KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY
COLLEGE OF ENGINEERING

WASTE TO ENERGY: COMPARISON OF THE QUANTITY AND QUALITY OF BIOGAS PRODUCED FROM FRUIT WASTE AND SLURRIES PREPARED WITH SLAUGHTER AND HUMAN WASTES

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BY

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CERTIFICATION

I hereby declare that this submission is my own work and that to the best of my knowledge, it contains no material previously published by another person or material which has been accepted for the award of my other degree of the University, except where due acknowledgement has been made in the text.

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DEDICATION

I dedicate this thesis work to my mother, Patience Dartey; my father, Jacob Amenorfe and the entire Royal Amenorfe Family. I also dedicate this work to the entire membership of the Yamfo Association of Tertiary Students (YATS) which I founded with the aim of supporting education,starting from Yamfo.

ABSTRACT

Waste management has become one of the major challenges facing today's world cities. The waste management problem is more pronounced in the cities of developing countries especially those of the Sub-Saharan Africa including Ghana. The high rate of rural-urban migration coupled with weak enforcement of settlement laws have led to the springing up of slums in most parts of these cities. However, the low commitment of city authorities to enforce environmental laws coupled with lack of funds has worsened the waste management challenges which are more pronounced in slums.

Meanwhile, the current technologies (open-dumping and disposal into the ocean) employed in managing the wastes generated in these cities are non-sustainable and highly detrimental to the environment. Also, the high organic fraction content of wastes generated in the developing countries coupled with high capital cost make it difficult to treat wastes with the technologies used by the developed countries. There is therefore the need to search for and employ organic waste treatment technology that is sustainable and thus best fitting for developing countries. This is the anaerobic digestion process in which waste is converted to energy (in the form of biogas) and bio-fertilizer.

This study was conducted to determine the amount of biogas (digester-specific and substrate-specific biogas production) and quality of biogas that will be produced by fruit wastes and slurries prepared with slaughter waste and human waste.The study was also to determine the slurry that will be suitable for optimum commercial biogas production.

A composite of mango, pineapple and papaw wastes was digested in a 450 m^3 digester at Adeiso while four different slurries (S_1 to S_4) prepared with varying proportions of slaughter and human wastes were digested anaerobically in two 8 m^3 fixed-dome (WASAZA design) digesters built at GIDA site in Ashaiman. The data obtained were analyzed with the 2007 version of Microsoft Excel.

Results obtained showedthatthe digester-specific biogas production of slurries S_1, S_2, S_3, S_4 and S_5 produced are0.167, 0.120, 0.278, 0.325 and 0.723 m^3 biogas/m^3 digester volume/dayrespectively while the substrate-specific biogas production was 0.121, 0.344, 0.432, 0.327 and 0.270 m^3 biogas/kg ODM/day respectively. The daily average methane (CH_4) produced by the slurries range from 52 to 66 % biogas by volume while their carbon dioxide (CO_2) production was from an average value of 32 to 38 % biogas by volume. Also, hydrogen sulphide (H_2S) produced by the slurries was from an average value of 216 ppm to 625 ppm.

Slurry prepared with about 50%HW and 50%SW was found to be the most suitable for optimum commercial biogas production.

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LIST OF ABBREVIATIONS AND ACRONYMS

AD	Anaerobic Digestion
AFPRO	Action for Food Production
ARI	Animal Research Institute
ARTI	Appropriate Rural Technology Institute
ASHMA	Ashaiman Municipal Assembly
BMW	Biodegradable Municipal Waste
BTC	Biogas Technology Centre
CAMARTEC	Centre for Agricultural Mechanization and Rural Technology
COD	Chemical Oxygen Demand
C/N Ratio	Carbon to Nitrogen Ratio
CSIR	Council for Scientific and Industrial Research
CSTR	Continuously Stirred Tank Reactor
DECC	Department of Energy and Climate Change
DM	Dry Matter
ETC/SCP	European Topic Centre on Sustainable Consumption and Production
FAO	Food and Agricultural Organization
GIDA	Ghana Irrigation Development Authority
GTZ /GATE	Deutsche Gesellschaft für Technische Zusammenarbeit/ German Agency for Technology Cooperation
HDPE	High-Density Polythene
HRT	Hydraulic Retention Time
HW	Human Waste
ISAT	Information and Advisory Service on Appropriate Technology
LPG	Liquified Petroleum Gas

MA	Mineral Ash
MC	Moisture Content
MCFC	Molten Carbonate Fuel Cell
NBEP	National Bureau of Environmental Protection
NMHC	Non Methane Hydrocarbons
NYCDS	New York City Department of Sanitation
NYCEDC	New York City Economic Development Corporation
ODM	Organic Dry Matter
OMW	Organic Municipal Waste
OLR	Organic Loading Rate
PAFC	Phosphoric Acid Fuel Cell
PEM	Polymer-Electrolyte-Membrane
PVC	Polyvinyl Chloride
RCSD	Resources Centre for Sustainable Development
SHU	Sheffield Hallam University
SI	Spark Ignition
SOFC	Solid Oxide Fuel Cell
SSBP	Substrate-Specific Biogas Production
SW	Slaughter Waste
TS	Total Solids
TMA	Tema Metropolitan Assembly
TNAU	Tamil Nadu Agricultural University
USEPA	United States Environmental Protection Agency
VFA	Volatile Fatty Acids
VS	Volatile Solids

WASAZA Water and Sanitation Association of Zambia

W_tERT Waste-to-Energy Research and Technology Council

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Glory be to the Lord God Almighty; for His everlasting love, grace and favour upon methroughout my study.He has protected and granted me travelling mercies and the ability to carry out both thought courses and the research study successfully.

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The data collected from the research would be meaningless and useless if they were not logically presented and properly analyzed. I thank Prof. Ebenezer Mensah (the Agricultural Engineering Departmental Head) for reading thoroughly through my work and making the necessary corrections in the work thus improving its quality. It is worth to mention Dr. Agyare's name here. I thank him very much for painstakingly guiding me through the analysis of my data.

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CHAPTER ONE

INTRODUCTION

1.1 Background

Waste management is one of the major challenges facing world cities, especially those in the developing countries in this 21st Century. It is almost always in the top five ofthe most challenging problems for city managers (UN-Habitat, 2010). While the developed countries are able to deal with the waste management problem, many African and other developing countries are still grappling with it.In the developing countries, the challenge is with the whole waste management system which includes waste collection, transportation, treatment and disposal.In the developing countries, many households in many cities receive no services at all,resulting in far too much waste ending up in the environment (UN-Habitat, 2010).

The conventional waste management method, which was employed in most developed countries until 1970 (UN-Habitat, 2010) and handles waste as a nuisance, does not treat municipal wastes in cost effective and environmentally friendly manner. It only tries to get rid of the waste from the immediate human vicinity by collecting, transporting and disposing it in landfills. These landfills may vary from open dumps or unsanitary landfills as in the case of most developing countries to sanitary landfills in most developed countries. First of all, the collection and transportation of municipal wastes and the management of landfill sites require heavy financial investments and the use of heavy equipment. This makes it difficult for cities with limited revenue base to meet the financial obligations associated with effective waste collection and proper management of the municipal wastes. Secondly, the rapid urbanization of cities is causing a corresponding rapid spatial growth resulting in the scarcity of lands which may hitherto be used for landfill sites development. Many communities are not willing to give their lands out to be used as landfill sites due to the stench and other environmental impacts associated

with landfill sites in developing countries. The high operating cost and the scarcity of lands make the conventional waste treatment method less cost effective and unsustainable.

Wastes, when not properly collected or managed have a lot of repercussions on public health, water bodies, climate change, and the environment and even facilitate flooding.Poorly collected or uncollected solid wastes end up in drains forming blockade to run-offs and waste water thus causing water stagnation in drains.The stagnated water provides breeding and feeding grounds for mosquitoes, flies and rodents,which cause diarrhoeal diseases including cholera, malaria, schistosomiasis, trachoma and various infectious and parasitic diseases.Leachate from unlined landfills percolates into groundwater and nearby surface water bodies thus contaminating them. Additionally,discharging untreatedblackwater or sewage into water bodies causes water pollution resulting in eutrophication.The biodegradable fraction of wastes temporarily stored in collection bins and those deposited at open landfills undergo anaerobic decomposition.Methane, one of the persistent greenhouse gases and carbon dioxide are released into the atmosphere contributing to climate change.

To be able to deal with the challenges posed by the conventional waste management method, many researchers and experts proposed and have been working on the introduction and implementation of sustainable waste managementtechnologies[(Winblad *et al.*, 2004) and (UN-Habitat, 2010)].These technologies manage waste sustainably by handling municipal wastes as resources from which energy and nutrients can be retrieved.Proceeds from sale of the energy and the nutrients generated could offset cost of waste collection and transportation. Also, the nutrients harvested can be used for soil amelioration thus reducing the use of synthetic fertilizers.

The anaerobic digestion of the organic fraction of municipal solid wastes is one of the sustainable waste management techniques. In this process, organic wastes decompose in the absence of oxygen giving off biogas which contains methane, the energy content of the biogas, carbon dioxide, hydrogen

sulphide and other traces of gas and a by-product called effluent. The effluent contains nutrients which are conducive for plant growth and soil amelioration. The energy in the biogas can be used for heating, cooking, lighting, running automobile engines and generator sets.

Even though the application of the anaerobic digestion process in energy production along other renewable energy sources has been in Ghana sincethe mid 1980s (Akuffo, 2008),thepotential contribution of thetechnology towardsthe growth of the country's energy sector was not given much attention compared to other renewable energy options such aswind and solar (Bensah and Brew-Hammond, 2010).

Consequently, not much research has been done in the anaerobic digestion of organic materials in general and organic wastes in particular to ascertain their biogas and energy potential. Also, the suitability of the gas generated from the organic wastes to be used for commercial purposes (running automobiles and generating electricity) remains unknown or uncertain.These unknowns have made it difficult for many possible investors and entrepreneurs, waste management companies, government agencies and even some agro-industries to see the commercial viability of producing biogas from these wastes.

This research therefore sought to determine the biogas generation potential and the energy potential of the biogas generated from fruit waste, slaughter waste and human wastes collected from the study areas.

1.2 Problem Statement

Since the introduction of sustainable waste management technologies which aim at resource recovery from waste, many studies have been undertaken worldwide. In Ghana, similar researches have been conducted in several sectors. Fobil *et al*. (2005) conducted a study on the possibility of treating the

municipal solid waste in Accra by incineration with the prime aim of energy generation.Also, Cofie *et al.* (2006) investigated the possibility of recycling nutrients in human excreta andmunicipal solid waste for use in agriculture.Additionally, a lot of research has been done on waste treatment by composting to recycle nutrients for soil amelioration.

However, the area that has to do with the anaerobic digestion of organic wastes which can provide a three-tier benefit: sanitation, energy and nutrient recovery, still remains at the developing stage.As a result, the quantity and the quality of biogas produced from the anaerobic digestion of organic municipal wastes remain unknown. Also,the anaerobic process conditions under which the generated energy can be used for commercial purposes remain uncertain.Consequently it has become difficult for potential sector (sanitation providers) investors to assess the viability of their business in case they invest in the anaerobic waste treatment for commercial purposes. Also, the health implications of the application of the effluentson crops have not been fully researched into.

1.3 Justification of the Study

Even though there are other sustainable waste management techniques like incineration, pyrolysis, composting, etc., the high organic and moisture content of municipal solid wastes found in urban areas of developing countries make anaerobic digestion the ideal treatment option.A study by Fobil *et al.* (2005) to determine the suitability of using solid wastes from Accra as a fuel for an incinerator for the purpose of generating energyrevealed that it will be impossible to use the wastes to fire the incinerator due to its high moisture content and low calorific value.Even though, municipal organic waste can be treated by composting[(Straus *et al*,2003) and (Cofie *et al*, 2006)], it does not give out energy as in the anaerobic digestion process making it less attractive for commercial purposes.

Determining the quantity and quality of biogas produced from organic wastes is very necessary. The quantity of biogas produced (biogas yield) is required to estimate the volume of biogas that would be produced by fermenting a kilogram of waste in an anaerobic plant. It is also required to estimate the volume of gas produced per cubic meter of the digester volume.Generally, these parameters are essential in determining the size of anaerobic plant that would be built in order to treat a known quantity of organic waste to produce a desired quantity of biogas for commercial application.Also, knowledge aboutthe quality of the biogas produced by the wastes is required in estimating the cost of using the biogas for commercial purposes since the treatment of the biogas or otherwise depends on its quality and specific application (Al Seadi *et al.*, 2008).

1.4 Project Objective

1.4.1 Main Objective

The main objective of the studyis to compare the characteristics of biogas produced from fruit wastes and slurries prepared from varying proportions of slaughter waste and human wastes and determine the conditions under which they are commercially applicable.

1.4.2Specific objectives:

The specific objectives were to:

1. Determine the biogas potential of fruit wastes and slurries (S_1, S_2, S_3 and S_4) prepared from slaughter waste and human waste in the form of:
    a) Digester-specific biogas production
    b) Substrate-specificbiogas production
2. Determine the quality of biogas generatedby the substrates in terms of:
    a) $\%CH_4$ (Percentage methane) content of the biogas
    b) $\%CO_2$ (Percentage carbon dioxide) content of the biogas
    c) $\%H_2S$ (Percentage hydrogen sulphide) content of the biogas
3. Determine the conditions under which the biogas generated from substrates can be used for specific commercial purposes

4. Estimate the commercial energy (electrical and vehicular) production potential of biogas from substrates when fermented in a 1000 m^3 commercial digester and when 1000kg ODM of the substrates are fermented in a biogas plant daily.
5. Determine among the various types of substrates (slurries S_1, S_2, S_3, S_4 and S_5) fermented in the study, the feedstock that is the optimum for commercial biogas production considering its biogas production quantity and quality.

1.5 Hypotheses

i. Feedstock made by mixingtwo or more organic materialsin different proportions has different biogas generating potential.
ii. The energy potential of biogas generated from different feedstock orslurries made from different proportions of same organic materials differs.
iii. The biogas produced from the slurries can be used for commercial purposes without any scrubbing.

1.6 Limitations

Like all other field experiments, this study was not without challenges. The challenges ranged from logistics,difficulty in determining the characteristics of substrates, late arrival of research protocols, and operational challenges.

First of all, logistical constraints made it difficult to collect wastes (slaughter wastes and human faeces) from all over Accra. The wastes however used in this study are those produced within the Ashaiman Municipal Assembly (ASHMA). The slaughter wastes were collected from the Accra Abattoir while the human faeces were from the GIDA site and a manhole within ASHMA.

The complete chemical and biological compositions of all the substrates used in the study were not determined. This difficulty is partly attributable tomalfunctioning of the required testing equipment at

the Animal Research Institute (ARI) where the tests were done. Also, financial constraints made it difficult to perform such compositional tests at other laboratories. In view of this, only the dry matter (DM), Moisture Content (MC), Mineral Ash (MA)and the organic dry matter (ODM) of each substrate used in the study were determined. Other chemical compositions such as carbon content and nitrogen content of the substrates were not measured.

Furthermore, the late arrival of some of the research protocols like the Gas Analyzer and the flow meter made it impossible to have data on the biogas yield and its composition from the start up phase through to the point where the plants were stabilized before the commencement of the tests.

Finally, operational challenges such as digester failure hampered smooth execution of the study. This is because feeding had to be stopped for the faulty digester to be repaired, resulting in non-continuous data collection. Also, if the repairs had to be carried out more than once – on the same digester – then the change in the recorded data may result from other factors apart from those being monitored in the study. This may further reduce the accuracy of the recorded data and any consequent inference that will be made.

1.7 Scope of the Study

Even though the anaerobic digestion process can be used to treat other organic wastes like vegetables (tomatoes, spinach, egg plant, cabbage,okra etc) and fruits (pineapple, water melon, orange, pear etc), this study waslimited to the anaerobic treatment of fruit waste (a composite of pineapple, mango and pawpaw wastes), slaughter waste and human waste. In the study, the biogas potential of (the quantity of biogas that can be generated from)the wastes and the energy potential (the percent methane content) of generated biogas are determined.Also, the conditions under which the generated biogas is suitable for commercial application are presented. Again, an estimation of electrical energy that can be produced

when the biogas is used to fuel a generator set, and the distance that can be travelled by a vehicle running on biogas generated by digesting the substrates in a 1000 m^3 plant are estimated in this thesis. Similar energy potentials are estimated for biogas that would be produced when the substrates are digested at 1000 kgODM/day.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In this chapter, an overview of Municipal wastes is made under which the definition of the term 'waste' as given by many authors is discussed. Also, the classifications of wastes, types of municipal organic wastes, waste management and the objectives of waste management, and available organic municipal waste treatment techniques are also discussed.

Furthermore, a comprehensive literature review is made on the biochemical process of anaerobic digestion process under which the stages of the process and the factors or parameters that affect the process are discussed. Also, the types of existing anaerobic digestion systems and the newly developed simple digesters (the WASAZA and the Deenbandhu 2000 model plants) are discussed in this chapter.

The operation of a digester, from the start-up phase through process monitoring and problem identification to its maintenance is discussed. Also, the production and characteristics or properties of biogas are discussed. Under this section, the established methane contents and biogas yields of some

organic substrates are presented. Also, the parameters used in monitoring the AD process, how to measure them onsite and the protocol/ instruments used in measuring them are discussed.

Finally, the techniques employed in upgrading biogas, biogas applications and the applications of effluents are discussed in this chapter.

2.2 Overview of Municipal Wastes Management

2.2.1 Definition of Waste

There is no single definition for the term "Waste" since the definition depends mostly on the perspective of interest.Srinivas (2008) defined waste as any unwanted substance that is invariably produced from day to day activity.Gaur (2008), on the other hand defined waste (of a process) as anything that has no further use in that process. However, the waste may be useful for other processes thus becoming a raw material for the new process; therefore a waste is a misplaced resource (Gaur, 2008).Gilpin, (1996)(cited by Baabereyir (2009)), with interest in the safety of the environment defineswastes as "all unwanted and economically unusable by-products or residuals at any given place and time, and any other matter that may be discarded accidentally or otherwise into the environment which occur in such a volume, concentration, constituency or manner as to cause a significant alteration in the environment.

With reference to the views expressed above and for the purpose of this study, the definition of waste is any substance (solid, liquid or gas) which is generated by human activities or an industrial process which, in its current form, is of no use for the generator but has the tendency to harm the environment if not well managed.

2.2.2 Classification of Wastes

Waste classification is a way of putting the various types of wastes into groups. Several criteria are used in classifying wastes. Some of these include their sources or origin, physical state, material composition, biodegradability, and the level of risk associated with the waste substances (Baabereyir, 2009). Table 2.1 shows the various types of wastes classified based on the criteria mentioned above.

Table 2.1.: Classifications of Wastes

Criteria for waste classification	Examples of waste types
Sources or premises of generation	Residential, commercial, industrial, municipal services, building and construction, agricultural
Physical state of waste materials	Liquid, solid, gaseous, radioactive
Material composition of waste	Organic food waste, paper and card, plastic, inert, metal, glass,textile
Level of risk	Hazardous, non-hazardous

Source: Baabereyir (2009)

Classification of waste by their source of Origin

Wastes are classified by their source of origin in order to provide information about the type and amount of waste generated by various sectors of the municipality or economy.

Table 2.2: Sources and types of wastes

Source of waste	Waste generators	Types of wastes
Residential	Domestic operations	Vegetable peels, leftover food, pieces of worn-out plastics, rages of clothes, waste papers, ashes etc
Commercial	Business establishments	Pieces of glasses, metals, ashes and food wastes from restaurants, markets, hotels etc
Institutional	Schools, colleges, hotels,	Papers, plastics, glasses etc

	offices	
Municipal	Street cleaning and maintenance of parks	Dust, leafy matter, building debris, treatment plant residual sludge and building demolition and construction wastes
Industrial	Industrial activities	Range from inert wastes to hazardous end products
Agricultural	Farms, Livestock operations and Poultry	Agricultural remains, spoiled food grains and vegetable peelings, cattle and pig dung and poultry droppings

Source: Srinivas (2008)

It helps in the proportionate distribution of logistics for effective waste management. Many authors have classified waste by their sources of origin.

A source classification performed by Srinivas (2008) categorizes wastes as residential, commercial, institutional, municipal, industrial and agricultural wastes. However, Gaur (2008), in implementing source classification grouped wastes as domestic, commercial,trade, industrial, agricultural, institutional, mining and public-services wastes.Elaborating more on agricultural wastes, Sarmah (2009) definesagricultural waste as waste in the form of the crop residues in the farm, manure from livestock operations, including dairy and piggery effluent, and poultry litter.

Classification of waste by its Composition

Another criterion by which waste can be classified is by its composition.Knowing the individual components a waste stream helps in identifying the best method for its treatment. Using this criterion, Baabereyir (2009) grouped wastes into Paper, Plastics, Glass, Metals, Organics, and Inorganic as shown in Table 2.3. In a study conducted by Fobil *et al.*, (2005), to evaluate the possibility of using municipal solid wastes in the Accra metropolis for energy production, the waste compositions were grouped into: organic or putrescible materials, paper and cardboard, plastics and rubber, glass, metals and cans, textile, inert or residues and miscellaneous or other waste.

Table 2.3: Classification of wastes by their material composition

Waste type	Examples
Paper	Newspapers, cardboards, office waste paper, magazine/glossy
Plastics	Bottles, expanded polystyrene, film plastic, other rigid plastic
Glass	Clear glass, green glass, amber glass, non-recyclable glass
Metals	Steel cans, aluminium cans, other ferrous, other aluminium
Organics	Yard waste-grass, yard waste, wood, textiles, diapers, fines, other organics
Inorganic	Electronics, carpets, drywall, other construction and demolition, other inorganic

Source: Baabereyir (2009)

While wastes classified by other criteria seem to be the same or uniform everywhere, the composition of wastes, together with the amount of wastes, varies significantly. Accordingto Gaur (2008), the composition and amount of a waste stream depend on the living standard, social customs, location of a place, climate and weather conditions. The higher the standard of living, the greater the amount of waste produced. Also, the waste composition is different for different income groups (Gaur, 2008).

Classification of Waste by its physical state

The physical states of wastes can be used to classify them. Using the physical state of waste substances, Baabereyir (2009) categorised the materials in the waste stream as liquid, solid, gaseous and radioactive wastes. Examples ofthese types are shown in Table 2.4.

Table 2.4: Classification of waste based on physical state of waste substances

Waste type	Example
Liquid waste	Sewage sludge, waste water from bath house and kitchens, blood from slaughter houses
Solid waste	Food waste, paper, plastic, metal, debris, poultry droppings etc.
Gaseous waste	Factory smoke, vehicle exhaust smoke, fumes from burning waste

	dumps
Radioactive waste	Radiation, uranium, plutonium, excess energy

Source: Baabereyir (2009)

Classification of waste based on its level of risk

Some wastes pose direct health risks to humans and the environment while others even though may be detrimental to the environment, do not pose serious direct health hazards. Based on this criterion, wastes are classified into hazardous and non-hazardous wastes. Hazardous wastes, according to Gaur (2008) are wastes of industrial, institutional or consumer origin which have physical, chemical or biological characteristics that make them potentially dangerous to human beings and the environment.Such wastes may be toxic, corrosive, reactive or ignitable. They therefore need to be carefully preserved and separately disposed off (Srinivas, 2008).However, non-hazardous waste does not pose a danger and can be dealt with easily. Typical examples are inert materials such as uncontaminated earth and excavatedwaste such as bricks, sand, gravel and concrete slates (Baabereyir, 2009).

Classification of waste by its biodegradability

The biodegradability of a substance is its property that makes it susceptible to degradation by the actions of microorganisms. Wastes can be classified based on their biodegradability. Biodegradable waste is a type of waste, typically originating from plant or animal sources, which may be broken down by other living organisms (Answers, 2012). Biodegradable waste can be commonly found in municipal solid waste (sometimes called biodegradable municipal waste, or BMW) as green waste, food waste, paper waste, and biodegradable plastics. Other biodegradable wastes include human waste, manure, sewage and slaughterhouse waste[(Answers, 2012) and(UN-Habitat, 2010)]. On the contrary, non-biodegradable wastes are those that cannot be decomposed by other living organisms. They are

wastes of inorganic origin and include plastics, metals and ceramics and glasses [(Answers, 2012) and(Lapidos, 2007)]

Drawing from the discussions on the overview of municipal wastes so far, the classifications suggest that no single criterion will be enough to fully classify a given waste. This is because a selected group of waste stream will fall under more than one category. Additionally, the composition of municipal waste makes them heterogeneous hence it is difficult to put them under one category of wastes. However, for the purpose of this studythe wastes types discussed above will be grouped into organic municipal wastes and nonorganic municipal wastes. With this categorization, nonorganic municipal waste comprises the waste substances under the categories discussed above that are not biodegradable. Organic municipal solid waste is discussed in the following sections.

2.2.3 Organic Municipal Wastes (OMW)

Organicmunicipal wastes (OMW) are the portions of municipal wastes that are biodegradable. Answers (2012) referred to them as biodegradable municipal wastes (BMW).

