrate digestions which served as control group; cow manure C.M, goat manure G.M, avocado pulp A.P and bagasse B, for comparison purposes. 4 Kg of each feedstock were collected and subjected to pre-anaerobic digestion treatments of homogenization through pulverization (maceration to obtain small size particle), screening (sorting, separation and removal of fibrous solids) and mixing with water in the ratio of 1:2. They were then fed into replicate 15 L plastic bio-digesters as homogenized slurry.

To eliminate the high volume of CO_2 in the entire reaction process, biogas produced was bubbled through concentrated potassium hydroxide solution to absorb it since it is a strong alkali. Hydrogen sulphide gas was trapped by passing the gas through iron wool (Wante et al., 2014).

Since biogas is insoluble in water, a pressure building up due to its production as a result of anaerobic digestion provided the driving force for displacement of water in the gas jar. The volume of displaced water was measured to represent the amount of biogas produced (Figure 3.2). Daily and cumulative biogas volumes were recorded throughout the HRT and presented in Table 4.3.

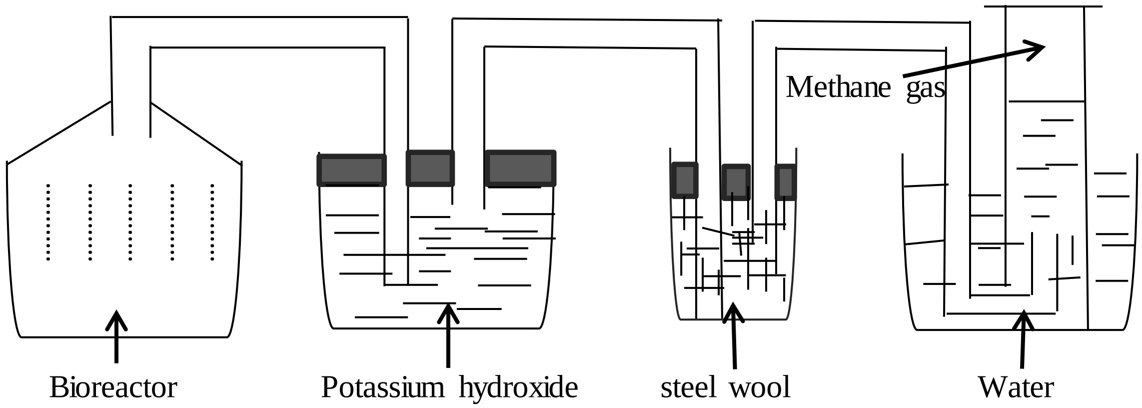

Figure 3.2: Experimental setup for anaerobic digestion data collection

3.9 Determination of biogas production from co-digestion

For the purpose of this research, there were four x:y proportions aimed at investigating the effect of co-digestion of cow manure with other substrates as in Table 3.2.

Table 3.2: Substrate treatment

Treatment	Description	Ratio
D1	CM+GM	1:1
D2	CM:AP	1:1
D3	CM:B	1:1
D4	CM:ALL	3:1:1:1

Water was added in the ratio of 1:2 to each substrate mixture and the experimental setups similar to Figure 3.1 were used.

3.10 Measurement and monitoring of different parameters

Biogas generated was measured at specific time of the day (8:00am) to ensure 24 hour gas production period. The volume of the gas in milliliters (ml) was measured by downward displacement of water in a measuring cylinder calibrated to 1ml scale range. The ambient temperature, A_T and slurry temperature, S_T were recorded periodically after every five days for the entire retention period (30 days).

3.11 Data Presentation and Analysis

To determine the average amount of energy used per household, the data collected in the experiment were used to compute it by relating ΔM to Q (from equation 9)

For the other experiments on biogas production, both by single substrate digestion and co-digestion, data collected were tabulated and subjected to Microsoft excel computer package for analysis.

CHAPTER FOUR
RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents data collected through interviews, experiments and additional relevant literature in an attempt to address all specific objectives in the Sub-section 1.4.1.

4.2 Sources of Energy

The study found out that firewood, kerosene, charcoal, liquefied petroleum gas and electricity were in use within the study area. The majority of the respondents interviewed used firewood (64.79%) while none of them used biogas energy because they had not been adopted (Table 4.1).

Table 4. 1: Household energy use

Energy Source	No. of households	Percentage, %	Quantity
Firewood	46	64.79	4 bundles/ week
Kerosene	5	7.04	4 liters/ week
Charcoal	12	16.90	1/4 a bag/week
LPG	6	8.45	1.5kg /week
Electricity	2	2.82	
Biogas	-	-	-
Others	-	-	-

Of the 71 households interviewed, 46 of them used firewood which translates to 65 % of the total respondents,7 % used kerosene,17% used charcoal, 8% used the LPG, 3% used electricity and 0% used biogas energy (Figure 4.1).

