KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF ENVIRONMENTAL SCIENCE
COLLEGE OF SCIENCE

BIOGAS PRODUCTION FROM KITCHEN WASTE GENERATED ON KNUST CAMPUS

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By

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DECLARATION

I hereby declare that this submission is my own work towards the MSc. and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the university, except where due acknowledgement has been made in the text.

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DEDICATION

This project work is dedicated to my friend, Stephen Amoako-Marfo and to all my loved ones. You filled the gap when I was busy attending lectures, researching and writing this project.

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ABSTRACT

The staggering potential environmental problems linked to organic fraction of municipal solid waste which is mostly landfilled have fostered the need for a biological treatment using anaerobic digestion. This is an attractive technology for waste stabilization with potential mass and volume reduction and significantly the generation of valuable by-products such as biogas and compost material.

This research work focused on the biogas production from kitchen waste generated on the KNUST campus. The experiment was carried out in a multi-stage anaerobic digestion system operated under mesophilic temperature. Various process parameters were measured including temperature, pH, conductivity, total solids, moisture content, BOD, percentage BOD removal, biogas production and biogas production rate. The waste degraded at a rate of 36.1±2.2% / day, with average biogas production of 8.9±3.15 litres per day. Maximum biogas production rate per kilogram of total solids (TS) was 4.5±1.6 L/kg TS of biogas per day.

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LIST OF ABBREVIATIONS

BMP	Biochemical Methane Potential
BOD	Biological Oxygen Demand
BOF-MSW	Biodegradable Organic Fraction of Municipal Solid Waste
BS	Buffer System
BSP	Buffer System Pump
BVS	Biodegradable Volatile Solids
COD	Chemical Oxygen Demand
CSTR	Continuously Stirred Tank Reactor
DM	Dry Matter
DOC	Dissolve Organic Carbon
F/M	Food to microorganism ratio
HL	Hydrolysis Leachate
HLB	Hydrolysis Leachate Bucket
HLBP	Hydrolysis Leachate Bucket Pump
HR	Hydrolysis Reactor
HRT	Hydraulic Retention Time
MC	Moisture Content
MO	Methanogenic Overflow
MOB	Methanogenic Overflow Bucket
MOBP	Methanogenic Overflow Bucket Pump
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
OF-MSW	Organic Fraction of Municipal Solid Waste
OLR	Organic Loading Rate

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RVS	Refractory Volatile Solids
SEBAC	Sequential Batch Anaerobic Composting
STP	Standard temperature and pressure
TOC	Total Organic Carbon
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solids
VSS	Volatile Suspended Solid
VS_{UP}	Unprocessed Volatile Solids

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Solid waste has been identified by most local governments and urban agencies as a major problem that has reached proportions requiring drastic measures (Visvanathan *et al*., 2004). The major problems which show certain key trend are observed as an increase in volume of waste generated by urban residents; change in the characteristics or make-up of waste generated and disposal methods of waste collected. In developing countries like Ghana, the problem is rooted in improper waste management practices, increasing population, inadequate facilities and lack of adequate technology required for waste management. Waste streams are shown to consist of entirely different proportions of the waste components (Fobil *et al*., 2005; Fei-Baffoe, 2006). In Kumasi Metropolis there is an average percentage composition of 55% organic or putrescible materials, 5% paper & cardboard, 7% plastic & rubber materials, 1% metal & cans, 1% glass, 1% wood, 1% fabric and 28% miscellaneous or other waste (Ketibuah *et al*, 2005).

About 1,500 tonnes of Municipal Solid Waste (MSW) is generated in Kumasi Metropolis in the Ashanti Region of Ghana on a daily basis (http://www.modernghana.com). Out of this an average of 0.18 kilogram per capita per day of waste is generated in Kwame Nkrumah University of Science and Technology (KNUST) campus alone, the greater percentage of which is biodegradable (Boadi-Danquah, 2005). Waste generated on this campus keeps increasing due to increasing student population and increasing commercial activities which put pressure on existing waste facilities. Thus, disposal of waste remains a major challenge on the campus and a cause of concern.

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Generally, effective handling of waste generated in communities in developing countries like Ghana with increasing population is a major challenge. The KNUST community is not an exception. Municipal solid waste could be treated using mechanical operation, thermal treatment, biological transformation and physico-chemical conversion.

Biological transformation is applicable to native organic matter in which case the organic waste is digested in bioreactors, fermented, rotted or composted (Boadi-Danquah, 2005; Fei-Baffoe, 2006).

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According to a report by Bouallagui *et al.* (2003), various studies have proved that anaerobic biological treatment of organic fraction of MSW is a process which has received an increased attention during the last few years. And according to Mata-Alvarez (2003), among biological treatments, anaerobic digestion (or known as biomethanization) is frequently the most cost-effective, owing to the high energy recovery linked to the process and its limited environmental impact. Anaerobic digestion of biomass waste is now an established and commercially proven approach for treatment and recycling (Vogt *et al;* 2002). Anaerobic digestion of MSW was the preferred approach and reliable technology for the provision of energy and reduction of greenhouse gas emissions when compared to combustion or incineration, aerobic composting, pyrolysis and landfilling or landfill gas recovery.

Notwithstanding the numerous benefits of anaerobic digestion, the level of its industrial application as a waste treatment technology has been limited due to the technical expertise required to maintain industrial scale anaerobic digesters coupled with high capital costs and low process efficiencies.

The United Nations Development Programme (UNDP) has however, recognized the anaerobic digestion facilities as one of the most useful decentralized sources of energy supply, as they are less capital intensive than large power plants (UNDP, 1997). Thus, it can be a better option for the treatment of the biodegradable fraction of the enormous solid waste generated on the KNUST campus.

1.2 Justification

Questions related to the final disposal and treatment of MSW constitutes one of the most serious problems of contemporary societies. The volume of waste has increased very quickly. The need for processes in the field of conservation of resources has become more than clear in recent years. More waste is generated at source and less of this waste is effectively handled in terms of recycling, treatment and disposal and thus waste generated is mainly landfilled without sorting. This is neither economical nor environmentally friendly and moreover there is the problem of land acquisition (Fei-Baffoe, 2006). Not only is the enormous generation of the quantities of waste a great concern but also improper management of this solid waste has both long and short term environmental effects. Incineration which is the quickest way of disposal is expensive due to high fuel demand and associated environmental problems due to emission of flue gases. Land filling is expensive, requires space and can have negative environmental impact if not well managed due to the production of leachate, methane, carbon dioxide and other nuisances like flies, odour, and vermins like birds and rodents. Leachate could pollute underground water and soil. Methane and carbon dioxide released in landfill sites are green house gases which can lead to global warming.

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Apart from these general challenges, as stated earlier, the increasing student population in KNUST with its corresponding increase in waste generation tends to put pressure on existing waste facilities (Boadi-Danquah, 2005; Fei-Baffoe, 2009). A large fraction of this waste is biodegradable material and can be efficiently converted to biogas. Nevertheless, less than half of this waste is properly managed as they are directly transferred into concrete skips and finally land-filled. A working framework for the solid waste management must therefore be developed by approaching the challenges from social, economic, technological, political and administrative dimensions.

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There is the need for more prudent measures to manage the enormous waste generated to reap economic benefits whilst protecting the environment. In such an endeavour an establishment of sustainable waste management practices which are effective, affordable, promote health and safety benefits to the public, prevents soil, air and water contamination, conserve natural resources, provide renewable sources of energy and generally environmentally friendly must be the priority (Fei-Baffoe, 2010).

