UNIVERSITY OF GHANA, LEGON

A PROTOTYPE OF AN ADAPTIVE, MULTI-FEEDSTOCK, ANAEROBIC BIOMASS DIGESTER FOR BIOGAS PRODUCTION

By

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THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF DOCTOR OF PHILOSOPHY, PHYSICS DEGREE

MARCH 2018

DECLARATION

I, Kofi Ampomah-Benefo, hereby declare that except for the references to other peoples' works, which have been duly acknowledged, this thesis is the result of my own research work towards earning a Ph.D. as a student of the University of Ghana, Legon, under the supervision of the Supervisory Committee as detailed below:

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DEDICATION

I dedicate this work to my wife, Ophelia Ampomah-Benefo.

ACKNOWLEDGMENTS

This study has become a reality due to the support and assistance of many individuals and organisations. I am sincerely grateful to all who contributed, however small or great, to make this work a success. However, I feel obliged to acknowledge the special contributions of some of these persons who helped me to complete this study.

First, I am deeply grateful to my supervisors, Dr. M. K. A. Addae-Kagyah, Prof. J. K. A. Amuzu, and Dr. V. C. K. Kakane, for the useful discussions we had throughout my study. I thank Dr. G. K. Nkrumah-Buandaoh, Dr. Allison Felix Hughes, Dr. Hubert Azoda Koffi, Dr. M. N. Y. H. Egblewogbe, Dr. Ato Yankson, and Dr. Godfred Bright Hagan, who are all lecturers in the Department of Physics, University of Ghana, for the keen interest showed and the useful counsel they offered me. I am also grateful to George Kusi-Appiah, Joanna A. Modupeh Hodasi, and Christine Acheampong, who were my colleagues PhD candidates in the Department of Physics. We shared experiences and worked together to achieve our common goals. I thank Harry Ntumi, Pamphile Tossou, Frederick Tatah, and Robert (all technicians) for the technical support they offered me, especially during the setup of my laboratory and assembly of the digester.

I deeply appreciate the support offered by the Council for Scientific and Industrial Research, Ghana, for granting me study leave to pursue this doctoral study. I am grateful to Dr. Gabriel Nii Laryea, Dr, William O. Oduro, Ebenezer N. Kotey, Maame A. B. Animpong, Gloria Boafo-Mensah, and Richard Bayitse, who are all research scientists at the CSIR-Institute of Industrial Research, Ghana. They placed their expertise in scientific

instrumentation at my disposal during the calibration of equipment and tests performed in their calibration and biomass laboratories respectively, as well as offer logistic support to enhance the effective design of the biodigester experimental setup. I extend a special appreciation to Dr. E. D. O. Ansa (CSIR-Water Research Institute, Ghana), for the useful discussions we had on microorganisms and their application to organic waste treatment for energy generation.

I am most grateful for the opportunity to participate in a training course on Biogas Technology for Developing Countries at Chengdu, P. R. China. This training was sponsored by Ministry of Commerce of the People's Republic of China and organised by Biogas Institute of Ministry of Agriculture (BIOMA), P.R. China. My special thanks to Prof Wu Libin, Liu-Ping, Luo Ximin, Lai-Chengxi, all staff of BIOMA, for the wonderful coordination of the entire training.

Finally, my heartfelt gratitude goes to my wife (Ophelia), children (Ernest and David), and mother (Grace) for their prayers and warm support given to me all these years.

ABSTRACT

In this work, the production of biogas from local biomass has been studied through the design, construction and operation of a single-stage, multi-feedstock anaerobic digester, with the aim of providing the scientific and technological bases for the mass assembly and deployment of modular and scalable bio-digester system, using components obtainable in Ghana. A horizontal cylindrical plastic tank (1 m^3) with torispherical ends has been developed into an air-tight (sealed) anaerobic digester. The factors considered in the design and operation include the type of organic material as feedstock and digester portability. The assembled digester was operated as a bench system for a cycle of 24 days under mesophilic temperature conditions. The maximum and minimum temperatures recorded during the operation of the digester were 38.5 ^oC and 32.4 ^oC respectively. The average operating temperature was 36.1 ± 1.5 ^oC. A slurry of fresh cow dung with calorific value of 26.45 MJ kg^{-1} was used as substrate for the study. The final composition of the biogas produced was 60.2 % CH_4 and 39.7 % CO_2, with the highest daily gas production of 0.474 m^3, which was measured on the 18th day. A motorized stirrer and a thermostatically operated heat exchanger system were used to ensure there were no temperature and concentration gradients during the operation of the digester. The performance of the digester is deemed satisfactory and confirms that this pilot-scale prototype is a valid proof of concept and can therefore be used as the basis for the design and assembly of production-scale digester systems.

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NOMENCLATURE

Acidogenesis: The second stage of the conversion of large organic molecules to volatile fatty acids.

Aerobic Digestion: Degradation and stabilisation of organic compounds by microbes in the presence of oxygen.

Anaerobic Digestion (AD): Degradation and stabilisation of organic compounds by microbes in the absence of oxygen leading to production of biogas.

Biodegradable: Material that can be broken down into basic molecules (e.g. carbon dioxide, water) by organic processes carried out by bacteria, fungi, and other microbes.

Biogas: A mixture of gases, predominantly methane, and carbon dioxide, produced by the process of anaerobic digestion.

Closed System: A system that has only energy interaction at its boundary. Mass interaction is absent.

Digestate: The solid and/or liquid material remaining after undergoing anaerobic digestion; often still high in nutrient content.

Digester: An enclosed tank or vessel in which anaerobic digestion of organic matter takes place. In this work, the term biodigester is used as synonym for digester and reactor.

Effluent: The liquid that remains after a treatment or separation process; it refers to liquid which has gone through some type of clarification, settling, or biological process, flowing out of the digester.

Feedstock: Organic input material for subsequent digestion by aerobic or anaerobic processes.

Gasholder: A separate unit (bag or tank) that receives and stores biogas produced in a digester. The digester and the gasholder are part of the anaerobic digestion system.

Household Waste (domestic waste): Municipal solid waste, which is generated as the consequence of household activities. In developing countries, up to two thirds of such waste consists of biodegradable material.

Hydraulic Retention Time (HRT): The (average) amount of time that liquid and soluble compounds stay in a digester. It has the unit of time and is calculated by dividing the volume of the digester by the material flow.

Inorganic Matter: Material, such as grit, inorganic salts, metals, glass etc., which is not degraded by microbes.

Mesophilic: Microbial processes that take place in the moderate temperature range of 20 – 40 °C.

Methane: A colourless, odourless, flammable, gaseous hydrocarbon present in natural gas and formed by the anaerobic decomposition of organic matter; chemical formula CH_4.

Methanogenesis: The final conversion stage of acetic acid and hydrogen into biogas.

Microorganism: Also referred to as microbe) A microscopic organism, which may exist in its single cell form or in a colony of cells.

Million Tonne of Oil Equivalent (Mtoe): The unit of energy defined as the amount of energy released by burning one tonne of crude oil.

Organic Loading Rate (OLR): The substrate quantity fed into the reactor volume in a given time.

Organic Matter: Material from animal and plant sources, which can be degraded by microbes.

Pre-treatment: Treatment of feedstock before being fed into the digester (size reduction, sorting, etc.).

Slurry: A semi-liquid mixture of organic material, microbes, and water *(see effluent).*

Solids Retention Time (SRT): The average length of time solid material remains in a reactor.

System: A system is a quantity of matter or region in space upon which attention is concentrated for the purpose of analysis.

Thermophilic: Microbial activity at a relatively high temperature, in the range of 45 – 60 °C.

Total Solids (TS): When a water or sludge sample is filtered and dried at 105 °C, the residue that remains is referred to as the Total Solids, also referred to as solid content. It is measured in mg L^{-1} (mass per volume) or as a percentage of wet weight. Moisture content plus TS (both expressed as percentage of wet weight) equal 100 per cent wet weight.

Volatile Solids (VS): The organic matter in a sample, usually expressed as a percentage of the Total Solids.

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CHAPTER ONE: ENERGY RESOURCES AVAILABLE TO MAN

1.0 General Overview

Energy is obtained from using physical, chemical, or biological resources to produce light, heat or do some form of work. Energy has applications in both living and non-living things for growth, movement, or metabolic processes. In addition, energy plays an important role in human's existence and society's development. It drives the economy of all sectors of a country, such as (i) powering of heavy duty manufacturing and agricultural machinery in the industries, (ii) lighting, space heating and cooling in commercial and household buildings and (iii) fuelling aeroplanes, ships and vehicles in the transport sector. Energy sources, which are classified mainly as (i) conventional and (ii) non-conventional energy sources, are available in various forms including fossil fuels, charcoal, electricity, nuclear energy, photovoltaics, solar thermal, wind, geothermal and biomass. These sources are not evenly distributed worldwide, and what is available may necessarily have to be converted to needed form. Developing countries, even though consumes relatively less energy, do not have enough. Similarly, there are large quantities of especially organic waste in these developing countries that can be tapped to generate energy. This study investigates the use of organic waste to generate energy for use in developing countries.

In this chapter, conventional and non-conventional sources of energy are discussed. This is followed by discussion on biomass resources, which forms a major component of energy source, especially in developing countries. Emphasis has also been laid on the

technologies of energy production using biomass, especially on anaerobic digestion (AD) technology, which is a biochemical process. The purpose of the study is outlined stating the objective and justification of the study. The chapter concludes by outlining the general form of the thesis.

1.1 Sources of Energy

As mentioned in the previous section, the sources of energy available to man are classified primarily as (i) conventional or non-renewable and (ii) non-conventional or renewable. Both conventional and non-conventional energy sources are used all over the world but in different proportions according to geographical location and country. (Sorensen, 2004). These differences are a result of the level of economic development of the various countries and the distribution of these energy resources. The following sections discusses both conventional and non-conventional sources of energy.

1.1.1 Conventional Sources of Energy

Conventional sources of energy, such as fossil fuels (crude oil, petrol, diesel, coal, natural gas, and kerosene), have been widely harnessed such that there is uncertainty surrounding its future sustainability. This is because of their rate of use being higher than their rate of production. Conventional energy sources are therefore classified as finite. It is envisaged that the known deposits will get exhausted someday. The discovery and exploitation of new deposits of conventional sources are becoming increasingly difficult. Also, there are currently not known technologies to recover conventional sources within short period enough to warrant higher rate of production than rate of consumption (Bently, 2002).

Conventional sources typically have high heating and calorific values. This enables high power to be produced to drive heavy-duty machines, for example. Fossil fuels can be burned directly, and those in the liquid and gaseous form are easily transported. The technology and machinery needed to use these sources as fuel are well developed and widely used.

One major setback of the use of conventional energy sources is their residual products such as CO, NO_x and SO_x produced during combustion. These dangerous gases released into the atmosphere contribute to environmental pollution. The effects of excess amounts of these gases in the atmosphere have been linked to global warming and acid rain in various places. For example, it is believed that the results of overall increase in global temperature have caused climatic changes with heat waves, flooding and typhoons occurring at increased frequency (Marais, et al., 2014; Lou, Liao, Yang, & Mu, 2015; Shang–Shyng, I–Chu, Ching–Pao, Li–Yun, & Cheng–Hsiung, 2015).The finite nature of the conventional fuel supply also does not make them sustainable. Fossil fuels are not distributed worldwide, and are concentrated in certain regions of the earth. They therefore require transportation to where they are demanded.

1.1.2 Non-Conventional Sources of Energy

Non-conventional sources of energy are naturally replenished in a continuous manner. These are also referred to as Green Energy, Clean Energy, or Renewable Energy. These include biomass, photovoltaics, solar thermal, wind, geothermal and biofuels. Non-conventional energy sources varies among geographical locations. For example, within

the equatorial regions, where most developing countries are located, biomass resources are most common (Duku, Gu, & Hagan, 2011).

Renewable energy offers an opportunity to reduce carbon emissions and reduce atmospheric pollution. This ensures a sustainable energy supply and climate protection. Renewable energy sources can be generated and consumed onsite, thereby making energy development decentralized. With such decentralised energy systems, individuals and local communities can manage their energy resources, and hence reduce the dependence on energy imports and national energy supply. National energy demands are thereby better managed and the county's energy reserve margin improved to allow for future energy systems planning and development. (Tezer, Yaman, & Yaman, 2017).

1.2 Energy Development

Energy development worldwide varies, where generally advanced countries use more energy than the developing countries. Figure 1-1 shows that world's total primary energy supply (by fuel type) for 1973 and 2014 has been largely from conventional energy sources. Oil and coal have been the leading sources of energy, while nuclear and renewable energy sources are the least accessed. Between 1973 and 2014, coal, oil, natural gas, nuclear and renewables (geothermal, biofuels, solar, wind and waste) increased by 162 %, 52 %, 197 %, 1097 % and 152 % respectively (IEA, 2016). It is evident that the supply of oil over the period had the least increase, whereas coal and natural gas nearly doubled. The relatively low increase in oil could be heeding to the call of resorting to more sustainable sources of energy. The dependence of the energy mix seem to shift toward increasing the use of nuclear and renewable energy sources. The

increase in the proportion of renewables is a positive approach for an increase in the integration of renewable energy sources in the energy mix.

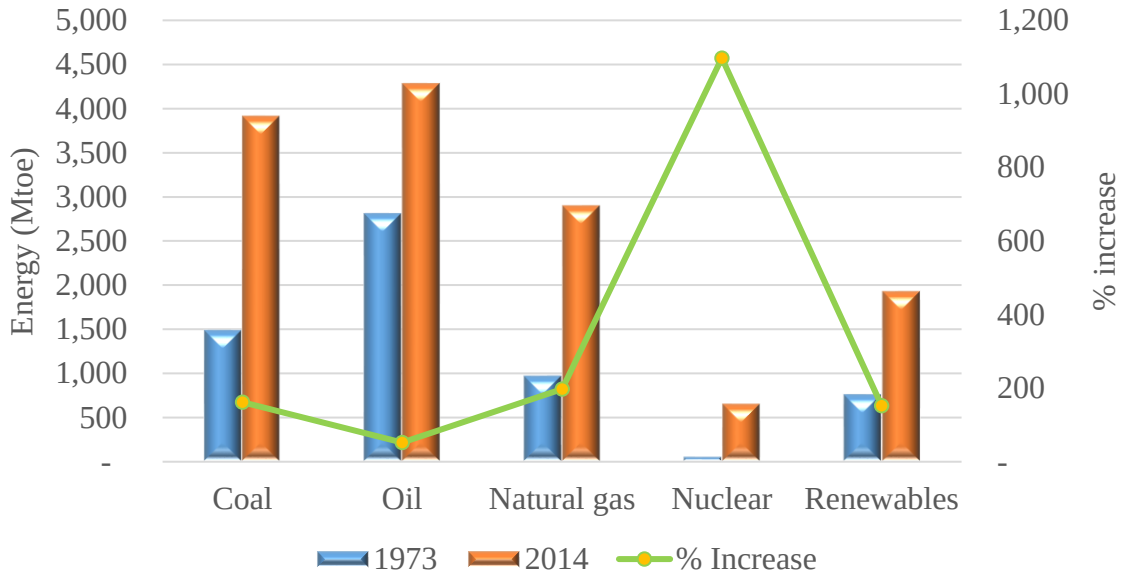

Figure 1-1: World total primary energy supply by fuel (1973 & 2014)

Projecting into the future, the development of technologies that will accelerate the incorporation of use of the renewable energy sources for economic growth and sustainable development is required. There is the need for quick response to global and local energy needs to shift from conventional to non-conventional sources, in order to keep the environment free of pollution especially due to anthropogenic sources.

Meanwhile, the demand for energy in the world increases as population increases and industrialization advances (Keho, 2016; Pohekara, Kumar, & Ramachandran, 2005). Even though various technologies for energy transduction are advanced, some equipment consumes so much energy resulting in wastage (Ampomah-Benefo, et al., 2013; Haiwen,

et al., 2015). Again, mass production and use of electrical and electronic devices increase energy demand.

Figure 1-2 shows world's primary energy consumption for 1965 and 2016. The total world's energy consumption grew from 3730.7 Mtoe in 1965 to 13276.3 Mtoe in 2016 (British Petroleum Company, 2017). By comparing 1965 and 2016, it is seen that the regions with largest increase in energy consumption are Asia Pacific (China), Euroasia (Germany and France), and North America (United States). These increases may be attributed to economic growth and industrialization. Even though Africa's consumption has increased by about 631 %, its consumption in 2016 is comparatively the least worldwide, about half of what Middle East or South and Central America consumed. The low level of energy consumption in Africa can be attributed to factors including poor or low economies and inability to access adequate modern technologies in energy production as well as over reliance on traditional biomass energy (Sovacool, 2012; Özaksoy & Bildirici, 2016; Wolde-Rufael, 2006).

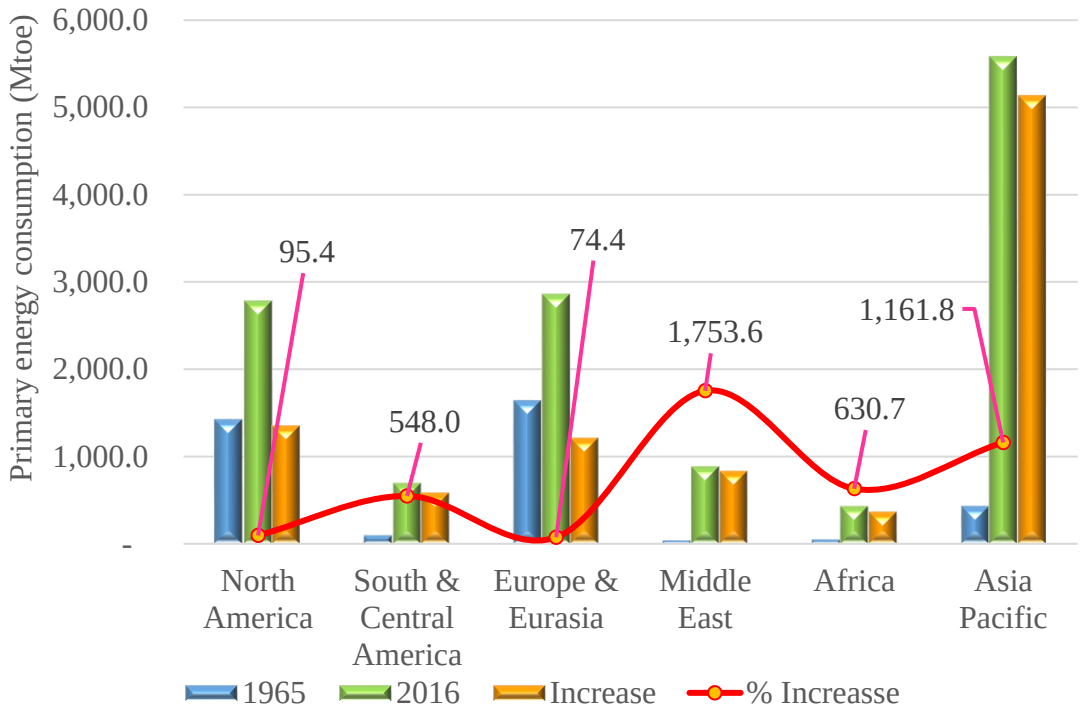

Figure 1-2: World primary energy consumption for 1965 and 2016

Developing countries with growing economy feel the impact of heightened energy needs more than developed countries (Bhattacharyya & Palit, 2016). They face sharp conflict between demand and supply of energy for their growing needs. Figure 1-3 shows a picture in Ghana, where people have queued with their gas cylinders waiting to purchase Liquefied Petroleum Gas (LPG). Developing countries that lack the requisite knowledge and skills to apply advanced energy technologies to meet their growing energy need can import expertise from the advanced countries. Otherwise, the energy gap between demand and supply may widen. For example, in some countries, because of inadequate power generation to meet their energy demand, they resort to load shedding. Load shedding is an emergency system of energy management, typically to address peak load.

This approach to energy management is not sustainable and affects the economic development of a nation.

Figure 1-3: Household LPG cylinders queued for gas purchase

Alternative sources of energy, such as renewable energy sources that are readily available and may not require high technological skills may be the way forward for global energy security. Particularly, these renewable energy sources such as biomass, which is widely available, can be developed and used onsite. The section that follows elaborates on biomass as an energy resource.

1.2.1 Biomass Resources

Biomass can be developed to contribute significantly to addressing the challenges of human energy needs. Biomass energy can be further developed to replace fossil fuels, which will eventually be exhausted (Weldemichael & Assefa, 2016). This section

discusses biomass resources available in view of its composition, bulk density, calorific value (CV) and their availability.

Biomass refers to all biodegradable matter. In the context of energy production, it is the organic material that can be converted to produce energy (McKendry, 2002). Biomass definition is extended to cover organic wastes derived from plant and animal matter. Organic waste includes agricultural and forest product residues (Bruni, Jensen, Pedersen, & Angelidaki, 2010; Pisutpaisal, Nathoa, & Sirisukpoca, 2014; Patel, 2017), household and municipal solid waste, (Zhu, et al., 2010) and industrial waste and waste waters (Gelegenis, Georgakakis, Angelidaki, & Mavris, 2007). Biomass energy is clean and sustainable energy for use in various forms (Ullah, Sharma, Dhingra, & Braccio, 2015). Chemical energy stored in biomass, which is a clean source of renewable energy (Evans & Furlong, 2003) could be exploited to increase the rate of integration of renewable energy into the existing energy supply mix. Biomass characteristics are mainly determined by their (i) composition, (ii) bulk density, (iii) calorific value, and (iv) moisture content. The contributions made by each of these characteristics informs the energy content of a material and how this stored energy can be derived for optimum yield. This is important in the development of the energy technology option selected in this study.

Biomass is composed of complex chemical substances categorized as (i) carbohydrates, (ii) proteins, (iii) lignin (iv) water and (v) traces of inorganic matter. The elemental composition of biomass is generally made up of carbon, hydrogen, and oxygen. A higher content of carbon is indicative of higher energy content (Mood, et al., 2013). Generally, biomass has low bulk density because of the amount of oxygen in its composition.

Bulk density refers to the ratio of the total mass (solids + moisture content) of a substance to its volume. The compactness of matter results in an overall small volume, whereas porosity of biomass leads to an overall large volume with small mass. High bulk density biomass gives rise to high-energy value (calorific value).

Calorific value (CV) expresses the energy content per unit mass or volume released when the material is combusted in excess oxygen. The excess oxygen is to ensure complete combustion of the material. High-energy values of biomass signify great potential for biomass use as fuels (Li, et al., 2017). Biomass is available in all countries and is presently estimated to contribute 10 – 14 % of the world's energy supply. (Duku, Gu, & Hagan, 2011).

Biomass may be classified as woody, herbaceous, aquatic, waste and weed. Woody biomass involves the by-products of logging of trees from the forest and farms (Simangunsong, et al., 2017). These may also be found in wood processing factories. Tree bark, branches, and leaves may not have direct need in such processing factories but can be used as a source of biomass energy. Herbaceous biomass includes grass, legumes, and food crops such as maize, rice, wheat, and sugarcane. Herbaceous plants usually have soft stems and do not grow as tall and big as the woody plants (Mohammed, Mokhtar, Bashir, & Saidur, 2013).

Aquatic plants are another form of biomass. These are intrinsically high-moisture plants adapted to living in aquatic environments, such as in fresh or marine water. Aquatic plants are partially or fully submerged in water bodies. These include water lily, water

hyacinth, and lotus. Both on land and in water there are weeds and wild growths that have no direct use to humans. They outgrow all other plants and colonize their area. Such plants can be harvested periodically and used as feedstock for energy production. Figure 1-4 shows various non-food biomass resources available for energy generation.

(a) Palm kernel shell (b) Municipal

(c) Paper waste (d) Animal

(e) Wood waste (f) Cassava waste

Figure 1-4: Non-food biomass resources from different communities available for energy generation. a) Palm kernel shell waste, b) municipal waste and wastewater, c) paper waste ready to be picked up by a tissue paper company, d) animal droppings from husbandry used for this study, e) wood waste, f) cassava waste at starch processing factory

Various technologies are well known and well developed for extracting energy from biomass. The following section discusses such technologies applied to biomass for energy production.

1.3 Technologies for Energy Production using Biomass

Biomass can be converted into chemical, electrical or heat energy. The energy obtained can be used either immediately or stored for future use. Fuel from biomass can be obtained as solid fuel (e.g. charcoal, and briquette), liquid fuel (e.g. ethanol), or gaseous fuel (e.g. methane). As has been mentioned above, various technologies for biomass conversion exist. Some of these are advanced technologies while others are suitable for adaptation by developing countries.

1.3.1 Thermochemical Conversion

There are three main types of thermochemical conversion processes: (i) incineration, (ii) pyrolysis and (iii) gasification. Incineration involves the combustion (complete oxidation) of biomass in the presence of O_2. Incineration is the combustion of material in excess O_2. The main product of incineration is energy in the form of heat that cannot be easily stored and therefore is used immediately. Incomplete combustion results when O_2 is not adequate and CO and other intermediate products like polycyclic aromatic hydrocarbons and dioxins are produced. Combustion is favoured when the moisture content of biomass is low, which is why drying is relevant. At high moisture contents, biomass would have to be heated to drive off the moisture therefore reducing the effective heating of the biomass (Komilis, Kissas, & Symeonidis, 2014).

Pyrolysis is the thermal decomposition of carbonaceous material that converts biomass to solid, liquid, and gaseous fractions depending on process variables such as temperature, rate of heating, particle size and residence time of biomass in a reactor chamber (Mohan, Pittman, & Steele, 2006). Pyrolysis is an endothermic, irreversible phenomenon that takes place in absence of O_2. The two main forms of pyrolysis are slow pyrolysis and fast pyrolysis. Slow pyrolysis occurs at around 350 ^oC with its final product being about 10 % oil and the rest being biochar. Fast pyrolysis occurs at around 700 ^oC. It is a rapid decomposition of organic compound to produces 70 % biofuel and very little biochar (Bolalumi, 2016). Gasification is the conversion of biomass into combustible gas mixture (syngas) by the partial oxidation of solid biomass fuel at high temperatures up to 1000 ^oC with air to fuel ratio ranging from 1.5:1 to 1.8:1 that produces mostly CO with some H_2 (Wang, Dai, Yang, & Luo, 2017).

1.3.2 Biochemical Conversion for Energy Production

Biochemical conversion for energy production is the process of turning organic matter into energy by the action of microorganisms. This conversion process involves the breakdown (catabolic processes) of complex organic materials (biomass) into simple compounds that can be absorbed and used as nutrients, usually by the microorganisms. New substances are also formed through anabolic processes. The microorganisms eventually use the nutrients to produce combustible biogas. Microorganisms metabolize nutrients for their survival and growth by producing enzymes (protein molecules) that break down specific substances. For example, proteases and peptidases breakdown proteins into small peptides and amino acids. Lipases split fat into three fatty acids and glycerol. Amylases split carbohydrates (polysaccharides and disaccharides) such as

starch into simple sugars (monosaccharides) such as glucose. Nucleases split nucleic acids into nucleotides.