The disparities in percentages were attributed to factors which ranged from the traditional know-how to the knowledge gaps on the worth and availability of other renewable energy sources. Though biogas technology was not so new to many respondents, technicalities behind its adoption, operation and implementation were quite evident.

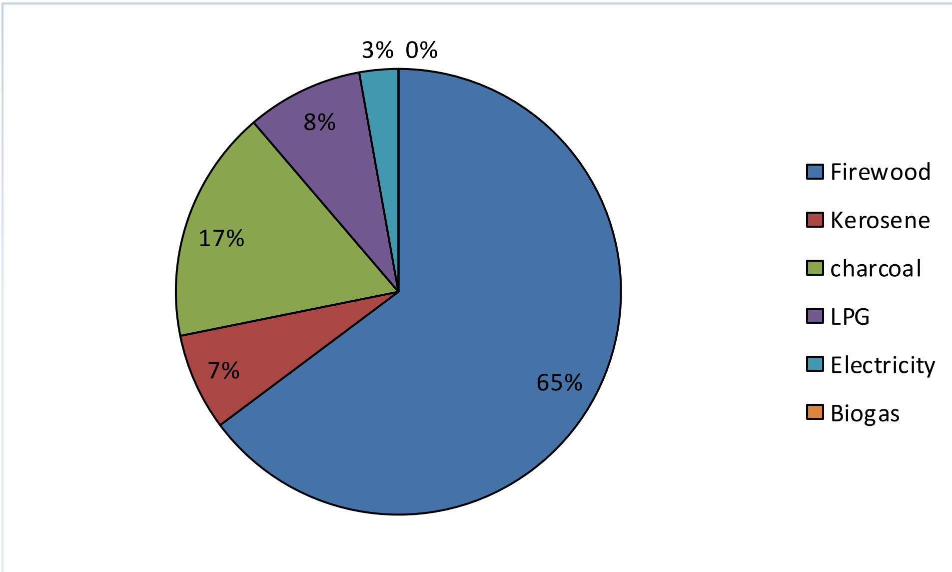

Figure 4.1: Percentage fuel energy use

The study found out that residents within the area of study had adequate feedstocks appropriate for biogas generation (Table 4.2). This could enhance forest cover by reducing overdependence on woodfuel, thus restoring the dwindling woodlands since challenges emanating from deforestation like decrease in water levels in the rivers were so pronounced.

4.3 Biogas production volumes

Several experiments were conducted and the average data for the daily and cumulative gas volumes recorded. Different feedstocks digested took different activation days before producing the gas (Table 4.3) and at the end of HRT, different peak cumulative volumes were realized.

Table 4.2: Availability of feedstocks

Feedstock	Households with direct access to the feedstocks	Households with potential access to the feedstocks
Cow manure	59	64
Goat manure	28	47

Sugarcane	63	71
Avocado plants	52	58

Table 4.3: Average daily/Cumulative gas production volumes

Average daily gas volume (ml) (DGV)/ Cumulative gas volume(ml) (CGV)																
DAY	C.M		G.M		A.P		B		CM + GM		CM + AP		CM + B		CM + ALL	
	DGV	CGV	DGV	CGV	DGV	CGV	DGV	CGV	DGV	CGV	DGV	CGV	DGV	CGV	DGV	CGV
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	5	8	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	7	15	1	1	2	2
7	0	0	0	0	0	0	0	0	0	0	6	21	3	4	4	6
8	0	0	0	0	0	0	0	0	1	1	9	30	5	9	6	12
9	0	0	0	0	0	0	0	0	3	4	9	39	4	13	5	17
10	0	0	0	0	0	0	0	0	5	9	7	46	6	18	9	26
11	2	2	0	0	0	0	0	0	9	18	4	50	3	21	4	30
12	3	5	0	0	0	0	0	0	8	26	11	61	5	26	7	37
13	4	9	0	0	0	0	0	0	7	33	11	72	4	30	7	44
14	5	14	0	0	1	1	0	0	9	42	11	83	7	37	6	50
15	5	19	0	0	2	3	0	0	7	49	13	96	7	44	4	54

16	7	26	0	0	2	5	2	2	5	54	6	102	4	48	3	57
17	9	35	0	0	2	7	2	4	2	58	3	105	4	52	3	60
18	3	37	3	3	2	9	5	9	1	59	4	109	3	55	1	61
19	1	38	2	5	4	13	5	14	-	59	1	110	-	55	2	63
20	3	41	4	9	2	15	4	18	1	60	2	112	3	58	1	64
21	4	45	3	12	3	18	7	25	2	62	2	114	6	64	1	65
22	-	45	5	17	4	22	-	25	2	64	1	115	2	68	-	65
23	3	48	-	17	3	23	3	29	2	66	1	116	3	71	1	66
24	3	51	7	24	3	26	4	33	2	68	1	117	2	73	2	68
25	4	55	5	29	5	31	4	37	-	68	3	120	-	73	-	68
26	1	56	4	33	2	33	7	44	1	69	3	123	2	75	1	69
27	1	57	5	38	5	38	5	49	1	70	1	124	1	76	1	70
28	-	57	6	44	4	42	3	52	1	71	1	125	-	76	2	72
29	1	58	4	48	4	44	-	52	-	71	1	126	1	77	-	72
30	2	60	-	48	3	47	3	56	2	73	2	128	1	78	1	73