1.3 Objectives of the Study

The main objective of this research project work is to determine the biogas production potential of kitchen waste generated on the KNUST campus. The specific objectives of the research include;

1) To design an appropriate anaerobic digester for the kitchen waste
2) To determine the chemical and physical characteristics of kitchen waste used
3) To determine the extent of waste degradation on biogas production
4) To determine the amount of biogas that can be produced per unit kilogram of kitchen waste used

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Historical Background of Anaerobic Digestion

Anaerobic digestion process is one of the oldest technologies as indicated by historical evidence. In Assyria during the 10th century BC and in Persia during the 16th century, biogas was used for heating bath water (http://www.biogasworks.com). Anaerobic digestion advanced with scientific research and, in the 17th century, Jan Baptista Van Helmont, Robert Boyle and Stephen Hale established that flammable gases evolved from decaying organic matter and from an observation when the sediment of streams and lakes were disturbed, flammable gases evolved. Count Alessandro Volta in 1776 also showed that there was a relationship between the amount of decaying organic matter and the amount of flammable gas produced (Lusk, 1997; Fergusen and Mah, 2006). Sir Humphry Davy in 1808 demonstrated the production of methane by the anaerobic digestion of cattle manure (Cruazon, 2007). In 1859, the industrialization of anaerobic digestion began with the first digestion plant in Bombay, India, built by a leper colony. By 1895, anaerobic digestion, had made inroads into England where biogas was recovered from a well-designed sewage treatment facility and fueled street lamps in Exeter. Further anaerobic digestion advances were due to the development of microbiology. Research led by Buswell and others (Lusk, 1997) in the 1930s identified anaerobic bacteria and the conditions that promote methane production.

Most of the anaerobic digestion took place in anaerobic ponds prior to 1920. More sophisticated equipment and operational techniques emerged as the understanding of anaerobic digestion process control and its benefits improved.

This led to the use of closed tanks and heating and mixing equipment to optimize the process. The primary aim of waste stabilization in due course led to the basic municipal sludge digester. This design then spread throughout the world. Methane production however suffered a setback as low-cost coal and petroleum became abundant. During World War II, anaerobic digestion systems made a comeback with fuel shortages hitting Europe. After the war, anaerobic digestion was once again forgotten. Also the increased interest in aerobic digestion systems led to declining interest in anaerobic digestion. Nevertheless, while the developed world shunned anaerobic digestion except as a wastewater sludge digestion technique, developing countries such as India and China embraced this technology (Humanik, 2007). These developing countries saw gradual increase in small-scale anaerobic digestion systems used mostly for energy generation and sanitation purpose. In the developed countries, aerobic composting and landfilling became the choice technology for waste treatment, until recent times due to the industrial expansion and urbanization coupled with low-cost electricity. A renewed interest in development of simple anaerobic digestion systems for methane production as an energy source was triggered by the energy crisis in 1973 and again in 1979 with India, China and Southeast Asia responding to the crisis with marked expansion of anaerobic digestion. Most of the anaerobic digestion systems were small digesters using combined human, animal and kitchen wastes as feedstock. There was the installation of many community digesters to produce large volumes of biogas for village electrification (Lusk, 1997).

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2.2 Anaerobic Digestion Defined

Anaerobic digestion is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen for industrial or domestic purposes to manage waste and/or to release energy.

The digestion process begins with bacterial hydrolysis of the input materials in order to break down insoluble organic polymers such as carbohydrates and proteins and make them available for bacteria (Lemmer & Oeschsner, 2004).

2.2.1 Anaerobic Digestion Process

The process of anaerobic digestion involves a number of microorganisms including acetic acid-forming bacteria (acetogens) and methane-forming archaea (methanogens). The initial feedstock is fed upon by these organisms and the feedstock undergoes a number of different processes converting it to intermediate molecules including sugars, hydrogen, and acetic acid, before finally being converted to biogas. In an anaerobic system the majority of the chemical energy contained within the starting material is released by methanogenic bacteria as methane (Fergusen & Mah, 2006).

Populations of anaerobic microorganisms typically take a significant period of time to establish themselves to be fully effective. Different species of bacteria are able to survive at different temperature ranges. Those that can live optimally at temperatures between 35–40 °C are mesophiles or mesophilic bacteria and those that can survive at the hotter and more hostile conditions of 55–60 °C are thermophiles or thermophilic bacteria. It is therefore common practice to introduce anaerobic microorganisms from materials with existing populations, a process known as "seeding" the digesters, and typically takes place with the addition of sewage sludge or cattle slurry (http://www.microbewiki.kenyon.edu; http://www. unu.edu).

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2.2.2 Biological and Chemical Stages in Anaerobic Digestion

There are four key biological and chemical stages of anaerobic digestion: Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. Biomass (waste) in most cases is made up of large organic polymers. In order for the bacteria in anaerobic digesters to access the energy potential of the material, the polymer must first be broken down into their smaller constituent parts. These constituent parts or monomers such as sugars are readily available by other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called hydrolysis. Therefore, hydrolysis of these high molecular weight polymeric components is the necessary first step in anaerobic digestion. Through hydrolysis the complex organic molecules are broken down into simple sugars, amino acids, and fatty acids (Sleat & Mah, 2006).

Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules such as volatile fatty acids (VFAs) with a chain length that is greater than acetate must first be catabolised into compounds that can be directly utilised by methanogens. The biological process of acidogenesis occur with a further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here, VFAs are created along with ammonia, carbon dioxide and hydrogen sulfide as well as other by-products. The process of acidogenesis is similar to the way that milk sours (Boone & Mah, 2006).

The third stage of anaerobic digestion is acetogenesis. Here simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid as well as carbon dioxide and hydrogen (http://www.biotank.co.uk). The terminal stage of anaerobic digestion is the biological process of methanogenesis.

Here, methanogens utilise the intermediate products of the preceding stages and convert them into methane, carbon dioxide and water. It is these components that makes up the majority of the biogas emitted from the system. Methanogenesis is sensitive to both high and low pHs and occurs between pH 6.5 and pH 8 (Martin, 2007). The remaining, non-digestible material which the microbes cannot feed upon, along with any dead bacterial remains constitutes the digestate. A simplified generic chemical equation for the overall processes outlined above is as follows: $C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$

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2.2.3 Feedstock to the Anaerobic Process

The feedstock to the process of anaerobic digestion is the most important initial issue when considering the application of anaerobic digestion systems. Although, digesters typically can accept any biodegradable material, if biogas production is the aim, the level of putrescibility is the key factor in its successful application. The more putrescible the material, the higher the gas yields possible from the system. Also substrate composition is a major factor in determining the methane yield and methane production rates from the digestion of biomass. There are techniques to determining the compositional characteristics of the feedstock (Jerger and Tsao, 2006; http://www.wisbiorefine.org). Anaerobes can breakdown material to varying degrees of success.

Short chain hydrocarbons such as sugars are broken down readily, whereas longer period of time is used in the case of cellulose and hemicellulose. Anaerobic microorganisms however, are unable to break down long chain woody molecules such as lignin (http://www.waste-management-world.com; http://www.aslo.org).

Anaerobic digesters were originally designed for operation using sewage sludge and manures. However, sewage and manure are not the material with the most potential for anaerobic digestion as the biodegradable material has already had much of the energy content taken out by the animal that produced it. Therefore, many digesters operate with co-digestion of two or more types of feedstock. A second consideration related to the feedstock is moisture content. The wetter the material the more suitable it will be to handling with standard pumps instead of energy intensive concrete pumps and physical means of movement. Also the wetter the material, the more volume and area it takes up relative to the levels of gas that are produced. The moisture content of the target feedstock will also affect what type of system is applied to its treatment. Another key consideration is the Carbon to Nitrogen (C:N) ratio of the input material. This ratio is the balance of food a microbe requires in order to grow. The optimal C:N ratio of the 'food' for a microbe is 20–30:1. Excess Nitrogen can lead to ammonia inhibition of digestion (Richards, 1991; http://www.bvsde.ops-oms.org).

The level of contamination of the feedstock material is also a key consideration. If the feedstock to the digesters has significant levels of physical contaminants such as plastic, glass or metals then pre-processing will be required in order for the material to be used. The digesters can be blocked and will not function efficiently if these physical contaminants are not removed. It is with this logic in mind that mechanical biological treatment plants are designed. The higher the level of pre-treatment a feedstock requires, the more processing machinery will be required and hence the project will have higher capital costs.

The feedstock material is often shredded, minced and mechanically or hydraulically pulped to increase the surface area available to microbes in the digesters and hence increase the speed of digestion (http://www. seas.ucla.edu).

2.2.4 Waste composition

Generally, the production and composition of MSW vary from site to site and are influenced by various factors, including region, climate, extent of recycling, collection frequency, season, and cultural practices. The wastes treated by anaerobic digestion may comprise of biodegradable, combustible and inert fractions. The biodegradable or organic fraction includes kitchen scraps, food residue, and grass and tree cuttings. The combustible fraction includes slowly degrading lignocellulosic organic matter containing coarser wood, paper, and cardboard. Finally, the inert fraction contains stones, glass, sand, metal, etc. This fraction ideally should be removed, recycled or used for land filling. The removal of inert fraction prior to digestion is important as otherwise it increases digester volume and wear or damage the equipment. For waste streams high in sewage and manure, microbes thrive and hydrolyses the substrate rapidly whereas for the more resistant waste materials, such as wood, digestion is limited.