Enzymes are obtained in thousands from living cells of animals, plant microbes and from fungi and yeast. They function by lowering the activation energy of biochemical reactions, thereby increasing reaction rates. Enzymes may be intracellular (located inside the cell) or extracellular (located outside the cell). They do not undergo structural changes at the end of the chemical reactions, hence they are used repeatedly. Enzymes (E) and substrates (S) combine to form an intermediate state, called enzyme–substrate complex (ES). A new product (P) is formed and the unchanged enzyme is ready to react again with the substrate (See equation 1-1). The factors and requirement for their effective function include carbon source, pH, temperature, time, and adequate moisture content (Grassian, 2005). These factors are discussed in section 2.2.

$$E + S \Leftrightarrow ES \Leftrightarrow E + P \qquad (1\text{-}1)$$

1.4 The Challenge

Access to clean, affordable and sustainable energy sources have become a major global problem. Biogas production from biomass and especially organic waste is promising. The technology is well known and advanced. In the advanced countries, large sizes of high rate digesters have been applied to meet specific demands (Yasar, Ali, Tabinda, & Tahir, 2015; Zhang, et al., 2014). However, in developing countries the technology is not well widely adopted, particularly the high rate digesters. The available technology, which is the slow rate digesters, are not commonly practiced because of lack of technical expertise and skills to design digesters for multi-feedstock. Digesters currently designed

in developing countries are for single feedstock processing, and a relatively few designs are for co-digestion (Mata-Alvarez, et al., 2014). Most digesters are fixed at the construction site and are not portable. One main challenge is that when a particular feedstock is no longer available on site, feedstock has to be carried from far distances. Considering the fact that local bio-waste comes in several varieties, there is the need for new design paradigms that cater for rapid adaptation for such diverse feedstock. A technical survey of biogas plants in three regions in Bangladesh found that 21% were not functioning (out of order), 76% were working but had challenges, and only 3% functioning without and fault. Some of causes of the challenges identified were low availability of feedstock, ineffective digestion processes, poor mixing ratio, improper design, size and construction (Khan & Martin, 2016). In Latin America, the promotion of domestic biogas usage faced challenges such as high cost on installation, high component of foreign construction materials and lack of training for digester maintenance by local artisans (Garfi, Marti-Herrero, Garwood, & Ferrer, 2016). Thus further efforts, which include detailed understanding of anaerobic digestion technology based on rigorous research that involves design, assembly, and operation of prototype should be undertaken to overcome these barriers and improve the technical performance, social acceptance, economic benefits and environmental impact in order to enhance wide-spread dissemination of biogas in energy poor communities

1.5 The Current Study

The current study involves the design, assemble, and operation of a single-stage mesophilic prototype of an anaerobic digester assembled from locally available and affordable materials for biogas production. The study also includes, investigating the temperature performance of the anaerobic digestion of cow dung to produce energy.

1.6 Objectives of the Study

The main objective of this study is to generate an understanding, based on prototype scale experimental design, assemble, and operation of $1m^3$ anaerobic digester assembled from locally available and affordable materials for biogas production. This broad objective requires the following specific objectives:

1. To study the fundamental aspects of the concepts, laws and the physical principles that govern the dynamic processes which occur during anaerobic digestion in a single stage anaerobic digestion system.

2. To apply the knowledge gained in the study to design, assemble, and operate a prototype anaerobic multi-feedstock digester system with easily available materials.

3. To demonstrate the potential of biogas production from the prototype low rate mesophilic digester for small-scale applications.

4. To study the operational behaviour of the prototype anaerobic digestion system through heating and mechanical mixing.

1.7 Justification and Scope of the Study

As energy demand increases, the drive to meet demand and have energy reserves to provide security also increases. It is therefore relevant to tap available energy, which is renewable and sustainable and which does not pollute the environment. Developing anaerobic digestion technology through the design of easily constructed digester with easily available resources can satisfy local energy demand. This is not to forget the

reduction in drudgery of women and children travelling long distances in search of firewood. Clean cooking would be done with the biogas, which will eliminate smoke and inhalation of poisonous gases such as CO and NOx from incomplete combustion from firewood and poorly designed stoves. Small quantities of organic wastes could be treated in a sustainable way.

The study of the concepts of the laws and physical principles, the dynamic processes and control theory of bio digester technology would provide the depth of technical knowledge on aspects of anaerobic technology applied for biogas generation. Such knowledge acquired is applied to demonstrate the potential of biogas production by operating an easily assembled portable one cubic meter digester with available biomass waste in the local conditions. Data generated in this study could be used as the basis for further studies to optimize the anaerobic digestion process design applied in this study.

The knowledge, with the hands on experience, is easily transferable to artisans for the purpose of job creation and on to business people as wealth creation. Through knowledge and skills transfer the knowledge gap that prevents the popularization and acceptability of anaerobic digestion technology by developing countries would be reduced. Hence, such technology accepted and used would be a pathway for resource recovery from biomass, especially waste for energy production, to enhance energy security within local communities. The other benefits such as the use of digestate on farms to improve crop yield expands the attraction to farmers to employ this technology on their farms. On a very large scale, the wide application of this renewable energy system would have significant impact on the energy mix as well as improve the energy security in a country's economy. It would contribute to carbon capture technology, reduce the influence of

climate change emission and the interdiction of disease transmission. Such energy development embodies in itself robust mechanisms that would contribute to the mitigation of global warming and climate change. Countries that do not already have an institutional framework could develop some by developing biogas standards for mass deployment across the country. Waste-to-energy projects would be better managed.

In the promotion of use of renewable energy resources, there is the conscious effort to minimize deforestation because of the practice of felling trees for use as firewood. The replacement of such practice could be to point people to the use of cleaner technology, awareness and skills for harnessing of organic waste resources, which is abundant but poorly managed. There is therefore no need to bypass the waste in and around our communities to travel into the forest for wood. The time saved in such travels can be good resource that can be channelled to profitable use.

The overall justification of this study is therefore to simplify the application of anaerobic technology for energy production, especially for people in the developing countries, who may have little or no knowledge of this technology. As indicated already, there are enormous benefit for this biomass to energy production. The benefit of this study is a step in the right direction towards "Transforming our World: The 2030 Agenda for Sustainable Development" goals 1, 2, 3, 6, 7, and 13 (United Nations, 2015).

This work involves the study of the fundamental concepts of anaerobic digestion technology. Aspects of the concepts have been applied to the:

- Design of a 1 m^3 single stage anaerobic batch digester

- Fabrication and assembly of the digester with easily available materials
- Use of fresh cow dung as feedstock
- Operation and monitoring of the digester for energy production.

1.8 Limitations of the Study

Although this study achieved its aims, there were some unavoidable limitations. As a result of limitation of time, the study was carried out with a single feedstock for the operation of the digester. For this reason, the digester should have been operated with other feedstock to ascertain the response of multi-feedstock.

1.9 General Form of the Thesis

This study concerns the design, assembly, and operation of a locally available material-based 1 m^3 digester for small-scale biomass to energy application. A general overview of energy resources have been provided in Chapter 1, with emphasis on biomass.

In Chapter two, the various stages involved in anaerobic digestion processes have been detailed. The process parameters that affect biogas production have been discussed. The characteristics, assembly, and operation of digesters are also discussed. Anaerobic batch digesters are described in detail.

Chapter three contains a description of the assembly of a digester prototype. The design parameters and conditions are described. The assembly of the thermostatic heat

exchanger, fabrication of motorized stirrer and the data acquisition systems are described in detail.

The operation and studies of the operational parameters of the digester are discussed in Chapter 4. These include the discussion on the full operation of the digester, the pre-operation tests, monitoring, and control of operational parameters. The production of biogas is also discussed in terms of quality, quantity, and rate of production. The chapter ends with brief discussion on the visual inspection conducted on the various components of the digester as well as ancillary test and a list of safety guide in the operation of anaerobic digester.

Chapter 5 outlines the conclusions made out of the study and offer recommendations for further study.

CHAPTER TWO: ASPECTS OF ANAEROBIC DIGESTERS

2.0 Introduction

This chapter presents aspects of the complex biochemical processes involved in microbial anaerobic digestion of organic matter are explained. The process parameters and their effect on biogas production are also discussed. A description and types of anaerobic digesters are further described. Of interest are the physical and thermodynamic principles governing the microbial activity of the biochemical processing of feedstock for biogas production. As it has been already pointed out, a thorough understanding of the operation of anaerobic digesters can go a long way in helping developing countries surmount some of the difficulties associated with energy security, organic waste management, sanitation, and health.

2.1 Anaerobic Digestion

The biochemical process by which complex organic materials are broken down into simple compounds to produce energy in the absence of O_2 is referred to as anaerobic digestion (AD). Anaerobic digestion is one of the clean energy technologies being exploited to augment energy supply for economic development (Abbasi, Tauseef, & Abbasi, 2012). This process loses little energy while the rest of the energy is stored as gas, mainly in the chemical bonds of CH_4. Carbon dioxide and other trace gases such as N_2 and H_2S are produced along with CH_4 in a form of combustible gaseous fuel (called biogas) comprising mainly of CH_4 (50 – 70%), CO_2 (30 – 45 %), and nutrient-rich sludge (Wagner, Malin, Gstraunthaler, & Illmer, 2009; Herrmann, Idler, & Heiermann, 2016).

The nutrient-rich sludge contains nitrogen, phosphorus, and potassium that can be used for agricultural purposes. The pathways of the biochemical processes are schematically represented in Figure 2-1. These biochemical processes occurs sequentially in steps as (i) hydrolysis, (ii) acidogenesis, (iii) acetogenesis and (iv) methanogenesis. These stages are described in the following sections under the sub-headings hydrolysis of biopolymers; acidogenesis and acetogenesis; and methanogenesis and production of biogas.

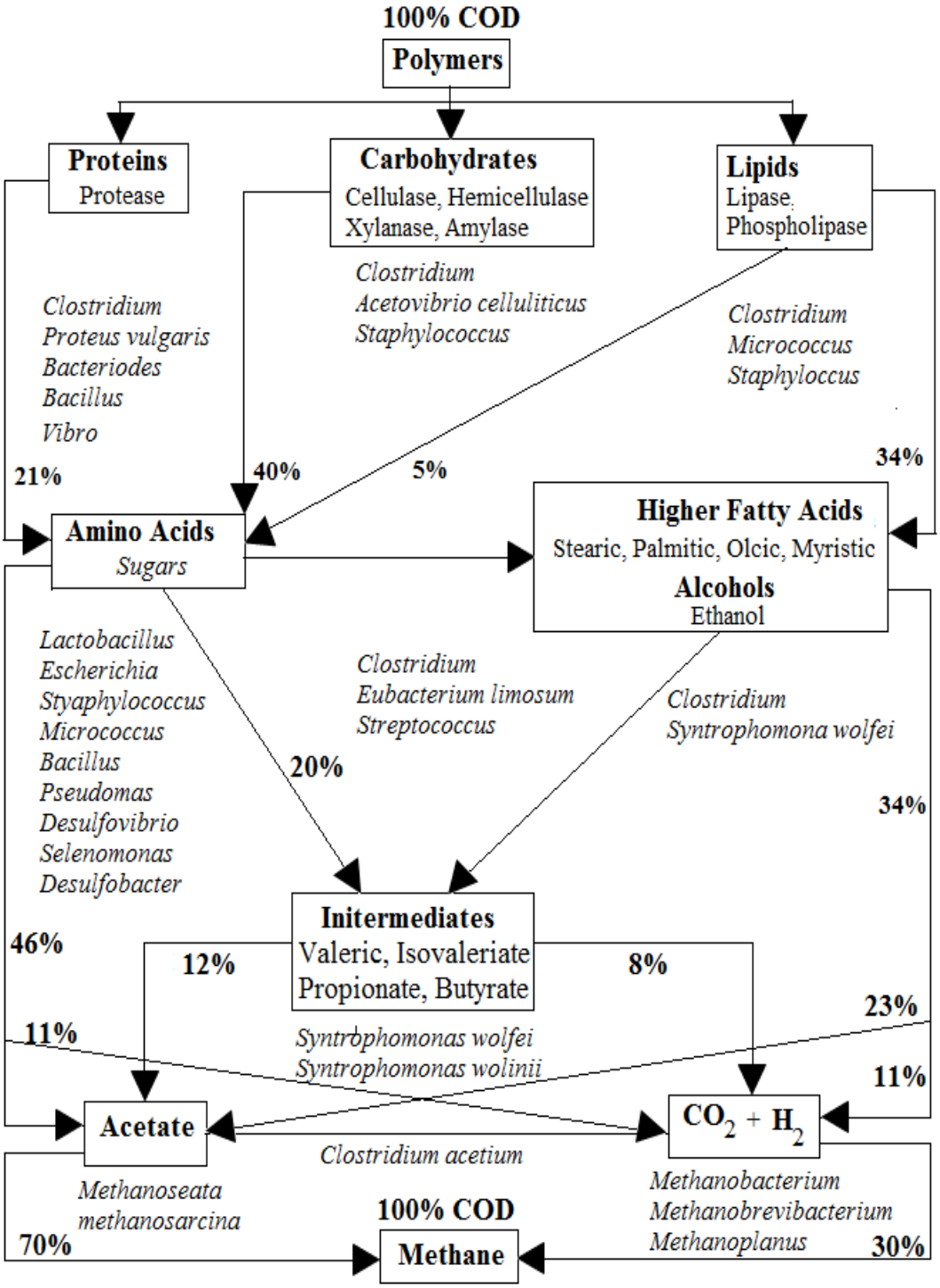

Figure 2-1: Metabolic pathways and microbial groups involved in anaerobic digestion of complex organic materials for biogas production
Source: Reproduced (Mara & Horan, 2003)

2.1.1 Hydrolysis of Biopolymers

Hydrolysis is the first step in the biodegradation processes of large complex organic polymers (21 % proteins, 40 % of carbohydrates, and 39 % of lipids), which are insoluble and cannot be directly absorbed and used by microbes (Vavilin, Fernandez, Palatsi, & Flotats, 2008). Hydrolytic microbes therefore, secrete different types of enzymes, called extracellular enzymes, which break down the larger molecules up into simpler soluble components. Cellulase, cellobiase, xylanase, and amylase break down carbohydrates into simple sugars such as monosaccharides and disaccharides. Protease degrades proteins into amino acids, while lipase degrades lipids into short chain fatty acids and glycerol (Saha & Cotta, 2007). A general reaction of hydrolysis is given as depicted in Equation 2-1.

$$(C_6H_{10}O_5)_x + XH_2O \xrightarrow{hydrolysis} XC_6H_{12}O_6 \qquad (2\text{-}1)$$

2.1.2 Acidogenesis and Acetogenesis

Acidogenesis is the next step after hydrolysis. During this step, the products from the previous hydrolysis stage are used as substrate by a number of different microbes. Many different organisms are active during this stage, more than during the other stages. Acidogenesis converts substrate mainly into various organic acids (acetic, propionic, butyric, succinic, lactic acid etc.), alcohols, ammonia (from amino acids), carbon dioxide, and hydrogen. Examples of microbes involved in the acid forming include bacteriodes, bifidobacterium, clostridium, lactobacillus, and streptococcus. The acidogens operate at optimum pH range of 5.5 – 6.5. Acidogenesis is considered the fastest step in the

anaerobic digestion process (Mata-Alvarez, et al., 2014) and their reaction is generally represented as:

$$XC_6H_{12}O_6 \xrightarrow{acidification} 3XCH_3CO_2H \qquad (2\text{-}2)$$

Acetogenesis is the step carried out by acetogenic microbes to convert products of acidogenesis (such as butyrate, propionate, lactate and ethanol) to produce H_2, CO_2, and acetate. Acetate can also be formed from CO_2 and H_2.

2.1.3 Methanogenesis and the Production of Biogas

The last step of the anaerobic digestion process is strictly anaerobic and referred to as methanogenesis. This step is the methane forming step. It is dominated by microorganisms known as methanogens. Some of these microorganisms are methanobacterium, methanococcus, methanosarcina, and methanosaeta. These microorganisms use hydrogen, acetate, and CO_2 as substrate to produce mostly CH_4 and CO_2 through three main pathways towards methane production referred to as: (i) acetoclastic methanogenesis, (ii) hydrogenotrophic methanogenesis and (iii) homoacetogenesis. Most of the CH_4 (above 60 %) is formed by acetoclastic methanogens (methanosarcina and methoanosaeta), where methanosarcina utilize acetate, hydrogen, formate, methylamines and methanol to form CH_4, and methanosaeta uses only acetate to form CH_4 (Conrad, 1999; Ferry, 2011). Hydrogenotrophic methanogenesis converts H_2 and CO_2 to produce CH_4 and H_2O, as homoacetogenesis converts the same reactants (H_2 and CO_2) to produce CH_3COOH and H_2O. Due to the comparatively high Gibb's free energy of hydrogenotrophic pathway (-135 KJ mol^{-1}), its forward reaction is

thermodynamically more favourable than the homoacetogenic pathway (-104 KJ mol^{-1}). Hydrogenotrophic pathway therefore has a potential to keep the H_2 pressure low in the digester through its consumption. Table 2-1 shows the main methanogenic reactions pathways indicating some of the microorganisms used as well as their corresponding standard Gibb's free energies.

Table 2-1: Reactions related to methanogenesis

Pathway	**Reaction**	**ΔG^o at 25 °C (KJ mol^{-1})**	**Microorganism**
Hydrogenotrophic methanogenesis	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$	-135.0	Methanobacterium, Methanobrevibacter
Acetoclastic methanogenesis	$CH_3COOH \rightarrow CH_4 + CO_2$	-31.0	Methanosaeta, Methanosacina
Homoacetogenesis	$4H_2 + CO_2 \rightarrow CH_3COOH + 2H_2O$	-104.0	Clostridium acetium

The maximum biogas yield can be estimated through the degradation efficiency of the biomass. An approximate equation enables the theoretical estimation of the maximum yield of CH_4 when the elementary composition of biomass is known. Equation 2-3 illustrates the modified form of Buswell's (1930) equation, which is a stoichiometric equation of biogas production from biopolymer.

$$C_nH_hO_oN_nS_s + yH_2O \rightarrow xCH_4 + nNH_3 + sH_2S + (c-x)CO_2 \quad (2\text{-}3)$$

Where $x = \frac{1}{8}(4c + h - 20 - 3n - 2s), and\ y = \frac{1}{4}(4c - h - 20 + 3n + 3s)$

The stoichiometric reactions of carbohydrates, fats, and proteins are shown in Table 2-2

Table 2-2: Stoichiometric reaction of biomass to produce biogas

Substrate	**Chemical reaction**
Carbohydrates	$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$
Fats	$C_{12}H_{24}O_6 + 3H_2O \rightarrow 4.5CO_2 + 7.5CH_4$
Proteins	$C_{13}H_{25}O_7N_3S + 6H_2O \rightarrow 6.5CO_2 + 6.5CH_4 + 3NH_3 + H_2S$

2.1.4 Characteristics and Properties of Biogas

Biogas in its normal (raw) production form, as stated already, is mainly 50 – 70 % of CH_4 and 30 – 45 % of CO_2. Biogas has molar mass of 16.04 kg $kmol^{-1}$, density of 1.2 kgm^{-3} and is flammable with energy content of 6.0 - 6.5 kWh m^{-3}. Biogas has a calorific value of about 26.45 MJ kg^{-1}. The calorific value improves to about 38 MJ kg^{-1} through cleaning (Tchobanoglous, Burton, & Stensel, 2004).The presence of CO_2 lowers the calorific value of the biogas. An amount of 6 – 12 % biogas in air can cause an explosion at an ignition temperature of 650 – 750 ^oC. The production of biogas is associated with odorous compounds mainly formed from sulphurous and nitrogenous compounds. This is discussed in the next session.

2.1.5 Odorous Compounds Associated with Anaerobic Digestion

In the process of waste to energy production, a smell is created from organic waste especially from animal manure during the production of biogas. Biogas is itself

odourless. The odour is due to other gases that are formed alongside biogas. Table 2-3 shows odours associated with biodegrading processes, mainly classified into sulphurous and nitrogenous compounds (Gostelow, Parsons, & Stuetz, 2001; Kim, et al., 2007). Organic sulphur and nitrogen are derived mainly from proteinaceous material, the source and quantity of which in an anaerobic digestion system would have an effect on the odour produced.

Table 2-3: Odorants associated with biodegradation

Class	**Compound**	**Formula**	**Characteristic odour**
Sulphurous	Hydrogen sulphide	H_2S	Rotten egg
	Dimethyl sulphide	$(CH_3)_2S$	Decayed vegetables, garlic
	Carbon disulphide	CS_2	Decayed vegetables
	Methyl mercaptan	CH_3SH	Decayed cabbage, garlic
	Ethyl mercaptan	C_2H_5SH	Decayed cabbage
	Thiophenol	C_6H_5SH	Putrid, nauseating, decay
Nitrogenous	Ammonia	NH_3	Sharp, pungent
	Methylamine	CH_3NH_2	Fishy
	Dimethylamine	$(CH_3)_2NH$	Fishy
	Pyridine	C_6H_5N	Irritating
	Indole	C_8H_6NH	Faecal, nauseating

2.1.6 Cleaning and Application of Biogas

In addition to the main products of CH_4 and CO_2 gases produced in anaerobic digesters, there are small amounts of H_2S, and water vapour that reduces the CH_4 combustion. The removal or minimization of these components improves the energy properties of the gas produced. The method of cleaning of biogas includes desulphurization and dehumidification. For example, about 2 – 8 % of air injected into the biogas oxidizes (dissolve) H_2S to form H_2SO_3 (Sun, et al., 2015; Vikromuarasiri, Champreda, Boonyawanich, & Pisutpaisal, 2017). The small quantity of air introduced into the digester is to ensure that (i) the air does not offset the production of CH_4 because of the effect of O_2 on methanogens and (ii) the formation of H_2SO_3 does not significantly reduce the pH of the slurry. Another process is by Sulfitobacter oxydans bacteria desulphurization. This process allows sulphur to chemically bond to prevent the release of H_2S into the biogas formed. It therefore remains in the digestate, and is eliminated as effluent.

Some amount of water vapour may be carried along with the biogas forming a humid biogas. As the gas travels through the pipes, the water vapour may form a condensate because of cooling due to the temperature gradient between the environment and the gas pipe. The condensate is a natural process of dehumidification of the biogas. Ensuring the gas pipeline is in a cool environment further removes traces of water from the biogas. A condensate trap is installed at a dip (lowest point) of inclining the gas pipe horizontally at about 1^o. In addition, biogas can be dried by adsorption by activated charcoal or silica - gel, or by absorption in glycol solutions. Drying removes ammonia and therefore does not need a special process to remove it (Papacz, 2011; Ferella, Puca, Taglieri, Rossi, & Gallucci, 2017).

With the development of anaerobic technology for biogas generation, there has been many applications of turning biomass to energy in many countries. These various application have been for lighting, heating, and cooking, electricity generation and used as fuels in vehicles. Other applications of this biochemical technology include sanitation and agriculture purposes (Lou & Ho, 2012; Igoni, Ayotamuno, Eze, Ogaji, & Probert, 2008; Bensah & Brew-Hammond, 2010; Pipatmanomai, Kaewluan, & Vitidsant, 2009).

2.2 Process Parameters and their Effect on Biogas Production

In this section, some of the essential parameters that influence anaerobic digestion are discussed. These include the feedstock, inoculum water, enzyme concentration, temperature, pH, and total solids. The inhibitory factors of the process are also discussed.

2.2.1 Feedstock and Slurry Preparation

Feedstock, also referred to as substrate, is the biomass material that is used in the digester for energy production. On a broad note, any biodegradable material can be used as feedstock for energy production. As long as the biomass material has energy stored in it, it can be extracted in one way or another. The choice of conversion method is usually influenced by the physical properties (moisture content, calorific value, and particle size) and chemical content (alkali metal content Na, K, Mg, P and Ca,) of the biomass. Biomass with low moisture content (< 15 %) are considered dry and are suitable for direct combustion, gasification, or pyrolysis, while biomass with high moisture content is suitable for anaerobic digestion. In anaerobic digestion such as in a wet digester, water forms the highest proportion (> 70 %). If for any reason biomass with low moisture

content has to be used in an anaerobic digestion, large quantities of water have to be added for optimum biogas yield, especially if wet digestion is being considered.

The feedstock is mixed with a proportional amount of water and seeded with a consortium of microbes known as inoculum to form a slurry. In co-digestion, feedstock is mixed with organic material that contains relevant microbes, such as cow or pig manure. The entire mixture is referred to as slurry and the seed of microbes to perform the biodegradation processes is called inoculum. Usually the slurry is prepared with one kind of feedstock, water, and inoculum. Some of the feedstock that have been used in anaerobic digestion are semi dried banana leaves, kitchen waste, pawpaw fruit peel, grass cuttings from lawns, and market wastes (Jena, Mishra, Acharya, & Mishra, 2017; Tasnim, Iqbal, & Chowdhury, 2017; Dahunsi, Oranusi, & Efeovbokhan, 2017). If two different feedstock is mixed with water and inoculum, such process of digestion is called co-digestion. Various studies have been conducted with co-digestion and the results have seen improvement over single feedstock digestion (Gashaw, 2014; Li, et al., 2015).

2.2.2 Inoculum

Inoculum is the seed of microbes added to biomass slurry to facilitate anaerobic digestion processes. These microbes secrete enzymes to catalyse the various reactions in anaerobic digestion processes. The source of inoculum could be either from an existing active digester or from animal dung (droppings), which are known to contain large quantities of consortium of microbes. Inoculum could also be extracted in the laboratory from a pure culture of microbes. High quantities of inoculum are able to adjust and populate

quickly, hence biogas production occurs within a short period. Favourable environmental conditions such as temperature, pH, and nutrients (feedstock) keeps the microbes active.