4.3.1 Cow manure alone

In single substrate digestion, cow manure took 10 days before the gas was produced. Within the entire retention time, there were two instances of zero gas production and a peak cumulative volume of 60 ml attained (Table 4.3).

A graph of cumulative gas volume against retention time for this experiment showed a volume gradient of 2.6028 and a goodness of fit (R^2) of 0.927 (Fig 4.2).

This could be attributed to the composition of cow manure since it has high percentage of nutrients required by the anaerobic bacteria for their multiplication as reported by Rousan and Zyadin, 2014.

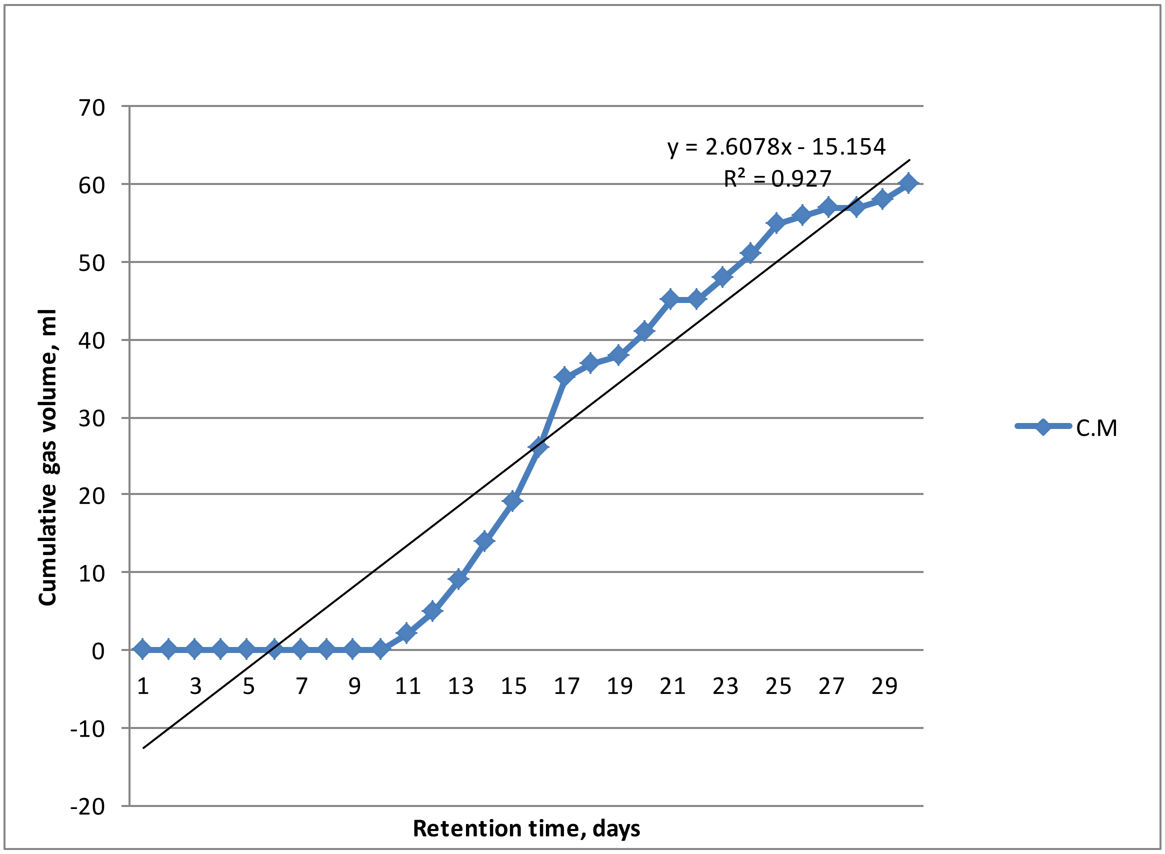

Figure 4.2: Cumulative gas volumes against Retention time for C.M

4.3.2 Cow manure and Goat manure

For the single digestion of goat manure, gas production began on the 18th day and within the HRT, there were two days of negligible gas volume. A peak cumulative gas volume of 48 ml was realized. When these feedstocks were co-digested, different results were obtained. The time taken for the first trace of the gas to be produced was reduced to 8th day and a peak cumulative volume of 73 ml was recorded.