Table 2.5: Types of organic municipal waste and their sources

Organic waste	Description/ sources	Examples
Green waste	garden or park waste	grass or flower cuttings, hedge trimmings, and domesticand commercial food waste
Brown waste	predominantly carbon based wastes	dry leaves, twigs, hay, paper, sawdust, corn cobs, cardboard, pine needles or cones, coconut husk trunk
Food waste	Left over foods, spoilt foods from restaurants, hotels, schools and prisons, waste from agro-industries	bones or shells, skins or scales, fat, blood, intestines, brains, eyes, and stomachs, fruit and vegetable wastes, peels and seeds
Paper	From offices, printing	Cardboards, paper wrappers, writing

	presses and packaging	pads, books etc
Human waste		Faeces and Urine
Slaughterhouse wastes	All animal parts from the slaughter house	lungs, spleen, kidneys, brain, liver, blood, bone, stomach, intestines and rumen contents
Manure	Bedding straw, animal faeces and urine	Cattle and pig dung, chicken litter etc.
Sewage	wastewater	Blackwater, grey water wastewater from citrus processing, dairy processing, vegetable canning, potato processing, breweries, and sugar production

The composition of BMW include green waste, brown waste, food waste, paper waste, and biodegradable plastics. Others are human waste, manure, sewage and slaughterhouse waste (Answers, 2012). Most organic wastes produced today originate in municipal, industrial and agricultural sectors (Zupančič and Grilc 2012). The municipal sector includes domestic, institutions, hotels and restaurants while the industries may be agro-industries. Table 2.5 presents the main constituents of the types of organic municipal wastes. With reference to waste listed in Table 2.5, OMW can either be in solid, liquid or slurry state.

Usually, the biodegradable wastes content of municipal wastes is high. It is estimated to be 60% on the average (ETC/SCP, 2009). This figure is higher in low-income (developing) countries. In Ghana, OMW is estimated to be about 60 – 65% [(Fobil *et al.*, 2005) and (Thompson, 2011)].

2.2.4 Waste management and its Main Objectives

Waste management, like waste, has been given different definitions by different authors. In an online dictionary (ecolife dictionary), waste management was defined as the collection, removal, processing,

and disposal of materials considered to be waste. However, Srinivas (2008), taking into consideration the economic and the public safety of managing the wastes, defined waste management as “the process of collecting, transporting and disposing solid waste in a systematic, economic and hygienic manner.”

However, Gbekor (2003)(cited by Baabereyir, (2009)) concerned about safety of the immediate public and the disposal site environments, defined waste management as “the collection, transportation, treatment and disposal of waste including after care of disposal sites”. On a broader perspective, which considered public health, environment safety and resource recovery, Gilpin (1996)(cited by Baabereyir, 2009)) defined waste management as “ a purposeful, systematic control of the generation, storage, collection, transportation, separation, processing, recycling, recovery and disposal of solid waste in a sanitary, aesthetically acceptable and economical manner.

From all the definitions outlined above, it is clear that the main objective of carrying out waste management is to protect the public and the environment from the negative impacts of wastes in the best economical way.

2.2.5 Current waste management Practices in Developing Countries

Currently, most developing countries manage their solid wastes by disposing them in landfill sites and abandoned quarries.

Figure 2.1: Conventional Waste Management employed in developing countries. A: Faecal matter being discharged into the ocean. B: A big trench dug for holding blackwater. C: Open-dumping. D: Animal carcass disposed in the open

Additionally, in areas where proper collection and transportation are not effective, solid wastes (which contain human faeces) are disposed in the open i.e. open-dumping. Similarly, dislodged liquid wastes (blackwater) and grey water are disposed directly into the ocean as shown in Figure 2.1(A).

2.3 Organic Municipal Waste Treatment Technologies

Waste treatment is the way of processing waste in order to reduce or eliminate its adverse effect on human health and the environment (Cofey and Coad/ UN-Habitat, 2010) or to convert it into a useful resource like energy and/ or nutrients (Gaur, 2008). Gaur (2008) grouped the methods of waste conversion to energy as thermochemical and biochemical waste conversion. Memon (2009) generally

categorized the waste treatment methods into: Chemical Treatment which involves hydrolysis process; Thermal Treatment which involves incineration and pyrolysis and Biological waste treatment which results in composting and biogas production.Also, in a report prepared for the New York City Economic Development Corporation (NYCEDC) and New York City Department of Sanitation (NYCDS) (NYCEDC/NYCDS, 2004) waste treatment technologies were categorized into five categories as: Thermal, Digestion (aerobic and anaerobic), Hydrolysis, Chemical Processing and Mechanical Processing for Fiber Recovery.

For the purpose of resources recovery from waste treatment, organic municipal waste treatment technologies will be grouped into Thermo-chemical, mechanical and Biochemical waste treatments. However, according to Gaur (2008), only Thermo-chemical and Biochemical (specifically anaerobic digestion) waste treatment processes result in the conversion of waste to energy.

2.3.1 Thermo-chemical Treatment

This process entails thermal decomposition of organic matter to produce either heat energy or fuel oil or gas (Gaur, 2008). As the name suggests, thermo-chemical treatment operates by employing the principles of both thermal and chemical treatment techniques.The thermo-chemical conversion processes are useful for wastes containing high percentage of organic non-biodegradable matter and low moisture content. The main technological options in this category include incineration, pyrolysis, gasification, depolymerisation, cracking and plasma [(Gaur, 2008) and (NYCEDC/NYCDS, 2004)].

2.3.2 Mechanical Waste Treatment

This is a process in which the organic wastes fraction of a municipal solid waste is mechanically processed to recover fibre which is used in paper making. In general, mechanical processing for fiber recovery starts with steam conditioning of the MSW in an autoclave, followed by mechanical screening to recover recyclables and separate the organic (or biomass) fraction from the inorganic fraction. The

biomass fraction is then pulped with water, to recover long-fibrepulp for paper making, and the sludge generated in the process is anaerobically digested (NYCEDC/NYCDS, 2004).

2.3.3 Biological or Biochemical Waste Treatment

This is the process of using microorganisms (usually naturally occurring organisms) to decompose or break down complex organic compounds which are mainly present in organic wastes. The microorganisms oxidize the wastes to provide themselves with sufficient energy to enable them synthesize the complex molecules such as proteins and polysaccharides which they need to build new cells and multiply in the process. Some of the microorganisms require oxygen to survive and carry out their metabolism actively while others can survive without oxygen, resulting in two types of microorganisms.

The two main types of microorganisms involved in biological waste treatment are Aerobes (those organisms that require oxygen to survive) and Anaerobes (organisms that do not require oxygen to survive). Consequently, there are two types of biological waste treatment, namely: Aerobic waste treatment or digestion and anaerobic waste treatment or digestion.

Aerobic Waste Treatment or Digestion

Aerobic waste treatment is the process in which aerobes are used to decompose biodegradable organic matter. It is the main digestion process employed in composting. Composting is the most effective way of treating agricultural wastes with very low moisture content or with high lignin content (Ugwuanyi, 2009). Organic wastes such as dried leaves and stalks of maize, rice hull, sea hyacinths, saw dust, tree cuttings, banana and plantain stems and stalks, cocoa pods, poultry droppings etc will be best treated by composting for the production of manure.

Anaerobic Waste Treatment or Digestion

Anaerobic waste treatment is the process in which anaerobic microorganisms are used to decompose biodegradable organic matter. This process results in the production of energy, in the form of methane, and nutrients which can be used as biofertilizer. It is most at times also called biomethanation (Mital, 2011). This process is a three-tier benefit process, in that it produces energy, nutrients (resource recovery) while treating organic wastes. The process is most suitable for treating wastes with low organic dry matter content up to about 35% ODM (Al Seadi *et al*, 2008). Wastes such as black water, slaughterhouse wastes, human wastes, cattle and pig dung, poultry manure, fruit and vegetable wastes, agro-industrial organic wastes etc are suitable to be treated with the anaerobic waste treatment process.

The anaerobic waste treatment process is the most suitable process for cities in developing countries. This is because, majority of the wastes generated in these countries are organic wastes with high moisture content. Anaerobic systems can be operated on decentralized levels. The resources retrieved from the process are highly valuable to farmers in developing countries. Also, most of the developing countries (especially in Africa) have the environment (in terms of temperature) for the success of the process in mesophilic digesters.

Even though the anaerobic digestion process seems to have more advantages over the aerobic, its successful application depends as already discussed on the moisture content, the rate of degradability, the type of anaerobic system to be employed. The biochemical process of the Anaerobic Digestion process is discussed in the next section.

2.4 The Biochemical Process of Anaerobic Digestion (AD)

Anaerobic Digestion is the breakdown or decomposition of complex biodegradable or organic materials which contain carbohydrates, fats and proteins by microorganisms in an oxygen-free environment. It is a naturally occurring process (Bagudo *et al.*, 2011), or a biochemical process whose end products are

biogas and digestate (Al Seadi *et al.*, 2008).The process occurs in natural environments wherever high concentrations of wet organic matter accumulate in the absence of dissolved oxygen. Most common natural environments where the AD process occurs include the bottom sediments of lakes and ponds, in swamps, peat bogs, intestines of animals and in the anaerobic interiors of landfill sites (Simpkins, 2005), (House, 2010). Similarly, the AD process can take place in engineered environments so far as favourable conditions (oxygen-free environment, temperature, pH etc.) are provided.

The AD process is a complexlinked multi-stage process which is carried out by different groups of microorganisms at different stages.The microorganisms successively decompose the products of the previous stage until the final products (methane and digestate) are produced (Al Seadi*et al.*, 2008).Different writers have grouped the AD process into different number of stages or sub-processes. While some: Wellinger(1999), Fulford(2006), Hoerz *et al*. (1999), House (2010), and Mang and Li (2010) separate the entire AD process into 3 stages as Hydrolysis, Acidogenesis and Methanogenesis, others: Eliyan (2007);Al Seadi *et al*., (2008); Gerber and Span (2008); Aklaku (2011a);Clisso (2012)and Zupančič and Grilc (2012) , separate it into 4 stagesas Hydrolysis, acidogenesis, acetogenesis and methanogenesis. For simplicity and easy understanding of the process, this document separates the AD process into four stages as done by the latter group of writers.Even though the AD process has been described as a four-step process, the various processes take placesymbiotically in a digester.The entire AD process is summarized in Figure 2.2.

2.4.1 Stages of the AD Process

Hydrolysis

Hydrolysis, also known as liquefaction, is the first step of the anaerobic digestion process.It is the breakdown of the complex organic matter present in the fresh substrates into simple and soluble molecules. According to Al Seadi *et al.*(2008), various hydrolytic microorganisms excrete hydrolytic

enzymes whichconvert biopolymers into simpler and soluble compounds. These microorganisms are facultative bacteria which use up all free oxygen that may be present in the feed or in the air trapped in the digester (Fulford, 2006).The hydrolysis is separated into three parts (Gujer & Zehnder, 1983 cited by Gerber and Span, 2008) and (Verma, 2002): Hydrolysis of carbohydrates to simple sugars,hydrolysis of fats and oil to glycerol and fatty acidsand the hydrolysis of proteins and nucleic acids to simple amino acids, and purines and pyrimidines.The enzyme that converts lipids to glycerol and fatty acids is called *Lipase* while *cellulase*, *cellobiase*, *xylanase*, *amylase* convert polysaccharideto monosaccharide. Similarly, the enzyme *protease* convertsprotein to amino acids.

The rate of hydrolysis is dependent on the type of biopolymer present in the substrate; – It is easier to degrade glucose than to degrade lignin. It is dependent also on substrate concentration, particle size, the pH value and the temperatureof the substrate in the digester (Veeken & Hamelers, 1999 cited in Gerber and Span, 2008). Hydrolysis is a slow process and is generallythe rate-limiting step ofthe AD process of waste substrates (Burke, 2001), (Insam *et al*., 2010). It may however be enhanced by mechanical, thermal or chemical pre-treatment of the substrate (Zupančič and Grilc, 2012)

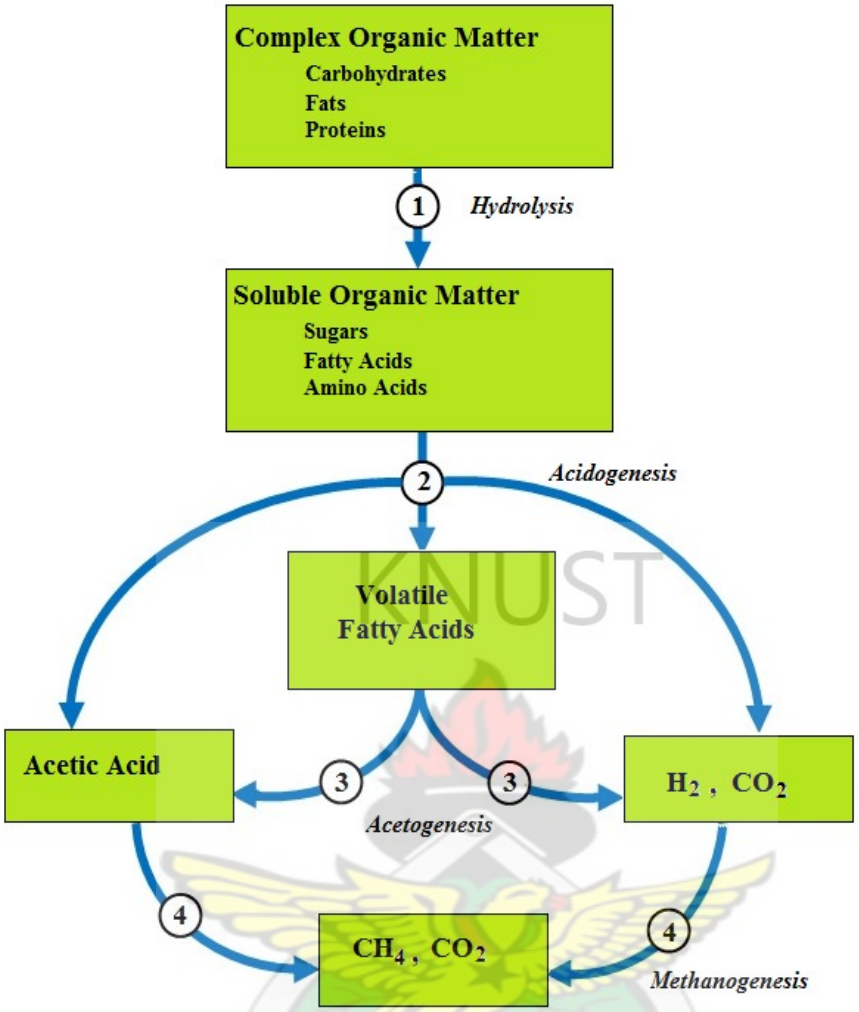

Figure 2.2: The Anaerobic Digestion Pathway (Adopted and modified from Zupančič, and Grilc (2012).

Acidogenesis

Acidogenesis is the second step of the Anaerobic Digestion process.At this stage, acid-formingmicroorganisms known as acidogenic or fermentative bacteria degradethe products of hydrolysis (simple sugars, amino acids and fatty acids) to acetate, carbon dioxide, hydrogen, volatile fatty acids and alcohols. According to Al Seadi *et al.* (2008) and Zupančič and Grilc (2012), 70% of the products of acidogenesis are acetate, carbon dioxide and hydrogen while the remaining 30% consists of volatile fatty acids (VFA) and alcohols along with ammonia and hydrogen sulphide. Acidogenesis is usually considered the fastest step in the anaerobicdigestion of complex organic matter (Vavilin *et al*., 1996 cited by Fang, (2010)).

Acetogenesis

This is the third step of the anaerobic digestion process. At this stage, VFA, alcohols and other products from the Acidogenesis stage which could not be converted to methane directly are converted to methanogenic substrates by acetogenic bacteria. VFA and alcohols are oxidised to acetate, hydrogen and carbon dioxide (Al Seadi *et al.*, 2008).

Methanogenesis

Methanogenesis is the final step of the anaerobic digestion process.During methanogenesis, methanogenic bacteria produce methane from acetate, and Hydrogen and carbon dioxide (Aklaku, 2011a) as shown below:

$$\underset{\textit{Acetic Acid}}{CH_3COOH} \xrightarrow{\textit{Methanogenic bacteria}} \underset{\textit{Methane}}{CH_4} + \underset{\textit{Carbon dioxide}}{CO_2}$$

$$\underset{\textit{Ethanol}}{2CH_3CH_5OH} + \underset{\textit{Carbon dioxide}}{CO_2} \xrightarrow{\textit{Methanogenic bacteria}} \underset{\textit{Methane}}{CH_4} + \underset{\textit{Acetic Acid}}{2CH_3COOH}$$

$$\underset{\textit{Carbon dioxide}}{CO_2} + \underset{\textit{Hydrogen}}{4H_2} \xrightarrow{\textit{Methanogenic bacteria}} CH_4 + \underset{\textit{water}}{2H_2O}$$

Majority of the methane produced is from acetate. About 70% of the methane is produced from acetate while the remaining 30% is produced from the conversion of hydrogen and carbon dioxide (Al Seadi *et al*., 2008).

Methanogenesis is the most sensitive biochemical reaction to process imbalances in digesters or engineered environments. It is therefore severely influenced by operational conditions such as composition of feedstock, feeding rate, temperature, and pH. Also, digester overloading, temperature changes or large entry of oxygen can result in termination of methane production (Briones and Raskin, 2003 cited by Insam *et al.,* 2010) and (Al Seadi *et al.,* 2008). Methanogenesis is – beside other factors – sensitive to both high and low pH values and performs well between pH 6.5 and pH 8 (Zupančič and Grilc, 2012) with optimum pH for most of them being between 7.0 and 8.0 (Al Seadi et al., 2008).

2.4.2 Applications of the Anaerobic Digestion Process

The anaerobic digestion process – as defined in section 2.4 – is applicable to the treatment of biodegradable wastes. There may be different applications for the AD process. However, currently, it is employed inenergy production and wastes (wastewater, blackwater, municipal solid waste, industrial waste and agricultural waste) treatment. In Germany for instance, biogas plants are operated only to produce renewable energy (Clemens,2010).Other applications focus on the treatment of wastes. The major aim of this application is to minimize the Chemical Oxygen Demand in the outflow of the biogas plant. In this case, the AD process is either used as primary treatment of an overall treatment process. The anaerobic part is followed by an aerobic part, where the aerobic composting process requires some degradable carbon to start the composting process (Clemens, 2010).Examples for such biogas plantscan be found in the food industry.

2.4.3 Parameters that affect the AD Process and Biogas Production

Many parameters or conditions affect the biogas production process. Basically, all the sub-processes are affected by ambient conditions such as temperature, pH value, alkalinity, inhibitors, trace and toxic elements (Gerber and Span, 2008). The growth and metabolic activity of the anaerobic bacteria especially the methanogens are influenced by these conditions. Consequently, the biogas production rate and the biogas quality are determined by these parameters [(Sasse, 1988),(Werner *et al.*, 1989), (Monnet, 2003),(Fulford, 2006),(House, 2010) and (Bagudo *et al.*, 2011)]. An in-depth review of how each of these parameters affects the biogas production process will help in explaining why the digestion of a given substrate at certain conditions results in certain biogas quantity and quality.

Even though no single literature (reviewed during this thesis work) has grouped the parameters as done in this document, the understanding of effects of these parameters is made easier by grouping them into the following: Process or Microbiological parameters, Properties of feedstocks or substrate and operational parameters.

2.4.3.1 Process or MicrobiologicalParameters

Process parameters are those that affect the activeness and growth of the bacteria by virtue of altering their environmental conditions (Fulford, 2006). Gerber and Span (2008) refer to them as ambient conditions and suggest that they affect all sub-processes. They include temperature, pH value, alkalinity, inhibitors, trace and toxic elements.

Slurry pH value

Slurry pH is a measure of the acidity or alkalinity of the slurry in the digester.The pH of the digester slurry is mainly a function of the properties of the raw material fed into the digester (Persson *et al*., 1979 & Al Seadi *et al.*, 2008). Slurry pH influences the growth of methanogenic microorganisms thus

affecting the rate of biogas production and the quality of the biogas. Therefore, for a stable biogas production process, the right slurry pH must be maintained in the digester.

Many values have been proposed as the optimum pH range for high bacterial activity in the biogas production system. While some of the pH values depend on the AD stage, others depend on the process temperature. On one hand, acidogenic microorganisms usually have lower optimum pH value. On the other hand, the pH-value in thermophilic digesters is higher than in mesophilic ones (Al Seadi *et al.*, 2008). According to Al Seadi *et al.* (2008), a slurry pH between 5.5 and 8.5 is suitable for methane formation. However, the optimum pH ranges given by most writers who have discussed the anaerobic digestion process fall within 6.4 and 8.5 [(Persson *et al.*, 1979), (Sasse, 1988), (Monnet, 2003), (Fulford, 2006) and (House 2010)].Nonetheless, the optimum pH value for most methanogens is between 7.0 and 8.0 (Al Seadi et al., 2008) and as soon as the slurry pH deviates from the optimum range, bacterial activity is seriously impaired, resulting in lower gas yields, inferior gas composition (excessive CO_2 content) and obnoxious odour (H_2S -like rotten eggs) (Werner *et al.*, 1989).

Even though the pH of slurryin a digester indicates whether the digestion process is proceeding without disturbance(Sasse, 1988), the pH-value is not recommended as a stand-alone process monitoring parameter (Al Seadi *et al.*, 2008).It should therefore not be taken as a measure of substrate acids and/or potential biogas yield(Hoerz *et al.*, 1999).

Temperature

Temperature describes how cold or hot the bacterial environment is and has a major influence on their metabolic activity.Consequently, the rate of biogas production, the quality of biogas produced from a substrate and the hydraulic retention time of the substrate in a digester are all affected by slurry temperature.

The rate of biogas production increases with increasing bacterial environmental temperature. According to House (2010), at a temperature range of 0°C to 5°C, substrate digestion takes place, but without biogas production. Furthermore, at temperatures below 15°C, biogas production is very slow even though digestion of the substrate continues[(Hoerz *et al*., 1999) and(House, 2010)]. However, the gas production rate roughly doubles every 10°C rise in temperature between 15°C and 35°C (Fulford, 2006). Even though the rate of gas production increases with increasing temperature, the ultimate gas yield or the biogas potential of a specific substrate is fairly the same within mesophilic and thermophilic digestion ranges [(Wellinger, 1999) and(Werner *et al.*, 1989)].

Another effect of temperature on the biogas production process is the methane content of biogas produced from a specific substrate. A study by Savery and Cruzan (1972)(cited by House (2010))shows that the methane content increases with increasing process temperature for a given substrate. In this study, 60% methane was recorded for digestion done in the thermophilic range as compared to 50% for that of mesophilic range.

On hydraulic retention time however, digestion at higher temperatures reduces the hydraulic retention time required to digest a substrate.It took twice the hydraulic retention time required to digest sewage sludge, cattle manure and pig manure at 22°C as it took to digest the same quantities at 35°C [(Fair and Moore, 1934),(Wellinger *et al*., 1985) and(Stevens and Schulte, 1979 cited in (Wellinger, 1999)]

In spite of all these benefits, higher process temperatures have negative effects on the anaerobic digestion process and biogas quality. Higher temperature is associated with higher H_2S concentration in biogas (House, 2010). Also, at higher temperatures, methanogenic bacteria are less tolerant to temperature changes. A sudden change of more than 5°C in a day can cause them to stop working temporarily, resulting in a build-up of undigested volatile acids (Fulford, 2006) and subsequent reduction in the rate of biogas production.On the contrary, the temperature fluctuations between day

and night are no great problem for plants built underground, since the temperature of the earth below a depth of one meter is practicallyconstant (Hoerz *et al.*, 1999).

Process Inhibition

The anaerobic process inhibiting factors are those that negatively affect the bacteria's metabolic activities resulting in lower gas production. Usually, they are toxins such as antibiotics, disinfectants, pesticides, detergents and chlorinated hydrocarbons such as chloroform and other organic solvents (Fulford, 2006).

The sources of these toxins include: substrates prepared from vegetables and fruits sprayed with pesticides and insecticides; substrates of agro-industrial sources; cow dung of cattle that has been given or injected with antibiotics; and detergents used for cleaning latrines attached to digesters.Other types of inhibitors are the by-products of the phases in the anaerobic digestion process. Ammonia, a by-product, is one of the most common inhibitors in anaerobic digestion and its concentration in the slurry increases with increasing process temperature (House, 2010). Another by-product which inhibits anaerobic digestion is volatile fatty acids.A high volatile-acid concentration at a lower pH value below 6.2 becomes toxic to methanogenic bacteria (Hoerz *et al.*, 1999).

2.4.3.2 Properties of Feedstock or substrates

Any organic material containing food substances such as carbohydrates, fats or proteins can be digested anaerobically to give off biogas. However, the rate of digestion and the efficiency of digestion of the feedstock depend on its physical and chemical structure (Fulford, 2006). Consequently, the rate of biogas production and the quality of the biogas produced do not depend only on the process conditions but also mainly on the nature or type of the substrate digested (Monnet, 2003);(House, 2010) and (Bagudo *et al.*, 2011).