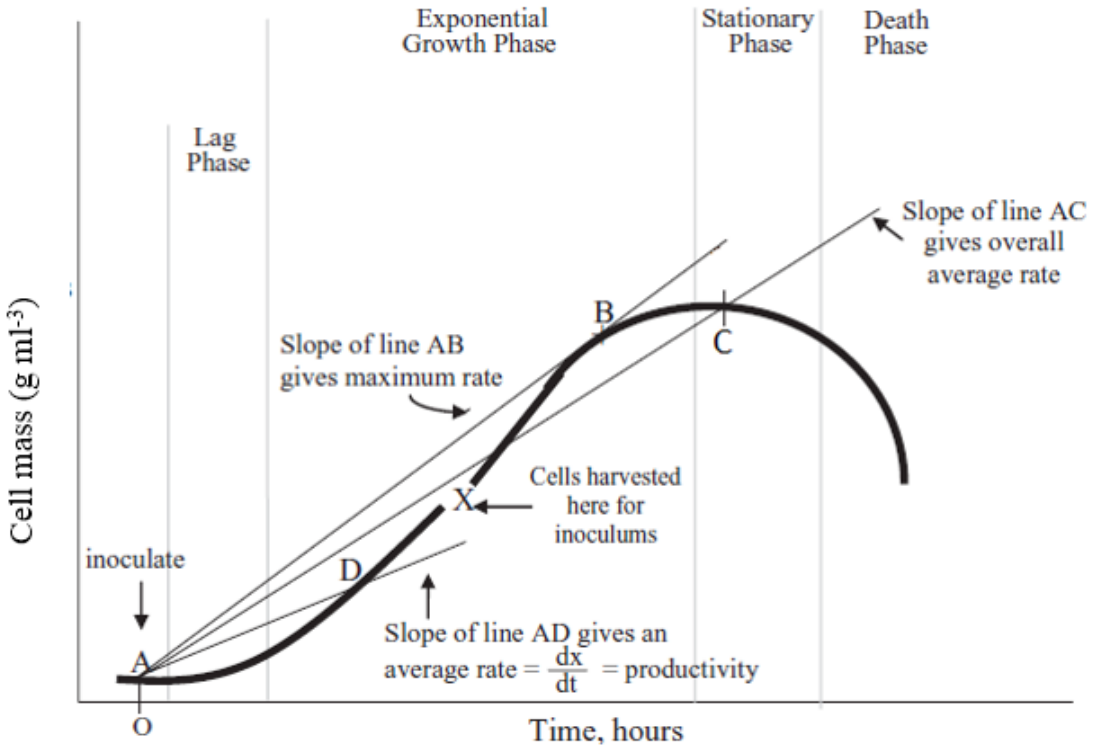

Figure 2-2: Growth of typical microbes in an anaerobic system

The activities of the inoculum slurry goes through a number of phases referred to as the (i) lag phase, (ii) exponential growth phase, stationary phase and the death phase, as shown in Figure 2-2 (Mosier & Ladisch, 2009). The lag phase is a period when the inoculated microbes adapt themselves to their new environment. This phase is also referred to as the incubation period. The duration of the lag phase is greatly influenced by the source of the inoculum and how easily it can adjust to its new environment. If the inoculum was obtained from an active digester with same kind of slurry as this new digester then the lag phase period will be minimized because there will be no need for an adaptation period. After the lag phase, the microbes begin to populate at an exponential

rate. At this period, substrate is consumed rapidly because of the population growth of microbes. Substrate consumption rate remains constant at maximum microbial growth. As substrate gets finished the microbes has nothing to feed on and goes to extinction (death phase).

This microbial growth rate has been described by Equation 2-4:

$$\frac{dx}{dt} = \mu x \tag{2-4}$$

$$x_t = x_o e^{\mu t} \tag{2-5}$$

where x is the concentration of microbial biomass, x_o is the initial biomass concentration, x_t is the biomass concentration, μ is the specific growth rate after a time interval t. measured in hours.

As stated in section 2.1, during anaerobic digestion processes various microbes play specific roles in a sequential manner. The anaerobes also exhibit different regeneration time of some anaerobes, which are used in anaerobic digestion processes. Acidogenic anaerobes can spend a matter of less than an hour to about 1.5 days to regenerate. Acetogenic anaerobes spend about twice as much of time (3.3 days to 3.75 days) used by acidogenesis to regenerate. Methanogenic anaerobes, which are the final microbes to convert substrate to biogas, spend between 5 days and 16 days to regenerate (Deublein & Steinhauser, 2008). A correct balance of time for regeneration of all these anaerobes are necessary for optimization of biogas generation. It therefore suggests that in an anaerobic digestion system biogas production can be expected between 5 days to 16 days. In the case where lag time is minimized, biogas can be realized within a day.

2.2.3 Water

In anaerobic digestion, the presence of water allows various chemical compounds to be hydrolysed, and this enhances extracellular activities of enzymes during nutrients transport into microbial cells. It enhances the mobility of microbes and nutrients as well as heat distribution within the slurry. It may be necessary to add water to all biomass. However, if the biomass consists mainly of water (e.g. waste water) this may not be necessary. Such amount of water should be added so that the slurry is neither too thick nor too dilute. If a slurry is too diluted the solid particles may settle down in the digester and may not be degraded properly or at a very slow rate. On the other hand. If the slurry is too thick, it may be difficult to stir and impede the movement of microbes and nutrients as well as release of trapped gas.

2.2.4 Temperature

Anaerobic digestion can occur at three different ranges of temperature: (i) psychrophilic < 20 ^{o}C, (ii) mesophilic 20 - 40 ^{o}C, and (iii) thermophilic 45 - 60 ^{o}C. These temperature ranges are suitable for specific microbes. Beyond these ranges the respective microbes are not able to withstand the temperature changes, hence are destroyed, or become inactive (Ryckebosh, 2011; Evans & Furlong, 2003). Generally, an increase in temperature increases the activities of the microbes, hence an increase in the rate of conversion of slurry to biogas. Studies show that the growth rate of the microbes (in each temperature range) increases exponentially with temperature. This growth continues until an optimum temperature is attained. Beyond this optimum temperature, further increase in temperature will impede the growth and result in the death of microbes. This

temperature pattern is expressed mathematically in the van't Hoff-Arrhenius equation (see Equation 2-6).

$$\frac{d(\ln k)}{dT} = \frac{E}{RT^2} \tag{2-6}$$

where k = reaction rate constant, T = thermodynamic temperature (K), E = is constant characteristic of the reaction (activation energy) $Jmol^{-1}$, R = ideal gas constant (8.314 $Jmol^{-1}K$)

Psychrophilic and mesophilic temperatures can be applied to digesters to operate at near ambient temperatures in the temperate and equatorial regions respectively. Such digester operations require low heating to attain the desired temperatures. In the equatorial region, where most developing countries lie, mesophilic digesters will be appealing because of low input energy and cost.

In anaerobic digestion, it is necessary to prevent the loss of heat to reduce temperature fluctuations of the slurry. This could be achieved by using a digester that is heat resistant, otherwise an insulation is provided to minimize conduction and convection. In addition, a vacuum could be created in between layers of the digester and its environment. Alternatively, an external heating source such as solar thermal system or electric heating source can regulate heat to the digester through a heat exchanger system. Particularly, in remote areas where there may not be access to the national grid, electrical heating would not be advisable. Solar heating would be the most appropriate, since solar energy is available and renewable.

Diamantis (2010) studied a pilot scale anaerobic digester that operated initially at 36.5 ± 0.6 ^{o}C (mesophilic) and consequently decreased to 29.8 ± 0.3 ^{o}C and 24.4 ± 0.3 ^{o}C. This was used to evaluate mesophilic anaerobic treatment of a pre-acidified fruit wastewater. Yusuf (2011), in his analysis of effect of waste paper on the kinetics of biogas yield with cow dung and water hyacinth used five 500 ml containers as digesters operated at 26 ^{o}C. The estimated biogas yield was between 0.282 l g^{-1} and 0.218 l g^{-1}. Kerroum (2010) applied the Anaerobic Digester Model No. I (ADM1) to monitor a 500-litre volume continuous stirred tank reactor (CSTR), hydraulic retention time (HRT) of 20 days and operated at 55 ± 2 ^{o}C and monitored for 3 months with the gas produced at an average of 0.39 m^3 per every cubic meter of feedstock daily.

2.2.5 pH

In anaerobic digestion processes, a measure of pH is indicative of the performance and stability of chemical reaction taking place. Acidogenesis forming step occurs around a pH of 5.0, whereas methanogenesis occurs at pH measured in the neutral range (Lin, et al., 2013; Ann, Kessel, & Russel, 1996). In a single stage anaerobic digester, where all the various digestion stages take place in a single tank, the system acts like a combined culture with pH range of 6.8 – 7.4, with neutral pH being the optimum (Boone & Luying, 1987). The rate of CH_4 production may decrease if the measured pH is either lower than 6.3 or higher than 7.8 (Kim, Hwanga, Jang, Hyun, & Lee, 2004). For low pH, acidogens populate and increase the production of volatile fatty acids and H_2 (Chen, Cheng, & Creamer, 2008). If the process is not corrected it could lead to failure of the anaerobic processes to produce biogas. The pH could be corrected by first reducing the organic loading rate and then the introduction of chemicals such as $NaHCO_3$, NaOH, or Na_2CO_3 to adjust the pH to neutral.

2.2.6 Pressure

High biogas pressure above the slurry in a biodigester causes CO_2 to dissolve in the slurry. This dissolved CO_2 increases the acidity of the digestate (Lemmer, Merkle, Baer, & Graf, 2017). As a result of increasing pressure, the rate of biogas formation is consequently reduced (Hamad, Dayem, & El-Hawagi, 1983; Mateescu, 2016). The results of the study on the variation of hydrostatic pressure with percentage yield of biogas conducted by Mateescu (2016) has been illustrated in Figure 2-3. The maximum biogas yield was obtained at 0 kPa (gauge pressure), which was above 60 % of CH_4. At 600 kPa, CH4 production was generally less than 20 %. To reduce the effects related with CO_2 solubility, large increase of pressure is avoided by regularly combusting the gas yield or by venting the accumulated gas regularly.

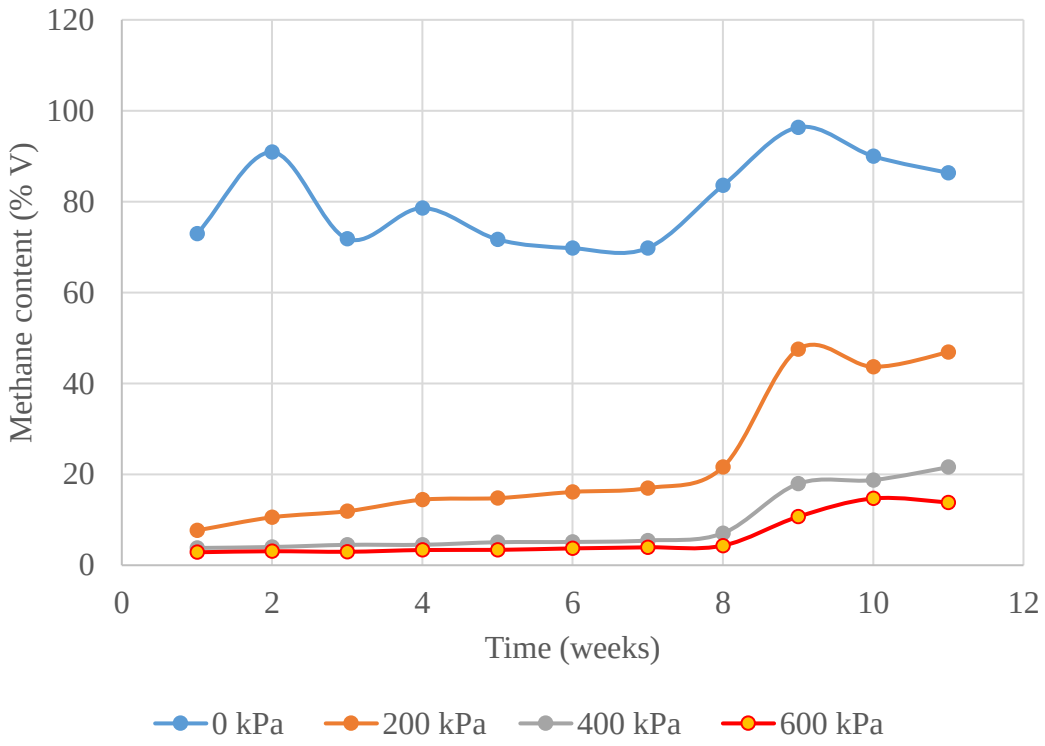

Figure 2-3: Variation of methane content in biogas with increasing hydrostatic pressures

2.2.7 Solid Content (Total Solids) of Substrates

An important physical characteristic of slurry is its total solids (TS) content. The slurry of organic waste contains a wide range of solid materials. It is usual to classify digesters according to their total solids content. Digesters have low solids content if TS < 15 % and high solids content if TS is about 25 - 30% (Evans & Furlong, 2003). Low solids content digesters are also referred to as wet digesters, while high solids content ones are said to be dry.

2.2.8 Mixing

Mixing increases the surface area for the microbes to have easy access to the feedstock (Karim, Hoffmann, Klasson, & Al-Dahhan, 2005). Mixing also avoids temperature gradients within the digester and prevents scum formation (or concentration gradient) (Lindmark, Thorin, Fdhila, & Dahlquist, 2014). Gas generated within the slurry gets easy access to escape into the gas chamber if mixing goes on. Usually, three mixing techniques are adopted: (i) mechanic, (ii) hydraulic and (iii) pneumatic mixing. Mechanical agitators use devices such as propellers or paddles powered by an electric motor. Without a motor, the design could be made to turn with manpower. Mechanical mixing is done with an agitator, constructed with an impeller, shaft and motor (if to be turned with an electric source).The agitator speed selection depend on the viscosity range.

Hydraulic and pneumatic mixing are done by pumping liquid or gas respectively into the digesting chamber to stir up contents of digester. This is achieved by circulating fluid from the digester. Hydraulic mixing draws out part of the liquid of the slurry and pumps

it back with pressure through a nozzle. Pneumatic mixing on the other hand pumps biogas under pressure back into the digester. (Paul, Atiemo-Obeng, & Kresta, 2004).

It is possible for digester content to continuously circulate and create vortex during mixing. Mixing could be improved by introducing baffles. Baffles are flow-directing or obstructing panels or gaps used in digesters to improve mixing and gas dispersion.

2.2.9 Inhibitory Substances

All the process parameters discussed above have positive influence on the production of biogas. This section discusses briefly some substances that inhibit the formation of biogas. Oxidizing agents such as O_2, NO_3, SO_4, and CO_2, destroy cells by oxidizing various cell components. Their product is a release of energy in the form of heat. For example, slurry in the presence of O_2 undergoes oxidation referred to as aerobic digestion, in which the reaction release energy. Table 2-4 shows the oxidization of glucose where free energy of ΔG^o =-2840 kJ mol^{-1} is released with the production of CO_2 and H_2O. In this reaction no CH_4 is formed. This is because methanogens, which forms CH_4, are very sensitive to oxygen and die when they are exposed to O_2.

Table 2-4: Aerobic reaction of biomass

Component	**Aerobic reaction**
Reaction	$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
Energy released	ΔG^o = -2840 KJ mol^{-1}
Energy balance	60 % biomass, 40 % heat released

Cheng (2008) indicated that other inhibitory substances include high concentration of ammonia, light metal ions (Na, K, Mg, Ca, and Al) and heavy metals (Cr, Fe, Co, Cu, Zn, Cd, and Ni) in the digester. Ammonia is produced from urea and proteins biodegradation and causes microorganisms to cease growth. The light and heavy metals may form salts, which may dehydrate microbial cells due to osmotic pressure. This could lead to the death of the microorganisms, which are the engine for biogas generation. Inhibitory action is therefore prevented in the biochemical process by total elimination or minimization of these inhibitors from the digester.

The elimination of O_2 is factored in the design of an anaerobic digester by having the ends of the inlet and outlet pipes inside the digester buried within the slurry. This ensures that sufficient amount of the slurry remains in the inlet and outlet pipes to prevent infiltration of air into the digester. Additionally, valves are placed on the ends of the inlet and outlet pipes outside the digester to ensure total seal to the environment (forming a closed system). This is most relevant when manometric method is used for gas collection.

2.3 Types of Anaerobic Digesters

An anaerobic digester is an airtight (closed) biochemical thermodynamic system that provides an enabling environmental condition for anaerobes (microbes that function effectively in the absence of O_2) to produce a target product such as biogas. The digester has a main chamber (the reactor tank), which is linked to component subsystems. The subsystems include inlet and outlet (feeding and discharge) units, gasholder, connecting pipes, stirrer and baffles. The anaerobic digester is also variously known as biodigester, bioreactor, fermenter, reactor, and digester. There are different types of digesters

classified as (i) dry and wet digesters (ii) low and high rate digesters (iii) batch, batch-fed and continuous feeding digesters and (iv) single-stage and multi-stage digesters. Further description of types of digesters follows in this section.

2.3.1 Dry and Wet Digesters

The total solids in a digester is an indication of the quantity of biomass used as slurry for biogas production. Dry digestion refers to slurry with biomass content of about 25 - 30 % whilst wet digestion, refers to a dry solids content of less than 15 %. For same volumes of wet and dry digesters, the dry digester contains more solids. Fluid flow in a dry digester has higher resistance and for that matter, if the system requires agitation much energy is required.

2.3.2 High and Low Rate Digesters

The rate of reaction of anaerobic digestion expresses how fast feedstock is treated to form the desired product. The rate of feedstock conversion is dependent on the architectural design and operation of a digester. There are three main types of low rate digesters. They are usually built with easily available materials, easy to handle, have few moving parts, and normally small size. These types of digesters are common in developing countries. Examples of the slow rate type of digesters are the fixed dome, floating drum and the plug flow types.

In a low rate digester, the desired product is obtained after a long period because of the nature of consortium of microbes that are active. The environmental conditions provided

for such system allows slurry to be retained in the digester for up to about 40 – 50 days (Tchobanoglous, Burton, & Stensel, 2004). The retention time is a function of the total solids and total water content of the slurry. Solid retention time (SRT) refers to the average period solids in the form of slurry spend in the digester before being dislodged. The SRT can be determined by the ratio of the mass of solids in the digester to the mass of solids discharged from the digester periodically.

$$SRT = \frac{mass of solids\ in\ digester}{mass\ of\ solids\ dischaged\ periodically} \tag{2-7}$$

Other factors which affect the determination of the SRT is the time in which microbes reach their optimum growth and the amount of slurry converted to its final product.

The hydraulic retention time (HRT) of a system refers to the average time the liquid component in a digestion process spends before discharge:

$$HRT = \frac{liquid\ volume}{periodic\ flow} \tag{2-8}$$

In a system where microbes grow fast, CH_4 yield is high; hence, retention time will be short. Shortened retention time implies a small size digester would be required. If the ratio of solid to liquid content is 1:1, the HRT = SRT. Otherwise, like in wastewaters where the solid content is very low, HRT < SRT.

High rate digesters use few hours to treat its content. This reduction in time allows the design of small digesters to treat large quantities of waste within short period. This has an advantage of generating continuous biogas and process stability can be assured. High

rate digesters are most suitable for wastewaters with low suspended solids content. It requires high amount of energy to complete its processes. This does not make it a suitable option for energy production. There are many designs of high rate digesters. They are usually expensive, require high skill and materials used in construction may have to be imported. These types are usually used in treating large quantities of biomass and are common in advanced countries. Some common examples of high rate digesters are up-flow anaerobic sludge blanket (UASB) digester, anaerobic fluidized-bed reactor and ultrafiltration (UF) membrane digesters.

2.3.3 Batch, Batch-fed, and Continuous Feeding Digesters

Feeding of a digester, also known as organic loading rate, refers to the amount of slurry fed into the digester over a given period. This feeding rate is associated with the desired output of the digester design. The applicable organic load ratings are known as (i) continuous feeding (ii) batch-fed and (iii) batch feeding. In the continuous feeding rate process, small quantities of feedstock are fed into the digester at regular time intervals (usually daily). An equal amount of effluent is drawn out of the digester every time it is fed. The advantage of the continuous feeding is that as long as feeding continues, anaerobic digestion is maintained and the production of the CH_4 gas is constant. A batch-fed anaerobic digestion system is a semi-batch operation in which slurry is fed intermittently or continuously but the product is harvested only at the end of the operational period. Thus no effluent is drawn out during operation of digester. Such operation causes the slurry volume within the digester to increase during operation. For the batch loading rate, the digester is fed with feedstock once. It is left to operate for the entire period without any further introduction of feedstock until the desired HRT is achieved. A batch digester is normally a constant-volume device (Nauman, 2001).

2.3.4 Single-stage and Multi-stage Digesters

The anaerobic digestion process is grouped in stages according to the consortium of the microbes that function. A single stage digester is one in which all the consortium of microbes exist in the same tank where all stages of biochemical reactions take place. The other is called multi-stage (usually two-stage) digester. This is the design in which two digesters are connected to each other to perform separate sequential operations to complete the process of anaerobic digestion. The first stage (the first digester) involves the hydrolysis and acidogenesis processes, while the second stage (the second digester) involves the acetogenesis and methanogenesis processes.

2.4 Aspects of the Design Consideration of Anaerobic Digesters

In section 2.3, different types of anaerobic digesters are classified according to some selected parameters. In this section, some other key considerations necessary for digester design are discussed. They include: (i) the type of materials used for construction, (ii) the shape of the digester, (iii) the feeding and discharge systems, (iv) biogas storage, and (v) connecting pipes and valves.

2.4.1 Materials Used for Construction of Digesters

The conversion of biomass to biogas through the biochemical processes involves a series of complex chemical reactions that could be reactive to its container in which the reactions occur. Furthermore, the thermodynamic behaviour of the closed system, the mechanical activities of the slurry as well as the pressure variations due to the various gases produced requires a careful selection of the container used for the digestion

processes. It is important to avoid seepage of the slurry into water bodies, since the deoxygenated chemical processes are toxic, especially to aquatic life. This section discusses the types of materials used for the construction and the basic shapes of the designs.

Tanks can be built from clay bricks, where the mortar for brickwork may consists of sand, water, and binding agents. Cement as binding agent results in stable, waterproof, but brittle mortar. Steel sheets are also used for digester construction. An enamel layer protects the entire steel surface. Such tanks are completely segmented but are quite easy to assemble. Glass fibre reinforced plastics have also been used.

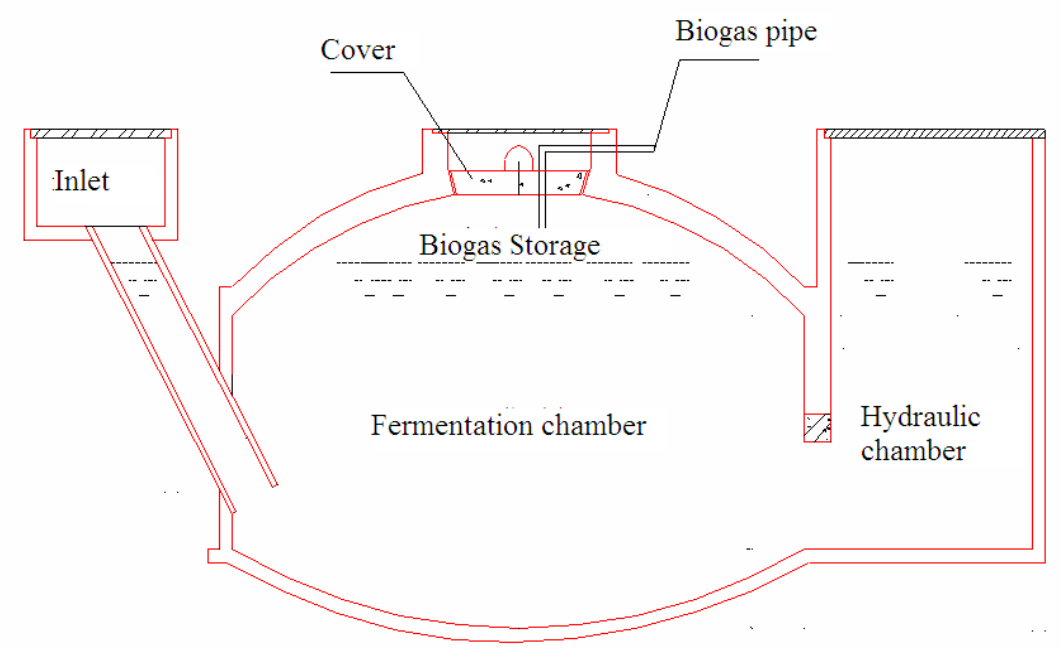

Figure 2-4: Schematic diagram of a fixed dome digester
Source: (BIOMA, 2013)

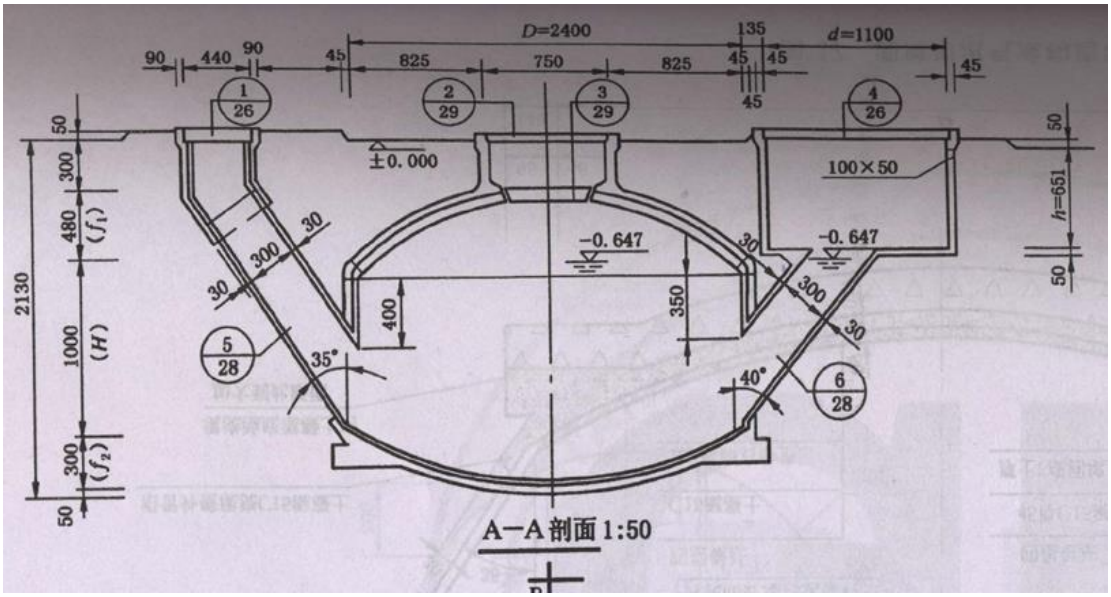

Figure 2-5: A Chinese standard fixed dome biogas plant
Source: (Chinese GB/T4750-2002)

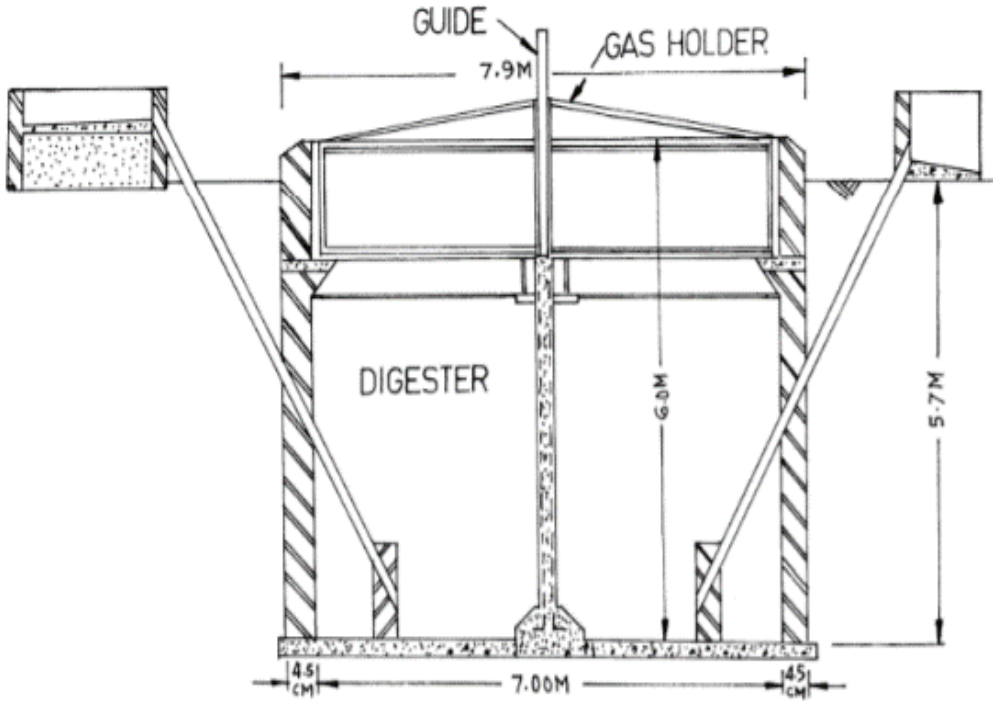

Figure 2-6: Floating drum digester
Source: (Kalia & Singh, 1999)

Figure 2-7: Production process of glass fibre reinforced plastic digester with mass production ready for deployment
Source: (Hongqi. P. R. C., 2013)

Figure 2-8: Stages of construction of a Chinese brick fixed dome digester
Source: (BIOMA P. R. C., 2013)

Figure 2-9: Soft polymer digester
Source: (BIOMA P. R. C., 2013)

Figure 2-10: High rate digester
Source: (BIOMA, P.R. C., 2013)

2.4.2 Reactor Tanks

Generally, three shapes are suitable for the construction of anaerobic digestion reactors (tanks): (i) cylindrical, (ii) spherical and (iii) egg shaped. These shapes provide mixing characteristics without creating excessive shear forces (Wu, 2010). In this study, a plastic cylindrical tank has been used. Consequently, in what follows, a detailed outline of the physical properties of these digesters (cylindrical tanks) is provided. This is followed in the next section by a detailed outline of the physical properties of this digester.