A graph of cumulative gas volume against retention time for the three experiments indicates varying gradients with C.M having a volume gradient of 2.61, G.M with 1.57 and the co-digested (C.M+G.M) scoring 3.21, R^2=0.91 and a lag phase (λ) of 7days (Figure 4.3).

Co-digestion improved the gas return and reduced the initial period before gas yield commenced. This improvement in the volume gradient was attributed to positive change in the net C/N ratio (Table 2.8).

Wante et al., (2014) reported that co-digestion of cow manure with goat manure results in increased gas production which agrees with this study.

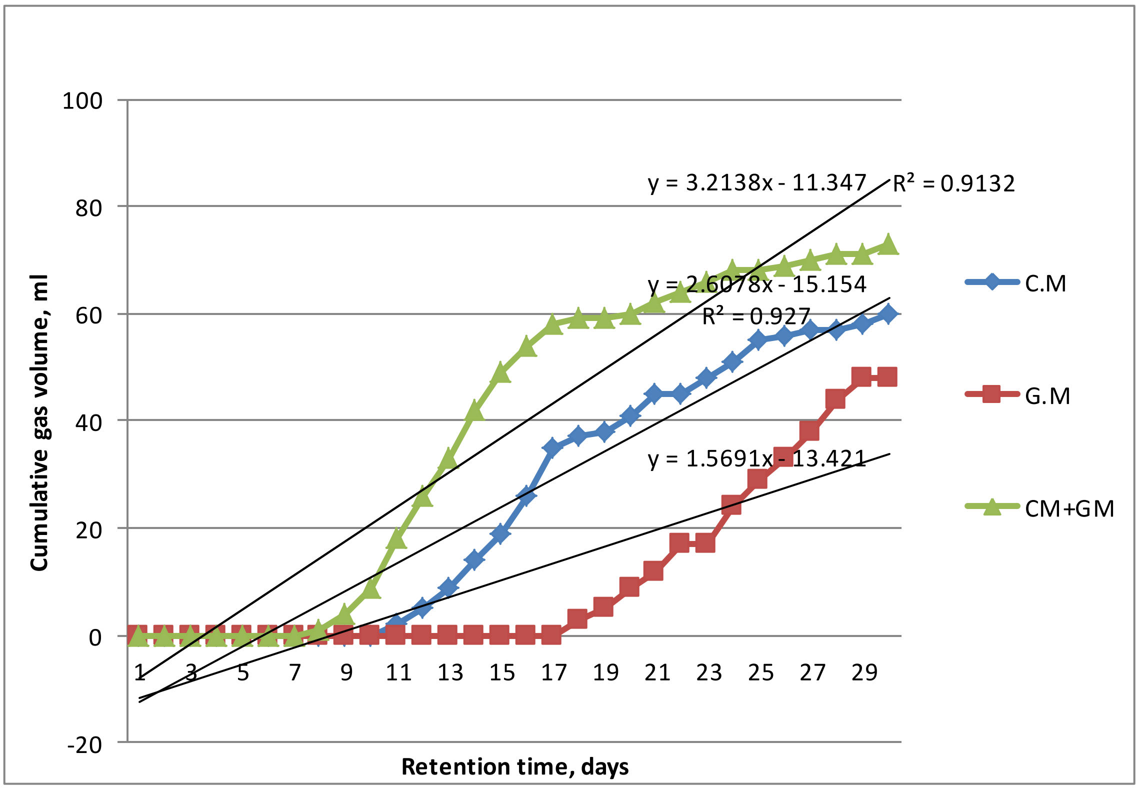

Figure 4.3: **Cumulative gas volumes against Retention time for C.M and G.M**

From the gradients, it is possible to calculate the volume ratio (V.R) of biogas produced from substrate co-digestion to single digestion. The V.R for co-digestion of cow manure with goat manure to single digestion of cow manure is given by;

$$V.R = \frac{(\text{C.M} + \text{G.M})\ \text{gradient}}{(\text{C.M})\ \text{gradient}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 12$$

$$V.R = \frac{3.2138}{2.6078} \qquad V.R = 1.2$$

Similarly the V.R for (C.M + G.M) to single substrate digestion of goat G.M is;

$$V.R = \frac{\text{(C.M + G.M) gradient}}{\text{(G.M) gradient}}$$

$$V.R = \frac{3.2138}{1.569} \qquad V.R = 2$$

Comparing the volume ratios, its evident that co-digestion increased the gas production volume by a coefficient of 1.2 & 2 summarized in equation 13.

$$(C..M + G..M) = 1.2\text{C.M},\ (C..M + G..M) = 2\text{G.M} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 13$$

4.3.3 Cow manure and Avocado pulp

Biogas production from anaerobic digestion of fleshy parts of avocado fruit started from 14th day of HRT and attained peak cumulative gas volume of 47ml (Table 4.3).Upon co-digestion with cow manure, the results obtained varied. The first volume of the gas produced was realized on the 4th day of HRT with a peak cumulative gas volume of 128ml being recorded.