2.2.5 Design of Anaerobic Digesters

According to Juniper (2005), anaerobic digestion may either be used to process the source separated fraction of municipal waste, or alternatively combined with mechanical sorting systems, to process residual mixed municipal waste. These facilities are called mechanical biological treatment plants. Parameters such as solids, elemental and organic analyses are important for digester design and operation (Jerger and Tsao, 2006).

Anaerobic digesters can be designed and engineered to operate using a number of different process configurations. The configurations include the batch or continuous, temperature (mesophilic or thermophilic), solids content (high or low solids) and complexity (single stage or multistage).

A batch system is the simplest form of digestion. Biomass is added to the reactor at the start of the process in a batch and is sealed for the duration of the process. Batch reactors suffer from odour issues that can be a severe problem when they are emptied. Typically biogas production will be formed with a normal distribution pattern over time. The operator can use this fact to determine when they believe the process of digestion of the organic matter has completed. As the batch digestion is simple and requires less equipment and lower levels of design work, it is typically a cheaper form of digestion (http://www. energy.ca.gov). In continuous digestion processes organic matter is constantly added (continuous complete mixing) or added in stages to the reactor (continuous plug flow; first in – first out). Here the end products are constantly or periodically removed, resulting in constant production of biogas. A single or multiple digesters in sequence may be used. Examples of this form of anaerobic digestion include, continuous stirred-tank reactors, upflow anaerobic sludge blanket, expanded granular sludge bed and internal circulation reactors (http://www.envirochemie.com; http://www.paques.nl).

According to Song *et al.* (2004), with respect to temperature, there are two conventional operational temperature levels (mesophilic and thermophilic) for anaerobic digesters, which are determined by the species of methanogens in the digesters.

In mesophilic digesters, degradation takes place optimally around 37-41 °C or at ambient temperatures between 20-45 °C where mesophiles are the primary microorganism present. On the other hand, degradation in thermophilic digesters takes place optimally around 50-52 °C at elevated temperatures up to 70 °C where thermophiles are the primary microorganisms present. There are a greater number of species of mesophiles than thermophiles. These bacteria are also more tolerant to changes in environmental conditions than thermophiles. Mesophilic systems are therefore considered to be more stable than thermophilic digestion systems (http://www.lrrd.org). Thermophilic digestion systems are considered to be less stable because the energy input is higher, and more energy is removed from the organic matter. However, the increased temperatures facilitate faster reaction rates and hence faster gas yields. Operation at higher temperatures facilitates greater sterilization of the end digestate (Jewell *et al.*,1993; http://www.ec.europa.eu). Anaerobic digestion systems can also be configured with different levels of complexity as one-stage or single-stage and two-stage or multistage. A single-stage digestion system is one in which all of the biological reactions occur within a single sealed reactor or holding tank. Utilising a single stage reduces construction costs, however it facilitates less control of the reactions occurring within the system. Acidogenic bacteria, through the production of acids, reduce the pH of the tank. Methanogenic bacteria operate in a strictly defined pH range. Therefore the biological reactions of the different species in a single stage reactor can be in direct competition with each other (http://www.missouri.edu).

In a two-stage or multi-stage digestion system different digestion vessels are optimised to bring maximum control over the bacterial communities living within the digesters.

Acidogenic bacteria produce organic acids and more quickly grow and reproduce than methanogenic bacteria. Methanogenic bacteria require stable pH and temperature in order to optimise their performance (http://www.interscience.wiley.com). Typically hydrolysis, acetogenesis and acidogenesis occur within the first reaction vessel. The organic material is then heated to the required operational temperature (either mesophilic or thermophilic) prior to being pumped into a methanogenic reactor. The initial hydrolysis or acidogenesis tanks prior to the methanogenic reactor can provide a buffer to the rate at which feedstock is added. Some European countries require a degree of elevated heat treatment in order to kill harmful bacteria in the input waste. There may be a pasteurisation or sterilisation stage prior to digestion or between the two digestion tanks in this instance. However, it is not possible to completely isolate the different reaction phases and often there is some biogas that is produced in the hydrolysis or acidogenesis tanks (Doelle, 2001; Svoboda, 2003; Friends of the Earth, 2004; http://www.defra.gov.uk).

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2.2.6 Residence Time in Anaerobic Digesters

The residence time in a digester varies with the amount and type of feed material, the configuration of the digestion system and whether it be one-stage or two-stage.

In the case of single-stage thermophilic digestion residence times may be in the region of 14 days, which is relatively faster than mesophilic digestion. The plug-flow nature of some of these systems will mean that the full degradation of the material may not have been realised in this timescale. In this event digestate exiting the system will be darker in colour and will typically have more odour. In two-stage mesophilic digestion, residence time may vary between 15 and 40 days (Finstein, 2006; http://www.gastechnology.org).

2.2.7 Principal Products of Anaerobic Digestion

There are three principal products of anaerobic digestion: biogas, digestate and water. In a typical composition of biogas, Methane, CH_4 is about 50–75%; Carbon dioxide, CO_2 is about 25–50%; Nitrogen, N_2 is about 0–10%; Hydrogen, H_2 is about 0–1%; Hydrogen sulfide, H_2S is about 0–3% and Oxygen, O_2 is about 0–2% (Madigan *et al*., 2003; http://www.oaktech-environmental.com). According to Veeken *et al*. (2000), methane is produced from acetic acid, hydrogen and carbon dioxide as well as directly from other substrates of which formic acid and methanol are the most important. Digestate is the solid remnants of the original input material to the digesters that the microbes cannot use. It also consists of the mineralised remains of the dead bacteria from within the digesters. Digestate can come in three forms; fibrous, liquor or a sludge-based combination of the two fractions. In two-stage systems, the different forms of digestate come from different digestion tanks. In single stage digestion systems, the two fractions will be combined and if desired separated by further processing. The digestate material resembles domestic compost (http://www.globalwarming101.com). The third by-product is a liquid (methanogenic digestate) that is rich in nutrients and can be used as a fertilizer dependent on the quality of the material being digested. The digestate may have varying levels of potentially toxic elements which will be dependent upon the quality of the original feedstock. Potentially toxic elements are low in clean and source-separated biodegradable waste streams than wastes originating from industry (http://www.waste.nl). The final output from anaerobic digestion systems is water. This water originates both from the moisture content of the original waste that was treated but also includes water produced during the microbial reactions in the digestion systems. This water may be released from the dewatering of the digestate or may be implicitly separate from the digestate.

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The wastewater exiting the anaerobic digestion facility will typically have elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), these are measures of the reactivity of the effluent and show an ability to pollute (http://www.clarke-energy.co.uk).

2.2.8 Uses of The Products Of Anaerobic Digestion

Methane and energy produced in anaerobic digestion facilities can be utilized to replace energy derived from fossil fuels, and hence reduce emissions of greenhouse gasses. This is due to the fact that the carbon in biodegradable material is part of a carbon cycle. The methane in biogas can be burned to produce both heat and electricity, usually with a reciprocating engine or microturbine often in a cogeneration arrangement where the electricity and waste heat generated are used to warm the digesters or to heat buildings. Excess electricity can be sold to suppliers or put into the local grid. Electricity produced by anaerobic digesters is considered to be renewable energy and may attract subsidies (Wheles and Pierece, 2004; Tower *et al*., 2006). This technology of electricity production from anaerobic digesters, however has not been started in Ghana.

Biogas does not contribute to increasing atmospheric carbon dioxide concentrations because the gas is not released directly into the atmosphere and the carbon dioxide comes from an organic source with a short carbon cycle. Biogas may require treatment or 'scrubbing' to refine it for use as a fuel (Mata-Alvarez, 2003). The digestate material resembles domestic compost and can be used as compost or to make low grade building products such as fibreboard. However a maturation or composting stage may be employed to help in the breakdown of its lignin content which may also contain anmmonia that is phytotoxic.