2.4.2.1 The Cylindrical Shaped Tank

The cylindrical tank has one curvature in one direction, determined by its radius. This single curvature makes it possible to vary the entire volume by changing the cylindrical height. Cylindrical digesters can be mounted either horizontally or vertically. The cylindrical shaped tank is capped at its ends. The shape of the end could be spherical, toroid, conical or a combination of these shapes such as torispherical (toroid and spherical). The choice of the shape of the digester depends on the designer's specification. For this study the horizontal shape of the digester was preferred. This was to allow shallow digging of the earth, if the digester has to be buried underground. The shallow digging of the earth will avoid the possible interference of high underground water table, which could lead to high fluctuation of the digester's temperature.

2.4.3 Feeding and Discharging Systems

The main chamber of the digester, where anaerobic digestion takes place is airtight. Access to this chamber is by three main routes; (i) the feeding (inlet), (ii) discharging

(outlet) subsystems and (iii) gas outlet system. Generally, slurry goes into the digester through the feeding system as influent, gets biodegraded by a consortium of enzymes and exits as effluent through the discharge system. These are designed such that they allow minimum or no entry of air into the chamber.

A feeding system is a mechanism, which transports slurry into the digestive chamber of the digester. A feeding subsystem may include holding tank, a feeder, and an inlet pipe. The holding tank temporarily stores the feedstock and could be used for pre-treatment of the feedstock and preparation of slurry. The pre-treatment may include washing of feedstock to get rid of sand and any other possible inhibitors, such as non-biodegradable matter found in feedstock. In the case where the feedstock particle sizes are large, the feedstock is shredded to reduced average size.

The slurry is finally transferred with a feeder, (using a screw feeder, or by gravity feeding, or pumping) into the digester through the inlet pipe (Fernandez, Cleary, & McBride, 2011; Molinder & Wiinikka, 2015). The process involved in gravity feeding requires the least amount of input energy. Such system that applies gravity feeding is normally installed underground with the slurry source above ground. Screw and pumping feeding systems are relatively energy intensive. These feed systems are relevant when digester is installed above ground. In small scale, low rate digesters, feeding is limited to inlet pipes. The slurry could be prepared in a bucket after which it is poured into the inlet pipe through a funnel.

The discharge system could be designed similar to that of the feeding system. Its function is to allow the spent slurry to be removed from the digester. For a complex digester the discharge system may include a holding unit to store the effluent for further treatment before finally discharging into the environment. At this point, the solids can be separated from the digestate. Small digesters are limited to only outlet pipes. In a series of digesters, the output pipe is connected to the inlet pipe of another digester.

2.4.4 Biogas Storage

Biogas produced can be used immediately or stored for future use. Storage of the biogas can be within (headspace) of the reactor tank or outside the tank in a storage device. The size of the biogas storage unit depends on factors such as (i) the rate of biogas production, (ii) the energy demand or storage gas pressure. The volume of storage is normally between 0.75 and 1.5 times the daily biogas production (Deublein & Steinhauser, 2008). Gasholders may be considered as (i) low pressure, (ii) medium pressure or (iii) high pressure systems. Deublein, (2008) has categorized the gasholders as indicated in Table 2-5. Biogas bags and double membrane are used for low-pressure biogas application, steel pressure tanks for medium digester applications and steel flask for high-pressure digester applications. Generally, it is observed that low-pressure digester applications use large storage devices, due to its low risk in case of an accident.

Table 2-5: Biogas holder categories

Pressure (kPa)		Size (m^3)	Design
Low	0.005 – 0.5	10 – 2000	Soft polymer bag
Medium	500 – 2000	1 – 100	Steel pressure tank
High	20000 – 30000	0.1 – 0.5	Steel flask

2.4.5 Connecting Pipes and Control Valves

A digester may have two main types of pipes being one set which connects the digester as either inlet pipe or outlet pipe. The other is the connecting pipes that carry the gas produced. Generally, large pipes are used for the feeding and discharge of slurry while smaller pipes are used to carry gas. Valves are connected to the pipes to control the flow of either the slurry or gas. Different types of valves such as piston valves, plug valves, ball valves, butterfly valves, check valves, and pressure control valves are commonly used in the design of biogas digesters. Biogas flowing through the pipes may contain some amount of steam, so along the pipe a steam trap is connected to collect any condensed water formed in the pipe. This prevents water from blocking the gas pipe, which can cause an unnecessary pressure build-up within either the reactor tank or gas pipes.

2.5 Thermodynamics of Microbial Function in Anaerobic Digestion

Thermodynamics deals with the study of the fundamental laws of transformations of heat into other forms of energy. It also explains the relationship between energy and work.

(Haynie, 2008). Fundamental knowledge in thermodynamics is therefore paramount to the study of anaerobic digestion since energy transformation and mass flow are the basic operations of anaerobic digestion system. This section discusses briefly the types of thermodynamics systems with emphasis on a closed system. This is because the type and operation of the digester involved in this study is a non-flow system characterized with only energy transformation with its boundary, but not mass flow. Furthermore, aspects of the first and second laws of thermodynamics are also discussed. Other important thermodynamic parameters such as Enthalpy and Gibb's free energy are also discussed.

2.5.1 Thermodynamic System

A thermodynamic system deals with any quantity of matter or region in space upon which attention is concentrated on energy and mass flow within the system and with its surroundings for the purpose of analysis. For the purposes of studies of this system, the wall or layer around the system is referred to as its boundary and anything beyond the boundary called surrounding. The system and its surroundings are located in the region called universe.

$$Universe = System + Surrounding \tag{2-9}$$

There are three types of thermodynamic systems namely, (i) an open system, (ii) closed system and (iii) an isolated system. An open system can exchange energy and mass with its surroundings and such interaction occurs at the system boundary. A closed system is a system that can exchange energy only, but not mass with its surrounding (see Figure 2-11). The third type of system is referred to as an isolated system. In this system, there is neither exchange of energy nor mass with the surrounding.

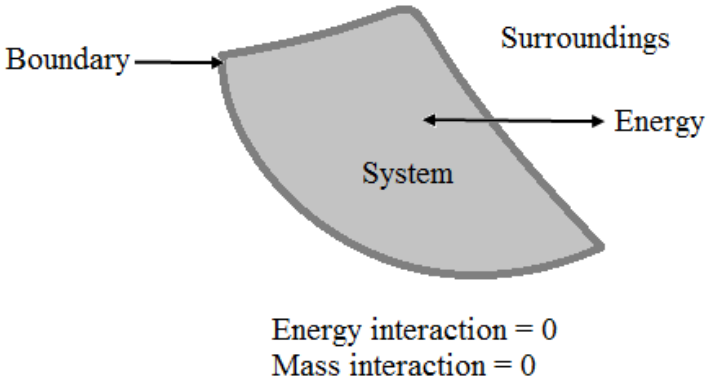

Figure 2-11: A closed system

The digester assembled in this study can be referred to as a closed system. The general characteristics of a closed system is listed in this section. A closed system has the following characteristics:

- The total mass of a closed system is fixed.
- The density of content may vary as operation proceeds
- The energy of each batch may vary.
- The retention time for all components of content are the same.
- It is assumed that the batch system is completely stirred hence system is homogenous.

2.5.2 The First Law of Thermodynamics

The first law of thermodynamics, also known as the law of conservation of energy is a function of the change in internal energy (du) of a closed system, which results from heat interaction with work on or by the system. This law is expressed mathematically as:

$$du = dq + dw \tag{2-10}$$

where du is the internal energy of the system, $dq = mc_v\Delta\theta$ is the heat energy and $dw = pdV$, the work done either on or by the system.

2.5.3 The Second Law of Thermodynamics

The second law (entropy) expresses the continuous increase in disorder in the universe. Entropy determines the spontaneity of a reaction, and the change in entropy ($ds = \frac{dQ}{T}$) of a reaction describes the direction of a reaction. A combination of the first and second law of thermodynamics results in:

$$dU = TdS - pdV \tag{2-11}$$

where T is the temperature of reaction, and pdV work done either by or on microbe, p represents the pressure of the system with volume change dV. An increase in temperature of a biochemical reaction increases its rate because the additional heat increases the entropy (random molecular movement).

2.5.4 Enthalpy

Two other useful concept of thermodynamics are the enthalpy (H) and Gibb's free energy. Enthalpy is the heat content (absorbed or emitted) during a biochemical reaction under an isobaric condition. It is a combination of internal energy (U) and energy flow (pV). Enthalpy is expressed mathematically as:

$$H = U + pV \tag{2-12}$$

where p is the pressure developed within the system and V is the volume of system. At constant pressure, the enthalpy change (ΔH) equals the energy transferred within the system. When the measured change in enthalpy is positive, the reaction is termed endothermic and when negative exothermic reaction would have taken pace.

2.5.5 Gibb's Free Energy

Gibbs free energy (G) explains how fast a metabolic process would occur. The Gibbs free energy is that portion of the total system energy that is available for useful work. The Gibbs equation incorporates the idea of temperature, the Zeroth, the First and Second laws of thermodynamics, resulting in specifying the maximum useful work that is obtainable from a thermodynamic system.

$$G = H - TS \tag{2-13}$$

We can derive

$$G = G^o + nRTln\frac{[C]}{[C_o]} \tag{2-14}$$

where $G^o$is standard free energy, $[C_o]$ is the concentration of reactants under standard condition, and $[C]$ concentration of product. A chemical reaction will not occur spontaneously when the value for the Gibbs free energy is positive, but when negative the process will occur spontaneously.

The stoichiometric equation for a reversible biochemical reaction occurring at standard temperature and pressure of 298.15 K and 101.3 kPa respectively can be represented as

shown in equation 2-15, where n_a, n_b, n_c and n_d refers to the number of moles of the compounds *A*, *B*, *C* and *D* respectively .

$$n_a A + n_b B \Leftrightarrow n_c C + n_d D \tag{2-15}$$

The stoichiometry of a reaction defines the proportions in which chemical elements combine. The change in free energy is generally expressed as:

$$\Delta Gr = \Delta Gr^o + RT\ log \frac{[C]^{n_c}[D]^{n_d}}{[A]^{n_a}[B]^{n_b}} \tag{2-16}$$

where [C] and [D] are the molar concentrations of the reaction products, and [A] and [B] the concentrations of the activities of the reaction feedstock, R is the gas constant = 8.31451x 10^{-3} [kJ·mol^{-1}·K^{-1}], T is the thermodynamic temperature in [Kelvin], ΔGr^o is the change of Gibbs free energy of reaction at standard conditions.

At equilibrium $\Delta Gr = 0$, equation (2-16) reduces to equation (2-17).

$$\Delta Gr^o = -RT\ log \frac{[C]^{n_c}[D]^{n_d}}{[A]^{n_a}[B]^{n_b}} \tag{2-17}$$

The values of free energy change (ΔG) determine the spontaneity of a reaction. Free energy values that are greater than zero ($\Delta G > 0$), equal to zero ($\Delta G = 0$) or less than zero ($\Delta G < 0$) represent that the reactions are not spontaneous, at equilibrium or spontaneous, respectively.

2.5.6 Heat Transfer in a Closed System through a Heat Exchanger

Psychrophilic, mesophilic and thermophilic digesters may operate above ambient temperatures; therefore, heat must be supplied to raise the temperature of slurry inside

the digester up to the desired temperature. Continuous or semi-continuous heating may be necessary to offset heat losses through the walls and connecting pipes of the digester. Various digester-heating systems that have been employed to heat the slurry include the hot-water coil in digester, steam injection into digester, hot-water injection in digester at slurry preparation, hot water jacket, and solar heating.

Considering the heat flow in a system, the rate of heat transfer $\dot{Q}$ is a function of a temperature gradient. According to Fourier's law of heat conduction, which is a one-dimensional heat conduction,

$$\frac{\dot{Q}}{A} = -k\frac{dT}{dx} \tag{2-18}$$

where k is the thermal conductivity of heat exchanger, A, is the cross-sectional area and dx is thickness of heat exchanger, the negative sign represents heat flow from a hot substance to a cold substance (heat lost).

2.6 Mass and Energy Balance Principles

2.6.1 Mass Balance

As has been stated in section 2.4.3, during anaerobic digestion processes, slurry enters the digester through the feeding system, gets biodegraded by a consortium of enzymes, and exits the digester as effluent through the discharge system. This behaviour of the feedstock flow in the digester obeys the mass balance principle which states that mass is neither created nor destroyed but transformed from one form to the other (such as from liquid to gas). This is also stated in another way as the law of conservation of mass. According to the law of conservation of mass, for a given volume (V) of a digester, the

sum of the mass flow into a system equals the sum of mass coming out of system and the amount that remains inside of the system. It offers a convenient way of defining what occurs within a confined region as a function of time. Assumptions associated with the mass balance principle include:

- The volumetric flow rate into and out of the system remains constant.
- The volume of the content of the system remains constant (isothermal condition, no evaporation).
- The system is considered completely mixed.
- A chemical reaction is considered to involve the reactant and takes place inside the system.
- The rate of change in the concentration of the reactant A that is occurring inside the system is governed by the first order reaction, which is $r = \frac{dC}{dt} = -kC$.

The mass balance is mathematically represented as:

$$Inflow - Outflow + Generation - Consumption = Accumulation$$

Thus,

$$QC_{in} - QC_{out} \pm rdV = \frac{dm}{dt} \qquad (2\text{-}19)$$

Where Q is the volumetric flow rate in and out of the system, C_{in} and C_{out} is the substance concentrations in and out of system respectively, r is the rate of generation/ depletion (reaction velocity).

2.6.2 Rate of Reaction

In operating a digester, slurry goes into the digester through the feeding system as influent. Biodegradation of material occurs by the action of a consortium of enzymes. The treated slurry then comes out as effluent through the discharge system. The rate of reaction (r), determines the changes that occur in a chemical reaction. Mass balance principle is therefore applied to the determination of the rate of a reaction, since the total mass in the system remains unchanged. For a batch system where the volume (V) of the system is constant with no material flow either in or out $Q = 0$. Therefore from equation (2-19):

$$rV = \frac{dm}{dt} = \frac{d(VC)}{dt} = V\frac{dC}{dt} \tag{2-20}$$

Therefore,

$$r = \frac{dC}{dt} \tag{2-21}$$

2.6.3 Order of Chemical Reaction

The order of reaction with respect to a given component of a reaction process is represented as an index to which its concentration term in the rate equation is raised. Typical reactions are represented as zero, first, and second orders. For an arbitrary chemical reaction such as:

$$aA + bB \rightarrow cC + dD \tag{2-22}$$

The change in concentration for the various components, both reactants and products would be:

$$-\frac{1}{a}\frac{d[A]}{dt} = -\frac{1}{b}\frac{d[B]}{dt} = \frac{1}{c}\frac{d[C]}{dt} = \frac{1}{d}\frac{d[D]}{dt} \tag{2-23}$$

where the minus (-) sign represent consumption and plus (+) represent accumulation.

Generally the rate of reactions given by:

$$r = \frac{1}{c_i}\frac{d[C_i]}{dt} \tag{2-24}$$

where the coefficient term $\frac{1}{c_i}$ is positive for product and negative for reactants.

Typical rate expressions for selected processes can be used to determine order of reactions. A graphical plot of the integral forms of the various rate equations can be compared with experimental data to determine the order of a reaction (see Table 2-6). The zero order reactions proceed at a rate independent of the concentrations of the reactants. A plot of concentration with time results in a straight line graph with the rate constant as slope. The first order reaction occurs at a rate directly proportional to the concentration of one of the reactants. A plot of *ln C* with time gives a straight line graph with the rate constant as slope. It follows that the second order reaction proceeds at a rate proportional to the second power of a single reactant. A plot of the inverse of the concentration of the reactant with time determines the rate constant, which is also produced from the slope of a straight line graph.

Table 2-6: Rate equation and reaction order determination
Source: (Tchobanoglous, Burton, & Stensel, 2004)

Rate expression	Integral form	Reaction order determination
Zero-order reaction		
$r = \frac{dC}{dt} = k$	$C - C_o = kt$	Plot *C* versus *t*.
First order reaction		
$r = \frac{dC}{dt} = kC$	$lnC - lnC_o = kt$	Plot $lnC - lnC_o$ verses *t*
Second order reaction		
$r = \frac{dC}{dt} = kC^2$	$\frac{1}{C} - \frac{1}{C_o} = kt$	Plot $\frac{1}{C}$ versus *t*

2.6.4 Energy Balance

The concept of energy conservation of a system can be expressed by an energy balance equation, where energy has been categorized as (i) Kinetic Energy (E_k), (ii) Potential Energy (E_p), and (iii) Internal Energy (U). These are expressed mathematically as:

$$E_k = \frac{1}{2}mu^2 \qquad E_p = mgz \qquad U = Q - W \tag{2-25}$$

where m is the mass of the object travelling with speed u, at an elevation z.

The total energy transformations as rates, such as by performance of work, or by flow of heat of a system composed of kinetic, potential, and internal energies.

CHAPTER THREE: CONSTRUCTION OF A PROTOTYPE OF A SINGLE STAGE ANAEROBIC DIGESTER

3.0 Introduction

This chapter describes in detail a 1 m^3 stirred tank digester designed and assembled with readily available materials. A plastic water tank, PVC pipes, copper tubing and a DC electric motor were used in the design. The inter-connections of the reactor tank and the various subsystems (inlet and outlet pipes, heat exchanger, and stirrer) are described. The fabrication of an innovative stirrer, using the electric motor is also outlined. The functions of the main measuring instruments installed on the digester have been explained. Steps taken in testing for water and gas leakages on the digester have been clearly set out. The chapter concludes by stating some key safety and operation measures that must be taken in a biomass conversion research laboratory.

3.1 Requirement for the Assembly of the Prototype Digester

Several materials were used in the assembly of the digester. The selection of materials was based on the design and application requirement. In this study, the selection of the materials and design considerations (criteria) included the following:

- Small size (portable) reactor tank (1 m^3) for onsite biogas production from small volumes of organic matter
- Reactor tank should be suitable for the treatment of different types of biomass, depending on their (biomass) availability

- Reactor tank should meet internationally accepted pressure tank code, applicable for intended purpose as digester, easily transportable to where feedstock is
- Reactor tank must be chemically inert such that it does not leach chemicals into its content
- Relatively low skills required to assemble digester
- Low energy requirement for physical operation
- Design must be modular to easily scale up to treat large quantities of available feedstock

3.2 Characteristics of the Tank and Assembly of the Digester

This section discusses the physical characteristics of the tank used as digester. It emphasises on the additional holes drilled on the tank and their function. Furthermore, it elaborates on the assembly of the digester.

3.2.1 Characteristics of the Tank

The reactor tank selected for this study is a 1 m^3 capacity double layer plastic water tank made from polyethylene. It is a horizontal cylindrical tank with torispherical heads at its ends. The outer and inner layers are coated black and white respectively. The black colour prevents UV from entry into the digester, while the white colour reduces heat losses. The tank was high strength, rust proof, light weight and durable (SINTEX Containers Gh. LTD, 2016). The tank had four openings with the largest one located at the middle portion at top of the digester. This largest hole was used for bulk loading of the digester, and it served as the entry point for all works that demanded entry into the digester. The other holes were located on the torispherical ends: two on one side (one close to the top and the other close to the bottom. Another hole was located lower down

but on the opposite side to the horizontal end). One of these openings served as the inlet pipe and the other as outlet pipe. The third opening was used as the connecting link between the copper heat exchanger, which is placed at the base of the tank, and the water-heating source. Three additional openings were provided by drilling holes on the upper end of the tank (two of them were drilled on the tank cover). These openings served as the gas collection outlet, thermocouples and the power cable for the stirrer motor inlet. Two saddles provided a firm support seat for the digester to be stable at its base. Within the tank, the saddle supports had groves that serve as baffles (see Table 3-1 for the dimensions of the plastic tank).

Table 3-1: Dimensions of 1 m^3 plastic water tank

Parameter	**Dimension (m)**
Thickness of material (digester wall)	0.00442 ± 0.00004
Length of digester	1.52 ± 0.01
Diameter of digester	0.94 ± 0.01
Diameter of covering	0.435 ± 0.001
Diameter of opening for inlet and outlet pipes	0.045 ± 0.002
Diameter of opening for gas outlet pipe	0.022 ± 0.001
Diameter of opening for the power cable	0.022 ± 0.001
Diameter of opening for thermocouples	0.046 ± 0.002
Length of saddle	0.19 ± 0.07

3.2.2 Assembly of the Digester

The reactor tank and its accessories were put together according to the construction design (Figure 3-1). PVC pipes with inner diameter 0.036 ± 0.003 m and thickness (0.0026 ± 0.0007 m were used for the fabrication of the inlet and outlet pipes. Gas hose was used for all the gas connections to and from the pressure gauge, gas meter, gasholder, and digester.

A platform, which took the curvature of the cylinder, was made with a half inch PVC pipe was glued to the base of the tank. The copper heat exchanger was fastened onto the platform. This was done to prevent the heater from touching the bottom of the tank in order to minimize heat losses through the bottom of the tank.

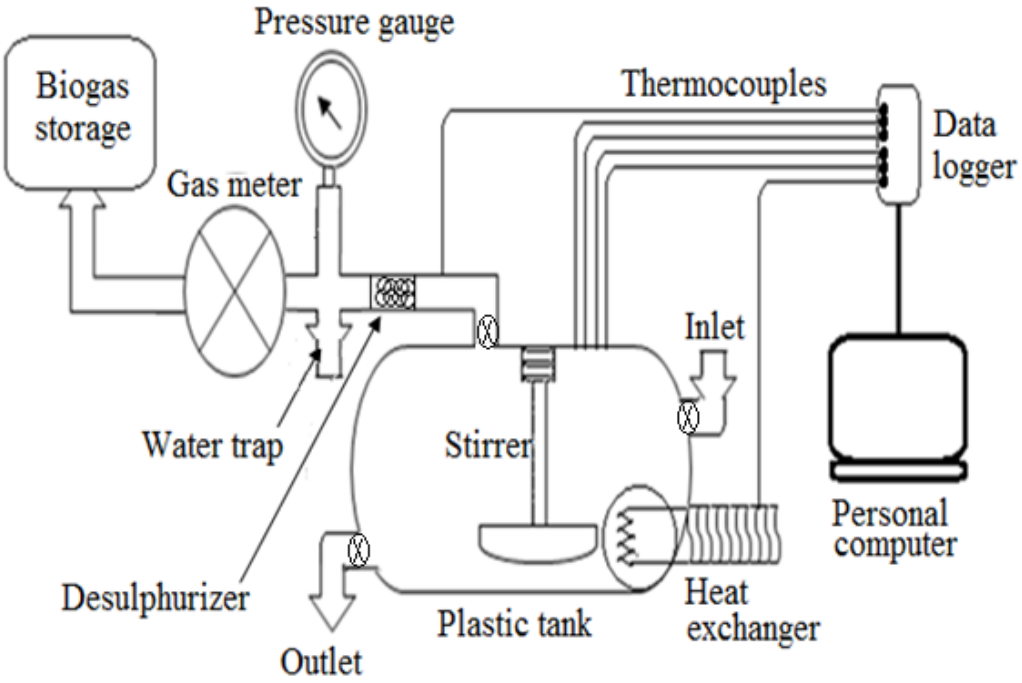

Figure 3-1: A schematic diagram of the general layout of the experimental setup

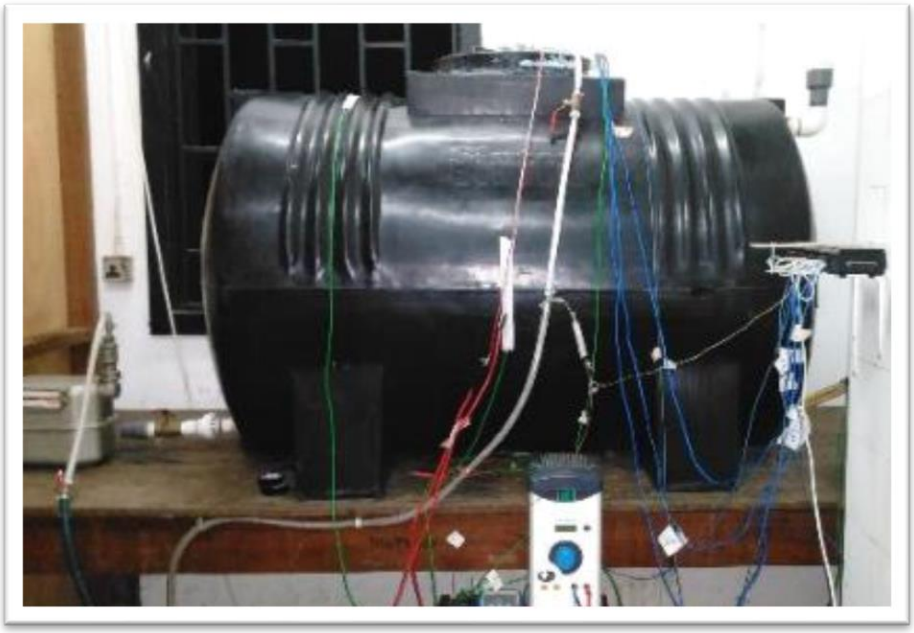

Figure 3-2: The anaerobic digester of the horizontal cylindrical plastic tank with torispherical ends, assembled and operated as a single stage batch system

3.3 Fabrication of the Subsystems

To complete the assembly of the digester, three major subsystems were fabricated and fixed onto the digester. The three subsystems are (i) the inlet and outlet pipes, (ii) heat exchanger and (iii) motorized stirrer. This section discusses the fabrication of each subsystem and their installation onto the tank to complete the digester assembly.