Usually, a substrate or slurry is made up of a mixture of water/ moisture and solids. According to Fulford (2006), the characteristics of the substrate fed into a digester is defined by measuring its total solids content, volatile solids content, fixed solids content and carbon to nitrogen (C/N) ratio.

Total Solids (Dry Matter)

The total solids (TS) is the measure of the dry matter (DM) of a substrate or slurry left after moisture has been removed from it by heating it to 105°C.It is one of the means of measuring the concentration of the substrate fed into a digester (Lohri, 2009) and used as one of the standard units of measuring the biogas production potential of a substrate (Clemens, 2010) and(Fulford, 2006).There are three main types of substrates based on their total solids content namely: Wet or low solids (LS) substrates which contain less than 12% TS; medium solids (MS) substrates which contain 15 – 20% TS and dry or high solids (HS) substrates which contain 22 to 40% TS (Nizami and Murphy, 2010) and (Tchobanoglous*et al.*, 1993 cited by Verma, 2002). Substrates with ODM content lower than 20% are used in wet digestion while those with ODM higher than 35% are used in dry digestion (Al Seadi *et al.*, 2008).According to Al Seadi *et al.* (2008), the former category includes animal slurries and manures and wet organic wastes from food industries while the latter consists of energy crops and silages.

The total-solids and water contents of different substrates vary widely from substrate to substrate (Werner *et al*., 1989). For example, the total solid content of animal dung for instance varies between 15 per cent and 30 per cent (Fulford, 2006) while that of fresh cattle dung is 15 to 25% (Sasse *et al.*, 1991).

The recommended total solid content for slurry fed into a continuous-fed digester is between 5 to 12 per cent (Werner *et al.*, 1989),(Sasse *et al*., 1991) and(Fulford, 2006).However, dry digesters, according to Fulford (2006) can digest slurries of up to 30 per cent total solid content.

Volatile Solids (Organic Dry Matter) and Fixed Solids (Mineral Ash)

Volatile solids (VS) or organic dry matter (ODM) is the measure of the portion of the dry matter lost when the dry matter is burnt at 500°C or 600°C while the fixed solids (FS) or mineral ash is the ash left after the burning.

According to Fulford (2006), FS is usually composed of soil particles, inert portions of vegetables matter (some grasses, e.g. rice, concentrate silica in their stalk) and some solid carbon left from the decomposition of foodstuffs. Monnet (2003) therefore defined volatile solids as the organic matter in a sample which is measured as solid content minus ash content, as obtained by complete combustion of the feed wastes.

Table 2.6: The total solids (TS) and volatile solids (VS) content of some organic materials

Substrate	TS (%)	VS in TS (%)
Rumen content (untreated)	12 – 16[a]	85 – 88
Cattle slurry	5 – 12[d]	80
Cattle excreta	25 – 30[a]	75 – 85
Pig manure	20 – 25[a]	75 – 80
Pig slurry	3 – 8[d]	70 – 80
Pig stomach content	12 – 15[a]	80 – 84
Chicken manure	10 – 29[a]	67 – 77
Fruit slurry (juice production)	4 – 10[a]	92 – 98
Vegetable residue/ waste	5 – 20[a]	76 – 90
Sewage sludge	3 – 5[a]	75 – 85
Brewery spent grain	20 – 26[a]	80 – 95
Corn Silage	20 – 40[a]	94 – 97
Municipal organic waste	15 – 30[a]	80 – 95
Sheep manure	18 – 25[a]	80 – 85
Human Faeces	14 – 22[b,c]	79 – 84; 93

Note: *a* = (Zupančič and Grilc, 2012)
b= (Chaggu, 2004)
c= (Nwaneri et al, 2008)
d = (Al Seadi et al, 2008)

Volatile solid is usually expressed as a percentage of the total solids. It represents that portion of the total solids or a substrate that is digestible (House, 2010). It therefore helps in knowing the concentration of the slurry fed into a digester and the amount of biogas produced from per unit weight of slurry fed into a digester. The volatile solids content of dung is usually 80% of the total solids (Fulford, 2006).

Carbon to Nitrogen (C/N) Ratio

The C/N ratio of a substrate is a measure of the number of carbon atoms in a substance divided by the number of nitrogen atoms (House, 2010). The C/N ratio of a substrate fed into a digester affects its biogas production potential and methane content (Sasse, 1988).

Table 2.7: C/N Ratio of selected substrates used in anaerobic digestion

Substrate	C/N Ratio	Reference
Cattle manure	20 – 35	*Fulford, 2006*
Cattle slurry	6 – 20	*Al Seadi et al, 2008*
Mixed slaughter waste	2	*House, 2010*
Pig manure	14	*Fulford, 2006; House, 2010*
Pig slurry	3 – 10	*Al Seadi et al, 2008*
Chicken manure	8	*Fulford, 2006*
Vegetable residue/ waste	11 – 19	*House, 2010*
Human faeces	6 – 10	*Fulford, 2006; House, 2010*

This is because the carbon component of the substrate is the ingredient converted to methane in the process while the nitrogen gives the bacteria energy to carry out the process efficiently (Persson et al, 1979).

However, according to Persson *et al*. (1979) and Werner *et al.* (1989), if the C/N is too low, the anaerobic digestion process is retarded or stopped due to the occurrence of toxic ammonia concentrations. On the other hand, high C/N ratio slows the rate of methane formation and increases the content of organic acids resulting in increased process pH (Al Seadi et al., 2008). Most writers give C/N range of 25:1 to 40:1 as the best range within which anaerobic bacteria thrive well (Sasse, 1988), (Werner *et al.*, 1989),(Sasse *et al.*, 1991)and(Persson *et al.*, 1979) with the optimum point varying

based on the substrate (Hoerz *et al.*, 1999). However, the ideal C/N ratio for fixed dome plants according to Fulford (2006) is 25:1.

The C/N ratio varies from substrate to substrate. Organic materials rich in carbohydrates (rice husks) have high carbon content but low nitrogen while those rich in protein are rich in nitrogen. Mixtures of nitrogen-rich feed material (e.g., poultry manure) and carbon-rich feed material (e.g., rice husks) give high gas production (Sasse, 1988).Table 2.7 shows the C/N ratio of some substrates.

Physical Nature of the substrate

The physical nature of the substrate is described by its particle size and whether it is fibrous or its lignin content. Even though the physical nature of the substrate does not affect its ultimate gas production potential, it affects the rate of gas production. According to Sasse *et al.* (1991), the gas production potential of a certain substrate is high when organic matter content is high and the C/N ratio ranges from 20: 1 to 40: 1. However, the speed (rate) of the gas production depends on the physical properties of the substrate and the temperature (optimum at 35°C). Dry and fibrous material takes longer to digest than fine-structured and wet substrate.

Consequently, the physical nature of the substrate also affects its hydraulic retention time (Wellinger, 1999). In instances where fruit wastes and other municipal solid waste will be used, size reduction is employed to speed up the decomposition process (Monnet, 2003) and (Fulford, 2006).

Percentage of Water added to substrate

The quantity of water added to a substrate to form slurry is crucial in biogas production especially in the running of simple continuous-fed plants.According to Sasse (1988), adding water to the substrate gives it fluid properties and makes it easier for the methanogenic bacteria to come into contact with the feed material. Consequently, the digestion process is accelerated (Sasse, 1988)and(House, 2010),

thereby increasing the rate of biogas production. Additionally, adding water to the substrate makes stirring easy and facilitates the uniform distribution of bacteria in the digester.

On the other hand, adding too much water to the substrate reduces the effective volume of the digester and facilitates scum formation (House, 2010). Meanwhile, according to House (2010), water per say does not add anything to biogas production.

It is therefore important to add the right quantity of water to the substrate in order to maintain the optimum solids content. The recommended solids content in slurries (especially in the case of simple continuous-fed plants) is 5 to 10% (Sasse, 1988)and(House, 2010), making the water content of the slurry to be 90 to 95%. For example, Fresh cattle manure is made up of 16 % solids and 84% water. The cattle dung is mixed with waterin the proportions of 1:1. The prepared fermentation slurry then has a solids content of 8% and a water content of 92% (Example is adapted from Sasse, 1988).

2.4.3.3 Operational Parameters

These parameters are those whose occurrences are controlled outside the immediate environment of the microorganisms. Usually, they are controlled by the one operating or running the digester.

Feeding or Organic Loading Rate (OLR)

Feeding/Organic Loading rate is defined as the amount of organic materials which is fed to the digester per day per unit volume of the digester (Wellinger, 1999) and (Persson *et al.*, 1979).According to Monnet (2003) and Werner *et al.* (1989), OLR is a measure of the biological conversion capacity of a digester or an anaerobic digestion system.It is expressed as kg COD or VS/ODM per cubic meter of the digester. The loading rate is related to the hydraulic retention time which determines the size of the digester. In so far as the loading rate does not exceed its designed limit (Monnet, 2003), a high loading rate will result in a high daily gas production and a high daily rate of volatile solids reduction.

However, it results in a smaller percentage conversion of the volatile solids to gas (Persson *et al.*, 1979).Excessive digester loading (feeding the digester above its sustainable OLR), can lead to process inhibition which will result in low biogas yield (Werner *et al.*, 1989) and (Monnet, 2003). Werner *et al*. (1989) however suggested that a digester load is primarily dependent on four factors: substrate, temperature, volumetric burden and type of plant. The OLR is related to the digester volume as shown in the equation below:

$$OLR = \frac{m \times c}{V_d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [2.1]$$

Where:

$m^3\,day$

$kg\,ODM/¿$

$OLR = Organic\ Loading\ Rate\ ¿$

$m = mass\ of\ substrate\ fed\ per\ time\ unit\ (kg/d)$

$c = concentration\ of\ organic\ matter\ ()$

$V_d = Digester\ volume\ (m^3)$

Hydraulic Retention Time (HRT)

HRT is the average time a substrate remains/ stays in a digester (Wellinger, 1999). It is an important parameter since it helps in dimensioning (determining the size of) the biogas digester (Al Seadi *et al.*, 2008). HRT is correlated to the digester volume and the volume of substrate fed per time unit,according to the following equation:

$$HRT(day) = \frac{V_d}{V} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [2.2]$$

Where:

$HRT = hydraulic\ retention\ time\ (days)$

$V_d = Volume\ of\ digester\ (m^3)$

$V = Volume\ of\ substrate\ fed\ per\ unit\ time\ (m^3/d)$

There is a close relation between the optimum HRT and temperature (Wellinger, 1999) such that for the same loading rate of a given substrate, the HRT required to completely digest the substrate decreases with increasing temperature in the digester. Similarly, according to the above equation, at constant digester volume, increasing the organic load reduces the HRT of the substrate fed in the digester. 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 (Al Seadi *et al.*, 2008). This is very vital when operating in lower temperature (mesophilic) ranges than in higher temperature (thermophilic) ranges.Wellinger (1999) gives the average HRT for the mesophilic digestion of cattle manure, pig manure and cattle manure with straw bedding as 12 to 18 days, 10 to 15 days and 18 to 36 days respectively.

A short HRT provides a good substrate flow rate, but a lower gas yield which may be due to uncompleted digestion. It is therefore important to adapt the HRT to the specific decomposition rate of the used substrates. Knowing the targeted HRT, the dailyfeedstock input and the decomposition rate of the substrate, it is possible to calculate the necessary digester volume (Al Seadi *et al.*, 2008).

Agitation or SlurryStirring

Agitation is the process of causing disturbance or turbulence to the slurry in a digester. Al Seadi *et al.* (2008) grouped the methods of agitation into passive and active agitation. The passive agitation occurs whenever fresh feedstock is fed into the digester as well as by the up-flow of gas bubbles. However,

Active agitation/ stirring is causing turbulence in the digester by using manual, mechanical, hydraulic or pneumatic stirring equipments (Al Seadi *et al.*, 2008).

Slurry stirring is very important for the optimum operation of engineered anaerobic digestion systems for several reasons. When efficiently done, stirring increases the rate of biogas production by 10 – 15% (House, 2010) and 50% in some instances (Al Seadi *et al.*, 2008). Other reasons why active stirring must be done in a digester are its tendency to: prevent formation of swimming layers (scum) and of sediments, bring the micro-organisms in contact with the new feedstock particles, facilitate the up-flow of gas bubbles and homogenize distribution of heat and nutrients through the whole mass of substrate. Stirring must therefore be done several times in a day.

Many stirring methods and devices have been developed. Some of the mixing methods include: tangential inlet and outlet pipes, separation walls, forced substrate flowvertical hand-operated rotors, horizontal, hand-operated paddle rotors and poking through inlet and outlet (ISAT/GTZ, 1999). Others include: Mechanical paddle rotors, submerged motor with rotor stirring, shaft-driven rotors, hydraulic mixing, and mixing through injection of biogas.

2.5 Classification or Types of Anaerobic Digestion Systems and Plants

A biogas plant or generator consists of two main parts: the digester or reactor and the gas storage space/gasholder (Sasse *et al.*, 1991). The digester houses the bacteria involved and provides the anaerobic environment required for their survival and success of the process. The storage space on the other hand accumulates and stores the biogas produced by the digester. According toHouse (2010), when a device as a huge municipal sewage plant is designed primarily to accomplish the decomposition purpose, it is called a digester or reactor while a generator is designed with the idea of producing (or generating or evolving) biogas.

In classifying biogas generators, it will be more comprehensive to use the types of digesters available, since a vast array of anaerobic digesters have been developed and placed in operation over the past fifty years (Burke, 2001). Even thougha variety of schemes could be used to classify the digestion processes in a digester, three fundamental schemes are used in this thesis. These include: Classification of digesters based on the mode of feeding, classification by the type of substrate fed into the digester and classification based on the sophistication of the technology employed in operating the digesters.Digesters of the last category are further grouped into simple Low-tech. digesters and High-tech. digesters like those used in the developed countries (Sasse, 1988) and (Muller, 2007). Practically, every digester belongs to a combination of two or more of the categories used in this thesis as shown in the explanations that follow.

2.5.1 Classification by Mode of Feeding the Plant/Digester

One of the fundamental ways of distinguishing one digester from the other is the way it is fed and how its effluent is removed.All digesters, either low-technology or high-technology fall under one of these classifications.

Batch-fed digesters

In batch-fed digesters, the digesters are filled with fresh substrates, usually with a starterand allowed to digest for a fixed retention time and then completely removed after the gas has been collected (Fulford, 2006); (Sasse, 1988)and Al Seadi *et al.*, 2008).Batch reactors function similar to a landfill, but at higher temperatures and with continuous leachate recirculation, the biogas yield is between 50 and 100 percent higher than in landfills (Vandevivere *et al*., 1999, cited by Verma, 2002). The advantage of batch-type digesters is that the substrate can contain lignin and other indigestible matter, as it does not have to be fed through inlet and outlet pipes (Fulford, 2006). Another advantage of this type of digesters is its ability to digest high solids (20 to 40% TS) content substrates making it suitable to be

operated as a dry digester. Thirdly, it does not require stirring as in the case of wet digestion (W,ERT, 2009); (Fulford, 2006) and (Al Seadi *et al.*, 2008).

Batch digesters are further put into three types namely: Single-stage batch system, Sequential batch system and the Hybrid-Upflow Anaerobic Sludge Blanket (UASB). The three types are shown in Figure 2.3.

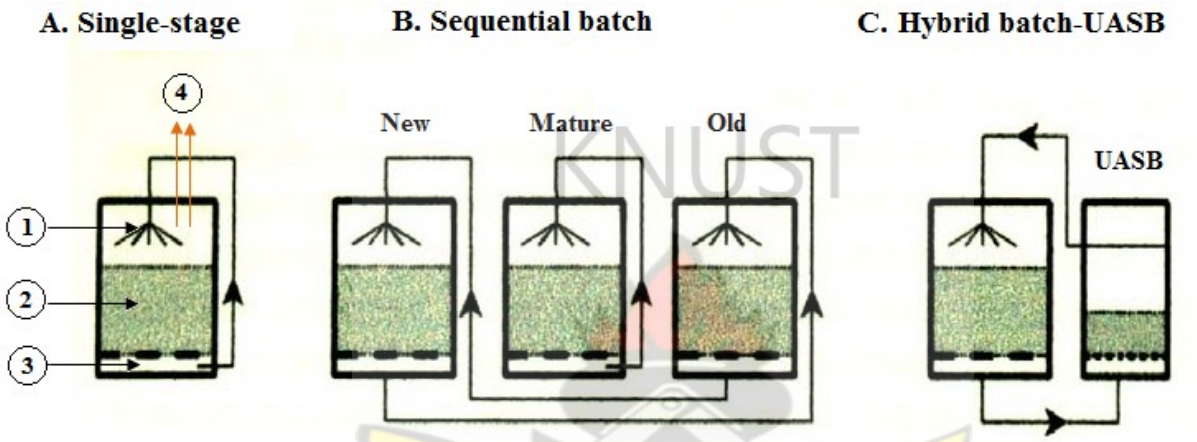

Figure2.3: Types of Batch digesters. 1. Leachate sprinkled over the substrate; 2. Substrate (20 - 40% TS); 3. Leachate from digested substrate; 4. Biogas*(Figure was taken and modified from Verma, 2002)*

Continuous digesters

In continuous-type digesters, the substrate is constantly fed (for example, daily) into the digester once it has been started (Al Seadi *et al.*, 2008) and (Fulford, 2006). Continuous-fed digesters have inlet and outlet where substrates enter the digester and spent slurries leave the digester respectively in continuum so far as feeding is done. The inlet and outlet of the digester are arranged such that the spent slurry overflows into a pond as new slurry is added (Fulford, 2006). The movement of the slurry through the digester can be achieved either mechanically or by the pressure of the newly fed substrate, pushing out the digested material; this phenomenon is known as the *Displacement Principle*.Unlike batch-type digester, once the digestion process has stabilised, the gas production rate is fairly constant (with

constant feed rate and temperature) and predictable (Al Seadi *et al.*, 2008) and (Fulford, 2006).Most simple digesters like the balloon plant, fixed-dome plants and the floating-drum plants are the continuous-fed types. Currently, most of the digesters (both Low-Technology and High-Technology) available in Ghana, Europe and other parts are continuous-fed digesters.

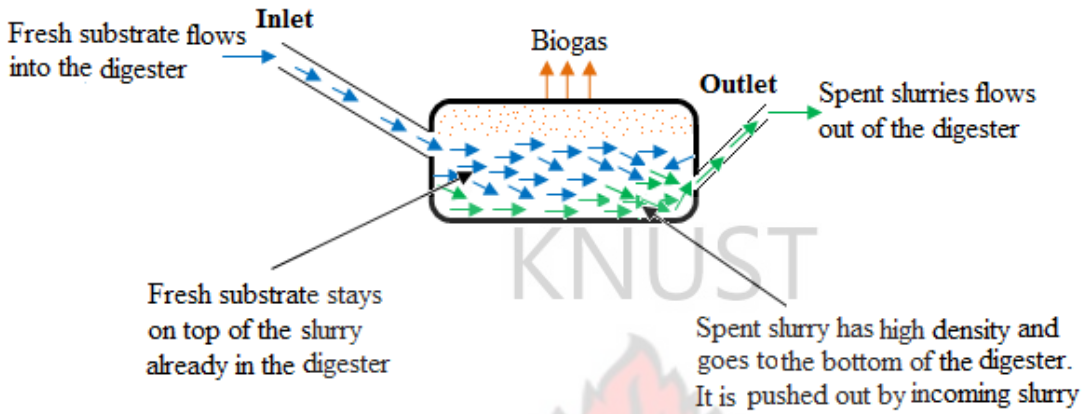

Figure2.4: Theoretical presentation of the displacement principle employed by the continuous-fed digester

Semi-Batch Digesters

Semi-batch digesters are those that are started as batch digesters and also fed regularly. This type of digester is suitable for the co-digestion of straw and dung. Many digesters in China are run in a semi-batch mode (Sasse, 1988and Fulford, 2006). The digesters are filled with vegetable matter, such as straw and garden wastes, and animal dung and a starter. In addition to the existing substrate, the digesters are fed daily with dung (usually from pig and attached latrine) and vegetable wastes. Gas production remains fairly constant due to the quick degradation of more digestible substrates and enhancement by the slow degrading substrates (Fulford, 2006). These digesters are emptied once or twice every year with the absent of gas during the emptying and restarting period, being the main disadvantage.

2.5.2 Classification by type of Substrate fed in the Plants/Digesters

The substrates digested in anaerobic digestion systems can be grouped into three main categories on the basis of their total solids (TS) content as already stated in Section 2.4.3.2. Under this category, the digesters are grouped into Wet (Low Solids) and Dry (High Solids)digesters (Verma, 2002).

Wet or Low-Solids Digesters

The Low Solids (Wet) AD systems are suitable for digesting substrates with total solids content less than 12%(Al Seadi *et al.*, 2008) and (Verma, 2002). Some of the digesters of this type are the anaerobic baffled reactor (ABR), continuously stirred tank reactor (CSTR) (Mang and Li, 2010) and most of the anaerobic digestion systems employed in wastewater treatment. Others include simple anaerobic systems like the balloon digesters, fixed-dome plants and floating-drum plants. Generally, the retention time is 14-28 days for high-tech digesters depending on the kind of feed and operating temperature(Verma, 2002) or more in the case of simple digesters. The low total solids content of the substrates increases the design volume of the digesters leading to high construction cost. It also promotes non-homogeneity in the reacting mass leading to the formation of a layer of heavier fractions at the bottom of the reactor and floating scum at the top. The bottom layer can damage the propellers while the top layer hinders effective mixing in digesters using mechanical mixers. Another flaw is the short-circuiting, i.e. a fraction of the feed passes through the reactor at a shorter retention time than the average retention time of the total feed. These (scum and the short-circuiting) lower the biogas yield and impairs the effective treatment of the wastes (Verma, 2002).

Dry or High Solids Digesters

These digesters are suitable for digesting substrates with total solids content between 20 to 40% (Nizami and Murphy, 2010). The HS systems can handle impurities such as stones, glass or wood that need not be removed as in LS systems. Contrary to the complete mixing prevailing in LS, the HS are plug-flow reactors hence require no mechanical device within the reactor (De Baere, 1999 cited by Verma, 2002).Dry digesters exhibit higher organic loading rates (15 kg VS/m^3 per day) with high biogas yield, as compared to wet digesters which have about 6 kg VS/m^3 per day. Also, dry digesters make use of very little water if any thus saving the amount of water used in mixing the slurry (Verma, 2002).

2.5.3High-Technology (High-Tech) Plants/Digesters

The high-tech anaerobic digestion systems employ relatively sophisticated technology in feeding and operating the digesters, and in monitoring the anaerobic digestion process. Consequently, they are complex and consist of a variety of elements.

Figure 2.5: High -TechAD Plants(Left) Vertical digester at Guiness Ghana Limited in Kumasi (Aklaku, 2011a) and (Right) Horizontal digester in Denmark (Al Seadi*et al.*, 2008)

The layout of such a plant depends to a large extent on the types and amounts of feedstock supplied which in turn influences the type of technologies that will be incorporated (Al Seadi *et al.*, 2008). They

may either be erected vertically or horizontally as shown in Figure 2.5. These digesters are fitted with feed or substrate pre-treatment sections, mechanical feeding system, mechanical stirring devices, heating systems and digestate storage systems. Such plants may have computerized process monitoring systems.

Figure 2.6: Parts of the Mechanical Stirrer. (Left) Mechanical Stirrer and (Right) its stirring engine (Al Seadi *et al.*, 2008)

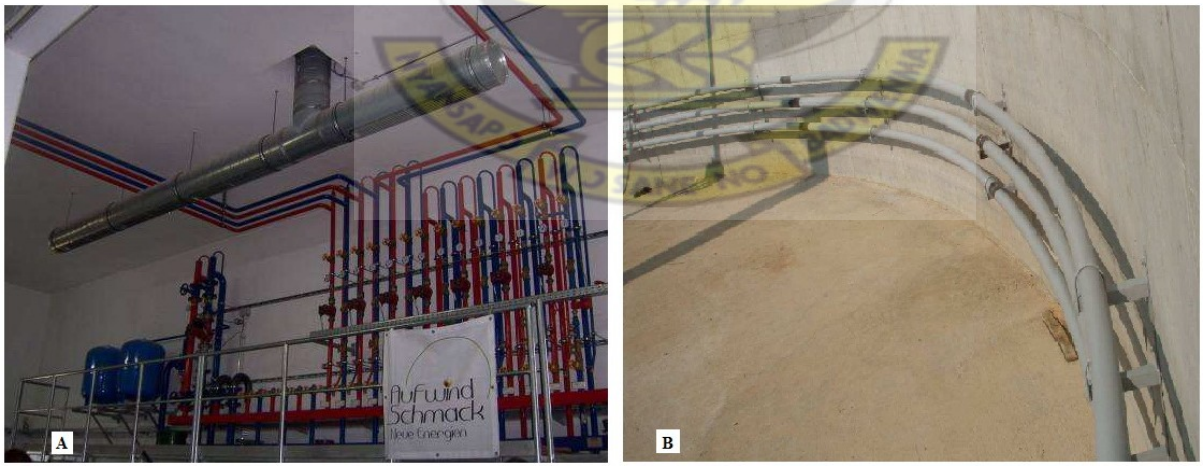

Figure 2.7:The Heating System of a High-Tech Plant. A: The heating system of a high-tech digester and the heating pipes installed in the digester (Rutz,*et al*., 2008 cited by Al Seadi *et al.*, 2008)

Based on the operational temperature of the digester, it may be a mesophilic or thermophilic plant.High-tech digesters are further groupedinto Single-stage digesters and Multi-stage digesters according to their complexity.