The volume gradient for the co-digestion of avocado with manure was 5.17, R^2=0.92 and λ=3 while that of single digestion of avocado was 1.63.Similary the gradient for the single digestion of cow manure was 2.61 (Fig 4.4).

Therefore the V.R,

$$V.R = \frac{\text{(C.M + A.P) gradient}}{\text{(A.P) gradient}}$$

$$V.R = \frac{5.172}{1.6283}$$

$$V.R = 3$$

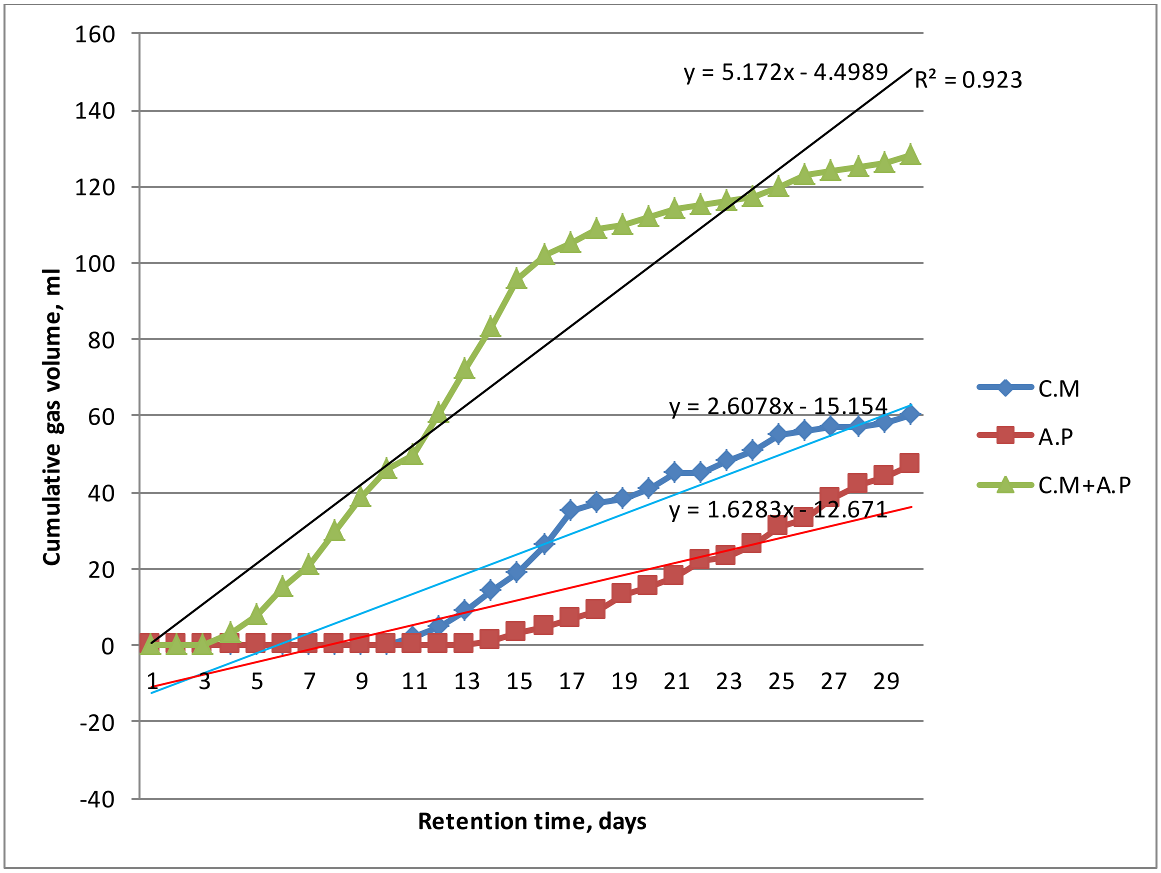

Figure 4. 4: Cumulative gas volumes against Retention time for C.M and A.P

Similarly the V.R for (C.M+A.P) co-digestion to single digestion of cow manure (C.M) is given by:

$$V.R = \frac{(\text{C.M} + \text{A.}P)\ \text{gradient}}{(\text{C.M})\ \text{gradient}}$$

$$V.R = \frac{5.172}{2.6078}$$

$$V.R = 2$$

This implies that co-digestion had a positive impact on the generation of the biogas in comparison to single substrate digestion.

$(C..M + A..P) = 3\text{A.P}$, $(C..M + A..P) = 2\text{C.M}$ ………………...…………………………14

The V.R obtained suggests that the volume of biogas produced from co-digestion of cow manure with avocado pulp is 3 times the volume produced from single digestion of avocado and twice that of cow manure (Equation 14) with a standard deviation of 3.69.