3.3.1 The Inlet and Outlet Pipes

The feeding and discharge systems were limited to an inlet and an outlet pipe. Two key parameters considered for the selection of the size of the inlet and outlet pipes were the particle size of the slurry used and their ability to flow. Slurry containing small size particles with high water content (low total solids) requires small diameter pipe.

Otherwise, large diameter pipe would be appropriate. This was to ensure flow of slurry in and out of digester was easy.

The inner end of the inlet pipe was buried in the slurry. It served as a trap to prevent entry of air into the gas chamber and gas escape out of the digester. When the screw cap is opened, the inlet tube creates a hydraulic system such that any pressure build-up forces the slurry to rise up in the tube (See Figure 3-3).

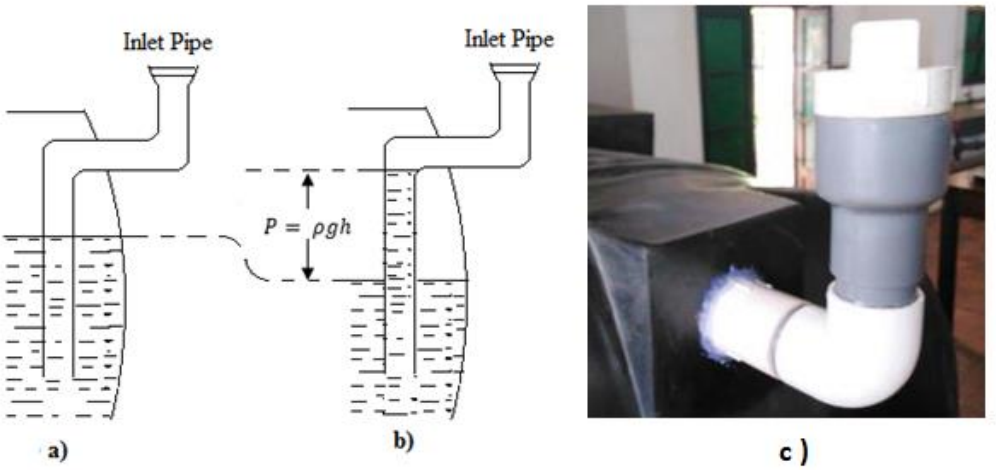

Figure 3-3: a) Inlet pipe buried in slurry. Entry of feedstock through the inlet pipe descends to the near bottom of the tank, where microbial activity is high. Air is prevented from contaminating the digester by the slurry inside the pipe. b) A differential pressure (P) is created within the pipe when pressure mounts within the digester. ρ is the density of slurry, h is level of rise of slurry in pipe and g acceleration of free fall. c) A picture of our closed inlet pipe

There are three possible configurations for the outlet pipe as shown in Figure 3-4 The outlet pipe at the bottom was adequate for use as the drainage pot. It was also used as the sampling pot. If a continuous system is run then the suggested outlet pipes b) and c) will be relevant.

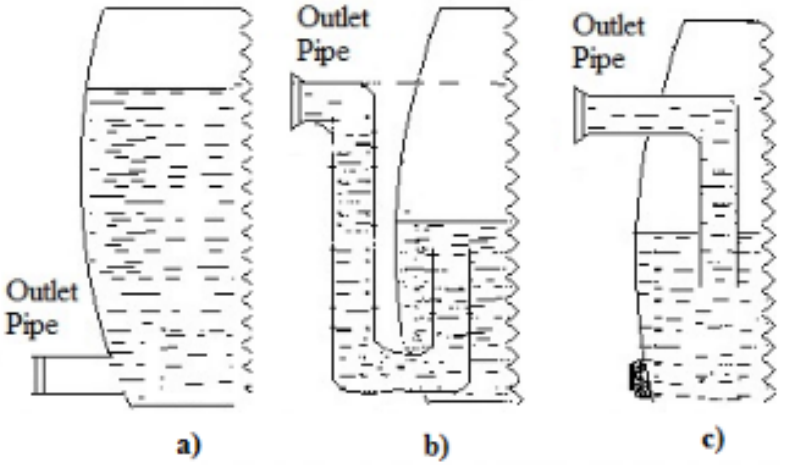

Figure 3-4: a) This shows a sketch of the outlet pipe used in this study. b) and c) are two suggested outlet pipes that can be used in place of a). b) and c) show that when the system is pressurized the outlet tube is filled with the digestate

3.3.2 Heat Exchanger

A heat exchanger was moulded with a 10.3 ± 0.1 m coil of copper tubing (with dimensions: outside diameter 8 mm, wall thickness 0.51 mm. A half-inch PVC pipe was moulded into a platform on which the copper pipe was positioned. This was to prevent direct heat loss between the copper tubing and the digester body. Both the PVC mould and the copper tubing took the shape of the tank. This was to reduce the space it covered and allow the stirrer to reach close to bottom of the tank (see Figure 3-5 and Figure 3-6). The heating was done with a circulating bath (0.010 m^3 capacity).

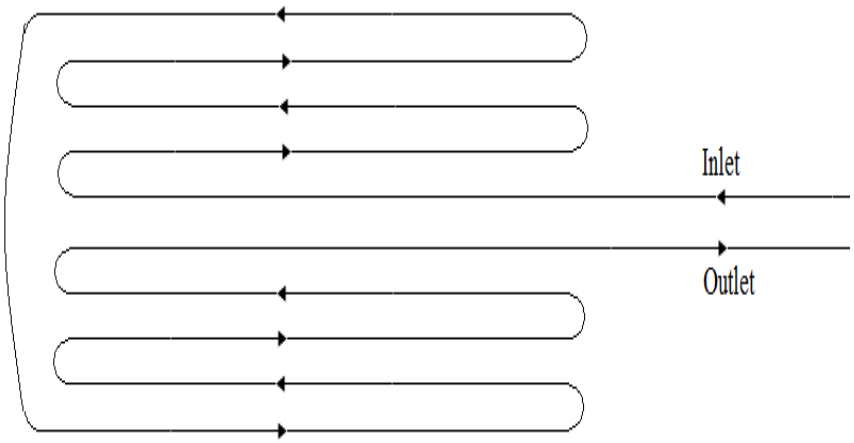

Figure 3-5: Schematic diagram of the copper tubing heat exchanger

Figure 3-6: Rectangular PVC platform with copper tubing heat exchanger. Distilled water was used as the liquid inside the tube for the heat water circulation

3.3.3 Motorized Stirrer

A motorized stirrer allows constant speed and longer period of mixing without human interference. An initial design of stirrer was to install the stirrer motor outside of the digester. After a series of test runs, recurring leakage around the bearing on the stirrer

warranted the redesign to the stirrer. The final design incorporated the stirrer within the digester. Both designs are discussed in the following section.

Initially the stirrer was designed with the stirrer motor being driven externally. The advantage of this was that any signs of motor failure could be readily observed or motor repair could have been achieved without opening the digester. An assembly of a stirrer with PVC pipe, two hydrodynamic rolling element bearings (6205 2RS C3), two flanges, and a digester cover was made. There were situations where the seal appeared adequate but, after days of test run, a leakage was detected on the ball bearing. Dynamic ball bearings are designed to operate at high speeds. At such high speeds, the grease on the bearings heats up and forms a thin oil film of lower viscosity, which enables the grease to form a seal. Since the slurry stirrer is a low speed system, the hydrodynamic ball bearings are unable to heat up the grease to form the seal. The slow speed of the bearings eventually only turn the grease around. This creates air spaces that allow gas to escape from the digester. An alternative bearing, which is a hydrostatic ball bearing works with a different technology. It has a pressure plate in its system of arrangement so that when there is an internal pressure increase, the plate pushes on the bearing to create a seal. This type of bearing was not readily available on the local market, thus the idea was modified to apply locally available material.

The stirrer shaft was designed as a top entry type and it was centre mounted. This was fabricated and affixed beneath the tank top cover. This means the agitator shaft, with its motor was completely immersed inside the tank. This was done as an alternative to using element bearing design for fabricating the agitator. With the element bearing, the best achievable design still provided tiny leakage bubbles. Therefore, the immersion was to

eliminate tribological challenges associated with the agitator shaft and the element bearing. This was possible to have both the stirrer and its driving motor completely contained in the digester. This contrasts with our first attempt at having the stirrer driven by the motor mounted outside the digester, when a major difficulty with leakage was encountered. It was necessary to remove the parts of the drill, which concealed the motor unit. Additionally, an adapter, fabricated with stainless steel, was lathe-manufactured for purposes of attaching the motor to the stirrer.

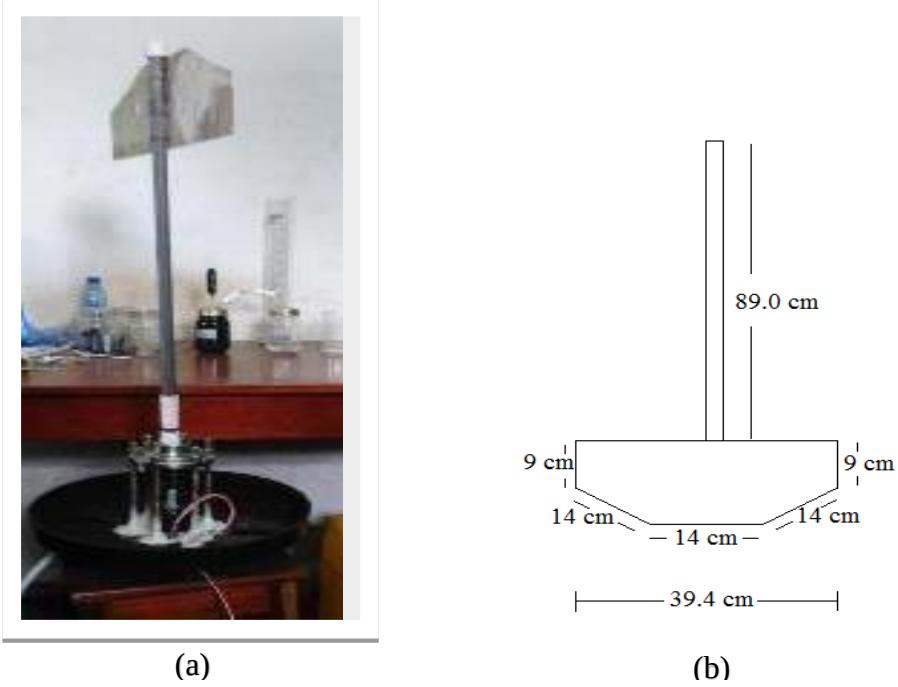

Figure 3-7: The final fabrication of the motorized stirrer: a) picture of the stirrer, b) schematic diagram of the stirrer shaft and impeller

Figure 3-8 shows the circuit diagram for the motorized stirrer application. A 10 V DC turned the stirrer in the slurry at 26 rpm, which was able to turn the slurry without undue stress. A digital multimeter was connected to the stirrer to monitor the voltage during stirring. In an environment where there may not be a digital multimeter an ammeter and

a voltmeter connection serves the same function. The use of the AC/DC power supply was to ensure a constant power supply source, such as from the national grid. The application of this system on the field can be powered with a renewable energy source, such as a PV or Wind energy system.

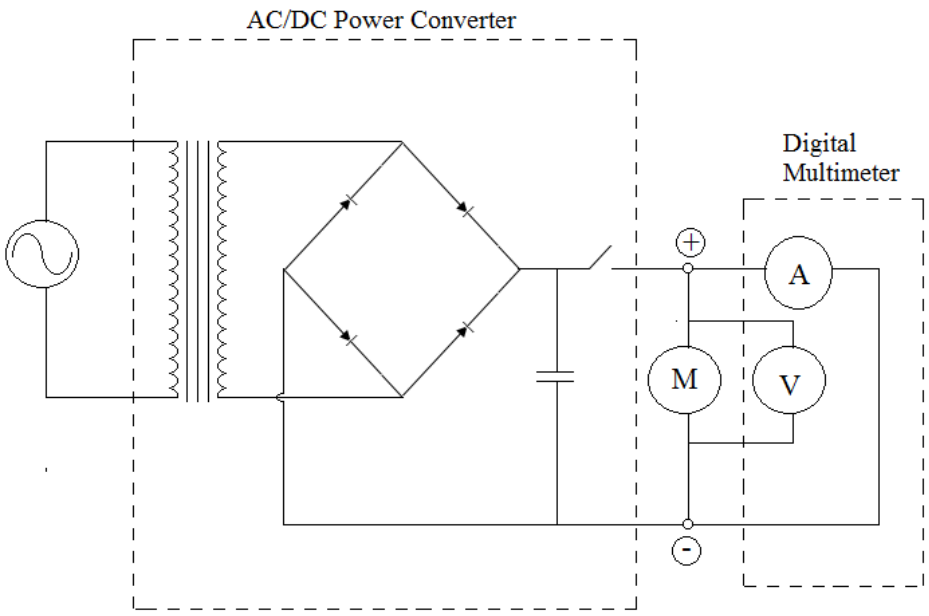

Figure 3-8: AC/DC power converter electrical circuit diagram to operate the motorized stirrer (M) indicating a digital multimeter

3.4 Instrumentation

Measuring instruments have been used to record some physical parameters involved in the anaerobic digestion processes of cow dung for biogas production. The parameters measured included (i) temperature, (ii) volume, (iii) gas concentration, (iv) pressure, (v) pH, (vi) moisture content, and (vii) energy consumption of ancillary electrical gadgets. The data gathered was used for monitoring, analysing, and decision-making, as well as control the operation of the digester. Various parameters were measured directly with specialized instruments, except for temperature and ambient pressure, which dataloggers

connected to a personal computer were used. This section discusses the parameters measured and the equipment used.

3.4.1 Temperature Measurement and Data Acquisition

Eight K-type of thermocouples were attached to the digester. Three thermocouples were connected inside it: one in the headspace to read temperature of gas, and the other two positioned vertically at same depth within the slurry at 0.38 ± 0.01 m apart from either ends of the torispherical heads. Three thermocouples were attached to the outside body (one on top of the digester to record temperature of the body), and the other two attached to the opposite sides of the cylindrical tank, positioned lower than the maximum level of the slurry. One thermocouple was inserted in the water heater. This was to log the temperature of the heating trend. Another thermocouple was allowed to hang in the laboratory environment to record the ambient temperature. All the thermocouples were connected to the IOtech datalogger and the logger to the personal computer. These thermometers were calibrated before use.

A two-point calibration measurement of the thermocouples was conducted at (i) pure ice melting point and (ii) at water boiling point. Distilled water was used to produce both the pure melting ice and boiling water. The pure melting point of ice and the boiling point of water are known physical property of water that occurs at exactly 0.0 °C and 100.0 ^{o}C respectively. This method of calibration meets the requirements for establishing traceability (EURAMET, 2011).The chest freezer in the laboratory was used to prepare ice cubes and a water bath used for the boiling of the water.

Table 3-2: Results of calibration of thermocouples at ice and water boiling points

Calibration set point	Standard reading (°C)	Thermocouple reading (°C)	Error (°C)
Pure melting ice	0.00	0.01	0.01
Water boiling	100.00	99.89	0.01

In addition to the two-point calibration, the linearity of measurement of the thermocouples were checked with Isocal-6 Temperature Calibration System (see Figure 3-9). A standard reference thermocouple and the thermocouple under test (TUT) were both inserted into the Isocal-6 temperature calibration system. The TUT was connected to a standard documenting process calibrator. Isocal-6 was set to operate between 6 °C and 110 °C and readings taken at 0.5 min interval. The results showed a perfect correlation between referenced and calibrated thermocouple correlation coefficient factor of 0.9998. This was to ensure that readings taken within the range of analysis could be confirmed to be accurate.

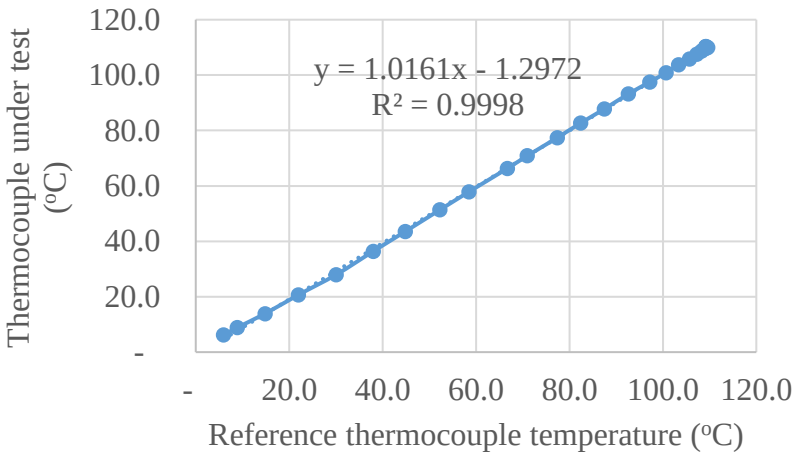

Figure 3-9: Correlation between standard and calibrated thermocouples

3.4.2 Data Logging with IOtech Personal Daq/3000 Series

The IOtech Personal Daq datalogger, with device power supplied at nominal 5 V, 200 mA was used in this study to record the temperature data of the experiments. The (+) and the (-) terminals of the thermocouple are connected to the Hi and Lo terminals of the logger respectively. The same connections are repeated for all connected thermocouples. The datalogger is then connected to a computer laptop where data is finally stored. The power used by the datalogger was sourced through the USB connection which served as the cord for data transmission.

3.4.3 Biogas Volume Measurement

Anaerobic biodegradability can be measured by the determination of the amount of slurry consumed or the products formed during an activity. By applying physical analysis, gasometrical measurement technique was used to measure the amount of biogas produced. Gasometrical technique applies (i) manometric or (ii) volumetric method to determine volume of product yield. The manometric method occurs at constant volume thereby pressure increases as gas is being produced. While the volumetric method deals with collection of gas produced at constant pressure.

Biogas produced was measured with an analog gas meter. It had inlet and outlet pipes. The inlet pipe of the gas meter was connected to the gas outlet from the digester, and the outlet of the meter was connected to the gasholder. There is a non-return valve located within the outlet component of the gas meter. This prevented the back flow of the gas. Table 3-3 contains the technical data of the gas meter.

Table 3-3: Technical data of gas meter

Type	Value	Unit
Maximum flow rate (Q_{max})	6	$m^3 h^{-1}$
Minimum flow rate (Q_{min})	0.01	$m^3 h^{-1}$
Maximum operating pressure	10	kPa
Display range max	99999.998	$m^3 h^{-1}$

3.4.4 Gas Concentration Determination

Biogas composition was measured using Gas Data GMF400 ATeX certified biogas analyser, with some measurable parameter specifications with range, accuracy, and response time indicated in Table 3-4. This is a handheld instrument designed to measure gas concentration as indicated in the table. Sample of the biogas was collected in tyre tube for analysis. The biogas analyser was then connected to the tyre tube gasholder.

Table 3-4: Technical data of gas analyser

Parameter	Range	Accuracy	Typical response (s)
CH_4	0 – 100 %	0.2 % @ 5%	20
CO_2	0 – 100 %	0.1 % @ 30 %	30
O_2	0 – 25 %	0.5 %	20
H_2S	1500 ppm	5 % of fs	30
Flow	0.03 $m^3 h^{-1}$	-	-
Atmospheric pressure	80 - 120 kPa	0.1 kPa	20

3.4.5 Gauge Pressure Measurement

Two pressure gauges were used in this study. One was setup on the biogas system to monitor the biogas system pressure, while the other was mounted to determine the ambient pressure in the laboratory. Both pressure gauges are explained briefly in this section.

The pressure of the biogas system was monitored with an analogue pneumatic pressure gauge designed mainly for family size biogas system. This is a low pressure gauge with a range 0 – 10 kPa, suitable for 0.8 – 1.0 cm hose. This pressure gauge was installed on the wall (at about the same height of the top of the digester), on the pipeline between the digester and the gas meter by connecting a "T" joint socket. One opening of the "T" joint socket was connected to the pipe from the digester, another opening of the "T" joint socket connecting to the pipe to the gas meter, and the last opening connected to the pressure gauge.

Rotronic Log-HC2, which is a stand-alone miniaturised universal datalogger with pressure and relative humidity sensors, was mounted in the laboratory to log atmospheric pressure of the laboratory (see specifications in Table 3-5). External processing of logger data is carried out using LOG PC software (compatible with Windows 2000, XP, Vista 7). Data captured by the logger can be viewed online in either tabular or graphical form, as well as exported data as a text file (*.csv).

Table 3-5: Specifications of Rotronic datalogger

Parameter	Range	Unit
Temperature	-20 – 65	^{o}C
Pressure	50 - 250	kPa (absolute)
Humidity	10 – 95	%

3.4.6 pH Measurement

A hand held pH tester (Vantakool) was used for the determination of the acidity (alkalinity) of the slurry. This is a digital pH meter with measuring range of 0.00 – 14.00, Automatic Temperature Compensation (ATC) of 0 – 50 ^{o}C (ATC accounts for changes in temperature automatically), and resolution of 0.01. Its electrode is simply immersed in solution (slurry sample) to get accurate fast reading. The electrodes were cleaned with distilled water every time before and after use.

3.4.7 Moisture Analysis

The moisture content of the cow dung, influent and effluent slurry were determined with PMB 202 moisture analyser by following moisture test stated in its manual. This was done by pre-weighing a sample of the cow dung with the in-built weighing scale moisture analyser, followed by using same equipment for the moisture determination. The test procedure of single temperature setting option to heat sample to 123 ^{o}C was followed. Table 3-6 indicates aspect of the specification of the moisture analyser. The moisture content is determined from the ratio of water evaporated to the total weight of feedstock with its water content.

Table 3-6: Specifications of PMB 202 moisture analyser

Parameter	Range	Unit
Capacity	200	g
Repeatability weighing	0.02	G
Maximum test time	99	Min
Heaters (halogen lamp)	400	W
Temperature of chamber (set in 1 ^{o}C steps)	50 – 160	^{o}C

3.4.8 Calorific Value Determination

The 1341 Oxygen Bomb Calorimeter was used to determine the heating value (HV) of the cow dung. The bomb calorimeter burns the dung sample and transfers the heat into a known mass of water. The temperature profile of the heat transfer is determined and with the other known parameters such as the mass of water, specific heat capacities involved are used to calculate the HV.

Table 3-7: Specifications of bomb calorimeter

Parameter	Range
Calorimeter Model	1341EE
Electrical rating	230 V AC, 0.15 Amps, 50/60 Hz
Operating temperature	15 ^{o}C to 40 ^{o}C
Relative Humidity	< 80 %

3.4.9 Power Monitor

The power consumed by some of the key equipment used in the study were measured with an energy monitor. This energy monitor is a single-phase energy audit tool with measuring capacity of 500 W, using the input voltage of 110 – 240 V. (Figure 3-10). The parameter it measures include AC voltage, AC current, power consumption, and power factor.

The equipment whose power is to be determined is plugged into the energy monitor and the monitor plugged to the electric mains. While the equipment of interest is actively working, its power consumption is determined among the other parameters. A maximum of two equipment can be connected to the power monitor, while both are working. The concurrent monitoring is good for a comparative study.

Figure 3-10: A single phase energy monitoring equipment

3.5 Seals

Various seals (Figure 3-11) were used at different times during the entire study. These include, the Teflon tape, hot glue with glue gun, silicone paste, epoxy steel glue, super

glue, and O-ring. One major note was to avoid any sealant, which contains any chemical such as anti-fungus. That would have had a negative impact on the growth of the microbes. The Teflon tape was mostly used on PVC joints, where there were threads around the joints being put together. The silicone was used as seals mostly on the bolt and nuts and on the holes where various thermocouples and power cable entered the digester. These joints were kept as soft seal for easy removal when need be. This prevented the damage of any of such wires. Epoxy and super glue were used at spots, which required permanent seals.

Preferably, most of the sealing were done from inside of the tank. This was to allow the seal to improve on the hydrostatic pressure created on the inner walls of the container by the contents of the digester. Any additional seal done from outside of the container was to provide an enforcement seal.

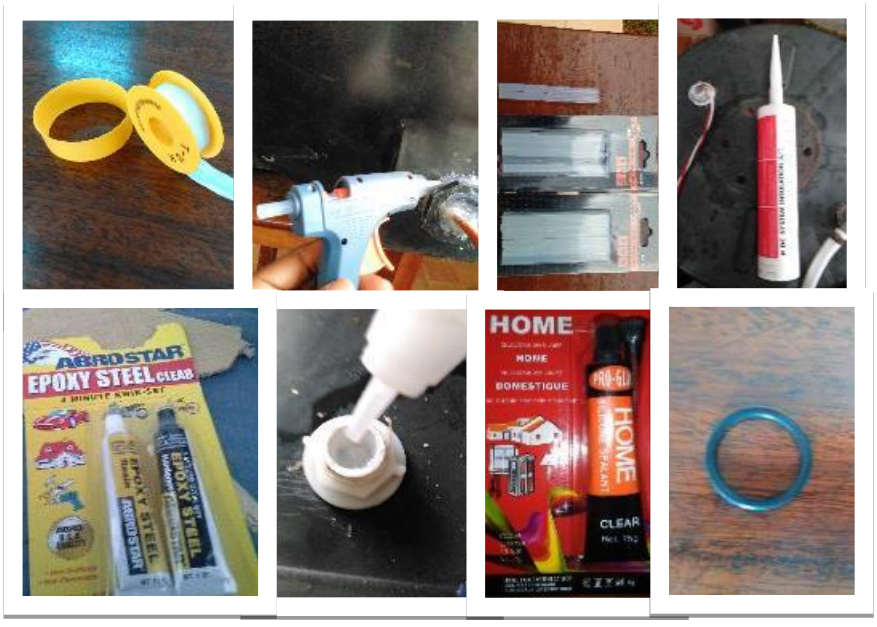

Figure 3-11: Seals applied at various stages during the assembly of the digester

CHAPTER FOUR: OPERATION AND STUDIES OF THE OPERATIONAL PARAMETERS OF THE DIGESTER

4.0 Introduction

In this chapter, an outline of the full operation of the digester is presented. The presentation includes such preliminary actions as the pre-treatment of the slurry and the charging of the digester, which are necessary for the operation of the digester. It was necessary to perform several tests in order to make the digester operational. These operations are presented and discussed. Finally, the various operational parameters that require monitoring and control are discussed.