Lignin and other materials are available for degradation by aerobic microorganisms such as fungi helping to reduce the overall volume of the material for transport (Richards, 1994; http://www.kompogas.ch; http://www.ows.be).

2.3. Important Operating Parameters in Anaerobic Digestion Process

The rate at which the microorganisms grow is of paramount importance in the Anaerobic Digestion process. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system. Other factors affect the rate and amount of biogas output. These include pH, water or solids ratio, carbon to nitrogen ratio, mixing of the digesting material, the particle size of the material being digested, and retention time (Mata Alvarez, 2003).

2.3.1 Volatile Solids (VS)

The volatile solids (VS) in organic wastes are measured as total solids minus the ash content, as obtained by complete combustion of the input wastes. The volatile solids comprise the biodegradable volatile solids (BVS) fraction and the refractory volatile solids (RVS). Kayhanian (1995) showed that knowledge of the BVS fraction of MSW helps in better estimation of the biodegradability of waste, of biogas generation, organic loading rate and C/N ratio. Lignin is a complex organic material that is not easily degraded by anaerobic bacteria and constitutes the refractory volatile solids (RVS) in organic MSW. Waste characterized by high VS and low non-biodegradable matter, or RVS, is best suited to AD treatment. The composition of wastes affects both the yield and biogas quality as well as the compost quality.

2.3.2 pH Level

Even though, the pH and VFA are linked to each other, their relation depends on the waste composition which may differ from the type of waste and the environmental conditions of anaerobic digestion process. The growth of anaerobic microorganisms like methanogens can be inhibited by acidic condition because they are sensitive to acid concentration. Moreover, pH plays a major part in anaerobic biodegradation in which pH influences the activity of microorganisms (Chugh *et al*., 1999).

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The acid concentration in aqueous systems is expressed by the pH value, i.e. the concentration of hydrogen ions. At neutral conditions, water contains a concentration of 10^{-7} hydrogen ions and has a pH of 7. Acid solutions have a pH less than 7 while alkaline solutions are at a pH higher than 7. It has been determined that an optimum pH value for AD lies between 5.5 and 8.5 (RISE-AT, 1998). During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestate affects the pH value and in a batch reactor acetogenesis occurs at a rapid pace. Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5 (Mata Alvarez, 2003).

Increasing the pH level is necessary and this can be done with the use of basic solutions like NaOH or KOH. In addition, the degradation of protein through the release of ammonia has a buffering capacity as the pH value can increase to above 8. Reduction in pH can also be controlled by the addition of lime or recycled filtrate obtained during residue treatment. In fact, the use of recycled filtrate can even eliminate the lime requirement. As digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8.

Nguyen (2004) reported that gravels which consist of limestone has the ability to buffer the hydrolytic leachate when mixed with the leachate. Once methane production is stabilized, the pH level stays between 7.2 and 8.2.

2.3.3 Temperature

A variety of factors affect the rate of digestion and biogas production. The most important is temperature. Temperature affects survival and growth of microorganisms and it also influences their metabolic activities. In general, higher temperatures that do not kill microorganisms result in higher metabolic activities (Angelidaki, 2002). There are mainly two temperature ranges suitable for anaerobic digestion of organic fraction of MSW for the production of methane. The mesophilic and thermophilic temperature ranges are 20-40 °C and 50-65 °C with the optimum temperature of 37 °C and 55 °C respectively. In general, the overall process kinetics doubles for every 10 degrees increase in operating temperature (O' Rourke, 1968) up to some critical temperature of about 60 °C and above, when a rapid drop-off in microbial activity occurs (Harmon *et al*., 1993). To optimize the digestion process, the biodigester must be kept at a consistent temperature, as rapid changes will upset bacterial activity. Increased destruction rate of organic acids and increased downfall of pathogen removal is also possible in thermophilic condition. Besides, thermophilic anaerobic digestion could produce high quality of residue that could be used further as soil conditioner or fertilizer instead of placing them on landfills.

2.3.4 Carbon to Nitrogen Ratio (C/N)

The relationship between the amount of carbon and nitrogen present in organic materials is represented by the C/N ratio. Optimum C/N ratios in anaerobic digesters are between 20-30.

A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with sewage or animal manure.

2.3.5 Total solids content (TS)

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Low solids (LS) AD systems contain less than 10 % TS, medium solids (MS) about 15-20% and high solids (HS) processes range from 22% to 40% (Tchobanoglous *et al.*, 1993). An increase in TS in the reactor results in a corresponding decrease in reactor volume.

2.3.6 Organic Loading Rate (OLR)

Organic loading rate (OLR) is a measure of the biological conversion capacity of the AD system. Feeding the system above its sustainable OLR results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry (Vandevivere, 1999). In such a case, the feeding rate to the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failures due to overloading. Thus, OLR should be considered in order to avoid system failures (RISE-AT, 1998). Overloading can cause imbalance activities of acid and methane producers which result to high VFA concentration and less gas production. When VFA concentration increases, feedstock should be reduced. Insufficient loading rate could lead to a reduction in the digester performance due to the lack of nutrients for microbial growth. (Fannin and Biljetina, 1987).

2.3.7 Retention (or residence) Time

According to Ostrem *et al*. (2004), the retention time is determined by the average time it takes for the organic material to digest completely as measured by the chemical and biological oxygen demand of the leachate. The required retention time for completion of the AD reactions varies with differing technologies, process temperature, and waste composition. The retention time for wastes treated in mesophilic digester ranges from 10 to 40 days. Lower retention times are required in digesters operated in the thermophilc range. A high solids reactor operating in the thermophilic range has a retention time of 14 days.

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2.3.8 Biochemical Oxygen Demand (BOD)

According to Kruis (2007), the biochemical oxygen demand (BOD) of a given sample is the amount of O_2, expressed in mg, consumed by microorganisms in 1 litre of a sample, when incubated in the dark at a fixed temperature for a fixed period of time. Qualitatively, microbial population must consist of microbes capable of attacking the organic matter present. If not available, such a population must be obtained in a preceding enrichment experiment which then furnishes suitable (acclimated) inoculation (seed) material. Quantitatively, the population must be large enough to overcome retardation in O_2 consumption: below a certain limit the size of the inoculum has a great influence on the time-course of growth and O_2 consumption.

In general, according to Habeck-Tropfke (1992) and Hütter (1994), the following assertions may be made:

• a high BOD indicates a high content of easily degradable, organic material in the sample

• a low BOD indicates a low volume of organic materials, or presence of substances which are difficult to break down or other measuring problems

• the shape of the BOD graph shows what further information may be gained from the measurements (conformance with the measurement range; problems; pattern of decomposition). BOD values are generally determined and evaluated in association with other parameters (e.g., COD, DOC, TOC) and this makes them more useful in formulating predictions. For example, if we consider a comparison of the measured BOD value with the COD value:

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• a small difference indicates that a large proportion of the organic materials can easily be degraded

• a large difference indicates either that the organic loading cannot be easily broken down, or that a problem is present.

BOD detects only the destructible proportion of organic substances and as a general principle is therefore lower than the COD value, which also includes inorganic materials and those materials which cannot be biologically oxidized.

2.3.9 Electrical Conductivity

Electrical conductivity (EC) estimates the amount of total dissolved salts (TDS), or the total amount of dissolved ions in the water. The more ions there is in a sample, the more conductive the sample resulting in a higher electrical current which is measured electronically. Distilled or deionized water has very few dissolved ions and so there is almost no current flow across the gap (low EC). As an aside, fisheries biologists who electroshock know that if the water is too soft (low EC) it is difficult to electroshock to stun fish for monitoring their abundance and distribution (Michaud, 1991).

The conductivity of a solution of water is highly dependent on its concentration of dissolved salts, and other chemical species that ionize in the solution. Electrical conductivity of water samples is used as an indicator of how salt-free, ion-free, or impurity-free the sample is; the purer the water, the lower the conductivity (the higher the resistivity). Conductivity measurements in water are often reported as specific conductance, relative to the conductivity of pure water at 25 °C. An EC meter is normally used to measure conductivity in a solution (Pashley, *et al*., 2005). The ability of the water to conduct a current is very temperature dependent. We reference all EC readings to 25°C to eliminate temperature differences associated with seasons and depth. Therefore EC 25°C data reflect the dissolved ion content of the water (also routinely called the TDS or total dissolved salt concentration) (Moore, 1989). Increase in conductivity has to be carefully considered as the conductivity of the reactor contents is not the same as the conductivity of the feed sludge due to an increase as a result of bicarbonate generation from the carbon dioxide evolution.