Mesophilic and Thermophilic Digesters

Mesophilic digesters are those in which the anaerobic digestion process takes place optimally around 30 to 38 °C, or at ambient temperatures between 20 and 45 °C (RTBOT, 2012).The mesophilic digestion process is done by a large diversity of mesophilic bacteria which are more tolerant to process temperature fluctuations thusmaking the process more stable and robust (Monnet, 2003). Heating systems may not be installed in mesophilic plants when they are installed in tropical areas.

Thermophilic plants on the other hand operate optimally in the temperature ranges of 49 to 57°C, or at elevated temperatures up to 70°C, where thermophiles are the primary microorganisms present (RTBOT, 2012 and Monnet, 2003). Heating systems are installed in these plants to provide the thermophilic temperature level required in the digester.Thermophilic digestion systems are considered to be less stable and require higher energy input than mesophilic plants. This notwithstanding, more energy is removed from the organic matter (RTBOT, 2012). This is because the increased temperatures facilitate faster reaction rates and, hence, faster gas yields. Additionally, operating at higher temperatures facilitates greater sterilization of the end digestate. However, the high energy input that is made in order to achieve the higher temperature levels, which may not be outweighed by the energy output from the systems is a setback to the operation of thermophilic digestion systems.

Single-stage digesters

In a single-stage (one-stage)digestion system, all of the sub-process or biological reactions occur within a single, sealed reactor or holding tank. Using a single stage reduces construction costs, but results in less control of the reactions occurring within the system (RTBOT, 2012). Since all the bacteria involved

in the sub-processes are in the same digester, the inactiveness or over-activeness of one group of bacteria affects the activities of other bacteria. For example, extra acid produced by the acidogenic bacteria reduces the pH in digester thus impeding the activity of the methanogenic bacteria thus affecting the biogas production by the digester.

Multi-stage digesters

Multi-stage anaerobic digestion system consists of two or more digesters arranged such that the sub-processes occur in different separate reactors. Typically, two reactors are used, such that hydrolysis, acidogenesis and acetogenesis occur within the first reaction vessel while methanogenesis occurs in the second (Verma, 2002) and (RTBOT, 2012).According to Verma (2002),hydrolysis of cellulose is the rate-limiting factor in the first reactor. However, in the second, it is the rate of microbial growth. For the purposes of attaining uniform temperature gradient and save the bacteria consortia from sudden temperature fluctuation, the substrate (organic waste material) is heated to the required operational temperature (either mesophilic or thermophilic) before being pumped into a methanogenic reactor (RTBOT, 2012).

Even though this system requires the construction of two digesters thus increasing its construction cost, it has some advantages over the single-stage digestion system. Firstly, in the multi-stages digesters, the rate of hydrolysis and methanogenesis can be controlled (and optimized) making it possible to control the anaerobic digestion process. For example, microaerophilic conditions, which can be provided by supplying a small amount of oxygen in an anaerobic zone, can be used to increase the rate of hydrolysis. Secondly, the system provides greater biological stability for very rapidly degradable wastes like fruits and vegetables. This is because with such substrates, the slower metabolism of methanogens relative to acidogens would lead to process inhibition in single-stage digesters (Monnet,

2003). In spite of all these advantages since, it is not possible to completely isolate the different reaction phases; some biogas is often produced in the first digester (RTBOT, 2012)

2.5.4 Simple or Low-Technology (Low-Tech) Plants/Digesters

Simple or Low-Technology digesters which are also referred to as small-scale digesters (Spuhler, 2012)are mostly suitable for digesting wet substrates and are continuous-fed plants. They usually operate in the mesophillic temperature range and have little if any movement parts. They do not have either computerized monitoring systems, heating systems nor mechanical feeding and mechanical stirring facilities.Theirconstruction is therefore, not as sophisticated as that of the High-Technology commercial plants used in the western part of the world. The main design elements of small-scale biogas digesters are: an inlet, an airtight reactor chamber, gas storage space (a vessel for biogas collection) and an expansion chamber(Spuhler, 2012). Simple plants are therefore moresuitable for rural households in developing countries in Africa (Sasse, 1988).

Sasse(1988) groupssimple plants intothree categories namely: Balloon Plants, Floating-Drum Plants and Fixed-dome plants.

2.5.4.1 Balloon Plants

The balloon plant consists of a plastic or rubber digester bag (e.g., PVC) in the upper part in which the gas isstored. It does not have any expansion chamber. The inlet and outlet are attached directly to the plastic skin of the balloon.

The gas pressure is achieved through the elasticity of the balloon and by added weights placed on the balloon whileagitation is achieved by the movement of the balloon skin. Balloon plants can be recommended wherever the balloon skin is not likely to be damaged and where the temperature is even and high.

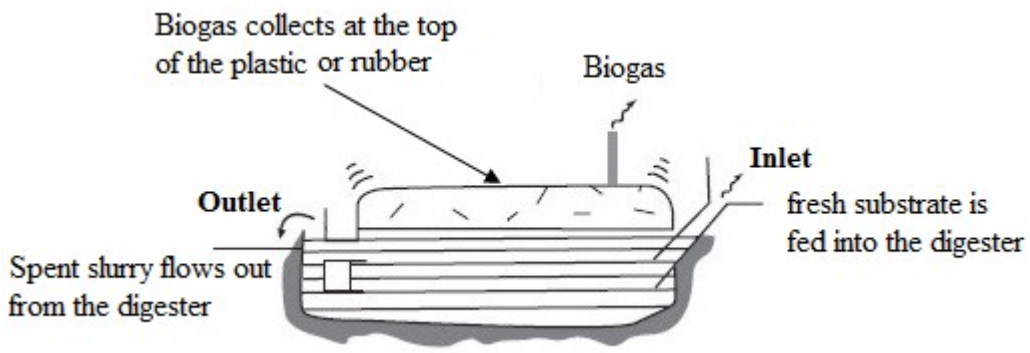

Figure 2.8: The Balloon Plant

The advantages of this system are its low cost, ease of transportation, low constructionsophistication, high digester temperatures, and its rather simple cleaning, emptying andmaintenance.

Its disadvantages on the other hand are its relatively short life span (about five years), high susceptibility to damage, and creation of little local employment and, therefore, limited self-help potential.

A variation of the balloon plant is the channel-type digester, which is usually covered with plastic sheeting and a sunshade (see Figure 2.9).

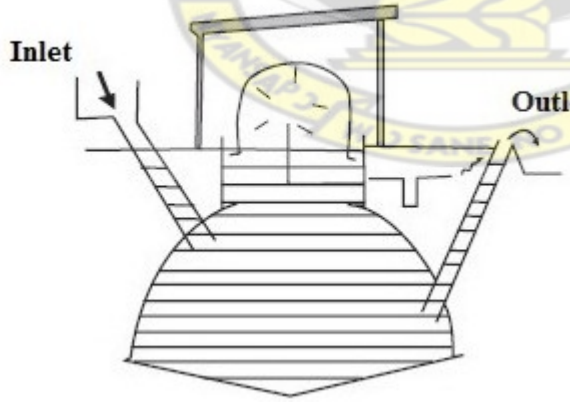

Figure2.9: Channel- type digester with plastic sheeting and sunshade (Sasse, 1988)

2.5.4.2 Floating-Drum Plants

Floating-drum plants consist of an underground digester and a moving gasholder (Fulford, 2006). The digester is usually built with concrete while the gas holder is built with stainless steel or metal sheets and painted to reduce its susceptibility to rust. The gasholder floats either directly on the fermentation slurry or in a water jacket of its own when gas begins to fill it. It is however prevented from tilting by guiding frames. The height to which the gasholder rises is directly proportional to the amount of gas stored in it.

The advantages of the Floating-drum digestersinclude the supply of gas at constant pressure. This is because the pressure of the gas in the gasholder is proportional to the weight of the gasholder. Also, the construction is relatively easy and construction mistakes do not lead to major problems in functioning and gas yield. The disadvantages on the other hand include high material cost the high susceptibility of all the steel parts to corrosion.

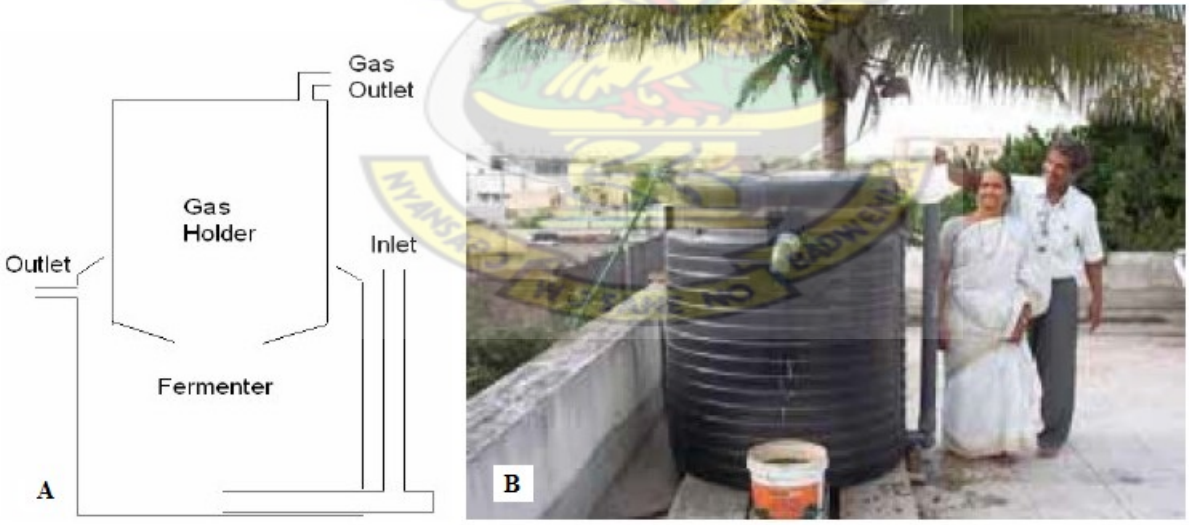

Figure2.10: The ARTI Compact Plant (A) Schematic diagram of small ARTI Compact digester. (B) ARTI Compact digester under operation (Adapted from Muller, 2007)

Also, floating-drum plants have shorter life span than fixed-dome plants and involve regular maintenance costs for the painting of the drum (Hoerz *et al.*, 1999).

Currently, new designs of the floating-drum plants are being made. In India, the Appropriate Rural Technology Institute (ARTI) designed floating-drum plants called the ARTI Compact Biogas Plant (Figure 2.10).

The plants are made from cut-down high-density polythene (HDPE) water tanks, which are adapted using a heat gun and standard HDPE piping. The standard plant uses two tanks, with volumes of typically $0.75m^3$ and $1m^3$. The smaller tank is the gas holder and is inverted over the larger one which holds slurry. Weights can be placed on the top of the gas holder to increase the gas pressure. (Müller, 2007).

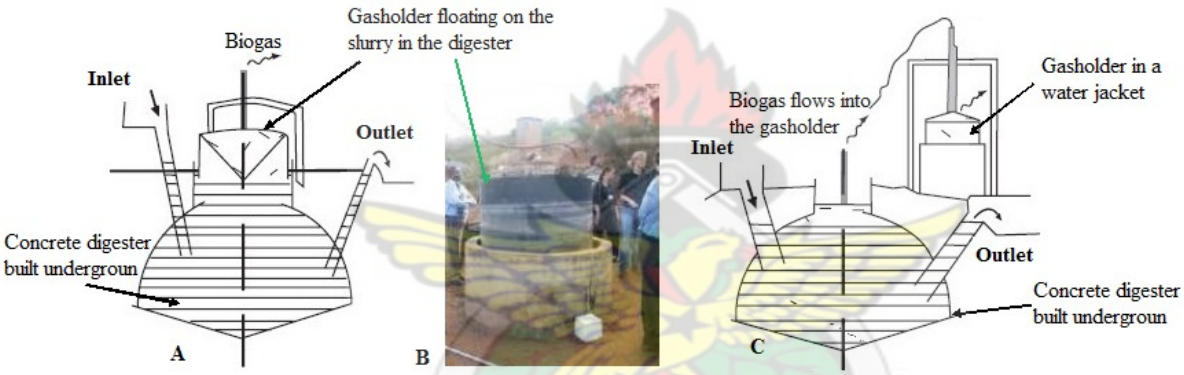

Figure 2.11: Floating-drum digesters. (A). Schematic diagram of the digester with the gasholder floating on the slurry. (B) Picture of an operating digester with the gasholder floating on the slurry. (C) Schematic diagram of digester with the gasholder in a water jacket (Adapted and modified from Sasse, 1988 and Mang and Li, 2010)

2.5.4.3Fixed-Dome Plants

The fixed-dome plant consists of a digester with a fixed, non-movable gasholder, which is fixed on top of the digester and a compensation tank also called the expansion chamber (Sasse, 1988),(Aklaku, 2011b)and (Spuhler, 2012). When gas production starts, the gas is collected in the gasholder on top of the slurry with the gas pressure pushing the slurry intothe compensation tank. This system of gas storage is known as the displacement principle (Fulford, 2006).The gas pressure increases with the

volume of gas stored and the height difference between the slurry level in the digester and the slurry level in the compensation tank.

Generally, the advantages of the fixed-dome plants include: Relatively low construction cost; no moving and rusting steel parts; if well constructed, fixed-dome plants have a long life span (its life span is estimated to be between 20 to 50 years (FAO, 1996)); saving of space and protection of the digester from temperature changes due to the underground construction;and the provision of opportunities for skilled local employment. The disadvantages, on the other hand includefrequent problems with the gas-tightness of the brickwork gasholder (a small crack in the upper brickwork can cause heavy losses of biogas).

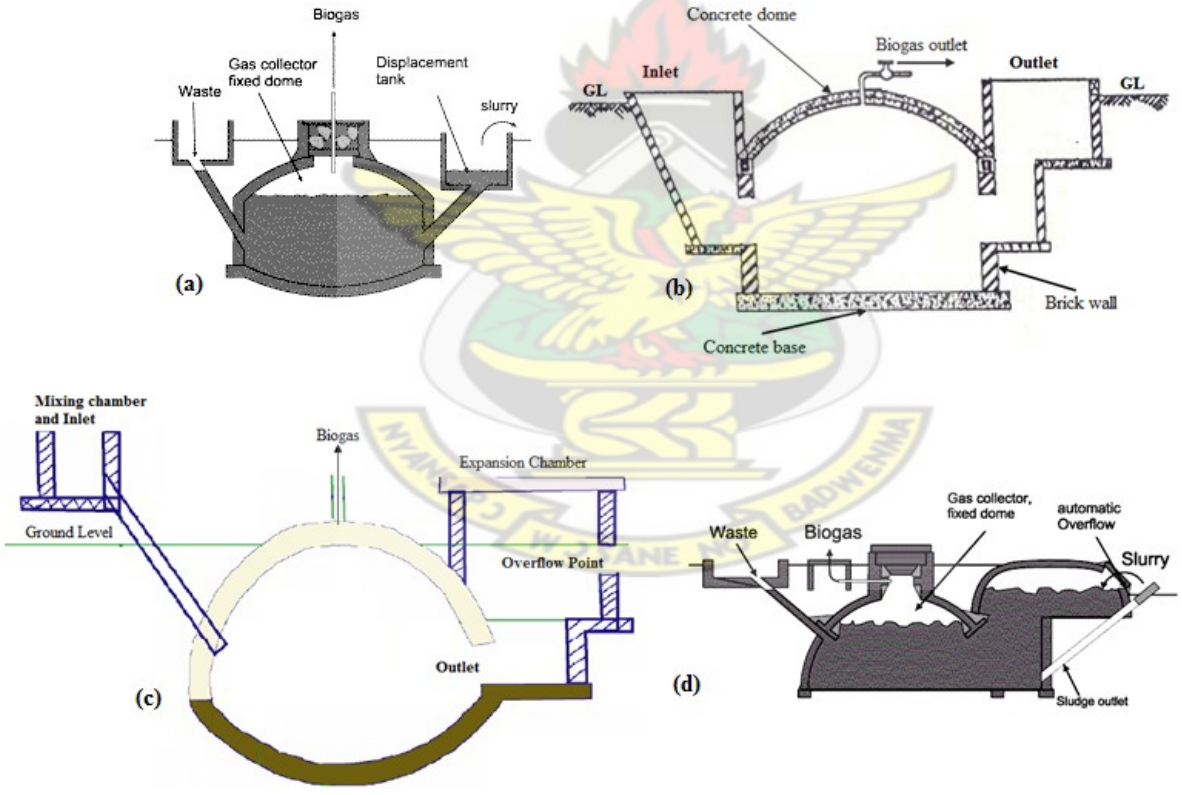

Figure 2.12: Early designs of Fixed-dome Plants: (a) The Chinese Fixed-dome plant, (b)The Janata fixed-dome plant (Adapted from AECRI/ TNAU, 2012); (c) The Deenbandhu Fixed-dome plant (Adapted and modified from RCSD, 2008) (d) CAMARTEC Fixed-dome plant (adopted from ISAT/GTZ (1999).

Also, construction requires the supervision of an experienced biogas technicians; substantial fluctuation in the gas pressure fluctuates since it is dependent on the volume of the stored gas.

Even though the underground construction buffers temperature extremes, digester temperatures are generally low.

The main types of the fixed-dome digesters that has been in existence are the Chinese Fixed-Dome plant, Janata model, Deenbandhu and CAMARTEC designs as shown in Figure 2.12 (Hoerz *et al.*, 1999) . The relatively newly designed fixed dome digesters are WASAZA design (Aklaku, 2011b) and the Deebandhu model 2000 design (AFPRO, 2005).

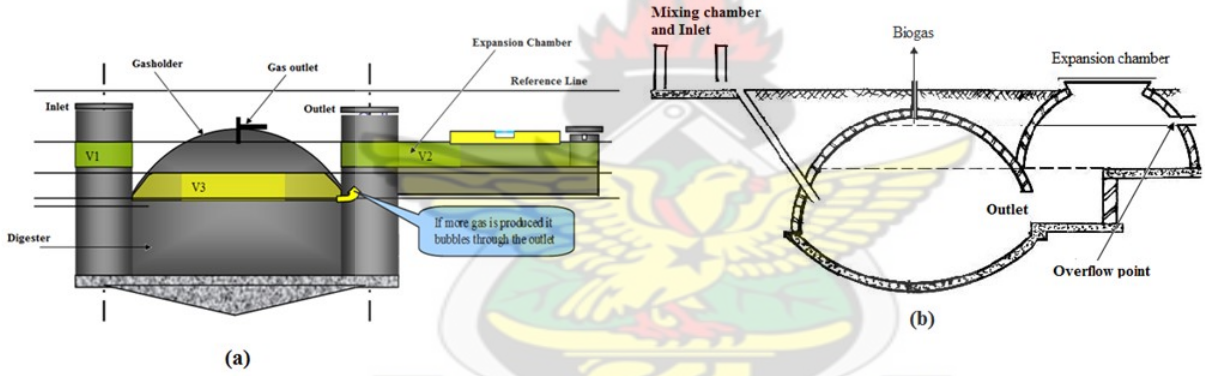

Figure 2.13: Newer designs of Fixed-dome plants. (a) The WASAZA plant (Adapted from Aklaku, 2011b). (b) The Deenbandhu 2000 model plant (adapted from AFPRO, 2005)

2.5.4.4The WASAZA Fixed-dome Plant

The WASAZA Plant is a fixed dome plant which, unlike the CAMARTEC design, has its inlet and outlet attached vertically and directly to opposite sides of the digester as shown in Figure 2.14. Another difference between the two designs is that the WASAZA design has its gasholder completely sealed except a small opening fitted with a metal pipe through which the gas flows to the using point. Furthermore, while the WASAZA plant usually has a rectangular expansion chamber while the CAMARTEC has conical one.

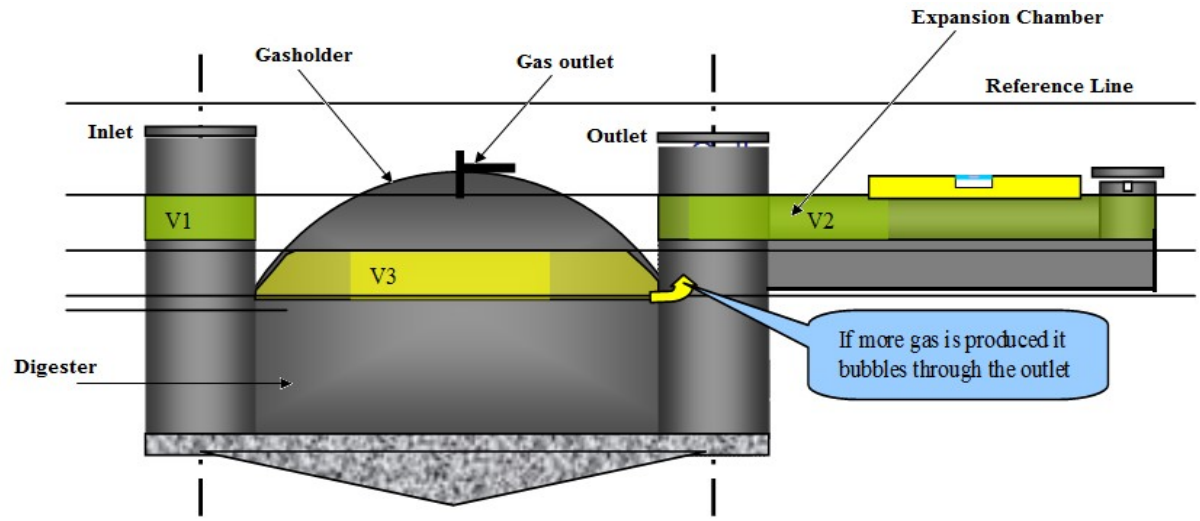

Figure 2.14: The WASAZA Fixed-dome plant (Aklaku, 2011b)

The main advantage of the WASAZA design is its ability to digest different types of biodegradable wastes such that:

- Particle size reduction of substrates is also not critical as the case with narrow pipes that might get blocked
- Fresh material gets contact with slurry in the inlet chamber for a while before getting into the digester
- pH of fresh, slightly acidic substrates may be adjusted before getting into the digester

Another advantage is that it does not get choked like the CAMARTEC since the inlet is directly connected to the digester (i.e. the use of pipes in the CAMARTEC design is excluded in the WASAZA design).

The type of plant selected for construction in an area depends on factors such as the capacity of the plant, the types of waste to be treated, the area available, the climate of the region, the demographics and the location of the plant.

2.6 Operating a Biogas Plant/ Digester

Once the digester has been tested and handed over to the user, its daily operation is the sole responsibility of the user.The operation of a newly constructed digester commences with the Start-up

phase (inoculation). The subsequent activities include regular operational activities, monitoring and maintenance.

2.6.1 Inoculation or the Start-up Phase

The start-up phase is the stage at which the anaerobic bacteria are introduced into the digester. It is a very crucial process since the success of the biogas production process and the time it will take for it to stabilize depend on the quantity of bacteria present in the digester before the first slurry is fed (Fulford, 2006).

The anaerobic bacteria are present in many places. They are present in the rumen, dung or dropping of cattle and other ruminants. They are present also in the marine sediments under water, marshes (Hoerz *et al.*, 1999) and effluent or slurry from existing biogas plants.Again, they are said to be present in certain species of trees (Ward, 1978 cited by House, 2010).

With optimum digester temperature (greater than 20°C), the main factor that affects the success of the start up phase is the quantity of inoculants present in the first slurry. Fulford (2006) proposed the use of 5 per cent to 30 per cent by volume of effluent slurry from a working digester to be mixed with the new feed. However, House (2010) proposed the use of heavy inoculants such as 50:50, inoculants to slurry ratio where the digester will be filled. The other option however, is to increase the volume of the slurry (e.g. 5% of the previous day's slurry) every day until the digester is full. Once the digester is full, it is left until gas formation starts (Fulford, 2006).

Biogas generated during the first few days of the start-up phase is of low quality and has odorous smell. It has higher carbon content (more than 60%) and lower methane content making it non-combustible (Werner *et al*., 1989) and (Fulford, 2006). Nonetheless, good biogascan be produced from purely cattle dung slurry within two days after the start-up while it may take several days or weeks when other

substrates are used (Werner *et al.*, 1989) and (House, 2010).The biogas can be detected by its odorous smell.