The findings are in agreement with Luostarinen et al., (2011) who reported that the substrates with a high percentage of fats produce more biogas compared to those with high percentage of proteins or carbohydrates. However, these results proved higher volume of biogas is realized when substrates with high fat content is co-digested with cow manure to supplement other nutrients required by anaerobic bacteria for their growth (Table 2.5).

These discrepancies in cumulative gas volumes could be tied to the chemical composition of avocado pulp. Avocado pulp contains high lipids content, which makes the pulp the portion of greatest interest. Lipids vary from 5 to 35%, being formed mostly by unsaturated fatty acids. High lipids and low carbohydrate levels remain in avocado pulp after water removal, conferring high dry matter content to the product. It is considered one of the cultured fruits presenting the lipid fraction as the major component (Patricia et al., 2016).

4.3.4 Cow manure and sugarcane bagasse

Single substrate digestion of bagasse recorded the initial gas from the 16^{th} day of HRT and attained a peak cumulative gas volume of 56 ml (Table 4.3). Upon co-digestion with cow manure, the time taken to produce the first gas volume was reduced to 6^{th} day of HRT and the peak cumulative volume of 78 ml reached.

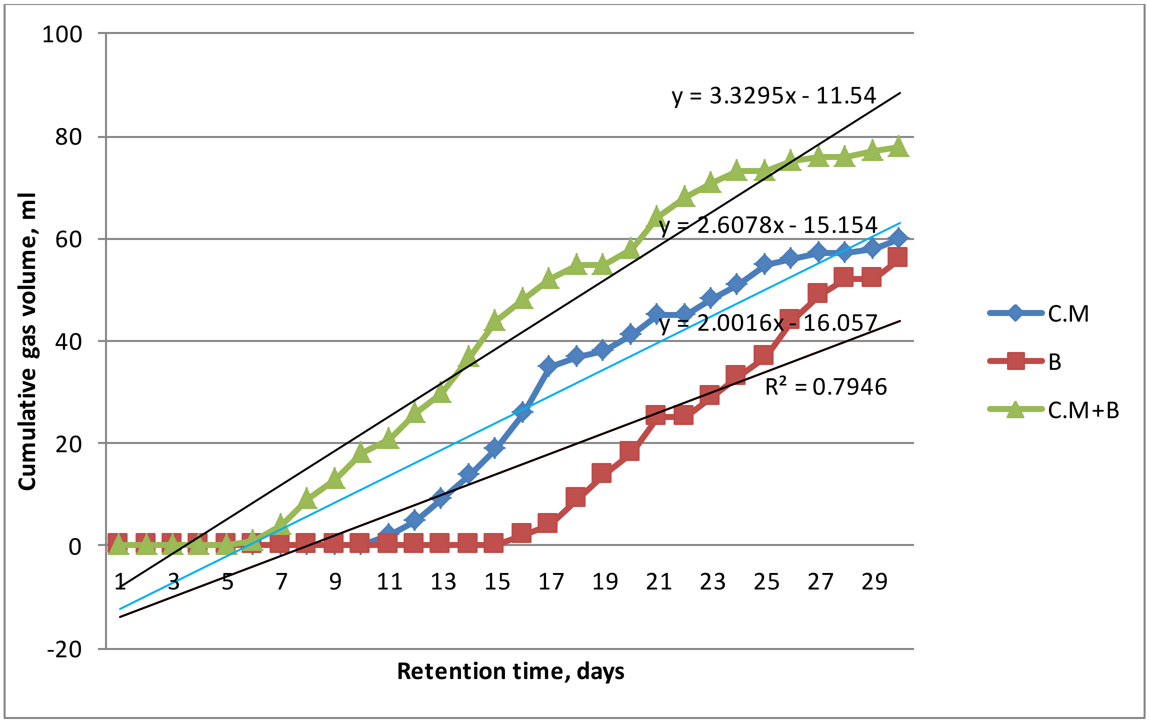

Figure 4.5: Cumulative gas volume against Retention time for C.M and B

The volume gradient resulting from co-digestion of bagasse with cow manure was 3.33, R^2 =0.79 and λ=6 while for single digestion of bagasse was 2.00. Similarly the single anaerobic digestion of cow manure gives a volume gradient of 2.61 (Fig 4.5).

By calculating the volume ratios;

$$V.R(C.M + B : B) = \frac{3.3295}{2.00016}$$

V.R=1.7

$$V.R(C.M + B : C..M) = \frac{3.3295}{2.6078} \qquad \text{V.R=1.3}$$

From the V.R derived from the equation, it's clear that more gas is produced during co-digestion than in single substrate digestions of bagasse and cow manure. This could be attributed to the fact that though bagasse is fibrous and hard to digest, it contains a lot of sugar. This sugar adds nutrients to cow manure which is easily digestible, thus increasing the cumulative gas production gradient. Bagasse is composed of cellulose (37% dry mass), hemicellulose (28% dry mass) and lignin (21% dry mass) (Bon, 2007).