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2.3.10 Volatile Fatty Acids (VFA)

It is well documented that high VFA concentrations in anaerobic processes cause the inhibition of methanogenesis (Anderson *et al*., 2003). Under conditions of overloading and in the presence of inhibitors, methanogenic activity cannot remove hydrogen and volatile organic acids as quickly as they are produced. The result is the accumulation of acids and the depression of pH to levels that also inhibit the hydrolysis or acidogenesis phase. It has also been shown that, even when process pH is optimal, the accumulation of VFAs may contribute to a reduced rate of hydrolysis of the solid organic substrate (Banks and Wang, 1999).

Organic acids such as acetic, propionic, butyric and isobutyric acids are central to evaluating the performance of anaerobic digestion (Rittmann and McCarty, 2001).

2.3.11 Hydraulic Retention Time (HRT)

Hydraulic retention time is the ratio of the reactor volume to the flow rate of the influent substrate (Mata-Alvarez, 2003). This is the time a fluid element spends in the reactor. The digester efficiency is affected by the HRT value with respect to the organic matter removal and to the specific gas production. The reactor temperature, feedstock composition; proportion of carbohydrates, proteins and lipids in the raw feedstock material also have a direct correlation to the efficiency of the digester. The degree of digestion in the digester is also controlled by the HRT. For instance when the HRT is estimated to be too short, the organic matter will not be fully degraded and this results in low gas yield.

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2.3.12 Reactor configuration

Kim and Speece (2002), evaluated the process stability and efficiency of five different reactor configurations. The reactor configurations used were the batch-fed continuously stirred tank reactor, continuously-fed CSTR, two-phase CSTR and non-mixed batch reactor. The results showed that during the start-up period, non-mixed batch reactor exhibits stability in short period of time compared to the other systems in terms of pH. Also with low VFA concentration even the organic loading rate (OLR) increased. Therefore, a non-mixed batch reactor showed a significant benefit in relation to gas production and stable volatile solids (VS) removal.

2.3.13. Inoculums

It is very important to find an appropriate amount of inoculum containing the necessary bacteria for the degradation process to proceed (Angelidaki, 2002). This is generally due the fact that the anaerobic process is a complex process requiring the presence of several different types of microorganisms. Therefore, balanced active inoculum is essential for the possible degradation to be carried out.

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2.3.14. Mixing

The purpose of mixing in a digester is to blend the fresh material with digestate containing microbes. Furthermore, mixing prevents scum formation and avoids temperature gradients within the digester. However excessive mixing can disrupt the microbes so slow mixing is preferred. The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester.

2.3.15 Leachate Recirculation

Leachate recirculation has been proven as very beneficial in providing moisture to the waste where moisture is responsible for simulating the degradation of the organic waste. It facilitates the provision of nutrients and bacteria necessary for the process. Among the advantages of leachate recycle include distribution of nutrients, enzymes and microorganisms, as a means of mixing and dilution of inhibitory compounds as well as accelerate the reduction of organic load. Increased moisture content and leachate contact with waste have a positive effect on the waste stabilization process (Warith *et al*., 2001).

2.3.16 Dilution of Waste

The waste characteristics can be altered by simple dilution. Water will reduce the concentration of certain constituents such as nitrogen and sulfur that produce products that are inhibitory to the anaerobic digestion process e.g. ammonia and hydrogen sulfide. High solids digestion creates high concentrations of end products that inhibit anaerobic decomposition. Therefore, some dilution can have positive effects. Greater reduction efficiencies occur at concentrations of approximately 6 to 7 percent total solids (Nguyen, 2004). Dairy waste "as excreted" is approximately 12 percent total solids and 10.5 percent volatile solids. Most treatment systems operate at a lower solids concentration than the "as excreted" values. Dilution also causes stratification within the digester. Undigested straw forms a thick mat on top of the digester while sand accumulates at the bottom. The optimum waste concentration is based on temperature and the quantity of straw and other constituents that are likely to separate within the anaerobic digester. It is desirable to keep the separation or stratification in the digester to a minimum. Intense mixing involving the consumption of power may reduce the stratification of dilute waste (Chynoweth et al., 2003).

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2.4. Performance Parameters

The following are key performance parameters that influence the anaerobic digestion process: Gas and methane yields, rates, and reduction in organic matter, VFA, pH and alkalinity.

The total gas and methane productions when related to organic matter are directly related to the extent and rate of conversion. Gas yields are related to organic matter added which is expressed as VS and this is also known as specific gas production.

These data are typically reported as gas volume per weight of volatile solids. Gas yield is directly proportional to the process efficiency. However, it is also important to note that a low gas/methane yield does not necessarily indicate a deficient performance but it is simply due to a low biodegradability of the substrate used. The use of volatile solids permits the calculation of a material balance between the feed, effluent solids and gas. Methane production rate is a measure of process kinetics and is determined as volume of methane per volume of reactor per day. This parameter is a product of loading rate ($kg/m^3/day$) and methane yield (m^3/kg VS added). Methane content of the gas is a good indicator of stability. Since methanogenic activity is the key factor leading to imbalance, a reduction of methane gas content is a key performance parameter (Chynoweth *et al*., 1994 and Hansen *et al*., 2004). This is useful for estimating the ultimate methane yield. Moreover, this test is used to evaluate the efficiency of anaerobic digestion in terms of gas production and composition.

Organic acids, pH and alkalinity are related parameters that influence digester performance (WPCF, 1987). Under conditions of overloading and the presence of inhibitors, the methanogenic activity may possibly inhibit especially when the organic acids are produced at fast rate. This will result in the accumulation of acids, depletion of buffer and depression of pH. If uncorrected via pH control and reduction in feeding, pH will drop to levels which stop the fermentation. A normal healthy volatile acid to alkalinity ratio is 0.1. An increase to ratio of 0.5 indicates the onset of failure and a ratio of 1.0 or higher is associated with total failure. The alkalinity needed to neutralize VFA is calculated by multiplying the VFA concentration (mg/L as acetic acid) by 0.833 times (Veeken *et al.,* 2000).

CHAPTER THREE

3.0 MATERIALS AND METHOD

3.1 Source of Waste and collection

The solid waste used for the experiment was collected from selected restaurants and canteens at the various halls of residence and faculties at the KNUST campus, kumasi. This was done every ten days for a period of four months.

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3.2 Waste Composition

The kitchen waste collected for the experiment was composed mainly of carbohydrate food substances which varied widely ranging from fried rice, plane rice, 'waakye', kenkey, ripe plantain, and gari. Other food substances present included fruits and vegetables residue, beans, meat, fish, bones. Also included were tissue papers, disposable plastic containers, cups and disposable cutlery which were sorted out (see plate 3.1).

Plate 3.1 Waste Composition

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NYANSAPƆ WƆ SANE NO BADWENIMA

3.3 Reactor Design

The experiment was carried out in a double stage reactor system - Hydrolysis and Methanogenic reactors which is presented in the schematic diagram below in Fig.3.1. Also shown in plate 2 below is the actual set up of the experiment.