4.1 The Full Operation of the Digester

As has been indicated already in chapter 3, a 1 m^3 plastic water tank, with PVC connecting pipes and accessories have been assembled into a single stage anaerobic digester. The function of this digester is to use the organic fraction of waste to generate CH_4 gas for energy use. The full operation of the digester as a batch system with a hydraulic retention time of 24 days is discussed, detailing the pre-treatment of the feedstock, slurry preparation and charging of the digester. This was sufficient to analyse the behaviour of the digester and the quality of the biogas generated. The information obtained from this operation represents the fundamental phase of this study that can be used to evaluate the feasibility of this new intervention.

4.1.1 Physical Characteristics of the Cow Dung

Fresh cow dung was collected from the farms of the Council for Scientific and Industrial Research-Animal Research Institute (CSIR-ARI), Ghana. Aspects of the dung's physical characteristics determined have been listed in Table 4-1. The amount of dry mass (22.9 %) of the dung is indicative that to operate a wet digestion water had to be added to the dung until the fraction of total solids reduces to less than 15 %. The calorific value of the dung was determined to be 26.45 MJ kg^{-1}, (equivalent to 7.35 kWh). The pH of the slurry 7.24 ± 0.01 falls within the range where methanogen are active (further explanation has been given in section 2.2.5. Hence, the slurry preparation was done without introducing any buffer solution. Fadalla & Omer (2003), stated that one cow with daily production of waste (dung) 10 kg, produce biogas at 0.25 - 0.40 m^3d^{-1}.

Table 4-1: Physical characteristics of the cow dung

Parameter	**Fresh cow dung**
Colour	Greenish
Dry mass	22.9 ± 0.4 %
pH	7.24 ± 0.01
Moisture content	77.1 ± 0.4 %
Gross energy value	26.5 ± 0.7 MJ kg^{-1}
Sulphur	0.096 ± 0.003 %

4.1.2 Physical Pre-treatment of Cow Dung

The pre-treatment of the feedstock was carried out to intercept large objects that could impede (i) the smooth operation of the stirrer, (ii) the rate of digestion and (iii) prevent

clogging. Visual inspection, screening, particle size reduction of lumps and removal of debris were carried out as the pre-treatment of the cow dung.

Visual inspection was done by stirring the feedstock while it was in its original container. This was not thoroughly done since coarse screening was to follow shortly. Coarse screening, which was done after preparing the slurry, was carried out with a plastic basket (screen opening 4 cm^2) during the transfer of the slurry into the digester. Figure 4-1 shows debris (twigs, plastics, etc.) seen and isolated, whereas lump intercepted were pulverised into reduced size.

Figure 4-1: Plastics and twigs removed during the slurry preparation

4.1.3 Cow Dung Slurry Preparation and Charging of Digester

To perform a wet digestion, the total solid content of slurry should be less than 15 % (Escudié, et al., 2012). The slurry (influent) prepared out of the cow dung was achieved by adding water with composition 0.35 m^3 of dung: 0.49 m^3 of water (ratio of 1:1.4) at 8.7 % total solids with moisture content of 91.3 ± 0.1 %. This resulted in slurry volume of 0.75 m^3, creating a headspace of 0.25 m^3 (which represents 75 % slurry volume with

25 % headspace). It was noticed that the coarse porous medium of the dung absorb water as air bubbles were expelled during mixing of dung and water. No chemical pre-treatment was applied because the pH 7.24 ± 0.01 was within the medium which methanogens are active. Since the dung contains the microorganisms needed for the operation of the digester there was no need to inoculate it. The next step was to charge the digester with the cow dung slurry.

Gravity feeding method was applied in transferring the slurry into the digester. Since bulk feeding was done, the largest opening of the digester (opening for cover) was used for the influent transfer. During this transfer of slurry into the digester, it was necessary to keep the inlet pipe opened. This was to prevent the built up of air pressure within the inlet pipe. The inlet pipe also served as an additional opening for air to be expelled from the digester. After charging the digester, the relevant openings were closed and the gas leakage tests repeated one more time. The repetition of the leakage tests was to ensure any opening accessed during the charging of the digester had been properly sealed. This day was reckoned as day one of the operation of the digester.

4.1.4 Activation of Accessories of the Digester

To operationalize the digester its accessories were activated. The activation included the specific steps taken at the start-up of the full operation of the digester. The following is an outline of the steps taken at the beginning of the operations to activate all various units involved.

- The datalogger, which had been configured to monitor the temperature of the operation of the digester, was triggered to acquire a 24-hour cycle data of the

temperature of the (i) slurry, (ii) digester headspace, (iii) exiting gas, (iv) inner and outer surfaces of the digester, (v) laboratory environment and (vi) hot water circulated.

- The stirrer was operated with an electric DC motor, powered with a variable AC/DC power converter. The laboratories at the Department of Physics, University of Ghana, had a backup electricity generator that was auto-powered. Either power cut or local electricity load shedding management would not interrupt the smooth running of the set-up. The stirrer was powered with a suitable speed of 26 rpm at 10 V DC. At start-up, the stirrer was run continuously for 4 hours. This was to monitor the behaviour of the stirrer in the slurry and to expel air initially in the digester, especially air bubbles in the slurry. The first sample of the slurry was taken in triplicate to determine the physical properties of the slurry. One of the three samples was used for the analysis and the other two stored in a chest freezer, set at -20.0 ^{o}C. At such low temperature the microorganisms become dormant, hence metabolic actions are slowed (Roy, 2008; Rahman, 2007).
- The circulating bath temperature controlled heater (0.010 m^3 capacity), which was used to heat distilled water for circulation in the digester, was set at 60.0 ^{o}C to facilitate the initial heating of the slurry. Once the slurry temperature reached 38.0 ^{o}C the thermostat of the water heater was reduced to 38.0 ^{o}C, which is 1.0 ^{o}C above expected operating temperature. The 1 ^{o}C was to provide a minimum heat flow into the digester when stirring had ceased. Using a high heating while stirring could set up a temperature gradient in the digester and was not done.

4.1.5 Daily Operation of the Digester

Periodic attention to the digester system and its accessories was an important component of its operation. Since the digester was not fully automated, it required daily physical presence of the operator to inspect all the various components. The necessary adjustments were then made for the continuous operation of the system. This section has itemized the key daily steps that were taken for the smooth operation of the digester. They include (i) visual inspection of the digester, (ii) temperature control and (iii) stirrer regulation.

- Visual inspection of digester and the various subcomponents were conducted daily. Adequate responses were provided to reset the digester to optimal operation.
- Whenever the temperature of the slurry dropped below 37.0 ^{o}C the circulating bath temperature controlled heating source was raised to 45.0 ^{o}C and the stirrer was activated. When the temperature reached 38.0 ^{o}C the temperature setting was reset to 38.0 ^{o}C. Stirring was usually done for the entire 3 hours. As stated already, stirring was done intermittently, and to coincide with the periods of heating. The duration of operation was 3 hours continuously, which was not exceeded. This was to prevent the stirrer motor from overheating.

4.2 Pre-operation Tests

Several pre-operational tests were performed on the digester prior to its full operation. Such tests were necessary in order to ensure leakage-free and uninterrupted operation of the digester. Water and gas leakages tests were conducted on the assembled digester. The dry mass, moisture content, and pH of the feedstock were among the physical

characteristics tests determined to enable slurry preparation for optimum biogas yield. This section elaborates on the various pre-operation tests conducted.

4.2.1 Leakage Tests

Leakage tests of the digester are necessary quality control steps. These tests assure that the digester is airtight and the probability of adequate performance within the stipulated duration is acceptable. For these purposes water and gas leakages tests were conducted on the digester. The Biogas Institute of Ministry of Agriculture, P. R. China's method of leakage tests were followed (BIOMA, 2013). All works that required entry into the tank were completed before these tests were carried out. This section outlines the water and gas leakages tests of the digester.

4.2.1.1 Water Leakage Test

Water leakage test was conducted on the tank. The tank was filled with water to its capacity and allowed to stand for 12 h. After the stipulated period, the tank was visually inspected. It was noticed that there was no significant drop in the level of the water, even though drops of water had stained the floor around the heat exchanger outlet around the sealing on the copper tubing of the heat exchanger(see Figure 4-2). This leakage was addressed by first emptying the tank and allowing it to dry. The old sealant was completely removed and the opening properly sealed from within the tank with a re-enforcement from the outside. The water leakage test was repeated to ensure leakage did not exist any longer.

Figure 4-2: Drops of water seeping out very slowly around seal on copper tubing

4.2.1.2 Gas Leakage Tests

Low pressure decay and soap solution bubble tests methods were used for the gas leakage tests. The pressure decay test detects the presence of a leakage while the soap solution bubble test locates the specific point of any gas leakage. All pipes and connections were fixed and relevant ones necessary for the test were closed before the tests were conducted.

4.2.1.2.1 Low Pressure Decay Test

Following the water leakage tests, the volume of the water in the tank was reduced to about 2/3 of its capacity. The tank was then pressurized to 8 kPa with air, using an electric air pump, after which the pump was detached from the set-up. The pressure gauge on the digester system was then checked after 24 h. The system is leak-free when there is no pressure drop during the period of the test and less than 3 % drop in pressure is accepted (BIOMA, 2013).

Initially, the pressure quickly dropped when pumping ceased. This was indicative of loose opening. Suspected loose ends, such as the tank cover was re-enforced with sealant (Teflon tape and silicone) and opening firmly closed and allowed to dry. Pumping was repeated but quick drop in pressure no longer noticed. Instead, there was a slow drop in gauge reading, which took about an hour to register. At this point soap solution bubble test was the necessary test to aid in the identification.

4.2.1.2.2 Soap Solution Bubble Test

Soap solution with low density, sensitive to tiny leaks, was prepared and used for the soap solution bubble test. While the digester system was pressurized, the soap solution was smeared on the joints and seals of suspected leakage points. Air escaping at leakage points formed tiny bubbles with the soap solution (see Figure 4-3). Forming and breaking of bubbles continued until either pressure completely decayed or soap solution layer dried up. Noticeable leaks were sealed and digester pressurized to about 8 kPa again. Finally, when there were no noticeable leaks and no pressure drop the pump was detached from the digester and gauge read after 24 hours. After 24 hours, it was noticed that the pressure had dropped from 8.15 ± 0.01 kPa to 8.00 ± 0.01 kPa, which was within the 3 % pressure decay. At this point, the digester was significantly airtight and ready for use.

Figure 4-3: Gas leakage tests showing escaping gas through soap bubbles

4.3 Operational Parameters: Monitoring and Control

Such operational parameters as the laboratory ambient temperature and pressure, temperature of various sectors of the interior of the digester and the pH of the slurry were closely monitored and controlled. This is a critical requirement for optimum operation of the digester. We have already presented, in chapter three, the ancillary components (stirrer, heating system, etc.) necessary for the monitoring and control. Here we discuss the operations of these components towards the achievement of optimum operation of our digester.

4.3.1 Pressure within the Gas Holder and the Digester Headspace

Since the gas holder and the digester are both connected and sealed from the atmosphere, the pressures in these sections of the set-up, after a while attains equilibrium. As gas begins to be generated by the digester, the pressure in the gasholder begins to rise. This rise in pressure begins to impede free-flow of gas from the digester since there is some resistance to the flow. This leads to a slight pressure built up in the space above the slurry in the digester. Higher pressures built up in the headspace reduces the production of methane, as has been explained in section 2.2.6. In order to optimize biogas collection, the digester was operated at ambient pressure and monitored with the pressure gauge connected to the digester. The highest gauge pressure recorded by the digester was 1.0 ± 0.1 kPa. The maximum and minimum ambient pressures of the laboratory were measured as 100.4 ± 0.1 kPa and 99.5 ± 0.1 kPa respectively.

4.3.2 Temperature Profile

The daily temperature profiles of various sections of the digester and the ambient temperature profile of the laboratory have been shown in Figure 4-4 . The temperature profiles of the various sections include that of the (i) slurry, (ii) digester headspace, (iii) gas exiting the digester and (iv) the ambient temperature. These temperature profiles are discussed in this section.

It was generally observed that the slurry temperature was higher than that of the gaseous headspace, and the gaseous headspace temperature higher than that of the ambient temperature. The exit gas temperature has a profile almost the same as that of the

headspace gas. In the section that follows emphasis have been laid on the slurry temperature.

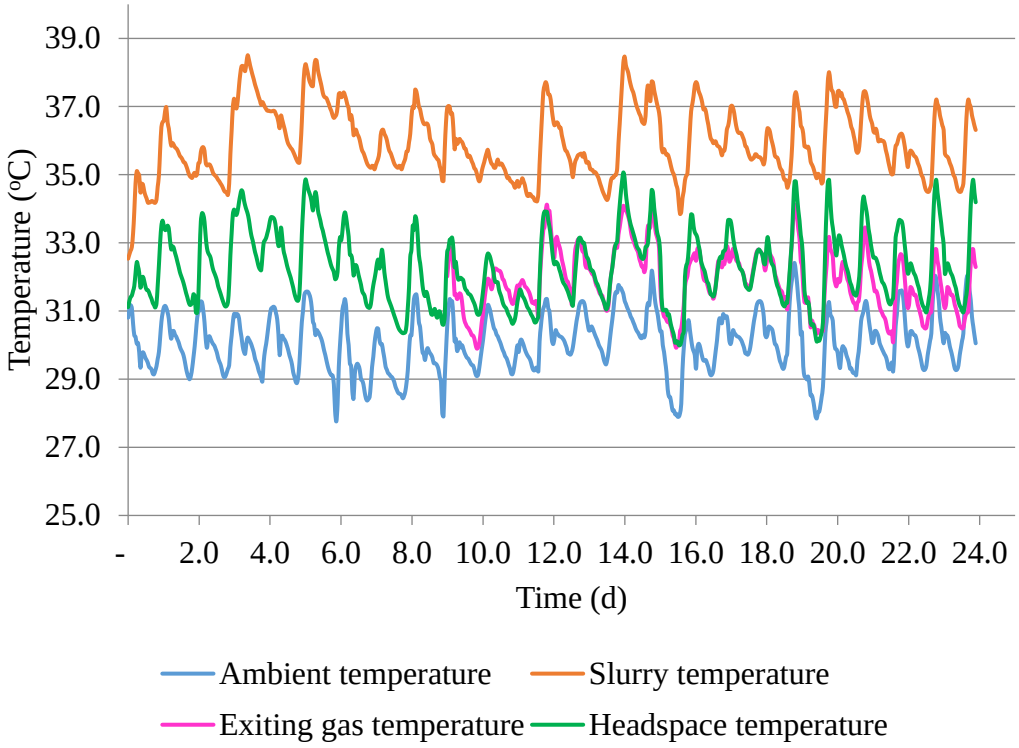

Figure 4-4: Temperature profile of various sections of the digester and the ambient temperature profile

- Temperature Profile of the Slurry

The temperature profile of the slurry represents the daily rise and fall of the temperatures during the heating and the non-heating periods of the slurry. Heating was done with an external electrical heating source that circulated hot water through copper tubing into the inner bottom of the digester. The general pattern of the temperature profile indicates steep positive slopes during the heating periods. This can be attributed to the rate of heat absorbed by the slurry being fast. Relatively, gentle negative slopes are seen during the non-heating periods. This slow rate of temperature drop can be associated with slow rate

of heat loss from the slurry to the environment. The high heat capacity of water also contributes to containing the heat for long period. On the first day, heating began with the slurry at 32.5 ^{o}C and was heated until an increase of 4.0 ^{o}C was attained. The maximum temperature of the slurry recorded during the study was 38.5 ^{o}C. It occurred on the 4th and the 15th days. The minimum value recorded was 32.5 ^{o}C, which occurred on the 1st day of operation of the digester. This was expected, since there was no preheating of the slurry before the slurry was introduced into the digester. The average of the daily maximum and minimum temperatures were 37.4 ± 0.7 ^{o}C and 34.9 ± 0.9 ^{o}C respectively. The average temperature of the digester was determined as 36.1 ± 1.5 ^{o}C.

- Temperatures of Digester Headspace and Slurry

The maximum, and minimum headspace temperatures recorded were 35.1 ^{o}C and 32.1 ^{o}C respectively. The temperature profile of the digester headspace follows a pattern very similar to that of the slurry but averagely 3.8 ± 0.2 ^{o}C lower than that of the slurry with a correlation coefficient of 0.6332. This general observation is due to the higher heat capacity of the slurry compared with that of the gas in the headspace.

- Temperatures of Digester Headspace and Exiting Gas

The temperature profile, as shown in Figure 4-5, of the exiting gas was almost same as the temperature profile of the headspace. This is expected and is indicative of an avenue for heat loss. In such a situation, copper tubing, which is a good conductor of heat, will not be advisable for use as gas pipe. It will increase the rate of heat loss by the digester to the surrounding. If the use of good conducting material cannot be avoided, two basic things have to be done. One approach to reducing heat loss through the gas pipe is to

insulate the pipe. The other approach will be to use a gas pipeline with small cross-sectional area. This reduces the total boundary surface of the pipe and its surrounding, hence the rate of heat loss to the surrounding will be minimized.

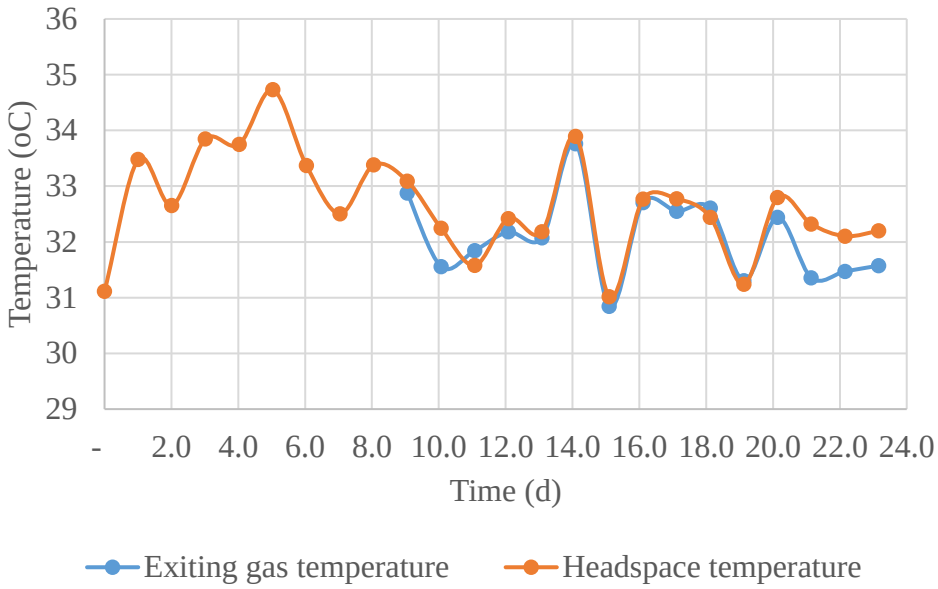

Figure 4-5: Profile of temperature of exiting gas and temperature of headspace

- Ambient Temperature

Figure 4-6 shows the daily ambient temperature variations. The minimum and maximum daily ambient temperatures recorded were 28.2 ^{o}C and 32.4 ^{o}C respectively, which occurred on the 6th and 18th days of the operation of the digester. The average daily variation of the ambient temperature was recorded as 2.6 ± 1.5 ^{o}C, with a corresponding average of the daily average ambient temperature of 30.0 ± 1.3 ^{o}C. One of the advantages of doing this experiment in the tropics is that the ambient temperature is already high with little (2.6 ^{o}C) daily variations, so very little heat input is required to reach a desired set temperature. Meanwhile, researchers in the temperate regions who design a digester

to operate mesophilically require to do harder work by adding more heat to reach desired temperature because they start from a very low temperature.

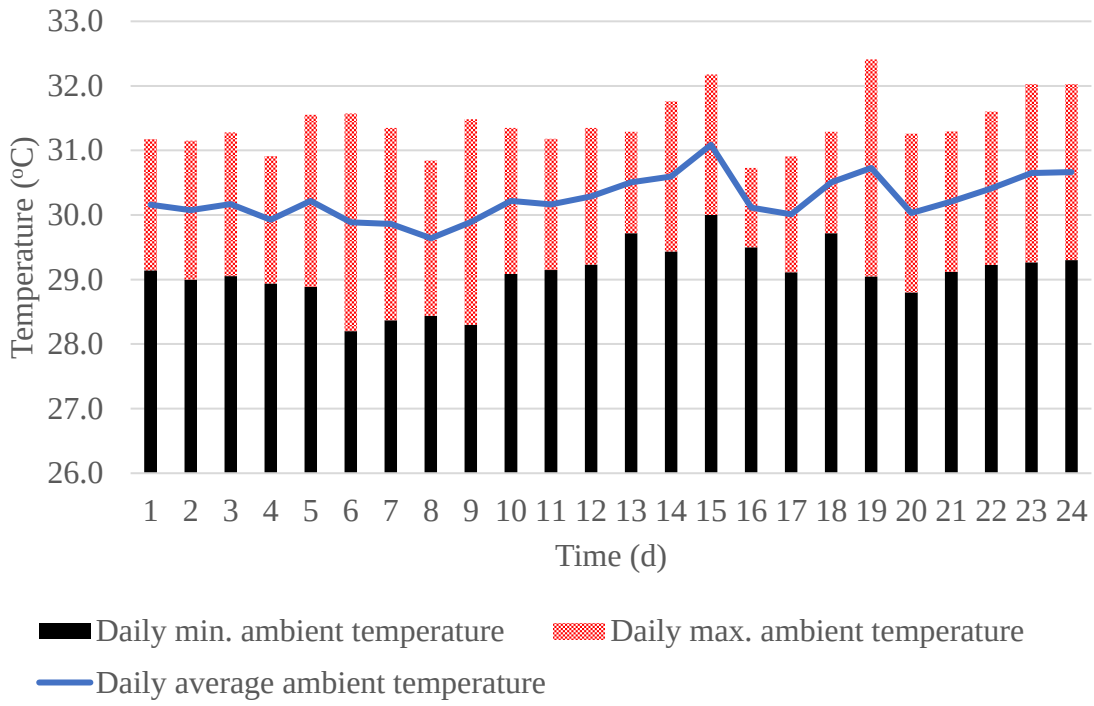

Figure 4-6 Daily maximum, minimum, and average ambient temperature variations

As shown in Figure 4-7, the temperature of the digester tank is slightly above that of the exiting gas, therefore in a biogas system designed to be heated, the gas pipe can be put to use by wrapping the gas pipe round the digester. This is possible for above ground digesters, especially for the cylindrical shaped types. In this case, the gas tube serves as a thermal insulating material for the tank.

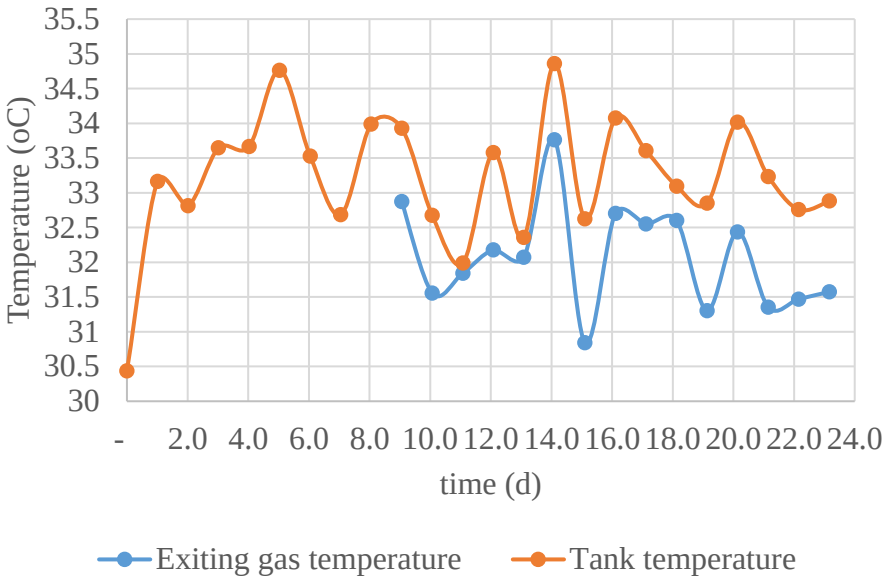

Figure 4-7: Temperature profiles of exiting gas and body of tank

The relation between the slurry temperature and that of the tank are shown in Figure 4-8 and. Figure 4-8 depicts the pattern of heat flow in the slurry and the tank, where the temperature of the slurry is higher than that of the tank. It shows that heat losses occurs through the tank. Figure 4-9 is a graph showing the correlation between the temperature patterns of the slurry and the tank. Change in the temperature of slurry corresponds directly with that of the tank, with a correlation coefficient factor of 0.85. To reduce such heat losses would require either using a tank material with relatively lower thermal conductivity or providing an insulation on the tank. In this study, even though there was very good relation between slurry temperature and tank temperature, there was no significant correlation between ambient temperature and tank temperature. This is because of the external heating that compensates for any heat lost. In the tropics, alternative sources of heating such as solar thermal can provide cheap heating. As long as such heat can compensate for heat losses by the digester, providing insulation is not

necessary. This will eliminate further complications in digester design; and hence reduce cost, as required skills remain low.