2.6.2 Operational and Monitoring Activities

After a successful start-up phase, the smooth functioning of the digester can only be maintained by carrying out necessary operational activities. The most important activities, according to Werner *et al.* (1989) are divided into daily, weekly or monthly and annual activities. The daily activities include daily plant feeding, cleaning the mixing pit, regular agitation of slurry in the digester andchecking gas pressure.Fulford (2006) and House (2010) added the measurement of daily gas production, temperature measurement, and measuring slurry pH to the daily activities if data is being recorded for anaerobic digestion process assessment. Weekly/monthly activities include cleaning and inspection of gas appliances;checking gas valves, fittings and appliances for leaks and inspecting fitted water traps. In the case of annual activities, inspection of scum formation and scum removal;inspecting the plant for water and gas tightness and the pressure-testing of the gas valves, fittings and pipes are included

2.7Determination of BiogasYield and Quality, and its Applications

2.7.1 Biogas

Biogas is a gas produced by the anaerobic digestion of biodegradable materials. It consists mainly of a combustible gas called methane (CH_4) and non-combustible/ inert gas called carbon dioxide (CO_2) (de Hulu *et al.*, 2008). Generally, the methane content is from 50 to 70% of the biogas volume while the carbon dioxide content is from 30 to 40%with low amount of other gases as shown in Table 2.8.However, since different organic materials have different bio-chemical characteristics, their potential for gas production and the composition of the biogas they produce also vary (FAO, 1996).

Table 2.8: Composition of biogas

Substance	Symbol	Amount (% Volume)
Methane	CH_4	50 – 75
Carbon dioxide	CO_2	25 – 45
Water Vapour	H_2O	2 (20°C) – 7 (40°C)
Oxygen	O_2	< 2
Nitrogen	N_2	< 2
Ammonia	NH_3	< 1
Hydrogen	H_2	<1
Hydrogen Sulphide	H_2S	< 1

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

Typically, biogas from sewage digesters contains from 55 to 65% methane, 35 to 45% carbon dioxide and <1% nitrogen and other trace gases; biogas from organic waste digesters contains from 60 to 70% methane, 30 to 40% carbon dioxide and <1% nitrogen and other gases, while in landfills biogas, methane content is usually from 45 to 55% , carbon dioxide from 30 to 40% and nitrogen from 5 to 15% (Jönsson *et al.*, 2003 cited by Rasi, 2009).

Table 2.9: Potentialbiogas yield of some organic materials

Substrate	Estimated biogas yield (m^3 biogas/ kg ODM)
Cattle manure	0.21 – 0.3[a];
Rumen content (untreated)	0.3 – 0.6[c]; 0.4 – 0.68[d]
Cattle slurry	0.2 – 0.5 [a, d];
Cattle excreta	0.6 – 0.8[c];
Pig manure	0.27 – 0.45 [a]; 0.34 – 0.55[b]; 0.2 – 0.5[c]
Pig slurry	0.3 – 0.7 [a]; 0.2 – 0.5[d]
Pig stomach content	0.3 – 0.4[c]
Chicken manure	0.25 – 0.45 [a]; 0.3 – 0.8[c]
Food leftovers	0.25 – 0.5 [a]; 0.5 – 0.6[d]
Fruit slurry (juice production)	0.5 – 0.8[c]
Vegetable residue/ waste	0.33 – 0.36[b]; 0.3 – 0.4[c]
Sewage sludge	0.31 – 0.74[b]; 0.3 – 0.5[c]
Rumen content	0.3 – 0.6[c]
Brewery spent grain	0.5 – 1.1[c]
Corn Silage	0.6 – 0.7[c]
Straw	0.15 – 0.35[d]
Municipal organic waste	0.5 – 0.8[c]
Sheep manure	0.3 – 0.4[c]
Human faeces	0.45[e]

Note: *a*= Clemens, (No date) *b* = ISATand GTZ (1999)
c = (Zupančič and Grilc, 2012) *d* = Al Seadi et al, 2008
e =0.45 m^3 biogas/kgODM will be produced from faeces with 93% ODM (Jekel *et al.*, 2006)

Many studies have been conducted to determine the biogas production potential and biogas methane content of many organic materials. Sasse *et al.*, (1991), found out that biogas from animal dung contains approximately, 60% methane while in a different study conducted by Elango *et al.* (2007) reveal that human excreta based biogas contains 65-66% CH_4, 32-34% CO_2 by volume with the rest

being H_2S and other gases in traces. The methane content of biogas from the food industry, according to Bruijstens *et al.* (2008) can be as high as 85% of the biogas volume. Table 2.9shows the biogas yield of some common organic materials used as substrate for anaerobic digestion

The properties of biogas can be likened to that of the natural gas. It is about 20% lighter than air and has an ignition temperature in the range of 650°C to 750°C and combustion temperature of 650°C. It is an odourless and colourless gas that burns with clear blue flame similar to that of LPG gas (Sathianathan, 1975 cited by FAO, 1996) and (BTC, 2009);(Lohri, 2009). Biogas with methane content higher than 45% is combustible (Lohri, 2009).The rest of the properties of biogas are shown in Table 2.10.

Table 2.10: Properties of biogas. (The biogas is assumed to have 58% CH_4 and 42% CO_2 contents and saturated with water vapour at 30 and standard pressure) Adapted from Fulford, (2006).

Property	Value	Range of values
Calorific value	21.5 MJ/m^3	20.1 to 25.9
Effective molecular weight	27.35	24 to 29
Density	1.0994 kg/m^3	0.96 to1.17
Specific gravity	0.94	0.82 to 1.00
Viscosity	1.297 x 10^{-5} kg/sec/m	
Optimum air to fuel ratio	5.5:1 (15% biogas)	
Flammability limits	9% to 17% biogas in air	
Wobbe number	22.2 MJ/m^3	
Burning velocity	1.25 /sec in air	

Source: Fulford (2006)

2.7.2 Monitoring Parameters during a Biogas Plant/Digester Operation

The successful operation of a biogas digester requires the analysis of the parameters that affect the anaerobic digestion process and the composition of the biogas produced.This is generally achieved by

analyzing the biogas produced, the substrate fed into the digester and the effluent/digestate from the digester. This analysis is important because: it is a way of monitoring the performance or stability of the biological (anaerobic digestion) process. Secondly, it helps to ascertain the biogas production potential of, and the quality of biogas produced by an organic material during anaerobic digestion. Even though biogas production is not constant (Zupančič and Grilc, 2012), a drastic reduction in its production and/or methane content is an indication of deficiency in the digestion process (Clemens, 2010); (USEPA-R9, 2008). Clemens (2010) indicated that parameters such as: amount of substrate fed into the digester, substrate's dry matter (DM) and organic dry matter (ODM) can be measured. Others include: biogas amount andbiogas quality (CH_4, CO_2, and H_2S). Furthermore, digester temperature, alkalinity, volatile fatty acids (VFA), EC, pH and ammonium content of the slurry can be measured. During the analysis, the amount of biogas (volume) produced and its compositions are measured.

While most of the parameters can be analyzed on site, some of them require a laboratory. In view of this, the rest of this section discusses only those parameters that can be analyzed on site namely: amount of substrate fed into the digester,biogas amount and biogas quality (CH_4, CO_2 and H_2S content of the biogas), and digester temperature andslurry pH.

2.7.2.1 Measuring the Amount of Substrate fed into a Digester

The amount of substrate fed into a digester daily is very important since it has a direct effect on the daily production of biogas and the retention time of the slurry. Its determination is made easy by analyzing the dry matter (DM) and organic dry matter (ODM) of the feedstock.

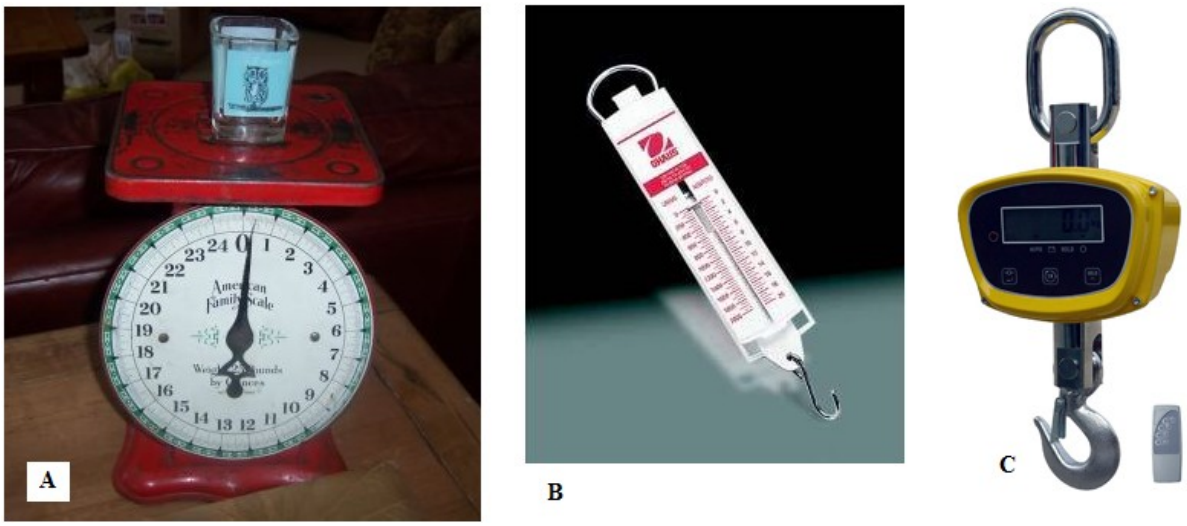

Figure 2.15: Types of weighing scales. A: Table-top analogue weighing scale(adapted from Photobucket, (2012 *a*), B. Analogue crane/ hanging scale (Photobucket, 2012 *b*) and C. Digital crane/ hanging scale (Zhengzhou Jinmai, 2010).

Basically, for solid or semi-solid substrates like manure, weighing balance (shown in Figure 2.15) may be used to measure the amount of feedstock fed into the digester.For liquid substrates which are pumped, the pumping rate can be used to determine the volume of slurry pumped into the digester. In both cases, the ODM or DM of the substrate is used in the estimation of the overall ODM fed into the digester. The amount of substrate fed into the digester is usually measured in grams, or kg ODM or DM per day.

2.7.2.2 Equipment used in Measuring Biogas Amount

Knowing the amount of biogas produced is a very important parameter, because it shows immediately if there are changes in the biological process. A drop in the production indicates either reduced organic loading rate in the digester or some kind of inhibition (Clemens, 2010). There are two distinct parameters that describe the biogas production:

i. Specific (Substrate-specific) Biogas Productivity - SBP (it's also called biogas yield).

It is defined as volumeof biogas produced per mass of substrate fed into a digester (m^3/kg). SBP shows how much biogas was produced from a chosen unit of substrate. It can be expressed in m^3 of biogas per kg of substrate: a) (wet) mass, b) totalsolids (TS), c) volatile organic solids (VS or ODM) or d) COD.Maximum possible SBP for certainsubstrate is called biogas potential. Biogas potential can be determined by a standardmethod (ISO 1998) (Zupančič and Grilc, 2012).

ii. Biogas Production Rate – BPR (it is also called digester-specific biogas productivity).

It is defined as the volume of biogas produced per unit volumeof the digester per day ($m^3m^{-3}d^{-1}$). BPR gives an indication of how much biogas that canbe gained from theactive volume of a digester in one day (Zupančič and Grilc, 2012) and (Aklaku, 2011b).

Differentprinciples are available to determine gas flow (Clemens, 2010) and these principles determine the types of meters available. The following are some of the meters used in measuring the amount of biogas produced in a digester.

a) ***Wet Test Meters***

These Meters operate on the positive displacement principle. They consist essentially of a gas tight casing containing a measuring drum, with 4 separate compartments, mounted on a spindle that is free to revolve. The casing is filled to approximately 60% of its volume with water (or light oil). For “Normal principle” Meters, the gas inlet is arranged so that the gas must pass through the measuring drum first; to do this, each compartment of the drum must in turn be emptied of water and filled with gas, thus forcing the drum to revolve. The calibration of the measuring drum (i.e. the quantity of gas passed for each revolution) is determined by the height of the water in the casing. The normal calibration point of the meters is shown by a water-level-indicating point that is visible in the sight box located on the right side of the Meter casing (see figure 2.16 B).The spindle through the drum is connected via a gearbox to a main pointer working over a dial graduated for the capacity of the Meter and to 3 small index

pointers, or a revolution counter, to record the quantity of gas passed through the Meter (ZEAL, 2012). These meters are tolerant and are therefore suitable for measuring the volume of a wide variety of gases. Also, they require very little maintenance and cover flow ranges from as low as 5 litres per hour to 9000 litres per hour (ZEAL, 2008)

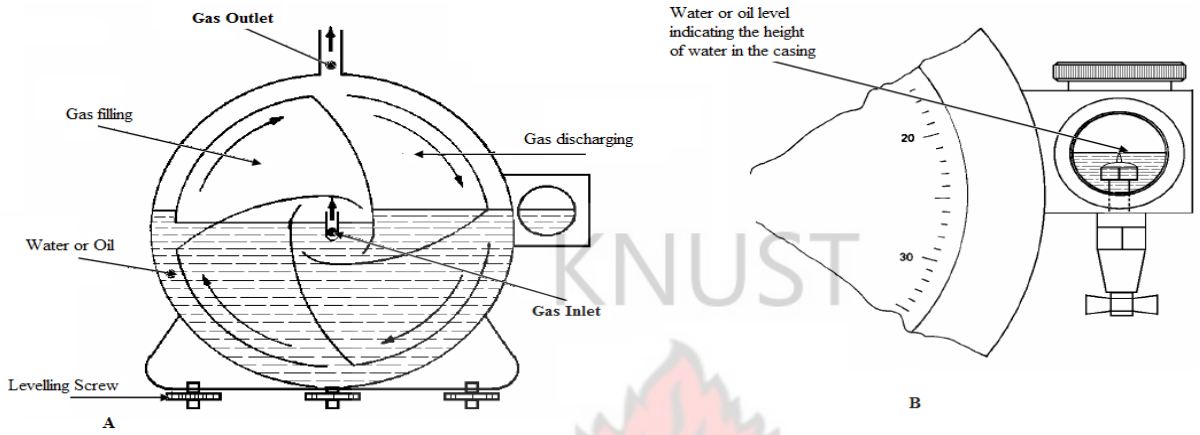

Figure 2.16: The operational principle of the Wet Test Meter. A: Schematic description of the operational principle of the Wet Test Meter. B:The water height indicate attached to the air-tight casing (Adapted from ZEAL, 2008)

Figure 2.17: Some models of Wet Test meters operating on the positive displacement principle. (a) The CMC Model (Maxiflo, online) and (b) The Ritter Model (Litremeter, online)

b) ***Diaphragm/bellows meters***

These meters have two or more chambers formed by movable diaphragms. With the gas flow directed by internal valves, the chambers alternately fill and expel gas, producing a near continuous flow through the meter. As the diaphragms expand and contract, levers connected to cranks convert thelinear motion of the diaphragms into rotary motion of a crank shaft which serves as the primary flow element (Clemens, 2010). These meters are usually analogue. However with technological breakthrough, digital diaphragm meters are now being manufactured, as shown in figure 2.18 B.

Figure 2.18: Diaphragm meters used in measuring biogas flow. A. (Adapted from Wikipedia*a*). B. (Adapted from Elster, online) C. (Picture by Author)

c) ***Ultrasonic (Doppler, transit time) flow meters***

An ultrasonic flow meters measure the velocity of a liquid or gas (fluid) by using the principle of ultrasound. Using ultrasonic transducers, the flow meter can measure the average velocity along the path of an emitted beam of ultrasound, by averaging the difference in measured transit time between the pulses of ultrasound propagating into and against the direction of the flow. Ultrasonic flow meters are affected by the temperature, density and viscosity of the flowing medium. For this reason, some models like theelster Q-Sonic plus (Figure 2.19c) can be equipped with temperature and pressure measurement function. They are inexpensive to use and maintain

because they do not use moving parts, unlike mechanical flow meters (Wikipedia, 2012a), (Yoder, 2010) and (Elster-Instroment, 2011).

Figure 2.19: Modern ultrasonic biogas meters. (A. Schematic view of a flow sensor; B, C and D: Various brands of ultrasonic meters. Adapted from Wikipedia (2012b) http://www.Dynasonics.com; and http://www.controlelectronics.com respectively)

d) ***Vortex flowmeters***

In these meters, a bluff body (called a shedder bar) is placed in the path of the fluid. As the fluid passes this bar, disturbances in the flow called vortices are created. The vortices trail behind the cylinder, alternatively from each side of the bluff body. The frequency at which these vortices alternate sides is essentially proportional to the flow rate of the fluid. Inside, atop, or downstream of the shedder bar is a sensor for measuring the frequency of the vortex shedding. This sensor is

often a piezoelectric crystal, which produces a small, but measurable, voltage pulse every time a vortex is created. Since the frequency of such a voltage pulse is also proportional to the fluid velocity, a volumetric flow rate is calculated using the cross sectional area of the flow meter.

Figure 2.20: Vortex Flow meter (left) Vortex flow meter connected to a digester(Adapted from ABB Vortex flowmeter)

Other many flow meters are available. However, due to space limitations, they have not been discussed in this thesis work. For more information on types of flow meters see online @ http://en.wikipedia.org/wiki/Flow_measurement.

2.7.2.3 Determining Biogas Quality (Biogas Analysis)

Knowing the quality of biogas produced in a plant or by a substrate is very vital for two reasons. First of all, it helps in monitoring the stability of the anaerobic digestion process in the digester. Usually, a

change in the biogas quality indicates that there is a change in the quality or composition of the substrate or possible problems in the biogas process. For example, when:

- CH_4 concentration is increasing at constant biogas production, it might be possible that the fresh fed substrate may contain more fatty ingredients
- CO_2 concentration is increasing; this may be an indication of a potential acidification in the digester.
- H_2S concentration is increasing; it might be due to change in the substrate or failure in the internal desulphurisation(Clemens, 2010).

Secondly, it helps in determining the level of cleaning (scrubbing) that is required to meet the standard or requirement for its use in engines.

Many equipments or devices are available for performing biogas analysis.Some of these devices are briefly discussed below.

a) ***The Gas Chromatograph***

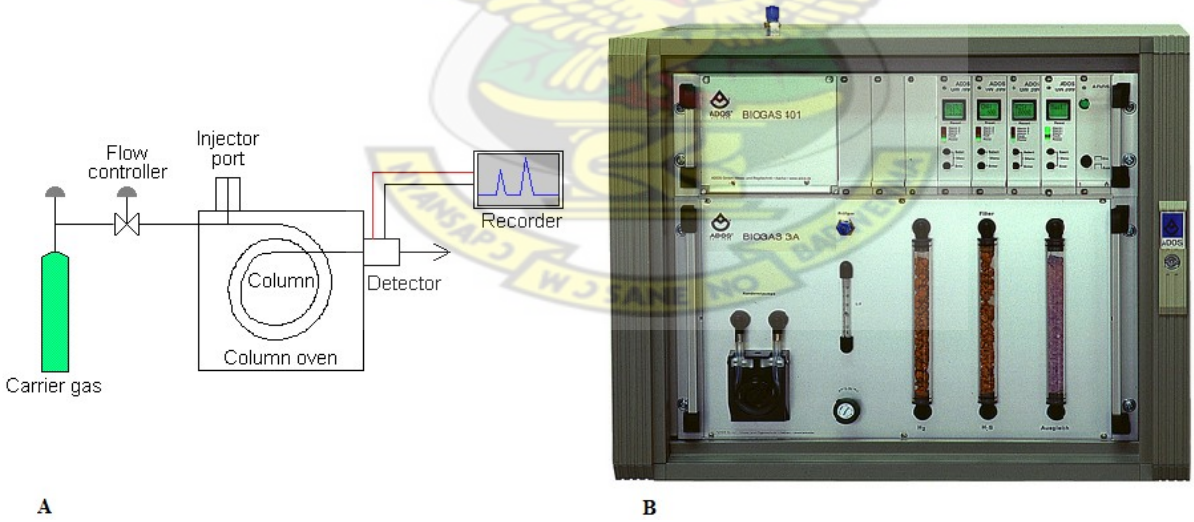

Figure 2.21: The Gas Chromatograph. A: A Schematic diagram of a chromatograph (SHU, 2012); B: Picture of a chromatograph (Images, 2012)

According to Fulford(2006), the best way to analyze biogas samples is to use a gas chromatograph. This is because it is accurate to better than 0.1 per cent. However, the chromatograph is an expensive and a delicate device (Fulford, 2006). Figure 15 A: shows a schematic diagram of a chromatograph.

Gas chromatography, specifically called gas-liquid chromatography, involves the vaporization of a sample of the biogas and injecting it onto the head of the chromatographic column. The sample is transported through the column by the flow of inert, gaseous mobile phase. The column itself contains a liquid stationary phase which is adsorbed onto the surface of an inert solid (SHU, 2012). More information on the function of the components and the operation of a chromatograph can be accessed on the internet @ http://teaching.shu. ac.uk/hwb/chemistry/tutorials/chrom/gaschrm.htm.

b) ***The Orsat Apparatus***

One of the less-expensive devices available for biogas analysis is the Orsat Apparatus. It consists of a series of bulbs(See Figure 2.22), full of suitable solutions to absorb different gases (Fulford, 2006). It is used mainly for the determination of CO_2 and O_2 concentrations and dry molecular weight of a sample from an effluent gas stream of a fossil-fuel combustion process, anaerobic digestion process (biogas), or other process. A typical Orsat analyzerrequires four reagents: a gas-confining solution, CO_2 absorbent, O_2 absorbent, and CO absorbent. These reagents may contain potassium hydroxide, sodium hydroxide, cuprous chloride, cuprous sulphate, alkaline pyrogallic acid, and/or chromous chloride (USEPA, 2012b). For more information on its operation see (USEPA, 2012b). During the analysis, a known volume of the biogas is passed to absorb a constituent. For example, potassium hydroxide absorbs carbon dioxide. Since methane cannot be absorbed directly, it is usually combusted over a catalyst such as platinum and the carbon dioxide produced is measured the Orsat apparatus can produce accurate results around 1 per cent if used properly (Fulford, 2006).

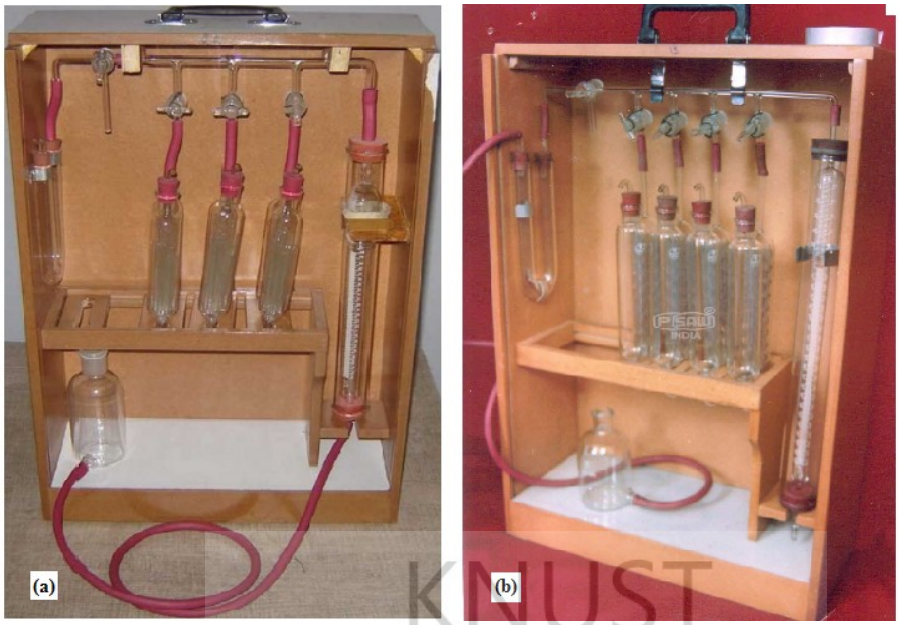

Figure 2.22: The Orsat Apparatus (a) with three bulbs in series (b) with four bulbs in series (both pictures were adopted from Google)

c) ***The Carbon dioxide Analyser***

The carbon dioxide analyser is a simpler version of the Orsat apparatus. It uses only one bulb filled with potassium hydroxide solution. As the carbon dioxide is absorbed, a rubber diaphragm allows the liquid to rise up the bulb, giving a measure of the original proportion of carbon dioxide in the biogas. While being much less accurate (2 to 3 per cent), it is robust and could be used for field tests (Fulford, 2006).

d) ***Electronic Methane Detector***

The Electronic Methane Detector draws a sample of gas through a cell in which the thermal conductivity of the gas is measure. The original designs of this device were calibrated to measure the methane content in air. Therefore using them measure the methane concentration in biogas reduces their accuracy which according to Fulford (2006) could not be better than 5 per cent. The need for portable electronic biogas analysers has led to the development of many models of electronic methane detectors.