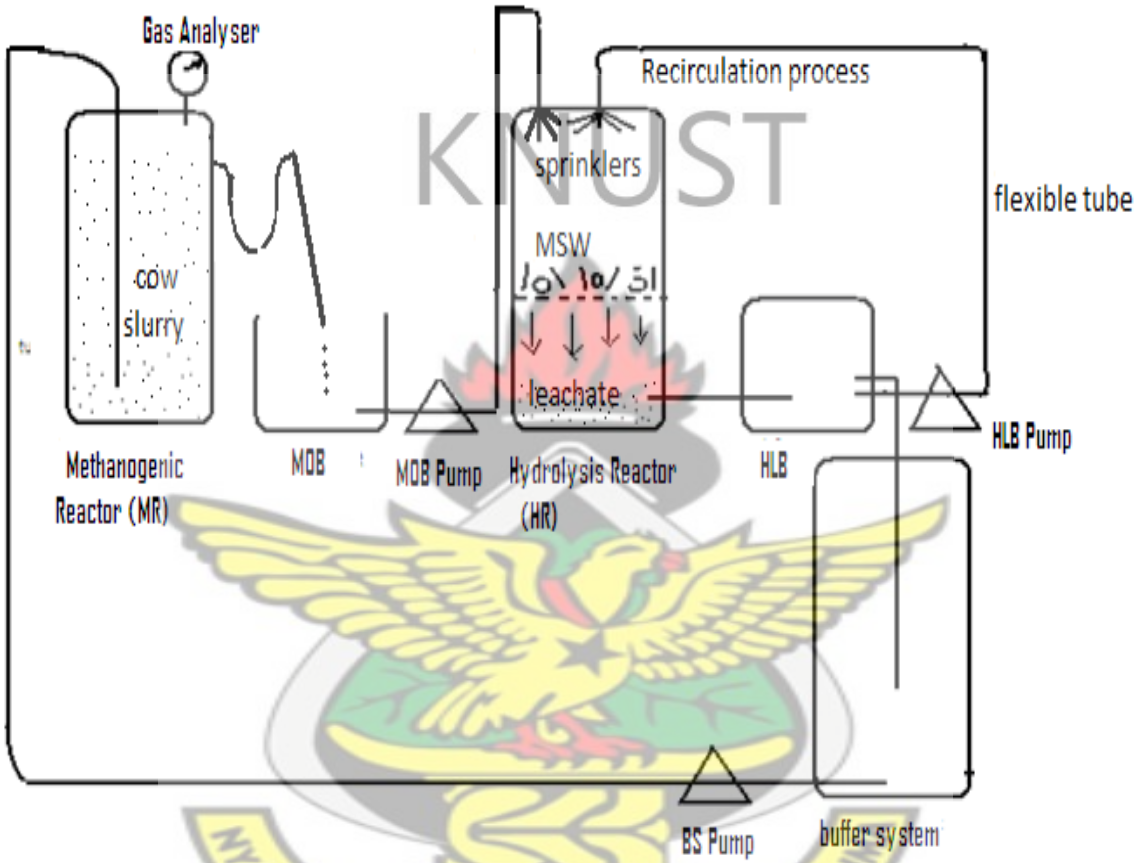

Fig. 3.1 Schematic Diagram of Reactor Design

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Plate 3.2 Actual Set Up Of The Experiment

Leachate from the Hydrolysis Reactor (HR) was collected into a 12 litre plastic bucket labeled as Hydrolysis Leachate Bucket (HLB) and connected to a low horse powered pressure pump (labeled as Hydrolysis Leachate Bucket Pump – HLBP) with the help of flexible plastic pipe, about 3 cm in length from the base of the HLB. The HLBP recirculated the leachate in the HLB to the top of the HR with the help of a sprayer. The spout for the connection of the HLB to the HLBP was also about 3 cm long from the base of the HLB but directly opposite to that of HR. Another connection with a flexible tube of similar size and diameter was made at the same side just about 0.5 cm above the spout connection leading to the HLBP. This was made to drain any overflowing leachate in the HLB by gravity into another system of similar dimensions as the HR labeled as Buffer System (BS).

The BS was also connected at about 3 cm from its base to another low horse powered pressure pump labeled as Buffer System Pump (BSP) to pump programmed calibrated amount of buffered leachate in the BS into a Methanogenic Reactor (MR) which was filled with the cow slurry. The MR was connected to a gas analyzer at its top with an air tight gas tube. A u-tube with its top slashed in a slanted manner was positioned 50 cm from the base of the MR such that any overflow beyond this level flowed into another 12 L plastic bucket labeled as Methanogenic Overflow Bucket (MOB). Another low horse powered pump labeled as Methanogenic Overflow Bucket Pump (MOBP) was connected at about 3 cm from the base of the MOB with flexible pipes to pump programmed amount of the overflown effluent slurry to the top of the HR. The reactor barrels were lagged and labeled accordingly. Each of the reactors including the BS had an internal diameter of 36 cm, a height of 59 cm and a total volume capacity of 70.5 litres. Each operating pump had timers to control their flow per period.

3.4 Reactors and System Operation

The HR was filled manually with 10 kg of kitchen waste collected from the restaurants and canteens on KNUST campus. The mass of the kitchen waste was measured with a digital balance. The kitchen waste was mixed with very large-sized wood shavings obtained from carpentry shops on campus and thoroughly mixed to reduce turbidity and provide a good structure for water percolation when put into the HR. Varying amounts of water dilutions of 8, 10, 12, 15 and 20 litres were used in the operation of the HR. The kitchen waste and their varying water dilutions were each detained for 10 days and each dilution repeated. The MR was filled with 10 kg cow slurry obtained from the Kumasi Abattoir which was variously diluted with water and sieved to remove the fibrous matter in it and there after diluted to the 50 L mark of the MR where the u-tube was fixed.

The cow slurry served as the source of inoculum that is the methane bacteria which were fed periodically with the buffered hydrolytic leachate collected into the BS to allow the bacteria to grow and perform biological activity. The HLBP had a flow rate of 0.1 L/min and was programmed with the help of timers to supply calibrated amounts of leachate to the various reactors. Specifically the leachate was recirculated four times at 6 hour intervals within the 24 hours for all the different dilutions. The reactors were maintained at an ambient temperature of 28^{o}C. The gas produced per day was measured with a Ritter TG05/5 Drum-type Gas Meter and daily readings recorded. The gas however was not stored but allowed to escape as there was no storage facility.

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3.5 Experimental Procedure

A daily monitoring of the reactors and system performance were conducted by undertaking various laboratory analyses: pH, Conductivity, Temperature, Biological Oxygen Demand, Hydraulic Retention Time, and Volume of gas produced per day. The moisture content and total solids of the kitchen waste were determined before and after the 10 days degradation period after which the percentage degradation was calculated. The following parameters were held constant for all the different dilutions: the type of waste (kitchen waste), mass of waste used (10 kg), degradation period (10 days) and number of times the experiment was repeated (2 x). A summary of the experimental run and conditions to which the kitchen waste was subjected to is presented in table 3.1.

Table 3.1 Summary of Experimental Run Performed on Kitchen Waste

Parameter/Dilution	8L/day	10 L/day	12L/day	15 L/day	20 L/day
Ambient Temperature /(^{o}C)	28.22 ±1.68	28.29±1.62	28.11± 1.82	28.24±1.54	28.32±1.47
Hydraulic Retention Time, (L/day)	1.5	1.2	1.0	0.8	0.6

3.5.1 pH Determination

The pH meter was calibrated, using two buffer solutions, of which one was the buffer with neutral pH (7.0) and the other in the range value of the pH of the sample. The pH was measured with a PC cyberscan Waterproof Handheld pH meter. 100 ml each of the hydrolysis leachate in HLB, buffered hydrolytic leachate in BS and Methanogenic overflown slurry in MOB were collected and put into labeled sample containers on a daily basis and sent to the Laboratory to measure their pH. Each sample in the sample container was well shaken to allow a homogenous mixture and poured into 100 ml beakers. The probe was then inserted and the pH value digitally read and recorded.

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3.5.2 Conductivity Measurement

The conductivity of the various samples taken to the laboratory on a daily basis was measured using a PC 300 cyberscan Waterproof Handheld Conductivity meter. The conductivity probe was calibrated with a conductivity standard solution of 12.88 µS. The conductivity probe was inserted into 100 ml of each sample from the HLB, BS and MOB; the conductivity values were digitally read and recorded. The probe was rinsed with distilled water after each insertion and recalibrated after taking several measurements to ensure accurate measurement.

3.5.3 Temperature Measurement

A 30 cm long mercury-in-glass thermometer was used to measure the temperature of the content of HR, HLB, BS, MR and MOB. This measurement was done at specific times of the day on regular basis by inserting the thermometer into its content and leaving it for some few minutes. The MR temperature was measured by inserting the thermometer into the slurry overflowing from the U-tube connected to the MR.

The thermometer was thoroughly cleaned by washing it with detergent and wiping it dry before inserting it into another sample.