4.3.5 Cow manure, goat manure, avocado and bagasse

When all the feedstocks were co-digested in the same digester, there was a positive deviation in the gas volume but could not get to the peak cumulative gas volume derived from the co-digestion of cow manure with avocado pulp. This could be attributed to the decrease in mass of avocado pulp as a result of new mass mixing ratio from 1:1 (CM:AP) to 3:1 (C.M:A.P) due to its chemical composition. Avocado pulp has different nutrients components that favor the production and performance of anaerobic bacteria.

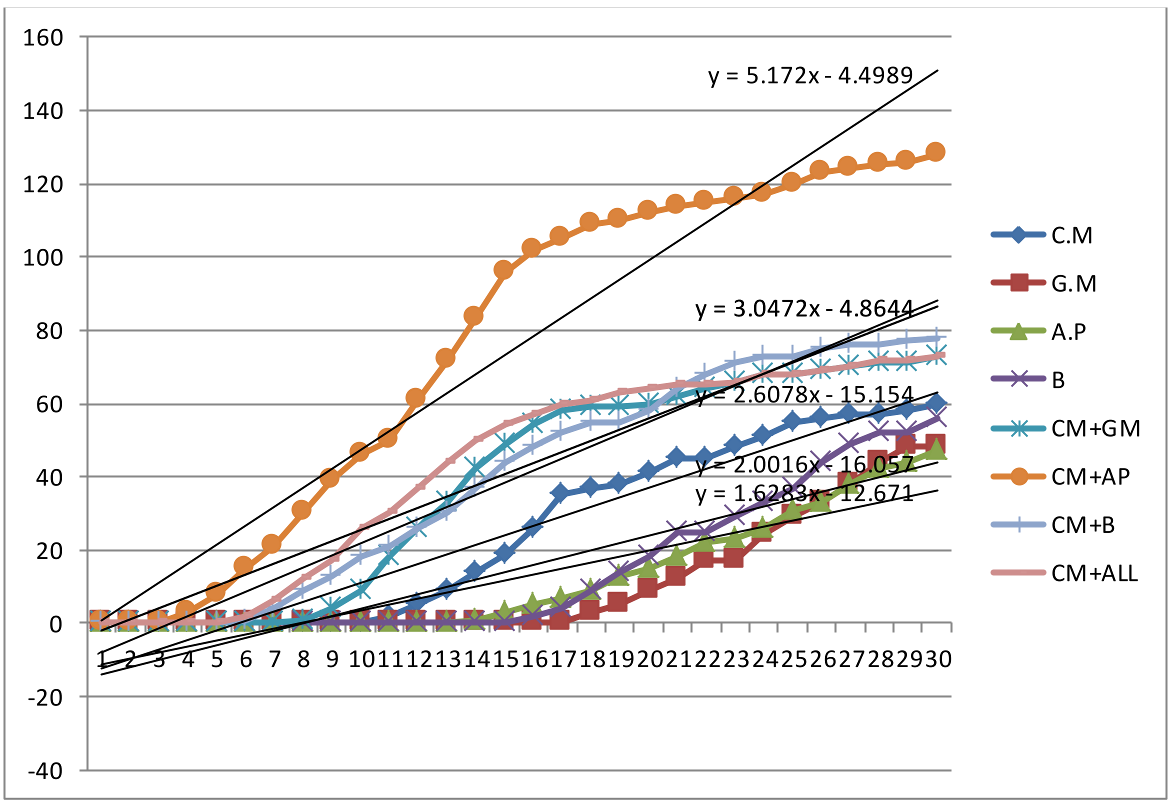

Figure 4.6: Cumulative gas volume against RT for all feedstocks digested

The ambient and slurry temperature values were monitored in determining the rate of digestion and retention of the process, since temperature is very important. Ambient temperature ranged between 25°c and 28°c while slurry temperature which was slightly higher ranged between 27°c and 33°c for all the experiments done. The ambient temperature affects the rate of digestion due to the outside walls of the digester surface make direct contact with the atmosphere, hence the digester walls absorb or loose heat to immediate environment.

4.4 Wood fuel savings derived from the adoption and use of biogas energy.

From the data collected, it was evident that woodfuel is the most used energy resource. The sum of firewood use (65%) and charcoal (17%) had the highest percentage, 82%. This percentage is equivalent to the rate of deforestation in search for woodfuel (Fig 4.1).

Since the highest percentage of the respondents used firewood, experiments on quantity of heat were conducted to ascertain the average energy use per household. The results (Table 4.4) were tabulated then subjected to the quantity of heat formula (equation 11).