Figure 2.23: Portable Electronic Biogas Analyzer: Multitec 540 and Multitec 560 manufactured by Sewerin Technologies (Adapted from www.sewerin.com)

One of such devices is that manufactured by Sewerin – (Multitec 540 and Multitec 560) shown in Figure 2.24 . The Multitec 540 biogas analyser is capable of measuring five gases simultaneously. It uses infrared measuring techniques for methane (CH_4) and carbon dioxide (CO_2) detection while it uses electro-chemical sensors in determining the concentration of H_2S, O_2 and CO (SEWERIN, 2012a). The measuring ranges and the sensors used used in measuring each gas is shown in Table 2.11.

Table 2.11: Specifications of the Multitec 540 Biogas Analyser

Gas Type	Measuring Range	Sensor Type
Methane (CH_4)	0.0 – 100% vol.	Infrared sensor
Carbon dioxide (CO_2)	0 – 100% vol.	Infrared sensor
Hydrogen sulphide (H_2S)	0 – 2000 ppm	Electro-chemical sensor
Oxygen (O_2)	0.0 – 25%	Electro-chemical sensor
Carbon monoxide (CO)	0 – 500ppm	Electro-chemical sensor

2.7.3 Measuring Environmental parameters

a. ***Measuring Digester Temperature***

Knowing the temperature in the digester is very necessary since it is one of the indicators used to ascertain the stability of the anaerobic digestion process. Its effect has been comprehensively discussed in Section 2.6.1. According to Fulford (2006) the easiest way to measure slurry temperature from full-scale anaerobic digesters is to place a thermometer in a sample of slurry dipped from the digester pit. For digesters that are not being heated like the simple or low-tech digesters, a single daily reading is sufficient since the temperature is very uniform and changes very slowly (Fulford, 2006).

b. ***Measuring Slurry pH***

The simplest way to measure pH is using indicator papers (pH Papers) which can be dippedinto a sample of slurry removed from the digester. The colour of the paper dipped into the slurry is compared to (matched with) standard colours with known pH values called the pH scale.

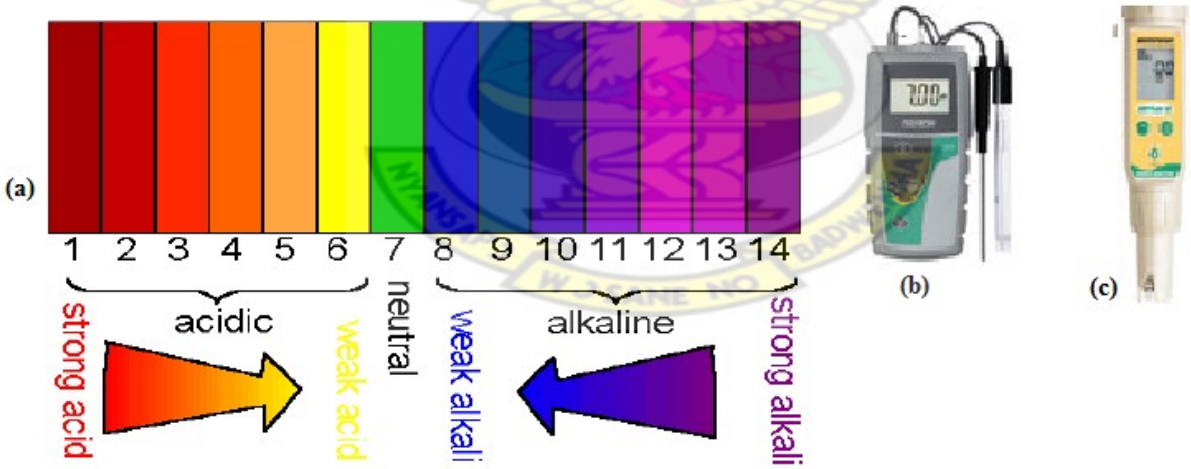

Figure 2.24: Instruments for measuring pH (a) The pH Scale. (b) and (c) pH meters (adapted online from Cole-Parmer, 2011)

The main problem with using indicator papers is the discolouration of the paper thus making the result difficult to see. This problem is overcome by using a pH meter. The pH meter is an electronic device

that uses a glass probe, which is dipped into the slurry. Most models are battery driven and robust enough to be used, with care, in the field (Fulford, 2006).

2.7.4 Biogas Upgrading Technologies

As already stated in Section 2.7.1, biogas is made up of methane (CH_4) and carbon dioxide (CO_2) andhydrogen sulphide (H_2S). Occasionally, it may containtrace amounts of hydrogen (H_2), nitrogen (N_2), saturated orhalogenated carbohydrates and oxygen (O_2) water vapour and organic silicon compounds (e.g siloxanes) (Persson *et al.*, 2006).

The overall energy content of biogas is dependent on its methane content. Therefore the presence of other gases in biogas apart from methane reduces its energy or heating value and its suitability for commercial purposes application. Carbon dioxide (CO_2) which is inert acts as a heat sink thus reducing the heating value of the biogas while hydrogen sulphide (H_2S) according to Persson *et al.* (2006) corrodes compressors, gas pipelines, gas tanks and engines. Consequently, to increase the energy content of biogas, its contaminants (CO_2, H_2S and other gas traces) content must be reduced to the possible minimum to meet the specifications of engines and equipments manufacturers.

The process of removing contaminants from biogas and increasing its methane content/ concentration is referred to as biogas upgrading.The resulting methane from the upgrading process which may contain over 95% methane is called biomethane (Al Seadi *et al*., 2008). The need for upgrading and the quality requirement of biogas is strongly dependent on its utilization. For example, if the biogas will be used in stationary gas engines, then only contaminants have to be removed from the biogas.However, if the gas will be used as vehicle fuel, then carbon dioxide and all contaminants need to be removed to attain the maximum gas quality (Persson *et al.*, 2006). Most manufacturers of gas engines set maximum limits of hydrogen sulphide and these limits must be known before selecting a biogas upgrading system

(BioCycle, 2010). Some limits for H_2S content and the need to remove CO_2 and H_2O from biogas before its particular application are shown in Table 2.12.

Table 2.12:Required Upgrading of biogas based on its Applications

Application	H_2S Removal	CO_2 Removal	H_2O Removal
Gas boiler	Required < 1000 ppm	Not Required	Required
CHP	Required < 1000 ppm	Not Required	Not Required
Kitchen Stove	Required <100 ppm	Not Required	Not Required
Vehicle Fuel	Required	Required	Required
Natural Gas grid	Required	Required	Required

Source: Persson *et al.*, (2006); BioCycle, (2010) and Extentsion, (2012)

The H_2S levels provided in Table 2.12 are not standardized figures; they are basically dependent on the specifications given by equipment manufacturers. While Aklaku(2011b) indicate that some engine manufacturers specify maximum allowable H_2S levels to be 1500 ppm (0.15% vol.), Al Seadi *et al.* (2008) give 700 ppm (0.07% vol) as the maximum H_2S level suitable for most engines used for CHP generation.

There are several technologies available for removing contaminants from biogas and upgrading the gas to vehicle fuel or natural gas quality (Persson *et al.*, 2006).The two common methods of removing carbon dioxide from biogas are absorption (water scrubbing, organic solvent scrubbing) and adsorption (pressure swing adsorption, PSA). Less frequently used are membrane separation, cryogenic separation and process internal upgrading, which is a relatively new method. Meanwhile Hydrogen sulphide removal (desulphurization) can be done biologically or chemically in the processes known as: Biological desulphurization in the digester, biological desulphurization outside the digester, chemical desulphurization in the digester and the chemical desulphurization outside the digester(Al Seadi *et al.*, 2008) and (Persson *et al.*, 2006). More information on biogas upgrading processes can be obtained

online from a document prepared by Persson *et al.*(2006), which is dedicated to this topicat: http://ww.biogasmax.eu/media/1__biogas_upgrading__075624200_1207_19042007.pdf or fromBiogas Handbook by Al Seadi *et al*. (2008).

2.7.5 Uses of Biogas

Biogas can be used the same way as natural gas once it is upgraded to contain more methane.Biogas that will be used in commercial quantities must meet the minimum requirements for the properties of combustible gases especially that set by CHP engine manufacturers (Al Seadi *et al*., 2008). This is presented in Table 2.13

Table 2.13:Minimum properties for combustible gases with relative oxygen content of 5% (Adapted from Al Seadi *et al.,* 2008)

Property	Symbol	Value
Heat value (lower heat value)	Hu	≥ 4kWh/ m^3
H_2S Content	H_2S	≤ 0.15 % vol.
Chlorine Content (total)	Cl	≤ 100.0 mg/m^3 CH_4
Fluoride content (total)	F	≤ 50.0 mg/m^3 CH_4
Sum of Chlorine and Fluoride	(Cl + F)	≤ 100.0 mg/m^3 CH_4
Dust (3 – 10 µm)		≤ 10.0 mg/m^3 CH_4
Relative humidity (at lowest intake air temperature, i.e. condensation in intake pipe and gas control path)	φ	< 90%
Flow pressure before entry into the gas control path	P_{Gas}	20 – 100 mbar
Gas pressure fluctuation		± 10% of set value
Gas temperature	T	10 – 50 °C
Hydrocarbons (>C5)		< 0.4 mg/m^3 CH_4
Silicon (at Si > 5 mg/$m^3$$CH_4$ oil analysis of metal content < 15 mg/kg oil observed)	Si	< 10.0 mg/m^3 CH_4
Methane e count (Biogas MC approx. 135)	MZ	>135

Currently, the major uses of biogas include heat production by direct combustion, electricity production by fuel cells or micro-turbines, CHP generation or as vehicle fuel (Al Seadi *et al*., 2008).

a) ***Heat Production by Direct Combustion***

Biogas may be combusted directly to produce heat. The heat so produced can be used for cooking, boiling water and lighting. This is the most common use of biogas from small-scale plants in developing countries (Persson *et al.*, 2006). Biogas burners can be produced locally. Additionally, conventional gas burners and gas lamps can easily be adjusted to biogas by changing the air to gas ratio.Biogas used for heating purposes, according to Al Seadi *et al*. (2008) does not need any upgrading

since the contamination level does not restrict the gas utilization as in the case of other applications. The heating value of $1m^3$ of biogas is equivalent to 0.46 kg of LPG, 0.67 litres of gasoline (petrol), 0.60 litres of diesel, 0.55 litres of heating and 1.50 kg of firewood (BTC, 2009)

b) ***Electricity Production***

Biogas can be used in fuel cells or to run internal combustions of electric generators. Al Seadi *et al.* (2008) describe fuel cells as electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. Fuel cells have a potential to reach very high efficiencies (>60%) and low emissions (Persson *et al.*, 2006). There are various types offuel cell that can be operated with biogas. They are named according to the type of electrolyte used in them as: The Polymer-Electrolyte-Membrane (PEM), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC). On the other hand, the two types of engines available are spark ignition (SI) engines and dual fuel engines into which at least 10% of diesel is injected. These engines drive the electrical generator to convert the chemical energy in the biogas to electrical energy.

Where biogas is not upgraded (methane content of about 60%), its electrical conversion efficiency is 35%. This means that $1m^3$ of biogas will generate 2.14kWh of electricity (Banks, 2012)

c) ***Use of Biogas as Vehicle Fuel***

Biogas, when upgraded into biomethane (biogas containing over 95% methane) can be used to run vehicles that run on natural gas. The number of cars running on natural gas is increasing. At the end of 2005, more than 5 million natural gas vehicles (NGVs) were in the world (Persson *et al.*, 2006). Due to the reduction of CO_2, NO_x and Non Methane Hydrocarbons (NMHC) offered by biomethane vehicles, many European cities are changing the engine of their buses to biogas driven engines (Persson *et al.*,

2006). According to Murphy (2005), 1 m^3 of biomethane (biogas enriched to over 97% CH_4) can drive a vehicle (Volvo V70) over a distance of 10km.

d) ***Biogas Injection into the gas grid***

In advanced countries like Sweden, Switzerland, Germany and France where gas grids are used to supply gas for domestic and industrial use, upgraded biogas can be injected into the natural gas grid. For this purpose, the gas must be upgraded to the standards set by each country.

e) ***Other uses of biogas***

Biogas, according to Sasse *et al.*(1991) can be used to operate refrigerators and chicken heaters. In some areas, biogas is used for coffee roasting, bread baking or sterilization of instruments. Consequently, there is no limitation to the utilization of biogas if its properties are observed.

Slurry	Average daily biogas Production *(m^3/ day)*	Average Slurry Effluent pH	Carbon dioxide (CO_2) Content of Biogas (%Volume)		
			Minimum	Maximum	Average
S_1	1.004	7.28	37	39	38
S_2	0.722	7.45	36	40	37
S_3	1.670	7.08	31	34	32
S_4	1.952	7.00	32	37	34
S_5	325.360*	6.90	31	38	35

2.8Uses of Digestate/ Effluent form Biogas Plants

Digestate or Effluent is the liquid (semi-liquid) portion of the by-products of the anaerobic digestion process which is left after the extraction of biogas. It is rich in nitrogen (N), potassium (K) and phosphorus (P) which are the most important nutrient required for plant growth. According to Mouat *et al.* (2010), the amounts of N, P and K supplied by typical digestateare in the approximate ratios of 2:1:3. However, this mayvary greatly depending on the feedstock.

The nutrient value of the digestate gives it a diverse application in agriculture. It can be used in its raw state or after it has been conditioned.

2.8.1 Direct Application of Effluent

The direct application of manure to land, which is the commonest single technique for its disposal and use in the world, increases water-holding capacity of the soil. It further lessens wind and water erosion, improves aeration, promotes the growth of beneficial organisms and maintains soil fertility thus improving plant growth. This practice is said to have increased yields by 6 - 10%, regardless of kinds of soil (FAO, 1992).The easiest way of applying the digestate directly is making it flow by gravity. This means that the overflow point of the digester is slightly higher than the farmland. A slope of 2.5% has been recommended for this for direct application over short distances (Sasse *et al.*, 1991). However, on small farms in developing countries where it is difficult to get the minimum slope, simple equipments like buckets, scoops, containers with straps, wooden wheelbarrows with lids, barrels on wheels and others can be used. These tools allow a precise application of digestate (ISAT/GTZ, 1999).

2.8.2 Use of Effluent for Algae Production

Secondly, the effluent can be used for the production of algae which according to Oligae, (2012), can be used for the manufacturing of pharmaceuticals and cosmetics. It can also be used in aquaculture, the production of biofuels and as human food. Ablue-green algae *Spirulina platensis*was grown in the effluent from a swine manure digester, productions of 7.3 and 9.7 g/m^3 (equivalent to 1.9 x 2.5 tonnes/ha/year) were achieved during winter and summer respectively. The harvested algae contained 57.5% protein (FAO, 1992)

2.8.3 Use of Effluent as Livestock Feed Supplement

In a complete waste recycling concept, cattle dung is digested anaerobically to produce energyand the slurry. The slurry is used to grow fodder which is in turn used to feed the cattle. This phenomenon is

shown in Figure 2.25.Aside using the effluent for the cultivation of fodder,it has nutrients which make it suitable to be incorporated into livestock feed (FAO, 1992). Many studies have been conducted to evaluate the chemical composition of biomass resulting from thermophilic anaerobic fermentation of cattle wastes (FAO, 1992).

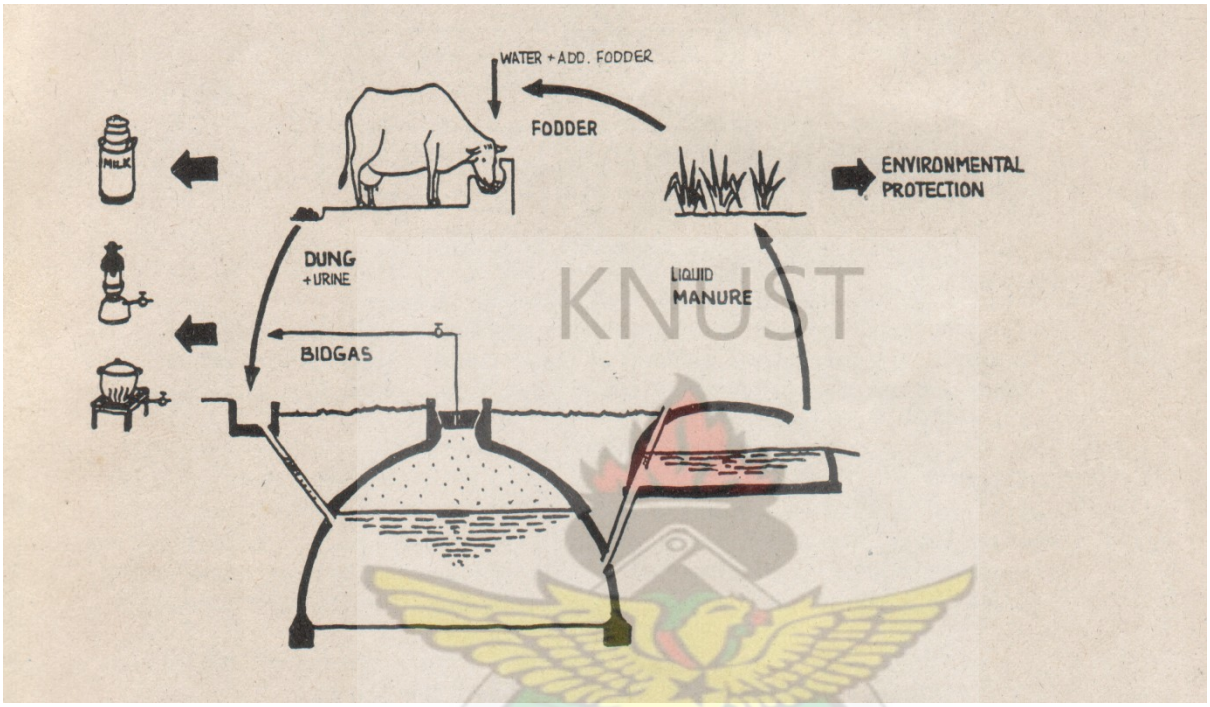

Figure 2.25: The Waste Recycling concept of Anaerobic digestion (Aklaku, 2011a)

Feeding cattle, pigs and poultry with digested animal wastes has been demonstrated to be a potential use of the effluent product. This is because the dry effluent contains considerable quantities of vitamin B12 concentrations (of over 3,000 mg B12 per kg dry sludge) (Maramba, 1978) which is even more than the main sources of B12 in animal feeds – fish and bone meal – which contain 200 and 100 mg/kg respectively. Therefore, digested sludge thus has potential as an animal feed supplement (FAO, 1992)

2.8.4 Use of Effluent as Feed for Fish

The fourth application of slurry is its use in aquaculture where it is used as fish feed. Like in the previous case, many studies have been made to ascertain the effect of feeding fish with digestate. A comparative study on fish culture fed only with digested chicken slurry was carried out by National

Bureau of Environmental Protection (NBEP), Nanjing China in 1989. Resultsshowed that the net fish yields of the ponds fed only with digested slurry and chicken manure were 12,120 kg/ha and 3,412.5 kg/ha, respectively. The net profit of the former has increased by 3.5 times compared to that of the latter (Heegde, 2010). In another study, in which the effects of biogas slurry on survival and growth of common carp were studied, it was concluded that growth rates of fish in terms of weight were 3.54 times higher in biogas slurry treated tanks than in the control. Biogas slurry proved to be a better input for fish pond than raw cow dung since the growth rate of common carp in raw cow dung treated tanks were only 1.18 to 1.24 times higher than in the control. With regards to fish survival, there was 100 percent survival of fish in ponds fed with digested biogas slurry as compared to only 93 percent survival rate in ponds fed with raw cow dung (Heegde, 2010).

2.8.5 Use of Effluent for growing Plants and Crops

The coarse fibre fraction of an effluent (called "Cabutz"), which is prepared by sieving the effluent through a vibration screen has been found to be a suitable growth medium.It is now used in Israel to many greenhouses and plant nurseries as a substitute to peat moss due to the following problems with the latter.

1. The price of horticultural peat is high, and shipping it long distances considerably increases its price
2. Peat resources throughout the world are limited and non-renewable
3. In some cases, sterilized peat serves as an enrichment medium for various phytopathogenic fungi species, such as *Pitum sp.* (FAO, 1992).

Cabutz is now used in the cultivation of horticultural crops and mushrooms

2.8.6 Use of Effluent inComposting

Digestate can be used in composting. Composting is best if distribution by gravity is not possible (Sasse *et al.*, 1991) and there is a need to store nutrients for future use; nitrogen will be lost if the

digestate is kept for a long time especially when it exposed to sunlight or windy weather. Composting is therefore a form of storing the slurry over some time without losing too much nitrogen. Compost is also a method of increasing the amount of organic manure which stabilizes the soil structure. According to Sasse *et al*.(1991), compost is superior to liquid slurry for long-term improvement of soil fertility. Compost releases its nutrients slowly and therefore, is applied in few but larger doses over the year.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter presents a brief description of the study areas. The location, size, population, occupation and the sanitation condition of the study areas, where applicable, are presented in this section. Also, it presents the materials used and a description of the procedures that were taken in carrying out the study.Information on the companies, Safi Sana Ghana Limited and hpw Fresh and Dry Limited which funded the studyis also given in this chapter.

3.2 The Study Area

3.2.1 Geographical Location

The study areas wereGhana Irrigation Development Authority (GIDA's) site in Ashaiman in the Greater Accra Region and Adeiso (HPW Fresh and Dry Limited Factory site) in the Eastern Region of Ghana. The GIDA site is precisely located between coordinates 5º 40' and 5º 43' N of latitude and longitudes 0º 05' and 0º 07' E at a distance of 26 km North East of Accra and almost directly north of Tema on the northern boundaries of Tema township(MOFA, 2011) while Adeiso lies between coordinates 5° 47' 00"N and 0° 29' 00"W.The GIDA site was selected due to its strategic location in a slum community and the availability of suitable land. The hpw Fresh and Dry Limited was selected because it had biogas plants already in place and produces huge amounts of fruit wastes. Figure 3.1 presents the location of the study areas on Ghana's map.

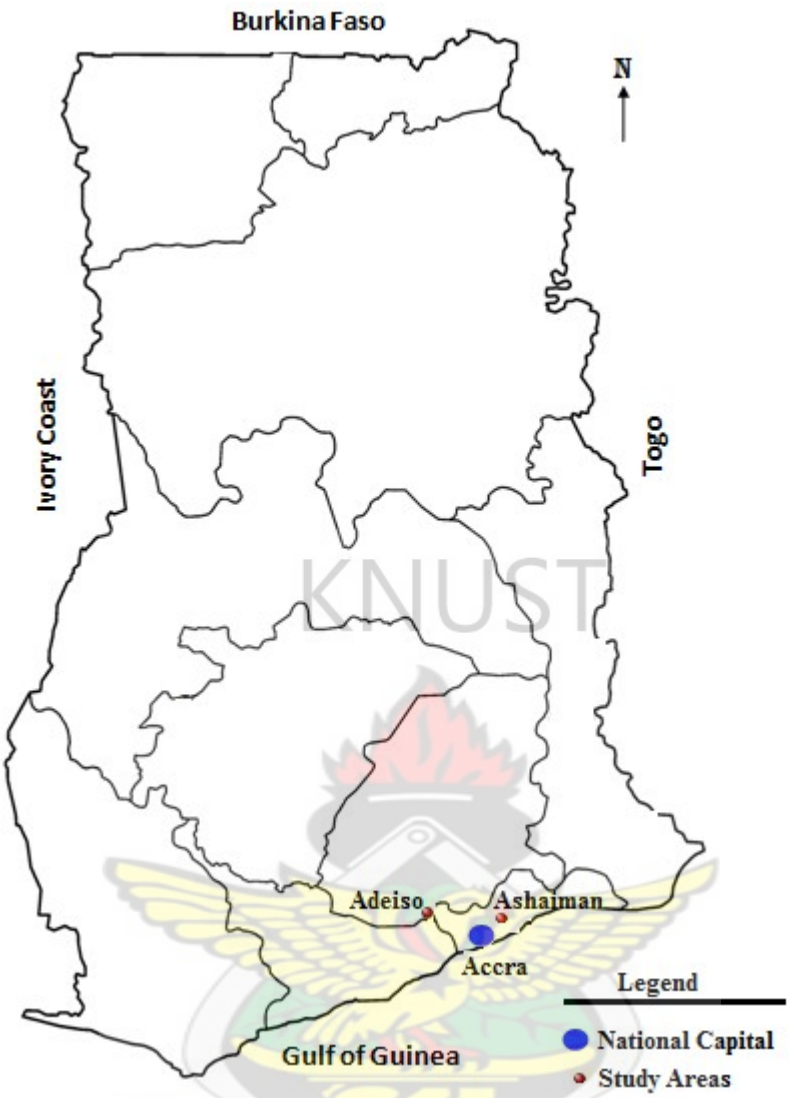

Figure 3.1: The Map of Ghana showing the study areas

3.2.2Brief Description of the Study Areas

The GIDA site is located at Roman Down in Ashaiman.The site which covers an area of approximately 155 ha, according to Abatemi-Usman *et al.*(2010), is one of the 22 irrigation projects run by GIDA, a governmentorganization under the Ministry of Food and Agriculture (MoFA).The area for farming is divided into two allotments called the Left and Right Banks as shown in Figure 3.2.