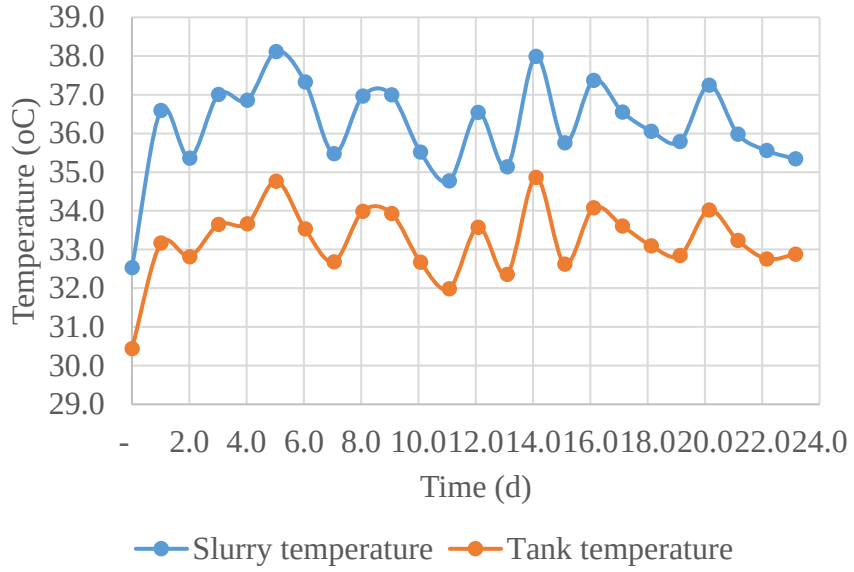

Figure 4-8: Temperature profiles of slurry and plastic tank

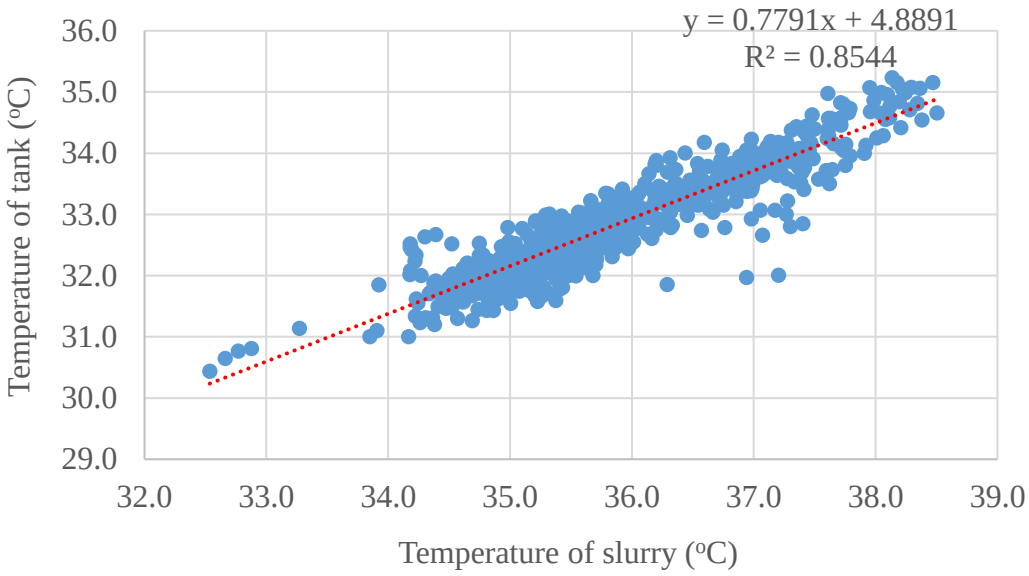

Figure 4-9: Correlation between temperature of slurry and plastic tank

Throughout the batch period, 79 % of the heating was done between 1.2 ^{o}C and 2.8 ^{o}C rise in temperature with 21 % of the heating done within 3.3 ^{o}C and 4.2 ^{o}C. Figure 4-10 is a graphical representation of the daily heating achieved. This shows that very low heating were required to operate the digester. This same digester would require more heating to attained desired mesophilic heating. Therefore low heating requirement in this study emphasize an advantage a low cost and less complication of the design and operation of a mesophilic digester in a tropical region over a temperate region.

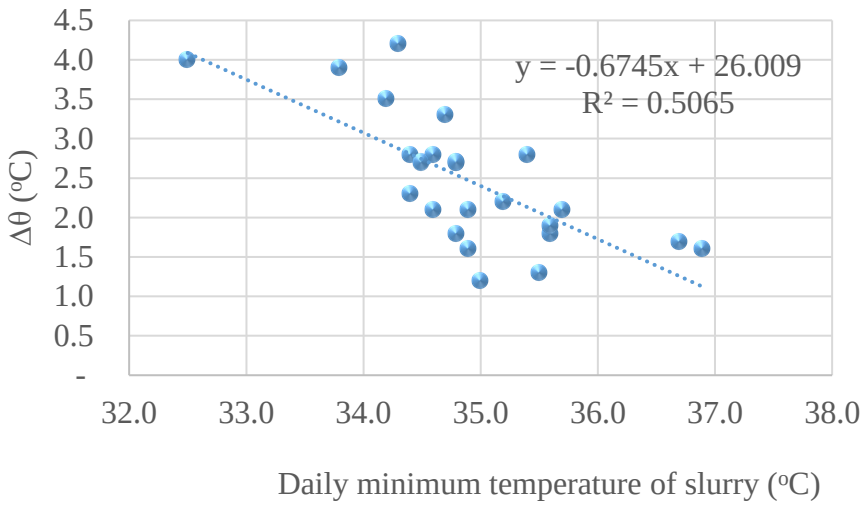

Figure 4-10: Daily heating of slurry using the circulating bath temperature controller heat exchanger system

4.3.3 pH Profile

The pH of the slurry varied slightly throughout the operation. This is because of the metabolic activities that go on at different stages of the biochemical processes of anaerobic digestion. At start-up of the operation, the pH was 7.21, which dropped to 7.1 after one week. This drop is attributed to the accumulation of volatile fatty acids (VFA) because of breakdown of complex organic substances to simple forms. This is explained by the on-set of the hydrolysis and acidification processes. Accumulation of VFA occurs

because the methanogens, which convert VFA into CH_4 had not been sufficiently formed. At the end of the batch operation, the pH had risen to 7.24. The slight increase toward the end of the operation is because of consumption of hydrogen during the formation of methane. Details of this explanation has been given in section 1.3.2.

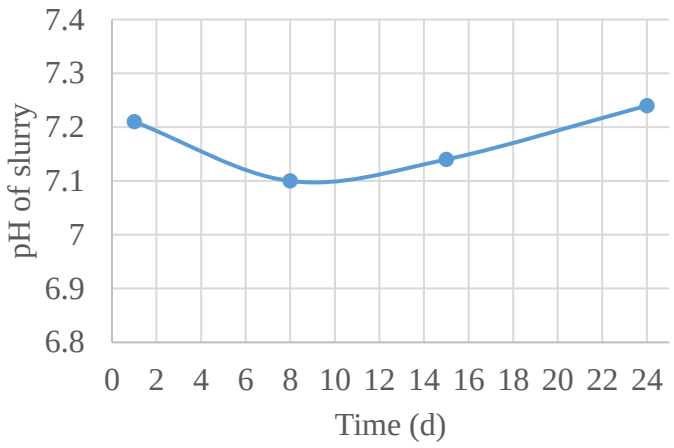

Figure 4-11: Variation of pH of the slurry during the operation of the digester

4.4 Biogas Production

The ultimate aim in assembling the digester is the production of biogas. This section reports the volumes of gas generated by the digester and the various tests performed in order to ensure its suitability for use as fuel. The rate constant and the order of reaction were determined using the cumulative biogas yield data to fit the first kinetic order equation.

The profiles of the daily biogas production has been illustrated in Figure 4-12. The measured biogas production began on the 4^{th} day of operation of the digester. Presumably, the first three days were used by the microorganisms present in the slurry

to adjust to their new environment as well as secrete enzymes necessary for the anaerobic processes. The volume of the 1st measurable volume of the biogas was 0.013 ± 0.001 m^3. This was obtained on the 4th day of operation of the digester. Daily biogas production was low during the first 12 days fluctuating between 0.008 ± 0.001 m^3 and 0.044 ± 0.001 m^3. The daily average biogas yield for the first 12 days was 0.032 ± 0.019 m^3. This initial low biogas yield could be due to (i) the high accumulation of VFA and (ii) low presence of methanogens. As has been discussed in section 2.1.1, the first step of the anaerobic processes which involves the breakdown of the complex substrates results in acid formation, thereby lowering the pH of the slurry. The low pH impedes the formation of CH_4. Low pH also slows the population of the methanogens such that CH_4 formation is slow. On day 16, there was a significant increase of biogas yield to 0.141 ± 0.001 m^3. At this time, the increasing methanogens had begun converting the accumulated VFA into biogas at a faster rate. The depletion of the VFA agrees with the rise in the pH of the slurry and an increase in the function of the methanogens. The highest daily gas yield of 0.474 ± 0.001 m^3 was recorded on the 18th day. The daily average biogas volume measured for the last 9 days of the cycle was 0.31 ± 0.11 m^3. The cumulative gas yield for the entire period (24 d) was 3.17 ± 0.03 m^3.

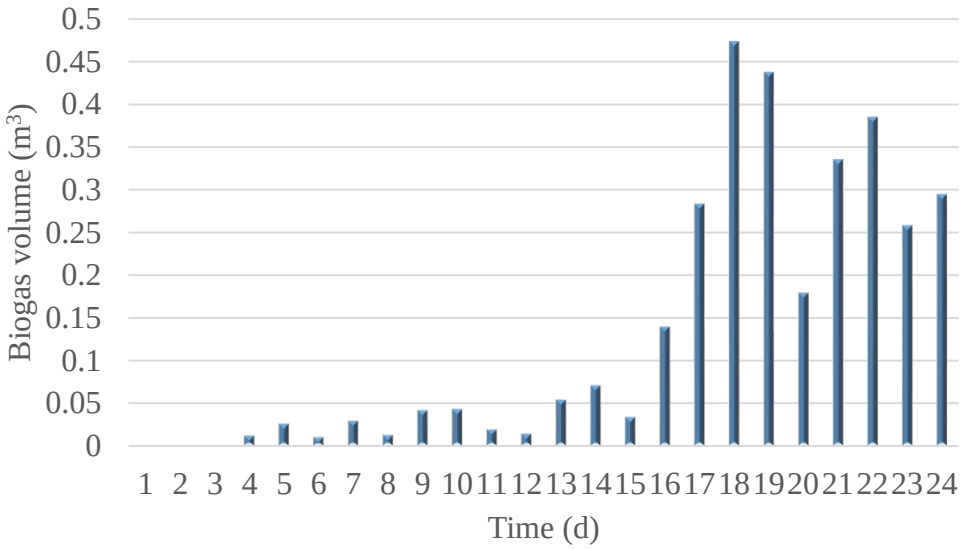

Figure 4-12: Daily biogas production. Gas was first measured on the 4th day

Generally, the volume of production of biogas with its associated fluctuation in the daily yield can be associated with (i) temperature (ii) enzymic activities, and (iii) the rate of decomposition of various components of the feedstock. These factors are considered in turn.

Even though external heating was provided to offset heat losses due to the environmental conditions in the laboratory, it was realized that the intermittent heating resulted in slight average daily temperature variation of 2.5 ± 0.8 ^{o}C. This temperature difference is sufficient to influence the microbial activity in the slurry.

The various enzymic activities can either speed up or slow down a particular stage of the anaerobic processes (Li, He, Ma, Wang, & Peng, 2015). This is done by the faster growing enzymes that colonize the slurry and assimilate substrates faster. Fast hydrolase can produce VFA to dominate the slurry, hence slowing methanogenic action. This action

of colonization of the substrates complements the effect of the overall reaction kinetics and the rate of decomposition of the particulate nature, cellulose, hemicellulose, and lignin content of biomass leading to biogas production.

Again, the rate of decomposition of the feedstock is greatly affected by the substrate composition. The dung, which is biomass, is mainly composed of cellulose, hemicellulose, and lignin. There is a high tendency for the cellulosic fraction to decompose faster, yet lignin, which provides protection for the cellulose, and hemicellulose has to be broken first to get access to the cellulose. This is a complex process that makes it difficult to explain what quantity of component has been decomposed at any particular moment, particularly when operating a batch system, which is a non-flow type of reactor is used.

4.4.1 Rate of Biogas Production

The rate of a reaction is a measure of how rapidly a reaction proceeds. In this section, the rate of formation of CH_4 during the operation of the digesters is determined. Considering the anaerobic process of conversion of substrate to CH_4, the rate equation for the biomass conversion reaction can be represented as:

$$R = k[CH_4]^m[CO_2]^n \tag{4-1}$$

where k is the rate constant.

Considering that gas yield depends on only CH_4 production, for a first order reaction

$$R = \frac{d[CH_4]}{dt} = k[CH_4] \quad (4\text{-}2)$$

An integral form of equation 4-2 results in:

$$[CH_4]_A = [CH_4]_{A_o} e^{k/t} \quad (4\text{-}3)$$

The cumulative yield of biogas production for the 24 days have been illustrated in Figure 4-13. As has been indicated already, biogas was not measured for the first 3 day. From the 4th day, the first volume was measured. On subsequent days, biogas were measured in very small quantities until the latter days when appreciable volumes of biogas were measured. Section 4.4 details reasons for the biogas production that has resulted to this cumulative. As shown in Figure 4-13 fit equation for the cumulative volume of the biogas measured is given as:

$$y = 0.011e^{0.2506t} \quad (4\text{-}4)$$

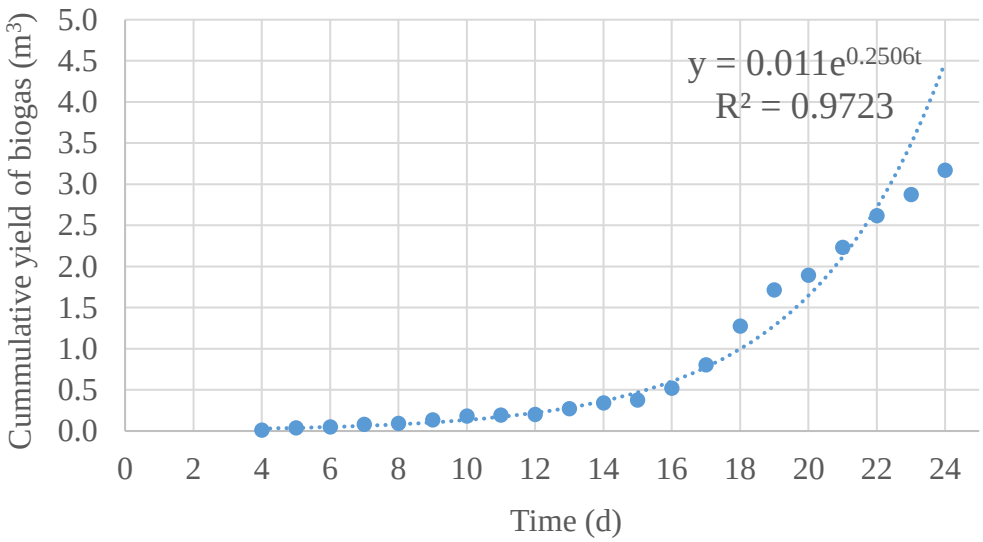

Figure 4-13: Cumulative yield of biogas generated

To determine the rate of biogas production various plots relating the volume of biogas measured and time were considered. The suitable graph, which is a first order plot, was

finally plotted. This graph has been shown in Figure 4-14. The negative values in Figure 4-14 is because of values of initial low biogas yield. Comparing equation 4-3 and equation 4-4, the rate constant k = 0.2506 s^{-1}, which is in agreement with the first order plot shown in Figure 4-14.

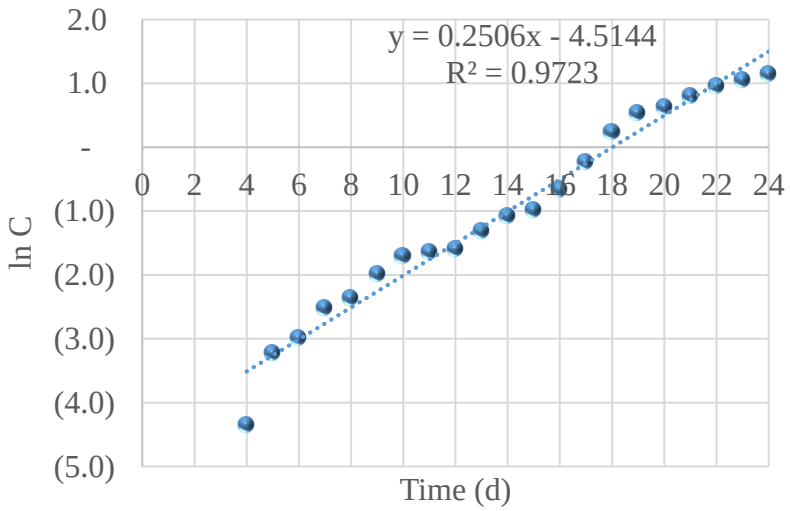

Figure 4-14: A fit of ln C (cumulative yield of biogas operated at mesophilic temperature) vs time, onto the linearized first order kinetic model

4.4.2 Biogas Composition

One of the main characteristics of biogas is its chemical composition, primarily being a mixture of combustible CH_4 and an inert CO_2, with traces of other chemicals. Figure 4-15 illustrates the weekly percentage compositions of the biogas generated from dung slurry. Samples of the gas drawn from the digester were analysed at the beginning of every week with a gas analyser. The first day of the experiment did not realize any collection of gas in the gasholder; hence, no biogas composition was recorded for the first week. As shown in Figure 4-12, biogas was first measured on the 4^{th} day. At the beginning of the second week, the gas sample analysed was composed of 29.0 ± 0.1 % of CH_4, which was

significantly lower than the 49.7 ± 0.1 % measured as CO_2. Very small quantities of O_2 and H_2S were measured in week two. The initial low yield of CH_4 reflects the low activity of the small population of methanogens present in the digester at such time. Methanogens take the longest time to grow and adjust to their environment. Therefore, it is most expected that CH_4 formation initially will be very small. In addition, in the anaerobic digestion processes, methanogenesis occurs last, after the sequential processes of hydrolysis, acidogenesis, and acetogenesis. So it is least expected that CH_4 can be formed in large quantities at the beginning of the operation of the digester. This is so, also because the slurry was prepared from fresh dung. There is therefore the microbial growth period, which must take place for successful operation of the digester. In studies, where slurry is taken from an active functioning digester, especially where slurry of both functioning digester and a new one are the same, the various microbes and enzymes have already populated and adjusted to their system. In such a situation, the introduction of the slurry from the existing one into the new digester does not require the lag phase. Production of gas in the new digester can start immediately because of the availability of the methanogens. These processes have been discussed in detail in section 2.1,

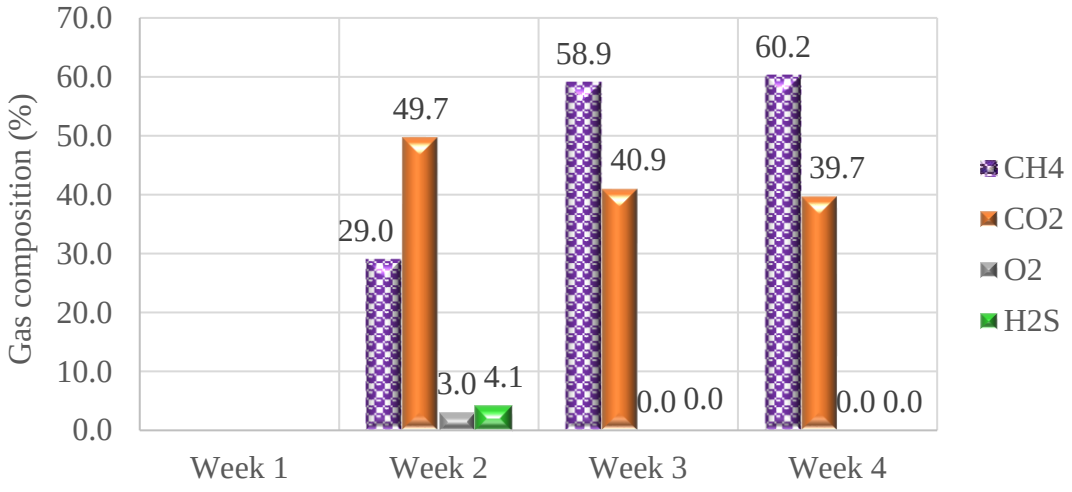

Figure 4-15: Biogas composition

The presence of large amount of CO_2 could be from two main sources (i) air inside the digester headspace at start of operation, and (ii) formation of CO_2 as an intermediate step of the CH_4 production. At the beginning, as the digester was charged with slurry, air inside the digester was gradually displaced. This goes on until the desired quantity of slurry had been fed to the digester. At this point, some amount of air (N_2= 78.09 %, O_2 = 20.95 % and CO_2 = 0.04 %) still occupy the headspace and possible some as air parcels in the slurry. In addition to this source of CO_2 is the chemically produced CO_2 as part of the anaerobic digestion processes the feedstock to produce CH_4. The formation of CO_2 is key to the final production of CH_4.

Further, on in the third and final weeks of the operation of the digester, it was noticed that the initial CH_4: CO_2 ratio of 1:1.71, with CO_2 being high and CH_4 being low had changed. Instead, CH_4: CO_2 ratios had become 1.44:1 and 1.52:1 in the third and fourth weeks respectively. This reduction in CO_2 is supported by the facts that both hydrogenotrophic and homoacetogenic methanogenic pathways consume CO_2 to produce CH_4. These chemical reactions have been indicated in Table 2-1, in section 2.1.3. The little amount of O_2 detected at the begging of week was non-existent in weeks 3 and 4. A small amount of H_2S was recorded in week 2, but none in the following and last week of data collection. This explains that the cow dung contains high proportion of cellulose, which is to be expected since the cow is a herbivore and as such feeds on only plant matter (grass).

4.4.3 Influent and Effluent Parameters

Table 4-2 shows the total solids of the slurry dropped by about 26.4 % with moisture content increase by about 2.52 %, while the pH did not show any significant change. The reduction in total solids can be attributed to the conversion of energy stored in biomass into CH_4 and CO_2. There was no significant change in pH of the slurry. This could be due to a balance between the reaction rates between the hydrolysis and methanogenesis stages. The initial greenish colour of the feedstock had become dark brown.

Table 4-2: Influent and effluent parameters

Stage	Total solids (%)	pH	Moisture content (%)	Colour
Influent	8.7 ± 0.1	7.21 ± 0.01	91.3 ± 0.1	Greenish
Effluent	6.4 ± 0.7	7.24 ± 0.01	93.6 ± 0.7	Brownish
% change	- 26.4±0.71	-	+ 2.52± 0.71	-

4.5 Inspection of Digester after Operation

At the end of the cycle of operation of the digester, it was completely emptied and all components physically inspected. This was necessary, since the anaerobic processes involves a series of biochemical process. This section discusses the colour change of the thermocouple coating and that of the PVC pipe, which were supposedly affected by some chemical reaction involved in the biochemical processes of anaerobic digestion. The tank remains visibly the same without change in colour.

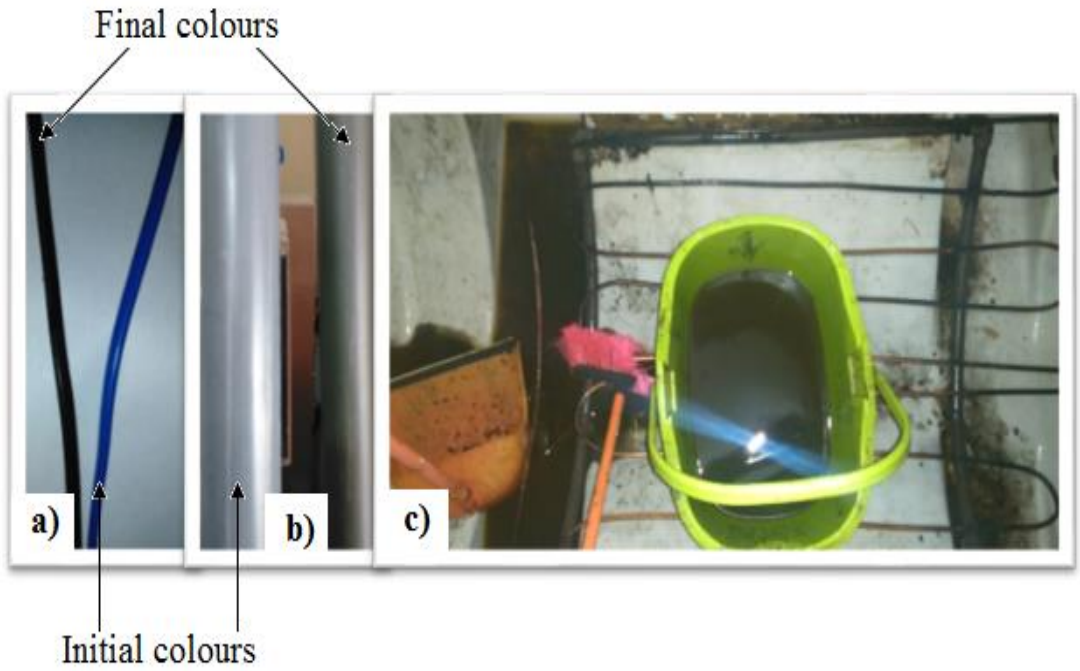

Figure 4-16: Inspection of digester after 24 days operation. a) & b) Initial and final colours of thermocouple insulation and PVC pipe (of the stirrer) inserted into the digester, c) cleaning of inside of digester after cycle of experiment

The thermocouples and the PVC pipe (of the stirrer) inserted into the digester were discoloured (see Figure 4-16). The blue colour of the thermocouple appeared black but still functioned. The PVC pipe had become darker in colour. This could be due to chemical reactions of the anaerobic digestion chemical processes. To prevent discolouring of the thermocouple, thermowells (elongated tubular fitting) housing thermocouples could be connected to the digester. The thermowells isolates the thermocouple from the slurry. It has added advantages of permitting instrumental interchange, calibration check, and replacement of failed thermocouple without opening the digester. Tapered and stepped shanks thermowells are preferred to straight types. The tapered and stepped types provides greater stiffness and improves the heat transfer between the walls of the thermowells and the thermocouple.

The PVC pipe could be tested for longer periods for further monitoring. If there is no further physical deformation of the pipe or noticeable chemical effect of the biochemical reactions of the anaerobic processes, then its use can continue. There was no noticeable change outside or inside the plastic vessel used as digester. Visual inspection at the end of the cycle showed that the plastic vessel did not change over the course of the experiment. All the connections made during the fabrications remained intact.

4.6 Ancillary Tests

Mains electricity was used to power the stirrer, water heater, laptop, and freezer. Knowledge about power consumption by such an operation is worth knowing, especially if an energy audit is to be conducted as well as study the management of power consumption for such operation. Table 4-3 has captured the instantaneous power consumption of the stirrer, laptop, and the freezer. This section entails information about various measurements made on power consumed by equipment used on the digester.