3.5.4 Biochemical Oxygen Demand (BOD_5) Determination

The biochemical oxygen demand (BOD) determination is an empirical test in which standardized laboratory procedures are used to determine amount of oxygen consumed by bacteria and other microorganisms while they decompose organic matter under aerobic conditions at a specified temperature. It is computed from the initial and final dissolved oxygen (DO) of a sample after incubating at 20 °C for five days. In determining BOD_5 of the samples collected, 100 ml of the sample was poured into a 300 ml BOD bottle and diluted with water to the 300 ml mark and then corked. Another standard 300 ml BOD bottle was filled with dilution water to represent the blank. The initial dissolved oxygen concentrations of the blank and diluted sample were determined using a DO meter. Both bottles were stored at 20 °C in the incubator for five days. The BOD was measured by taking composite samples of 50 ml a day. Several serial dilutions were conducted on the samples to obtain the best results. After 5 days the amount of dissolved oxygen remaining in the samples were measured with a DO meter. The 5-day BOD was computed using the equation below:

$$BOD_5, \, {}^{mg}/_{L} = \frac{D_1 - D_2}{P}$$

D_1 = DO of diluted sample immediately after preparation, mg/L,

D_2 = DO of diluted sample after 5 day incubation at 20 °C, mg/L,

P = decimal volumetric fraction of sample used

The 'P' was calculated by dividing the volume of sample taken (i.e. the 100 ml poured into the BOD bottle) by the total volume of the diluted sample in the BOD bottle).

3.5.5 Moisture Content Determination

Principally, the moisture contents of cooked food vary widely and give an indication of its shelf-life and nutritive value. Low moisture content is a requirement for a long storage life. In practice, the guiding principle for moisture determination has been to prefer the method that gives the highest moisture values, provided decomposition of organic components and volatilization of compounds other than water are negligible. The following materials were used to determine the moisture content by drying method: analytical balance, dessicator, thermostatically controlled oven and glass dishes. Moisture content determination was determined before and after degradation of the kitchen waste. The determinations were conducted immediately after the kitchen waste was put into the HR and just after removing the degraded food waste from the HR to the reduce any loss or gain of moisture. In determining the moisture content using the drying (air-oven) method, a known mass of the kitchen waste sample was transferred to previously dried and weighed dish. The dish (with waste) was then placed in an oven and thermostatically controlled at 105 ^{o}C for 5 hours. The dish was afterwards removed and placed in a dessicator to cool at room temperature and weighed. It was dried again for 30 minutes, cooled down and re-weighed. The drying, cooling and weighing were repeated until a constant weight was obtained. The determination was repeated and the average determined where necessary. The moisture content was expressed in percent weight by measuring the loss of weight after drying the sample using the formula below:

$$\textbf{Percentage moisture} = \frac{\text{(Wet weight – Dry weight)}}{\text{Wet weight}} \times 100$$

3.5.6 Total Solids Content Determination

The total solids content is known to be a measure of the amount of material remaining after all the moisture has been evaporated. Percentage total solids was calculated using the formulae below:

Total solids (%) = (100 - *% Moisture content*).

The percent total solids content per kilogram of kitchen waste before and after the period of degradation was extrapolated using the formula below:

$$\textbf{Total solids (kg)} = \frac{\text{(percentage moisture content)}}{100} \times \text{Mass of food waste (kg)}$$

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3.5.7 Percentage Degradation

The rate of degradation of the kitchen waste put into the HR over the period of retention was calculated using the formula below:

$$\textbf{Degradation(\%)} = \frac{\text{(TS before (kg) – TS after (kg))}}{\text{TS before (kg)}} \times 100$$

Where TS before represents total solids content of the mass of kitchen waste in (kg) put into the reactor before degradation and TS after represents the total solids content of the mass of kitchen waste in (kg) taken out of the reactor after the period of degradation.

3.5.8 HRT Determination

The HRT is the ratio of the reactor volume to the flow rate of the influent substrate. It indicates the time that a fluid element spends in the reactor. The HRT of the different dilutions were calculated using the formula below:

$$\text{HRT} = \frac{\text{Reactor Volume, V}(m^3)}{\text{Flow rate, Q}(m^3/\text{day}).}$$

3.5.9 Determination of the Volume of Gas Produced

The volume of gas produced per day by each input sample was measured with a TG05/5 Drum-Type Ritter Gas Meter. The meter was filled with 2.5 liters water as its packing liquid. The measuring drum which rotates in the packing liquid formed the actual measuring unit in conjunction with the liquid.

3.5.10 Biogas Production Rate (L/kg TS)

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The biogas production rate in litres per day per kilogram total solids was calculated using the formula:

$$\textbf{Biogas production rate} = \frac{\text{Biogas production/ (L/day)}}{\text{Total Solid /(kg)}}$$

3.5.11 Percentage BOD Removal in MR

The percentage BOD removal in the MR was determined from the mean BOD values of the various dilutions using the formula

$$\textbf{BOD}_5\textbf{ Removal in MR} = \frac{(\text{BOD}_5 \text{ in BS}) - (\text{BOD}_5 \text{ in MO})}{\text{BOD}_5 \text{ in BS}} \times 100\%$$

3.5.12 Statistical Analysis

One-way ANOVA was used to analyze the various treatments at 95% confidence level and 5% probability level.

CHAPTER FOUR

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4.0 RESULTS

The tables and figures presented below represent the results obtained from the monitoring of parameters measured during the anaerobic digestion process.

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4.1 Composition of Waste

The kitchen waste collected was shown to consist of entirely different proportions of the waste components, with an average percentage composition of about 80% carbohydrate foods, 10% bones and other animal protein; 5% vegetables and fruit remains; 3% plant protein; 0.5% oils; 2.5% tissue paper & plastic disposable cups. The kitchen waste contained an average of 65±2.06% and 35±0.5% moisture content and total solids respectively.

4.2 Degradation in the Hydrolytic Reactor

The degradation in the hydrolytic reactor at various dilutions is presented in table 4.1. From the Table, the highest degradation of 36.13±2.2% was achieved at a dilution rate of 20 L/day while the lowest degradation of 10.45±1.2% was achieved at a dilution rate of 8 L/day. The 10, 12 and 15 L dilutions recorded a degradation of 26.65±0.9%, 30.79±2.8% and 29.30±1.6% respectively.

Table 4.1 Particulate Matter Degradation In The Hydrolytic Reactor

Parameter/Dilution	8L/day	10 L/day	12L/day	15 L/day	20 L/day
Degradation/(%)	10.45±1.2	26.65±0.9	30.79±2.8	29.30±1.6	36.13±2.2

4.3 Characteristics of Leachate Produced in the Hydrolytic Reactor

Leachate produced in the hydrolytic reactor recorded very low pH values and relatively high conductivity values. The 20 L dilution recorded the highest pH of 3.93±0.20 while the 8 L dilution recorded the lowest pH of 3.2±0.07. The 10, 12 and 15 L dilutions recorded pH of 3.61±0.08, 3.39±0.11 and 3.59±0.13 respectively. The highest conductivity of 6.37±1.02 µS/cm was recorded by the 12 L dilution and the lowest conductivity of 4.55±0.48 µS/cm was recorded by the 8 L dilution. The 10, 15 and 20 L recorded 4.99±0.29 µS/cm, 5.69±0.42 µS/cm and 6.03±0.21 µS/cm respectively. The 20 L recorded the highest BOD of 22212±8034 mg/L while the 8 L recorded the lowest BOD of 10880±2516 mg/L. The BOD of the 10, 12 and 15 L dilutions were 8614±3786 mg/L, 15861±2882 mg/L and 17347±5253 mg/L respectively as shown in Table 4.2. below.

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Table 4.2 Characteristics of Leachate Produced in the Hydrolytic Reactor

Parameter/Dilution	**8 L/day**	**10 L/day**	**12 L/day**	**15 L/day**	**20 L/day**
pH	3.2 ± 0.07	3.61± 0.08	3.39 ± 0.11	3.59 ± 0.13	3.93 ± 0.20
Conductivity, µS/cm	4.55 ± 0.48	4.99 ± 0.29	6.37 ± 1.02	5.69 ± 0.42	6.03 ± 0.21
BOD_5 of Buffered Hydrolytic Leachate /(mg/L)	10880 ± 2516	8614 ± 3786	15861 ±2882	17347 ±5253	22212 ±8034

4.4 BOD Removal in the Methanogenic Reactor

Presented in Table 4.3 are the results of percentage BOD removal from the MR. The Table compares the percentage BOD removal with their gas production rate.