Most of the farmers'on the irrigation scheme cultivate about 1 – 2 acres of land.The farmers cultivate maize, rice, cowpea, okra, egg plant and other vegetables. The site is also inhabited by some religious bodies that have formed praying grounds on the site where they come occasionally to have prayers.

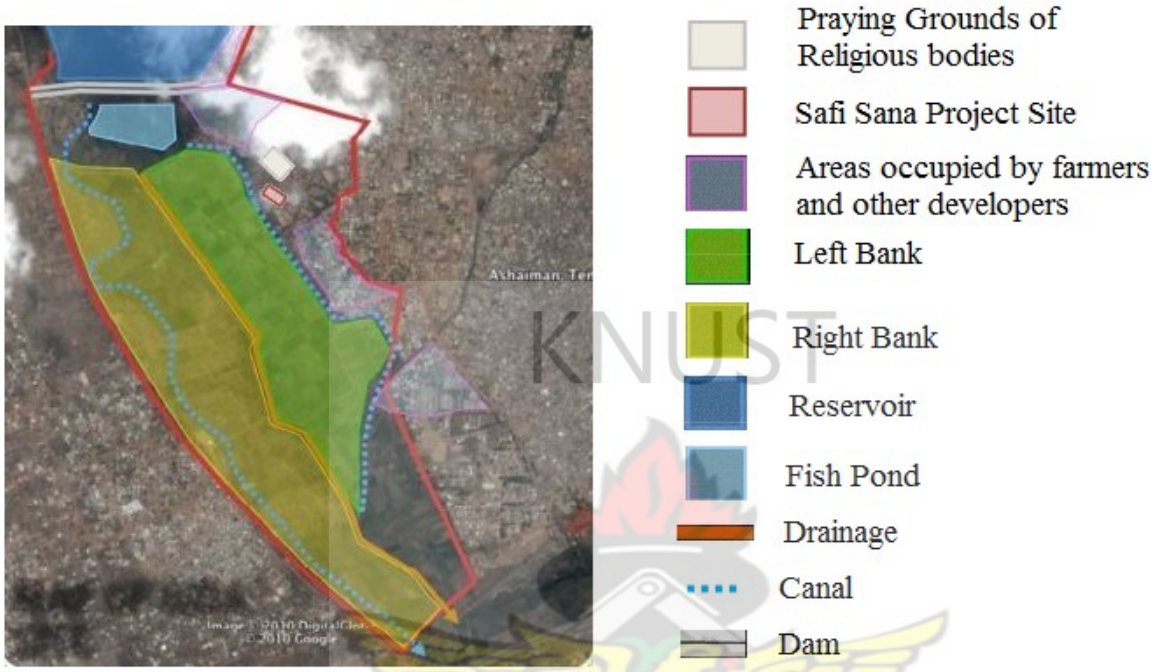

Figure 3.2: Safi Sana Project Site at GIDA in Ashaiman (Adapted and modified from Abatemi-Usman et al (2010)

Hpw Fresh and Dry Limited is a free-zone company located on the left side of Adeiso – Bawjiase road. It dries fruits such as pineapple, mango and coconut for export. The company has constructed two 450 cubic meters anaerobic digestion plants for digesting its fruit wastes. Figure 3.3 shows the premises of the company indicating the manufacturing sector (1), waste storage and slashing chamber (2), mixing chamber (3) and slurry mixing and pumping system (4).

Figure 3.3 hpw Fresh and Dry Limited Company premises

3.4 Data Collection

3.4.1 Source of Data

The data used in this study were obtained from two sources, namely, primary sources and secondary sources. The Primary data was obtained from the research site and included the organic loading rate (OLR), bacterial environmental conditions parameters (slurry pH and temperature), daily gas yield and biogas CH_4 (%), CO_2 (%) and H_2S (ppm) content. The secondary data included the chemical properties (total solids (TS), organic dry matter (ODM) and the moisture content) of the substrate. These data were taken from the Animal Research Institute (ARI) of the Council for Scientific and Industrial Research (CSIR). The Animal Research Institute is located in Frafraha off the Adenta – Dodowa road.

3.4.2 Materials Used in the Study

The list of materials used in conducting this study is presented in Table 3.1.

Table 3.1: List of Materials used in the study

Material	Description	Use
Digesters	Two 8 m^3 WASAZA (with 6 m^3 digester volume) plant constructed onsite at GIDA and two 450 m^3 cylindrical digesters constructed at Adeiso.	Creation of the Anaerobic Digestion environment required for the gas production
Weighing Scale (Analogue Crane)	Spring balance (shown in Figure 2.15B.	Measuring the fresh weight equivalent of the ODM to be fed into the digester
Plastic Barrel, plastic buckets	DECORPLAST, 55litres barrel and 15 litres bucket	Measuring the amount of water to be added to the substrate
Pig feet containers		For collecting, transporting and storing slaughter wastes
pH Meter, pH Paper		Measuring the pH of the slurry and the digestate
Thermometer	Mercury Bulb Thermometer	Taking daily temperature of the slurry in digester
Gas meter	CMC Wet Test type gas meter	Measuring daily gas production
U-Manometer	Constructed and mounted on site by BEL	Taking daily measurement of pressure in each digester
Gas Analyser	Sewerin Multitec 540	Measuring the gas quality
Gas burner	South African made straight burner shown in Figure 3.9	Flaring daily gas produced
Stirrer	Stick purposely made for stirring	For stirring the slurry in the digester

MS EXCEL	MS EXCEL version 2007	In the graphical presentation and analysis of data collected

3.4.2.1The Biogas Plants or Digesters

The digesters used for the study were two Fixed Dome WASAZA plants and two cylindrical plants which were located at the GIDA site and the premises of the HPW Fresh and Dry Limited respectively.The WASAZAplants were covered completely with earth while the cylindrical plants were constructed such that half of its height was buried in the earth with the other half above ground level as shown in Figure 3.4.Each WASAZA digester (Figure 3.3)was 8 m^3 with 6 m^3as operational volume and had a designed retention time of 30 days while the cylindrical plants had 450 m^3 digestion volumes with separate balloons for storing the produced biogas as shown in Figure 3.4.

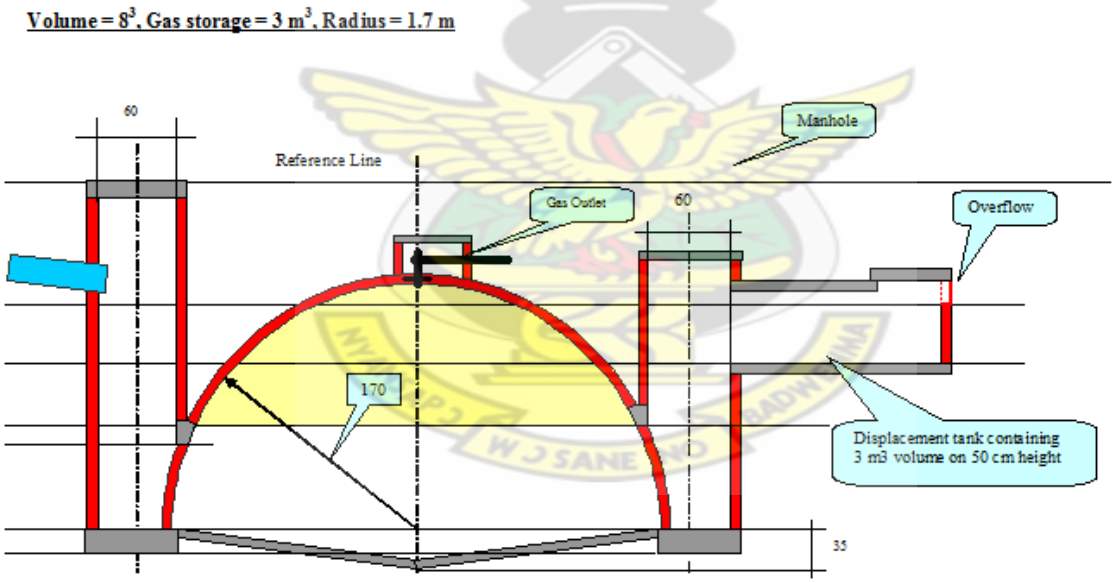

Figure 3.3: The design of the WASAZA plant used in the Study (Aklaku, 2011b)

Figure 3.4: The two 450 cubic meter (m^3) AD plants constructed at the hpw Fresh and Dry Limited premises at Adeiso

3.4.2.2 The Substrates

The substrates that were digested in the WASAZA plants were prepared by mixing different ratios slaughterhouse waste (SW) and human waste (HW) into slurries which were labelled from S_1 to S_4 such that the kilogram organic dry matter (kg ODM) of SW/HW ratios for S_1, S_2, S_3 and S_4 were 5.78, 0, 1.21 and 0.55 respectively. The exact compositions of the individual slurries are presented in Table 3.4. The slaughterhouse waste was collected in pig feet containers (Figure 3.5 B) from Accra and Tulaku abattoirs while the human waste was collected from a 3-seater pour flash toilet built at the site.The collected toilet was temporarily stored in a chamber called Buffer Chamber (Figure 3.5 A2)

The substrate fermented in the cylindrical digesters constructed at Adeiso is a composite of fruit wastes (FW) consisting mainly of pineapple, mango, pawpaw and traces of other fruit wastes mixed with wastewater from the factory's laundry and washrooms forming a slurry labelled S_5. The actual composition of FW was not readily available since they were mixed from source (the production room of hpw or as transported from Blue Skies Limited).

Figure 3.5: Source of Substrate used in the study. A: 3-Seater aqua privy pour flash toilet B: Slaughter Waste (SW) brought (in Pig feet containers) from the Accra abattoir. C: Pineapple waste D: Mango waste

3.4.2.3 The slurry preparation and Feeding System

Generally, the slurry preparation and feeding system consisted of the temporary waste storage chamber, the mixing chamber and the feeding system. The volumes of the mixing chambers were marked by calibrating them.

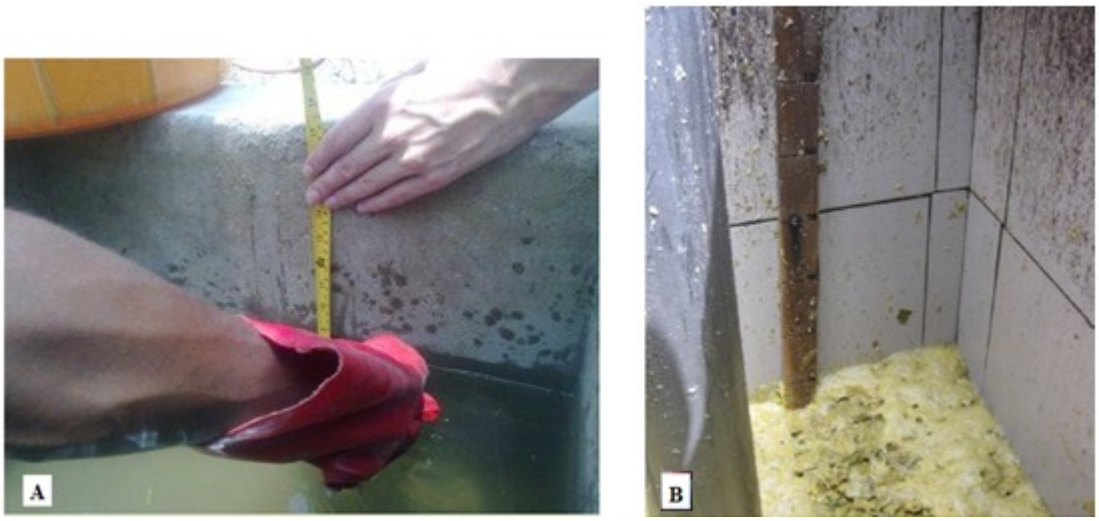

Figure 3.6: Calibrated Mixing Chambers. A. One of the Site operators making a 25 litre mark on the mixing chamber wall at GIDA site. B. Wooden rule inserted in the mixing chamber at Adeiso (Picture by Johanna Grim & Maria Johansson)

The mixing chamber attached to the WASAZA plants was calibrated by pouring 25 litres of water in it and marking the water level on the wall (Figure 3.6A) until the mixing chamber was full. The marks were then painted with white paint as 25, 50, 75, 100, 125, 150, 175 litres.The cross-sectional area and depth of the mixing chamber attached to the cylindrical plants at Adeiso were estimated to be 6.76 $m^2$and 4 m respectively. A graduated wooden rule was attached to the inner partof the chamber to help in calculating the volume of substrate pumped into the digester as shown in Figure 3.6B.

The slurry preparation and feeding system attached to the Adeiso plant consisted also of a shredder (Figure 3.7 A) and an electrical mixing and pumping system (Figure 3.7 B).

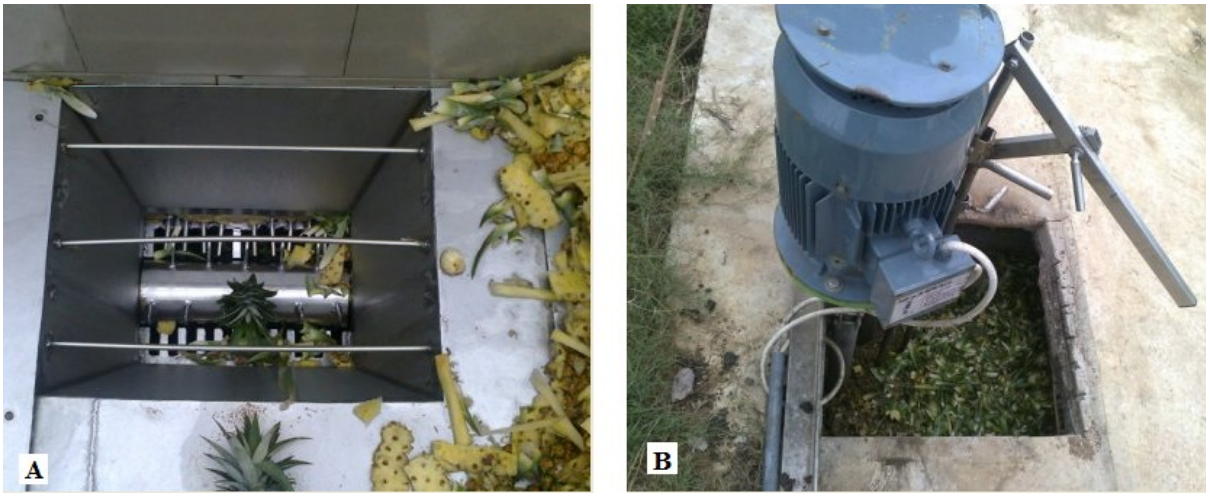

Figure 3.7The Shredding and Pumping system. A: The Shredder B: The mixing and pumping system mounted in the mixing chamber

3.4.2.4 The Gas Meter

The Gas meter used for measuring daily gas production in this study was the Wet Test type which operates on the positive displacement principle (Section 2.7.2.2 (a)). It has a lever which rotates at five litres per revolution (5l/r). The volume of gas that has flown through the gas meter is recorded and presented by a revolution counter. The various parts of the meter and its specifications are shown in Figure 3.8 and Table 3.2 respectively.

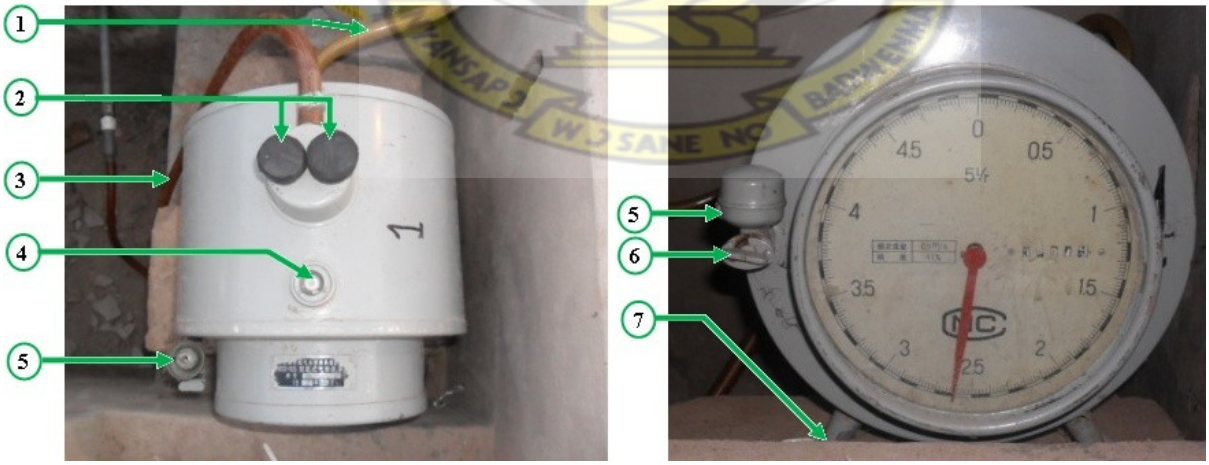

Figure3.8: Parts of the Wet Test meter used in the Study (1) Biogas Inflow into the gas meter. (2) Gas plug. (3) Gas outflow from the gas meter. (4)Meniscus. (5) Sight box (6) Water height adjustment screw (7) Levelling Screw

Table 3.2: The Specifications of the Wet Test Gas Meter (CMC Model) that was used in measuring the daily gas production

Property	Value
Drum Size	5L/R
Flow Rate	0.5 m^3/h
Maximum Flow Rate	0.75 m^3/h
Minimum Flow Rate	0.005 m^3/h
Full Reading	100 m^3
Operating Pressure	500 – 3000 Pa
Operating Temperature	5 – 35 °C
Accuracy	1 %

3.4.2.5 The Gas Analyzer

To identify the quality of the biogas produced from the digester, the gas must be analyzed. An electronic Gas Analyzer (Hermann Sewerin Multitec 540) was used to analyze the biogas that was produced daily. The properties of the analyzer used in this study are presented in Table 3.3.

Table 3.3: The measuring ranges of the Gas Analyzer used in the study

Gas Type	Measuring Range	Sensor Type
Methane	0.0 – 100% vol.	Infrared sensor
Carbon Dioxide	0 – 100% vol.	Infrared sensor
Oxygen	0.0 – 25% vol.	Electro-chemical sensor
Hydrogen Sulphide	0 – 2000 ppm	Electro-chemical sensor
Carbon Monoxide	0 – 500 ppm	Electro-chemical sensor

3.4.2.6 The U-Manometer

The U-Manometer was used to measure the pressure of biogas in the WASAZA plants only since none was provided for the plants at Adeiso. It was made with a plain plastic tube which has been formed into a U-shape as shown Figure 3.9.Clear water was poured into the U-shaped tube. One end was connected to the gas outflow from the digester while the other was opened to the atmospheric pressure.

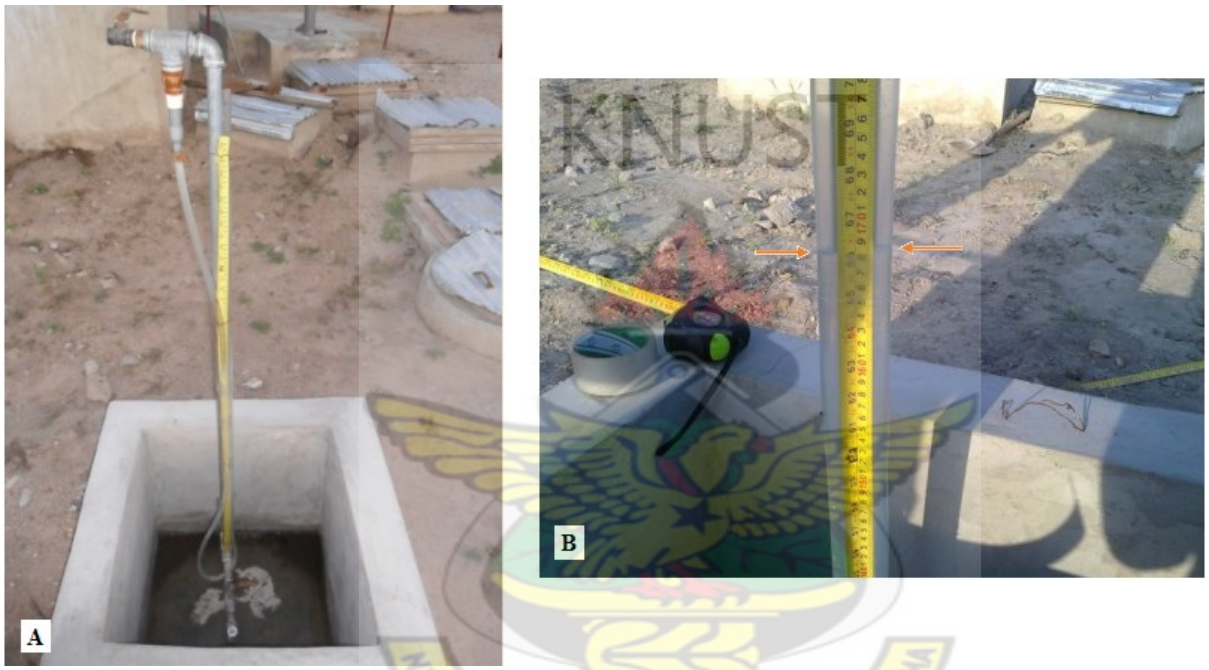

Figure 3.9: The U-Manometer used on site. A: The full manometer mounted on the digester. B: Brown marks indicating water level in the U-Manometer

3.4.2.7 Biogas usage

Since methane (CH_4) is a potent greenhouse gas, biogas produced on the site must not be released into the atmosphere, but rather be burned. The biogas produced at the GIDA site was combusted directly with a burner (Figure 3.10A) after it has flown through the gas meter. However, the biogas produced at the hpw Fresh and Dry Limited premises is used in running the boiler (Figure 3.10B), generator (Figure 3.10C) or cooking in the company's kitchen.

Figure 3.10Equipments that were ran on the biogas. A: Gas burner used for direct combustion of biogas. B: Boiler used for drying the fruits. C: Generator set

3.4.3 General Approach used in Data generation and Collection

Generally, the data required for this study consisted of the organic loading rate (OLR), the environmental conditions of the slurry in the digesters, the daily gas production and the quality of gas produced per slurry mix.The activities that were performed during the data collection can be grouped into two phases: the Pre-Field phase and Field work phase. Again, the activities performed during the Field work stage to facilitate data collection were grouped into on-site activities and off-site activities. Details of activities conducted during these stages are explained in the following sections.

3.4.3.1 Pre-Field Work Phase

The pre-field work phase included activities that were performed to get the AD plants ready, making arrangements for obtaining the substrates and putting the research protocols together. During this phase, thetwo digesters and the 3-seater toilet facility from which human waste (HW) will be collected and the buffer chamber in which it will be temporarily stored were also constructed at GIDA. Similarly, the two plants at hpw Fresh and Dry Limited were also constructed. Furthermore, arrangements for the collection, transportation and storage of substrates that were brought from external sources (slaughter waste and fruit waste) coupled with where substrates chemical characteristics will be determined (the ARI) were made.

3.4.3.2 Field Work Phase

During this phase, tests were run and data were collected. The data was grouped into two categories: on-site and off-site data. The off-site data was taken from the Animal Research Institute at Frafraha in Accra. It formed the secondary data and included the total solids (TS) and the volatile solids (VS) of the SW, HW and FW. The on-site data on the other hand included all the data that were measured directly at the site thus being the main primary data. These included: organic loading rate, slurry pH, Effluent pH, Slurry Temperature, daily gas production and gas quality.

a) Tests

In all, five different tests were carried out with each test being differentiated from the other by the ratio or types of substrates used in forming its slurry. The tests were coded Test 1, Test 2, Test 3, Test 4 and Test 5. The quantity of SW was weighed as fresh weight while the quantity of HW was measured in litres.In the case of Tests 1 to 4, with a known weight of SW (kg) and its organic dry matter content (%) which is a secondary data obtained from ARI, the amount of ODM of SW fed into digester was determined using equation 3.1. The amount of ODM of HW fed into digesters in Tests 1 to 4 was determined using equation 3.2 while the total ODM fed into the digesters daily was determined by using equation 3.3. In the case of Test 5, the total ODM fed in a day was computed by using equation 3.4. The slurries prepared in each test and their resulting total ODM fed into each digester is shown in Table 3.4.

$$OLR_{SW}=\frac{F_{SW}(kg/day)\times ODM_{SW}(\,)}{V_d(m^3)}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..[3.1]$$

$$OLR_{HW}=\frac{V_{HW}(l/day)\times \rho_{HW}\times ODM_{HW}(\,)}{V_d(m^3)}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[3.2]$$

$$OLR=OLR_{SW}+OLR_{SW}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[3.3]$$

$$day$$

$$m^3/¿\times \rho_{FW}\times ODM_{FW}(\,)$$

$$¿$$

$$V_{FW}¿$$

$$OLR_{FW}=¿$$

Where: $OLR_{SW}=Quanti\,ty\,of\,slaughter\,waste\,present\in the\,slurry\,(kgODM/m^3/day)$

$OLR_{HW}=Quanitity\,of\,human\,waste\,present\in the\,slurry\,(kgODM/m^3/day)$

$OLR_{FW}=Organic\,Loading\,rate\,of\,Fruit\,wastes\,(kgODM/m^3/day)$

$$OLR = Total\ organic\ dry\ matter\ fed\ into\ the\ digesters\ (kgODM/m^3/day)$$

$$F_{SW} = Weight\ of\ fresh\ slaughter\ waste\ present \in the\ slurry\ (kg/day)$$

$$ODM_{SW} = Average\ Organic\ dry\ matter\ content\ of\ slaughter\ waste = 14.12$$

$$V_{HW} = Volume\ of\ human\ waste\ present \in the\ slurry\ (l/day)$$

$$\rho_{HW} = Relative\ density\ of\ human\ waste = 0.934$$

$$ODM_{HW} = Average\ Organic\ dry\ matter\ of\ human\ waste = 1.46$$

$$V_d = Volume\ of\ digester\ (m^3)$$

b) Organic Loading Rate (OLR)

The organic loading rate of slurries digested in each study was calculated using equations 3.1 to 3.3 and values are presented in Table 3.4.