Table 4-3: Equipment and their power consumption

Equipment	Power Consumption (W)	Voltage (V)	Current (I)	Power Factor
Stirrer (with its AC converter)	76.6 ± 0.6	238.6 ± 0.1	0.315 ± 0.001	0.98 ± 0.01
Laptop	14.1 ± 0.9	231.6 ± 2.7	0.123 ± 0.001	0.44 ± 0.01
Freezer (Motor in operation)	221.1 ± 0.9	238.9 ± 0.6	1.269 ± 0.004	0.72 ± 0.01
Freezer (Motor on standby)	26.3 ± 0.6	239.9 ± 0.2	0.163 ± 0.004	0.69 ± 0.01

As stated earlier the DC V stirrer was powered with an AC/ DC power converter. Both consume 76.6 ± 0.6 W at power factor of 0.98 ± 0.01. The power factor of stirrer designed shows a high efficiency in the power conversion. The use of the AC/ DC power converter served two main functions: first to provide constant power as well as take advantage of the standby electric generator. Secondly, the AC/ DC power convertor has a variable voltage source. This was necessary to regulate the stirrer motor for the desired speed.

This data on power consumption by a 1 m^3 plastic tank anaerobic digester operated with a 10 DC V is a good benchmark data. Further studies can be developed with this knowledge. Furthermore, periodic energy audit will be relevant to determine power consumption state of the various components. For example, in this current design, the laptop consumed the least power, yet it was the equipment with the least power factor. It therefore needs an attention. The benefit of energy audit is to determine potential energy wasters and either eliminate them or minimize their contribution to a system.

4.7 Safety and Operation in Anaerobic Digestion Laboratory

- Cleaning and maintenance works must be carried out in a well ventilated area.
- Regular leak checks is necessary for the prevention of gas emissions.
- As mentioned earlier, methane can cause explosions even at concentrations as low as 5 percent to 15 percent in air. It is desirable to install a gas detector (to monitor either the level of oxygen or methane in the laboratory or space) and alarm devices in buildings with potential explosion hazards.

- Apart from being explosive, methane can displace oxygen in a confined space and may result in injuries such as choking to death. Firetraps should be placed in the gas line between the digester and the gas storage system.
- An appropriate fire extinguisher must be installed within the plant facility as a precautionary measure against fire accident.
- Pressure safety valves can be installed to manage excessive pressure build-up.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

This thesis is concerned with the sustainability of energy sources and systems in human endeavour. It is now generally accepted that conventional energy resources are depletable and environmentally unfriendly. Consequently, there are global efforts to explore such non-depletable sources as solar, wind, geothermal, hydro, and biomass. One such effort focuses on the production of biogas from organic waste materials. Extensive studies have been conducted, especially in countries with advanced economies. The tendency is to use results of such studies from such countries for decision-making in other regions of the world, such as the developing countries, which have different climatic. For example, results of studies in the temperate regions are not necessarily completely applicable in the tropical climate of the developing countries. Hence, the need has arisen for these studies to be undertaken using local material, systems, and resources.

5.1 Conclusions

In this study, a 1 m^3 plastic water tank was used as the reactor for an anaerobic digester system to produce biogas from biomass. The feedstock used was fresh cow dung. Such operating parameters as temperature, pH, pressure, volume of biogas yield and biogas composition were closely monitored. The temperature of the slurry was controlled by using an external electrical thermostatic heating system. Intermittent stirring was provided with an internally mounted 10 DC V motorized stirrer.

From the results and discussions presented in the previous chapters, the following conclusions can be drawn:

1. The fundamental laws, aspects of the concepts and the principles of thermodynamics have been successfully applied to the design, assembly, and operation of a single stage, low rate anaerobic digester using cow dung as feedstock for biogas production.

2. Anaerobic digestion of slurry prepared with fresh cow dung of 22.9 ± 0.4 % solid content and moisture content of 77.1 ± 0.4 % was used in a locally available plastic water tank to produce combustible biogas. The mixing ratio of the cow dung to water was 1:1.4 to obtain a slurry of 8.7 ± 0.1 % solid content that allowed the stirrer to operate without overloading the stirrer motor. An initial 1:1 ratio was too viscous to allow the stirrer to turn easily.

3. The volume of the first measurable biogas was 0.013 ± 0.001 m^3. This was obtained on the 4^{th} day of operation of the digester. Daily biogas production was low during the first 12 days fluctuating between 0.008 ± 0.001 m^3 and 0.044 ± 0.001 m^3. Daily biogas production for the last 9 days increased to an average of 0.31 ± 0.11 m^3. The highest daily biogas yield of 0.474 ± 0.001 m^3 was recorded on the 18^{th} day. The cumulative biogas yield for the entire period (24 d) was 3.17 ± 0.03 m^3.

4. The rate of biogas production was found to be 0.14 ± 0.02 $m^3\ d^{-1}$ with gas production rate constant of 0.2506 s^{-1}. As has been shown, the rate confirms a first order reaction. Here the microorganisms initially adjust to their environment, then increase exponentially.

5. Analysis of the biogas produced from our digester shows that:

    a. after one week, the biogas produced contained 29.0 ± 0.1 % of CH_4 and 49.7 ± 0.1 % as CO_2. The high percentage of CO_2 made the biogas incombustible.

    b. by the final week of the operation of our digester, the CH_4 composition increased to its highest volume of 60.2 ± 0.2 %, with CO_2 dropping to 39.7 ± 0.2 %. These results are comparable to those obtained by Chen, et al., (2016) and Igoni, et al., (2008).

    c. An insignificant amount of 4.1 ppm of H_2S was recorded in the second week. During the final week, the biogas sampling did not record any H_2S.

6. The parameters monitored had the following values:

Stage	**Total solids (%)**	**pH**	**Moisture content (%)**	**Colour**
Influent	8.7 ± 0.1,	7.21 ± 0.01	91.3 ± 0.1,	Greenish
Effluent	6.4 ± 0.7	7.24 ± 0.01	93.6 ± 0.7	Brownish
% change	- 26.4 ± 0.7	-	+ 2.5 ± 0.7	-

7. The daily maximum slurry temperature exceeded the daily maximum ambient temperature by an average of 6.1 ± 0.9 ^oC. The average of the daily average temperature was 36.1 ± 1.5 ^oC.

5.2 Recommendations

From the above conclusions the following recommendations for further studies, can be made:

1. One of the key points of this study was the design of the digester with locally available materials and to operate it for biogas production. With this objective only one feedstock (cow dung), which had the needed microorganisms was used. In addition, for want of time, another feedstock could not be tried. It will be necessary to use other organic material waste to operate the digester.

2. During the design process, one major difficulty encountered was the design of a stirrer to operate without leakage around its seals. The final design resulted in installing the motor driving the stirrer inside the digester. It will be useful for a design to allow the stirrer to be driven by a motor installed outside the digester without introducing leakage.

3. It was not possible for this work to study the effect of our digestate on the environment. Further work to do this will be useful, studying the parameters as chemical oxygen demand (COD), biological oxygen demand (BOD), and total dissolved solids (TDS)

REFERENCES

Abbasi, T., Tauseef, S. M., & Abbasi, S. A. (2012). Anaerobic Digestion for Global Warming Control and Energy Generation—An Overview. *Renewable and Sustainable Energy Reviews,* **16**, 3228– 3242.

Ampomah-Benefo, K., Boafo-Mensah, G., Animpong, M. A., Oduro, W. O., Kotey, E. N., Akufo-Kumi, K., & Laryea, G. N. (2013). Thermal Efficiency of Charcoal Fired Cookstoves in Ghana. *Global Advanced Research Journal of Engineering, Technology and Innovation, 2*(**3**), 102-110.

Ann, J., Kessel, V., & Russel, J. B. (1996). The Effect of pH on Ruminal Methanogenesis. *FEMS Microbiology Ecology*, **20**, 205-210.

Bensah, E. C., & Brew-Hammond, A. (2010). Biogas Technology Dissemination in Ghana: History, Current Status, Future Prospects, and Policy Significance. *International Journal of Energy and Environment*, **1**, 277-294.

Bently, R. W. (2002). Global Oil & Gas Depletion: An Overview. *Energy Policy,* **30**, 189-205.

Bhattacharyya, S. C., & Palit, D. (2016). Mini-grid Based Off-grid Electrification to Enhance Electricity Access in Developing Countries: What Policies May be Required? *Energy Policy*, **94**, 166-178.

BIOMA. (2013). *Training Course on Biogas Technology for Developing Countries.* Chengdu: BIOMA.

Bolalumi, D. (2016). Preliminary Study of Pyrolysis and Gasification of Biomass and Thermosetting Resins for Energy Production. *Energy Procedia*, **101**, 432 – 439.

Boone, D. R., & Luying, X. (1987). Effects of pH, Temperature, and Nutrients on Propionate Degradation by a Methanogenic Enrichment Culture. *Applied and Environmental Microbiology*, **7**, 1589-1592.

British Petroleum Company. (2017). *BP Statistical Review of World Energy.* London: British Petroleum Co.

Bruni, E., Jensen, A. P., Pedersen, E. S., & Angelidaki, I. (2010). Anaerobic Digestion of Maize Focusing on Variety, Harvest Time and Pretreatment. *Applied Energy*, **87**, 2212–2217.

Chen, Y., Cheng, J. J., & Creamer, K. S. (2008). Inhibition of Anaerobic Digestion Process: A review. *Bioresource Technology*, **99**, 4044-4064.

Conrad, R. (1999). Contribution of Hdrogen to Methane Production and Control of Hydrogen Concentrations in Methanogenic Soils and Sediments. *FEMS Microbiology Ecology*, **28**, 193-202.

Dahunsi, S. O., Oranusi, S., & Efeovbokhan, V. E. (2017). Journal of Cleaner Production. *Cleaner Energy for Cleaner Production: Modeling and Optimization of Biogas Geneaton from Carica Papayas (Pawpaw) Fruit Peels*, **156**, 19-29.

Deublein, D., & Steinhauser, A. (2008). *Biogas from Waste and Renewable Resources: An Introduction.* Weinheim: WILEY-VCH Verlag GmbH & Co.

Diamantis, A., & Aivasidis, V. (2010). Kinetic Analysis and Simulation of UASB Anaerobic Treatment of a Synthic Fruit Wastewater. *Global NEST Journal,*, 175-180.

Duku, M. H., Gu, S., & Hagan, E. B. (2011). A Comprehensive Review of Biomass Resources and Biofuels Potential in Ghana. *Renewable and Sustainable Energy Reviews*, **15**, 404–415.

Escudié, R., Abbassi-Guendouz, A., Brockmann, D., Trably, E., Dumas, C., Delgenès, J.-P., & Steyer, J.-P. (2012). Total Solids Content Drives High Solid Anaerobic Digestion via Mass Transfer Limitation. *Bioresource Technology*, **111**, 55-61.

EURAMET, E. M. (2011). *Calibration of Thermocouples.*

Evans, G. M., & Furlong, J. C. (2003). *Environmental Biotechnology: Theory and Application.* Chichester: Johy Wiley & Sons.

Fadalla, Y., & Omer, A. M. (2003). Biogas Energy Technology in Sudan. *Renewable Energy*, **28**, 499-507.

Ferella, F., Puca, A., Taglieri, G., Rossi, L., & Gallucci, K. (2017). Separation of Carbon Dioxide for Biogas Upgrade to Biomethane. *Journal of Cleaner Productioni*, **164**, 1205-1218.

Fernandez, J. W., Cleary, P. W., & McBride, W. (2011). Chemical Engineering Science. *Effect of Screw Design on Hopper Drawdown of Spherical Particles in a Horizontal Screw Feeder*, **66**, 5585–5601.

Ferry, J. G. (2011). Fundamentals of Methanogenic Pathways that are Key to the Biomethanation of Complex Biomass. *Current Opinion in Biotechnology,* **22**, 351-357.

Garfi, M., Marti-Herrero, J., Garwood, A., & Ferrer, I. (2016). Household Anaerobic Digester for Biogas Production in Latin America: A Review. *Renewable and Sustainalbe Energy Reviews*, 599-614.

Gashaw, A. (2014). Anaerobic Co-Digestion of Biodegradable Municipal Solid Waste with Human Excreta for Biogas Production: A Review. *American Journal of Applied Chemistry,* **4**, 55-62.

Gelegenis, J., Georgakakis, D., Angelidaki, I., & Mavris, V. (2007). Optimization of Biogas Production by Co-digesting Whey with Diluted Poultry Manure. *Renewable Energy*, **32**, 2147–2160.

Gostelow, P., Parsons, S. A., & Stuetz, R. M. (2001). Review Paper: Odour Measurements for Sewage Treatment Works. *Water Research*, **3**, 579-597.

Grassian, V. (2005). *Environmental Catalysis.* New York: Taylor & Francis.

Haiwen, S., Lin, D., Jing, S., Xin, J., Zhiyong, R., & Haiyang, Y. (2015). Field Measurement and Energy Efficiency Enhancement Potential of a Sea Watera Source Heat Pump District Heating System. *Energy and Buildings*, **105**, 352-357.

Hamad, M. A., Dayem, A., & El-Hawagi, M. M. (1983). Rural Biogas Technology: Effect of Digester Pressure on Gas Rate and Composition. *Journal of Engineering and Applied Sciences,* **2**, 49-57.

Haynie, D. T. (2008). *Biological Thermodynamics.* Cambridge: Cambridge University Press.

Herrmann, C., Idler, C., & Heiermann, M. (2016). Biogas Crops Grown in Energy Crop Rotations: Linking Chemical Composition and Methane Production Characteristics. *Bioresource Technology*, **206**, 23-35.

IEA. (2016). *Key World Energy Statistics.* Paris: OECD/IEA.

Igoni, A. H., Ayotamuno, M. J., Eze, C. L., Ogaji, S. O., & Probert, S. D. (2008). Designs of Anaerobic Digesters for Producing Biogas from Municipal Solid-Waste. *Applied Energy*, **85**, 430-438.

Jena, S., Mishra, S., Acharya, S., & Mishra, S. (2017). An Experimental Approach to Produce Biogas from Semi Dried Banana Leaves. *Sustainable Energy Technologies and Assessment*, **19**, 173-178.

Kalia, A. K., & Singh, S. P. (1999). Case Study of 85 Cubic Meter Floating Drum Biogas Plant under Hilly Conditions. *Energy Conversion & Management*, **40**, 693-702.

Karim, K., Hoffmann, R., Klasson, T., & Al-Dahhan, M. H. (2005). Anaerobic Digestion of Animal Waste: Waste Strength versus Impact of Mixing. *Bioresource Technology*, **96**, 1771-1781.

Keho, Y. (2016). What drives energy consumption in developing countries? The experience of selected African countries. *Energy Policy*, **91**, 233–246.

Kerroum, D., Mossaab, B.-L., & Hassen, M. A. (2010). Use of ADM1 Model to Simulate the Anaerobic Digestion Process used for Sludge Waste Treatment in Thermophilic Conditions. *Turkish J. Eng. Env. Sci*, **34**, 121 – 129.

Khan, E. U., & Martin, A. A. (2016). Review of Biogas Digester Technology in Rural Bangladesh. *Renewable and Sustainable Energy Reviews*, 247-259.

Kim, I. S., Hwanga, M. H., Jang, N. J., Hyun, S. H., & Lee, S. T. (2004). Effect of Low pH on the Activity of Hydrogen Utilizing Methanogen in Bio-hydrogen Process. *International Journal of Hydrogen Energy*, **29**, 1133 – 1140.

Kim, K. Y., Ko, H. J., Kim, H. T., Kim, Y. S., Roh, Y. M., Lee, C. M., . . . Kim, C. N. (2007). Sulfuric Odorous Compounds Emitted from Pig-Feeding Operations. *Atmospheric Environment*, **41**, 4811-4618.

Komilis, D., Kissas, K., & Symeonidis, A. (2014). Effect of Organic Matter and Moisture on the Calorific Value of Solid Wastes: An Update of the Tanner Diagram. *Waste Management*, **34**, 249–255.

Lemmer, A., Merkle, W., Baer, K., & Graf, F. (2017). Effects of High-Pressure Anaerobic Digestion Up to 30 bar on pH-value, production kinetics and specific methane yield. *Energy*, **138**, 659-667.

Li, L., He, Q., Ma, Y., Wang, X., & Peng, X. (2015). Dynamics of Microbial Community in a Mesophilic Anaerobic Digester Treating Food Waste: Relationship between Community Structure and Process Stability. *Bioresource Technology* **189**, 113-120.

Li, L., Zhang, R., He, Y., Wang, W., Chen, C., & Liu, G. (2015). Anaerobic Digestion Performance of Vinegar Residue in Continuously Stirred Tank Reactor. *Bioresource Technology*, **18**, 338-342.

Li, Y., Liu, H., Yan, F., Su, D., Wang, Y., & Zhou, H. (2017). High-Calorific Biogas Production from Anaerobic Digestion of Food Waste Using a Two-phase Pressurized Biofilm (TPPB) System. *Bioresource Technology*, **224**, 56-62.

Lin, L., Chunli, W., Xiang, L., Duu-Jong, L., Zhongfang, L., Zhang, Y., & Tay, J. H. (2013). Effect of Initial pH on Mesophilic Hydrolysis and Acidification of Swine Manure. *Biore source Tec hnology*, **136**, 302–308.

Lindmark, J., Thorin, E., Fdhila, R. B., & Dahlquist, E. (2014). Effects of Mixing on the Result of Anaerobic Digestion: Review. *Renewable and Sustainable Energy Review*, **40**, 1030-1047.

Lou, S., Liao, H., Yang, Y., & Mu, Q. (2015). Simulation of the Interannal Variations of Tropospheric Ozone Over China: Roles of Variations in Meteorological Parameters and Anthropogenic Emissions. *Atmospheric Environment*, **122**, 839-851.

Lou, X. F., & Ho, J. N. (2012). Field Performance of Small Scale Anaerobic Digesters Treating Food Waste. *Energy for Sustainable Development*, **16**, 509-514.

Mara, D., & Horan, N. (2003). *The Handbook of Water and Wastewater Microbiology*. London: Academic Press.

Marais, E. A., Jacob, D. J., Wecht, K., Lerot, C., Zhang, L., Yu, K., Sauvage, B. (2014). Anthropogenic Emissions in Nigeria and Implications for Atmospheric Ozone Pollution. A view of space. *Atmospheric Environment*, **99**, 32-40.

Mata-Alvarez, J., Dosta, J., Romero-Güiza, M. S., Fonoll, X., Peces, M., & Astals, S. (2014). Renewable and Sustainable Energy Reviews. *A critical review on anaerobic co-digestion achievements between 2010 and 2013,* **36**, 412-427.

Mateescu, C. (2016). Influence of the Hydrostatic Pressure on Biogas Production in Anaerobic Digesters. *Romanian Biotechnological Letters*. Romania.

McKendry, P. (2002). Energy Production from Biomass (part 1): Overview of Biomass. *Bioresource Technology,* **83**, 37–46.

Mohammed, Y. S., Mokhtar, A. S., Bashir, N., & Saidur, R. (2013). An Overview of Agricultural Biomass for Decentralized Rural Energy in Ghana. *Renewable and Sustainable Energy Reviews,* **29**, 15-22.

Mohan, D., Pittman, C. U., & Steele, P. H. (2006). Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review. *Energy & Fuels,* **20**, 848-889.

Molinder, R., & Wiinikka, H. (2015). Feeding Small Biomass Particles at Low Rates. *Powder Technology,* **269**, 240–246.

Mood, S. H., Golfeshan, A. H., Tabatabaei, M., Jouzani, G. S., Najafi, G. H., Gholami, M., & Ardjmand, M. (2013). Lignocellulosic Biomass to Bioethanol, a Comprehensive review With a Focus on Pretreatment. *Renewable and Sustainable Energy Reviews,* **27**, 77–93.

Mosier, N. S., & Ladisch, M. R. (2009). *Modern Biotechnology: Connecting Innovatioins in Microbiology and Biochemistry to Engineering Fundamentals.* Canada: John Wiley & Sons.

Nauman, B. (2001). *Chemical Reactor Design, Optimization and Scaleup.* New York: The McGraw-Hill Companies.

Özaksoy, F., & Bildirici, M. (2016). Woody Biomass Energy Consumption and Economic Growth in Sub-Saharan Africa. *Procedia Economics and Finance*, **38**, 287 – 293.

Papacz, W. (2011). Biogas as Vehicle Fuel. *Journal of KONES Power Train and Transport, 18*.

Patel, V. R. (2017). Cost-effective Sequential Biogas and Bioethanol Production from the Cotton Stem Waste. *Process Safety and Environmental Protection*, **111**, 335-345.

Paul, E. L., Atiemo-Obeng, V. A., & Kresta, S. M. (2004). *Handbook for Industrial Mixing: Science and Practice.* New Jersey: John Wiley & Sons .

Pipatmanomai, S., Kaewluan, S., & Vitidsant, T. (2009). Economic Assessment of Biogas-to-Electricity Generation System with H2S Removal by Activated Carbon in Small Pig Farm. *Applied Energy*, **86**, 669-674.

Pisutpaisal, N., Nathoa, C., & Sirisukpoca, U. (2014). Production of Hydrogen and Methane from Banana Peel by Two Phase Anaerobic Fermentation. *Energy Procedia,* **50**, 702 – 710.

Pohekara, S. D., Kumar, D., & Ramachandran, M. (2005). Dissemination of Cooking Energy Alternatives in India—A Review. *Renewable and Sustainable Energy Reviews*, **9**, 379–393.

Rahman, S. M. (2007). *Handbook of Food Preservation* (2nd ed.). London: CRC Press.

Roy, A. (2008). Maintenance and Preservation of Microbial Cultures. *Hygiene Science, I*(4), 4.

Ryckebosh, E. (2011). Techniques for Transformation of biogas to biomethane. *Biomass and Bioenergy*, 1633-1645.

Saha, B. C., & Cotta, M. C. (2007). Enzymatic Hydrolysis and Fermentation of Lime Pretreated Wheat Straw to Ethanol. *Journal of Chemical Technology and Biotechnology*, **82**, 913-919.

Shang–Shyng, Y., I–Chu, C., Ching–Pao, L., Li–Yun, L., & Cheng–Hsiung, C. (2015). Carbon Dioxide and Methane Emission from Tanswei River in Northen Taiwan. *Atmospheric Pollution Research*, 52-61.

Simangunsong, B. H., Sitanggang, V. J., Manurung, E. G., Rahmadi, A., Moore, G. A., Aye, L., & Tambunan, A. H. (2017). Potential Forest Biomass Resource as Feedstock for Bioenergy and its Economic Value in Indonesia. *Forest Policy and Economics*, **81**, 10-17.

SINTEX Containers Gh. LTD. (2016, February 22). Leaflet Obtained from Manufacturer. Accra: SINTEX.

Sorensen, B. (2004). *Renewable Energy, Its Physics, Engineering, Use, Environmental Impact, Economy and Planning Aspects.* Elsevier Science.

Sovacool, B. K. (2012). The Political Economy of Energy Poverty: A Review of Key Challenges. *Energy for Sustainable Development*, **16**, 272–282.

Sun, Q., Li, H., Yang, J., Liu, L., Yu, Z., & Yu, X. (2015). Selection of Appropriate Biogas Upgrading Technology- A Review of Biogas Cleaning, Upgrading and Utilisation. *Renewable and Sustainable Energy Reviews,* **51**, 521-532.

Tasnim, F., Iqbal, S. A., & Chowdhury, A. R. (2017). Biogas Production from Anaerobic Co-digestion of Cow Manure with Kitchen Waste and Water Hyacinth. *Renewable Energy,* **109**, 434-439.

Tchobanoglous, G., Burton, F. L., & Stensel, D. H. (2004). *Wastewater Engineering: Treatment and Reuse.* Singapore: MCGraw Hill.

Tezer, T., Yaman, R., & Yaman, G. (2017). Evaluation of Approaches Used for Optimization of Stand-Alone Hybrid Renewable Energy Systems. *Renewable and Sustainable Energy Reviews,* **73**, 840–853.

Ullah, K., Sharma, V. K., Dhingra, S., & Braccio, G. (2015). Assessing the lignocellulosic biomass resources potential in developing countries: A critical review. *Renewable and Sustainable Energy Reviews,* **51**, 682–698.

United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development.* New York: United Nations.

Vavilin, V. A., Fernandez, B., Palatsi, J., & Flotats, X. (2008). Hydrolysis Kinetics in Anaerobic Degradation of Particulate Organic Material: An Overview. *Waste Management,* **28**, 939–951.

Vikromuarasiri, N., Champreda, V., Boonyawanich, S., & Pisutpaisal, N. (2017). Hydrogen Sulphide Removal from Biogas by Biotrickling Filter Inoculated with

Halothiobacilus Neapolitanus. *International Journal of Hydrogen Energy*, **42**, 18425-18433.

Wagner, A. O., Malin, C., Gstraunthaler, G., & Illmer, P. (2009). Survival of Selected Pathogens in Diluted Sludge of a Thermophilic Waste Treatment Plant and in NaCl-solution under Aerobic and Anaerobic Conditions. *Waste Management*, **29**, 425–429.

Wang, S., Dai, G., Yang, H., & Luo, Z. (2017). Lignocellulosic Biomass Pyrolysis Mechanism: A State-of-the-Art Review. *Progress in Energy and Combustion Science*, **62**, 33-86.

Weldemichael, Y., & Assefa, G. (2016). Assessing the energy production and GHG (greenhouse gas) emissions mitigation potential of biomass resources for Alberta. *Journal of Cleaner Production*, **112**, 4257-4264.

Wolde-Rufael, Y. (2006). Electricity Consumption and Economic Growth: A Time Series Experience for 17 African countries. *Energy Policy*, **34**, 1106–1114.

Wu, B. (2010). CFD Simulation of Mixing in Egg-Shaped Anaerobic Digesters. *Water Research*, **44**, 1507-1519.

Yasar, A., Ali, A., Tabinda, A. B., & Tahir, A. (2015). Waste to Energy Analysis of Shakarganj Sugar Mills ;Biogas Production from the Spent Wash for Electricity Generation. *Renewable and Sustainable Energy Reviews*, **43**, 126–132.

Yusuf, M. O., & Ify, N. L. (2011). The Effect of Waste Paper on the Kinetics of Biogas Yield from the Co-digestion of Cow Dung and Water Hyacinth. *Biomass and Bioenergy*, 1345-1351.

Zhang, P., Lin, C.-J., Liu, J., Pongprueksa, P., Evers, S. A., & Hart, P. (2014). Biogas Production from Brown Grease Using a Pilot-Scale High-Rate Anaerobic Digester. *Renewable Energy*, **68**, 304-313.

Zhu, B., Zhang, R., Gikas, P., Rapport, J., Jenkins, B., & Li, X. (2010). Biogas Production from Municipal Solid Wastes Using an Integrated Rotary Drum and Anaerobic-Phased Solids Digester System. *Bioresource Technology*, **101**, 6374–6380.