Table 4.4: Woodfuel energy changes

	M_c (g)	**M_w (g)**	**C_c (J/kg/k)**	**C_W (J/kg/k)**	**M_1 (g)**	**M_2 (g)**	ΔM	**T1**	**T2**	ΔT
Trial 1	175.6	1000	900	4200	200	22.8	177.2	20	88	68
Trial 2	175.6	1000	900	4200	200	39.3	170.7	20	91	71
Average	175.6	1000	900	4200	200	31.1	174.0	20	89.5	69.5

To determine the wood fuel energy; Quantity of heat, $Q = M_C C_C \Delta T + M_W C_W \Delta T$

$Q = (1kg*4200J/kg/k*69.5k) + (0.1756kg*900J/kg/k*69.5)$

$Q = 291900J + 10983.78J$

$\mathbf{Q} = 302883.78\ J$, But $1MJ = 10^6 J$

Therefore $Q = 0.3MJ$

1 bundle of firewood = 10kg, 4 bundles = 40kg per week

0.174kg (ΔM) yields 0.3MJ, equivalent to1.7MJ/kg

40kg of firewood equates to 68.97MJ

≈70MJ/week

The heating value of methane is 39.82MJ/m^3, therefore 70MJ/week is equivalent to 1.75m^3 of methane which is approximately 2m^3.

82% of the total household population (602) is about 495 households.
70MJ/week equates to3640MJ/year/household

*For 495 households it equates to (3640*495) =1,801,800MJ/Year*
1kg of wood fuel =1.7MJ,

1,801,800MJ = 1,132.35 tonnes of woodfuel

The study found out that if renewable energies like biogas energy are adopted in place of woodfuel, forest cover will be enhanced since about 1,132.35tonnes of woodfuel will have been substituted. The benefit will even be realized if the same is implemented in the entire County of Kericho and the country at large.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter highlights significant findings that the research has been able to establish. They are presented in the order of the specific objectives. Conclusions are drawn and recommendations made.

5.2 Conclusion

From the research findings, the most commonly used form of fuel by households in Kaitui location was wood fuel. 64.79% of the respondents used firewood while electricity was least used (2.81%). The other forms of fuel used by households in the study area were charcoal (16.9%) kerosene (7.05%) and LPG (8.45%). It was found that biogas technologies had not been adopted (0%). Some of the factors identified to have limited the adoption of woodfuel conservation technologies like biogas energy were the tradition, cost implication and technicalities behind installation, maintenance and the use.

From the experiments conducted using firewood which was the main energy source, it was found out that the average energy use per household is 70 MJ per week which equates to $2m^3$ of biogas if adopted.70 MJ/week translates to 3,640 MJ/year per household.

The anaerobic digestion of substrates was found to be more effective during co-digestion than in single substrate digestion. The co-digestion of avocado pulp with cow manure produced the highest cumulative gas volume (128 ml) within the hydraulic retention time of 30 days with a volume gradient (m_v) of 5.172. Single digestion of cow manure reached a peak volume of 60 ml ($m_{v=}$2.6078) while single digestion of avocado pulp had a peak volume of 47 ml ($m_{v=}$1.6283). Other co-digested feedstocks with cow manure were; goat manure which attained a peak volume of 73 ml, and bagasse with a peak volume of 78 ml.

The findings showed that the total energy usage per household was 3640MJ/year which equates to 1,801,800MJ/Year for an average of 495 households. From the calculations done, this energy is equivalent to 1,132.35 tonnes of firewood. This means that if each household adopts biogas technology, 1,132.35 tonnes of wood fuel saving would be realized resulting in better forest cover.

5.3 Recommendation

i) Biogas energy Centre needs to be established in Kericho County for dissemination of biogas energy technologies.

ii) Avocado plants need to be adopted not only for subsistence or commercial purposes but also for energy.

iii) Further research to be done to establish the best variety of avocado that yields more biogas energy with a less market price since the variety used in this study was Hass type.

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APPENDICES

Appendix 1: Interview questions

1. Sources of energy used

Energy source	mostly used	Rarely used	Never used	Not sure
Firewood				
Kerosene				
Charcoal				
LPG				
Electricity				
Biogas				
Other(specify)				

2. Knowledge in Biogas energy technology

i) Have knowledge and uses biogas energy ☐

ii) Have knowledge but not using biogas ☐

iii) No knowledge, just heard of it ☐

iv) No knowledge, never heard of it ☐

3. Availability of biogas feedstocks

Number	0	1	2	3	>3
Cows					
Goats					
Avocado plant					
Sugarcane					

4. Efficiency of Biogas energy technology

i) Excellent ☐

ii) Very good ☐

iii) Good ☐

iv) Poor ☐

v) Don't know ☐