Table 3.4: The composition of the slurries used in the study

Slurry (S)	Total Organic Dry Matter Fed into the digesters (kg ODM/day)	Percentage Composition (%)			Organic Loading Rate (kg ODM/m³/day)	Water (m³/day)
		Slaughter Waste	Human Waste	Fruit Waste		
S1	8.27	85.6	14.4	0	1.4	0.033
S2	2.10	0	100	0	0.3	0.015
S3	3.87	55.5	44.5	0	0.6	0.010
S4	5.97	36.1	63.9	0	1.0	0.010
S5	341.23 – 2477.05	NA	NA	100*	0.8 – 5.5	0 – 23.187

Note:

******* *= Poultry Manure was fed into the digesters occasionally to raise the pH of the slurry.*

i. ***Weighing Fresh Wastes (slaughter wastes and fruit wastes)***

The slaughter wastes that were used in the study were divided into empty pig feet containers and weighed according to the feeding plan for each test. Example, for Test 1, the SW in each pig feet container was 50kg excluding the weight of the pig feet container. The weighing process is shown in Figure 3.11.

The weights of the fruit wastes wereestimated from the quantity of wastes recorded as wastes generated byBlue Skies Ltd and PEELCO Ltd. However, the weight of wastes from HPW Ltd was estimated by measuring the fruits (pineapple, mango and banana) processed at the factory using equation 3.5.

$$W_{FW} = [¿¿Total - W_{Cut} - (W_{Total} \times F_{Seed})] + W_{Rejects} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [3.5]$$

Where:

$W_{FW} = Weight\ of\ fruit\ waste$

$W_{Total} = Weight\ of\ unprocessed\ fruit$

$W_{Cut} = Weight\ of\ edible\ part\ of ffruit\ which\ is\ cut\ for\ further\ processing$

$F_{Seed} = Fractio\ n\ of\ unprocessed\ fruit\ that\ is\ seed$

$W_{Rejects} = Weight\ of\ rejected\ fruits$

Figure 3.11: Weighing SW in the required quantities. 1: SW is shared into empty pig feet containers; 2: The pig feet container is hanged on the spring balance with the help of a nylon.

ii. ***Slurry Preparation and Feeding of digester***

Slurries S_1, S_2, S_3 and S_4 were prepared by discharging the appropriate volume (example, 87 litres *for slurry* S_1) of HW into the mixing chamber by opening valve V_3(Figure 3.12). A known weight (example *50kg for slurry* S_1) of fresh SW was poured into the HW in the mixing chamber. The two substrates were mixed thoroughly until homogeneity was reached after which the pH of the slurry was taken as shown in Figure 3.12. The slurry was then discharged into either digester 1 or digester 2.

The digesters were fed alternatively such that when D_1 was fed first on day 1, D_2 was fed first on day 2. Also, after the retention time (30 days) of one slurry mix has elapsed, the next slurry was fed in to the digesters without evacuating the previous slurry from the digester since the WASAZA plant is a continuous-fed system. Water and a short broom were used to rinse the mixing chamber into the digester that was fed. The volume of water added every day in the case of each slurry mix is shown in Table 3.4

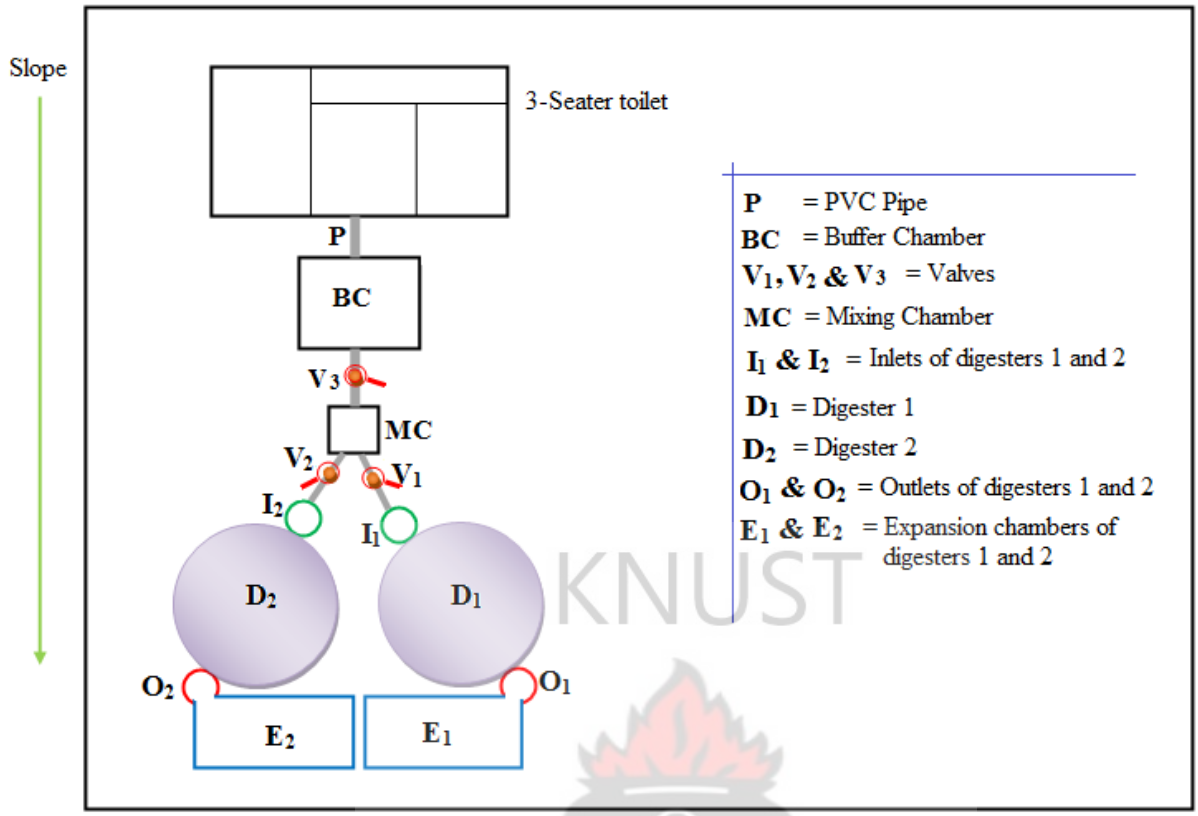

Figure 3.12: Safi Sana Site Layout indicating the positions of various structures.

Figure 3.12: Slurry Preparation. 1: Required quantity of HW discharged from the buffer chamber into the mixing chamber, awaiting SW. 2: pH of Slurry being taken before discharging slurry into the digester

Slurry S_5 was prepared by slashing the fruit wastes into smaller sizes (2 – 5cm) by an electrical shredder (Figure 3.7 A).Water was occasionally added into the shredder's chamber to facilitate its operation. The shredded fruit

wastes entered the mixing chamber which already contained the sewage (black water and grey water) that had flowed from the washrooms on the previous day and wastewater from HPW's processing rooms – when preservatives were not used. The layout of the structures at the HPW's premises is shown in Figure 3.13.

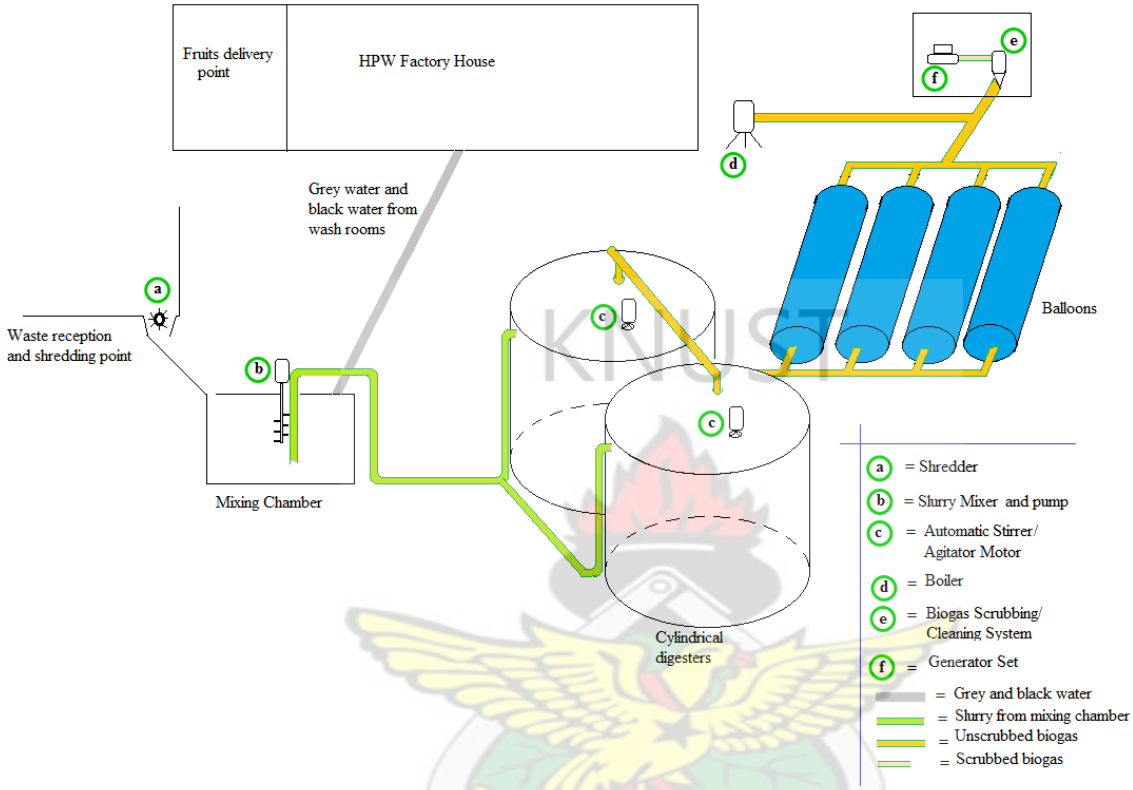

Figure 3.13: Layout of HPW's site indicating the positions of various structures.

c) Measuring the Environmental Parameters

The digester internal (slurry environmental) conditions were measured to ascertain the stability or otherwise of the anaerobic digestion process taking place in the digester. The parameters measured here include the slurry pH and the slurry Temperature.

i. ***Slurry pH***

The slurry pH was measured with the pH meter. A sample effluent was fetched from the expansion chamber of the digester. The pH meter was placed in the sample effluent and the reading checked until it stabilized. The stabilized value was recorded as the pH of the slurry from that digester.

ii. ***Slurry or Digester Temperature***

For slurries S_1 to S_4, the temperature of the digester was measured in the morning (every 10:00 am) with a mercury bulb thermometer. A nylon string was attached to the heard of the thermometer and its sensitive part descended into the digester through the outlet. The string was long enough (about 90cm) to enable the thermometer reach the digester part of the plant. The thermometer was left in the digester for 10 minutes before the final reading was taken as the temperature of the digester (i.e. daily temperature of Digester D_1. The thermometer was then taken to the outlet of the other digester (i.e. Digester D_2) and the process was repeated. In the case of slurry S_5, the temperature was measured by taking samples from the outlet of the digesters as shown in Figure 3.14(a) and immediately dipping the electrodes of an electronic thermometer in it as shown in Figure 3.14(b).

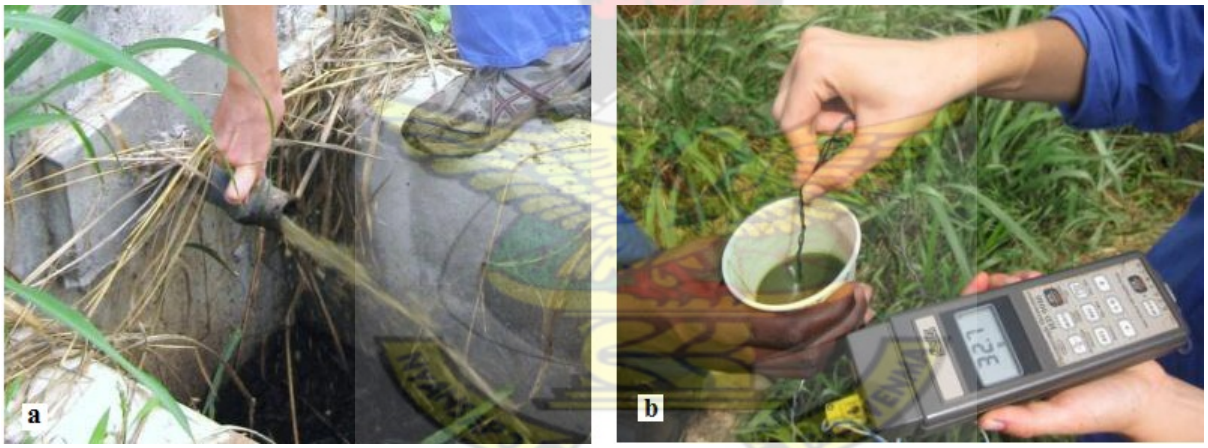

Figure 3.14: Measuring the Temperature of slurry S_5 at Adeiso*(Pictures by Johanna Grim and Maria Johansson)*

The gas production parameters measured on site included gas pressure, daily gas production and gas quality analysis.

i. ***Measuring Gas Production***

The amount/quantity or volume of gas produced (daily gas production) by slurries S_{1-4} was measured with the Wet Test Type gas meter shown in Figure 3.8. Prior to every daily measurement, the meter was

checked to ensure that it waslevelled and had the required amount of water in it. The current meter reading was also recorded in the data book before the gas was released through the meter.

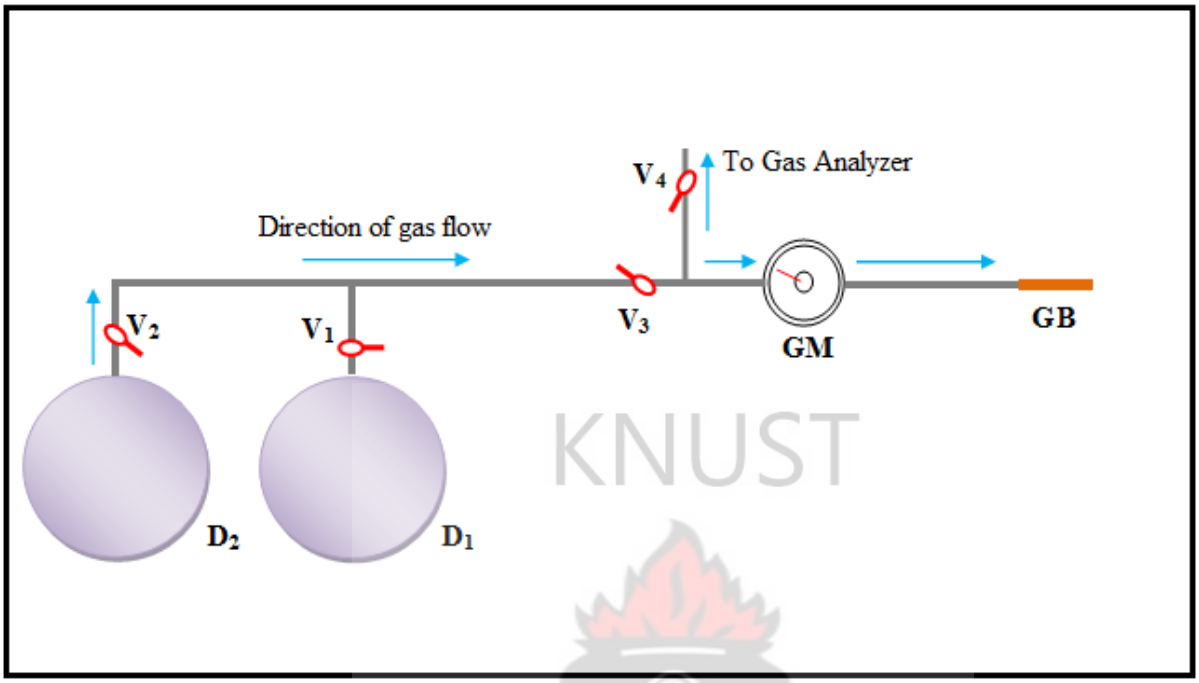

Figure 3.15: Schematic diagram of arrangement of equipments on site.These are typical valve positions for measuring Gas Production and performing Gas Analysis of digester 2; valve 1 (V_1 is closed).

To measure the volume of gas produced by digester D_2 as shown in Figure 3.15, valvesV_1 andV_4 were closed whileV_2 was opened to allow the gas to flow through the gas meter (GM) to the gas burner (GB). Valve V_2 is then closed and the meter reading was taken as the current reading. The difference between the current reading and the one recorded before the commencement of the measurement was recorded as the amount of gas produced by digester D_2 on that day. The same thing was done for digester D_1 in which case valves V_2 and V_4 were closed.

In the case of slurry S_5, the daily biogas production was estimated and corrected with the equation

$$\frac{V_{eb}}{V_c} = \frac{T_{atm}}{T_b} \quad \text{.....[3.6]}$$

where;

$V_{eb} = Volume\ of\ emptied\ balloon$

$V_c = Corrected\ volume\ of\ biogas$

$T_{atm} = Atmospheric\ Temperature$

$T_b = Temperature\ of\ biogas \in balloon$

It is assumed that the gas in the balloon is at atmospheric pressure. The volume of one of the balloons was estimated by measuring its width and length when it was emptyand assumed to be a perfect cylinder, as $90m^3$.The temperature of the shady side of the full balloon was measured with an infraredthermometer, PCE-891 from PCE Deutschland GmbH as shown in Figure 3.16.

Figure 3.16: Measuring the temperature of biogas in the balloon (*Picture by Johanna Grim and Maria Johansson)*

Gas Analysis

The gas analysis was performed with the Sewerin Multitec 540 gas analyzer. The analyzer was switched on and allowed to suck in fresh air (this process is known as purging) which occurs during its booting process. When booting was completed, the readings on the screen for the parameters turned 0.0% in the case of CH_4 and CO_2, but 0ppm for H_2S; indicating that the device was ready to be used.

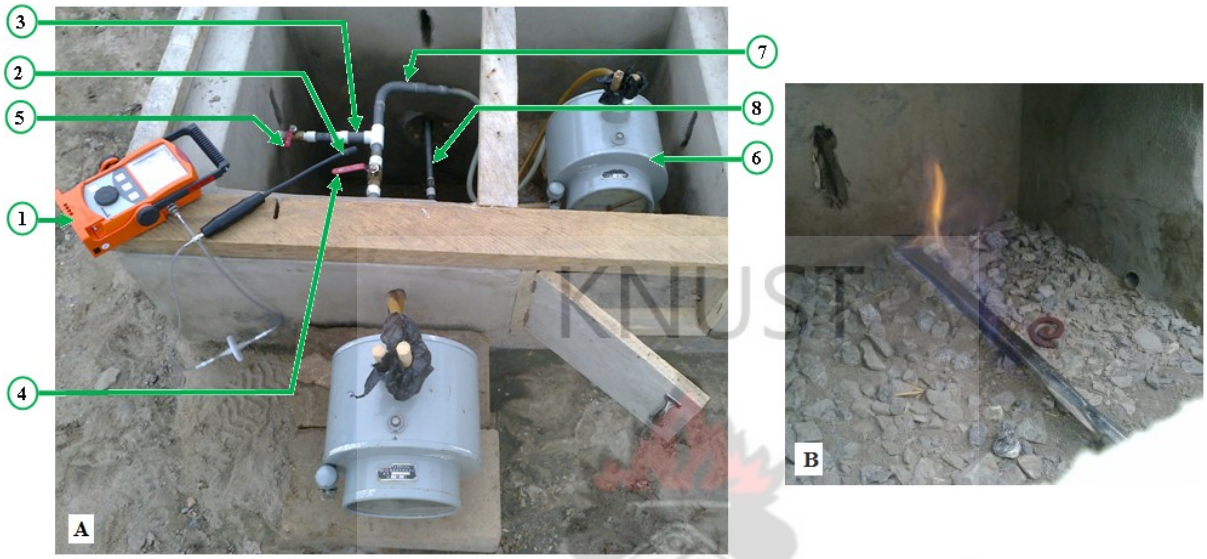

Figure 3.17: Setup of equipments for measuring Gas Production and performing Gas Analysis at the GIDA site A: Various parts of the setup include (1: Gas Analyzer; 2: Suction point of the Gas Analyzer; 3: Pipe through which gas flows from the main line to the Gas Analyzer; 4: Valve V_3 as shown in Fig. 3.15; 5: Valve V_4 as shown in Fig. 3.15; 6: Gas meter; 7: Pipe through which gas flows into the Gas meter; 8: Pipe through which gas flows to the burner) B: Gas burner shown as 'GB' in Fig. 3.15.

Analysis of gases produced by slurries $S_{1\text{-}4}$was performed while the gases were being flared as explained in Section 3.4.3.2.d.*ii*. Valve V_4 was opened a few seconds (about 5 seconds),to flush the pipe and flexible conduit to which the Analyzer will be connected in order to get rid of stray gases that might have been left in it from previous readings. The suction point of the analyzer (shown in Figure 3.17 A) was connected to the flexible conduit and valve V_4 was opened to allow sample of the biogas being flared to pass through the analyzerfor 3 minutes. In the case of slurry S_5, the gas was analyzed by channelling a portion of it through an access point which is controlled by valves (1, 2 and 3) as shown in Figure 3.18A.The CH_4, CO_2 and H_2S values registered on the screen were recorded in a data recording book and also saved in the internal memory of the analyzer.

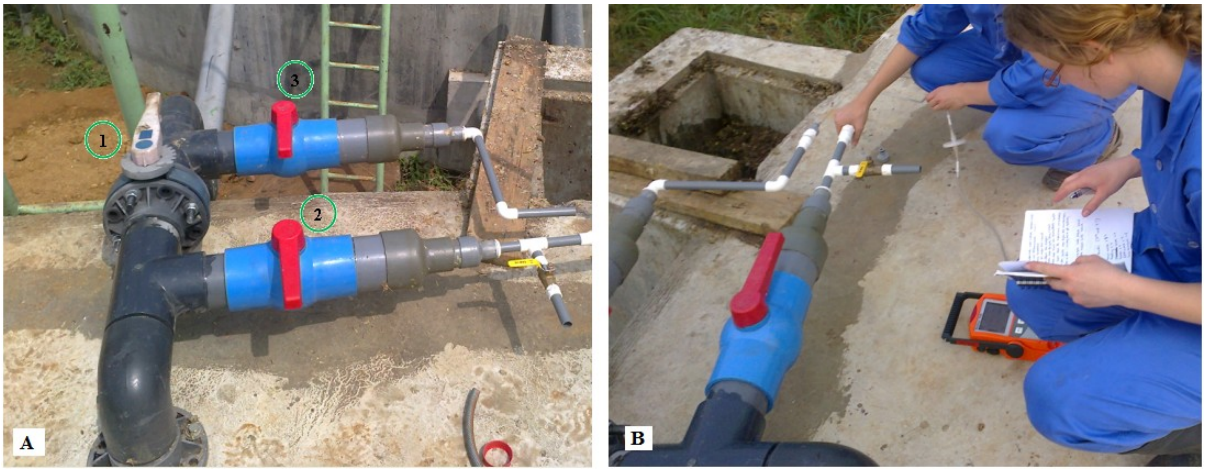

Figure 3.18: Performing Biogas Analysis at Adeiso. A: The valves that control the access point at where biogas analysis is done. B: Biogas Analysis being performed

d) Slurry Stirring/Agitation

Slurries S_{1-4} were stirred manually with a lumber cut and prepared for that purpose as shown in Figure 3.19A. The slurries were stirred from the inlet of the digesters. It was done continuously for about 3 minutes when the slurry was freshly fed into the digesters and performed several times in a day. Slurry S_5 was stirred continuously for five minutes in every hour with an automatic mechanical axial stirring device which was driven byan 11 kW electric motor shown in Figure 3.19B. Stirring was done approximately from the centre of the digester.