Table 4.3 BOD Removal in Methanogenic Reactor and Biogas Production Rate

Parameter/Dilution	8 L/day	10 L/day	12 L/day	15 L/day	20 L/day
Percentage BOD_5 Removal /(%)	2.28 ± 0.16	5.22 ± 0.39	9.90 ± 0.28	5.60 ± 0.01	4.06 ±0.07
Biogas Production Rate/(L/kg TS)	0.21±0.09	0.28±0.10	0.52±0.14	2.96±0.63	4.5±1.59

In Table 4.3 above, the highest BOD removal of 9.90±0.28% occurred at a dilution of 12 L and the lowest BOD removal of 2.28±0.16% occurred at a dilution of 8 L. And though the 12 L dilution achieved the highest percentage BOD removal it nevertheless, recorded a biogas production rate of 0.52±0.14 L/kg TS which was smaller than that of the 15 L and 20 L.

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4.5 Biogas Production in the Methanogenic Reactor

Presented in table 4.4 are the means of the daily biogas production and the corresponding BOD_5 of the various dilutions.

Table 4.4 Biogas Production in the Methanogenic Reactor

Parameter/Dilution	8 L/day	10 L/day	12 L/day	15 L/day	20 L/day
BOD_5/(mg/L) of Methanogenic effluent	10633 ±2124	8164 ±2327	14290 ± 3980	16375 ± 5205	21311 ± 7486
Biogas production/(L/day)	0.65±1.36	0.73±0.26	1.36 ±0.3	7.42 ±1.58	8.91±3.15

In the Table 4.4 above, the 20 L dilution recorded the highest BOD_5 of 21311±7486 mg/L and also recorded the highest biogas production of 8.91±3.15 L/day while the 8 L dilution which recorded the lowest BOD_5 of 10633±2124 mg/L also recorded the lowest biogas production of 0.65±1.36 L/day. The 10, 12 and 15 L showed a similar trend that is, biogas production increased with increasing dilutions.

CHAPTER FIVE

5.0 DISCUSSION

This chapter presents a discussion on the composition of waste; degradation in the hydrolytic reactor; characteristics of leachate produced in the hydrolytic reactor; BOD removal in the methanogenic reactor and biogas production in the methanogenic reactor.

5.1. Composition of Waste

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The waste components and characteristics of the kitchen waste used are presented in this section.

5.1.1. Waste Components

The greater proportion of the kitchen waste was carbohydrate food substances which constituted about 80% of the waste. Carbohydrate foods seems to be the most consumed food on the KNUST campus probably because it is an energy giving food and needed in higher quantities. Proportion of protein foods in the kitchen waste was about 10% probably because not much protein foods were consumed on the campus and rarely was a kitchen waste collected which contained a big chunk of meat or fish (except bony, cartilaginous and internal structures) unconsumed. Most kitchen waste collected contained some amounts of vegetables and fruits salad, which constituted about 5% of the overall waste. Most foods were served with some amount of vegetable and or fruit salads because of the belief that it promotes the health of consumers. Foods from most restaurants and canteens on the campus are served in disposable plastic containers with disposable cutlery wrapped in tissue paper. These disposable plastics and tissue were normally discarded directly with the unconsumed food and drinks.

Generally, proportions of different food components consumed by people vary with age, sex, occupation, environment and knowledge of what a balanced diet is to different categories of people (Fraser *et al.*, 2000).

5.1.2 Characteristics of Waste

The waste generally had high moisture content and high total solids.

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Moisture content

The waste used for the research contained an average of 65% moisture. The moisture content after degradation for each of the dilutions increased generally due to the fact that the some amount of water was added to the waste at the start of the experiment and the leachate produced was recirculated. The wetter the feedstock the more suitable it is to handle with standard pumps and the more volume and area it takes up relative to the levels of biogas that are produced (Warith et al., 2000 and Mata Alvarez, 2003).

Total solids

The waste fed into the HR recorded an average of 35% total solids. According to Tchobanoglous *et al.* (1993), high solids AD processes range from 22% to 40%, thus, the kitchen waste fed into the HR had high solid content. However, this percentage decreased with increasing dilutions as the addition of water and leachate recirculation enhanced to some extent the hydrolysis of the feedstock and consequently its degradation.

5.2 Degradation in the Hydrolytic Reactor

The 20 L dilution recorded the highest percentage degradation of 36.13% and the 8 L dilution recorded the lowest percentage degradation of 10.45%.

It was expected that the percentage degradation would have shown a certain trend with respect to their dilution rates, however this was not the case as the 12 L dilution rather had a slightly higher degradation than the 15 L dilution. Perhaps the proportion of woodshavings used to improve the structure of the feedstock during the 15 L dilutions was a little higher and might have hindered degradation due to the presence of lignin material which is not degradable or most likely the proportion of lipids in the waste was high. And according to Sanders (2001), the highest degradation rate could be obtained with starch, protein and cabbage but lipids seem to degrade very slowly. Degradability generally is enhanced when feedstock is putrescible and through the addition of water and leachate recirculation. The feedstock used contained a greater proportion of carbohydrate which is putrescible. From the chemical point of view, as indicated by Schieder *et al.* (2000), hydrolysis is the breakdown of long-chain biomolecules by the reaction with water. In this sense, water is essential for the enhancement of the process. Biologically, hydrolysis works through the influence of enzymes. For solid substrate, hydrolysis is often the slowest and limiting-step in anaerobic degradation process. The waste characteristics can be altered by simple dilution. Water reduces the concentration of certain constituents such as nitrogen and sulfur that produce products (ammonia and hydrogen sulfide) that are inhibitory to the anaerobic digestion process. High solids digestion creates high concentrations of end products that inhibit anaerobic decomposition. Therefore, some dilution can have positive effects.

According to Chantikul *et al.* (2004), leachate recirculation provides moisture to the waste where moisture is responsible for simulating the degradation of the organic waste. Furthermore, this process facilitates the provision of nutrients and bacteria necessary for the process.

And although, digesters typically can accept any biodegradable material, if biogas production is the aim according to Sander (2001), the level of putrescibility is the key factor in its successful application.

5.3 Characteristics of Leachate Produced in the Hydrolytic Reactor

In this section the pH and conductivity of the hydrolytic leachate produced as well as the HRT are discussed.

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5.3.1 pH

Average pH of all the samples taken ranged between 3.20 and 3.93 meaning that the waste had a high acid content. The different dilutions with respect to their average pH varied very marginal although it showed a little trend that as dilution increased pH increased with the exception of the 10 L dilution that had a pH of 3.61 which was higher than the averages of both the 12 L and 15 L dilution. Water was used as the sole buffer to help increase the pH to an optimum level for the process in this research work. However, this did not make any significant changes. The waste used for the experiment was characteristically acidic as stated earlier. Veeken *et al.* (2000), demonstrated that the digestion of organic compounds is affected by the fermentation constraints such as the biodegradability of substance, the degrading capability of microorganism and the environmental conditions like pH. Moreover, pH is considered as the primary process variable in controlling the hydrolysis rate of anaerobic digestion of solid state fermentation. It seems that pH control even during pre-stage is imperative.

According to Dayanthi (2003), low pH do not enhance degradation and that the initial stage of anaerobic degradation is inhibited by low pH and a pH of around 6 can promote degradation. In this view, pH must be meticulously observed and adjusted if necessary. Dayanthi (2003) further indicated that the hydrolysis of particulate kitchen waste was improved from 33 to 55% according to the increase of pH from 5.3 to 6.9. Thus, for an enhanced hydrolysis rate, a neutral pH is recommended. Schwartz and Keller (1982) who performed an experiment on acid production reported that, pH 6 and 7 showed the highest acetic acid production. It has been said that there is a positive relation between the hydrolysis rate and the biodegradability of a substance. Chaplin and Bucke (1990) showed that the biodegradability slightly increase with increasing pH and this is true in terms of hydrolysis rate. The 20 L dilution recorded relatively the highest level of degradation and comparatively recorded highest average pH among the pH values recorded whereas that of the 8 L with the comparatively lowest pH recorded the lowest degradation. During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestate affects the pH value and in a batch reactor system acetogenesis occurs at a rapid pace. Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5. Rapid rate of acetogenesis is believed to have also accounted for the low pH observed in the various dilutions during this experiment. The growth of anaerobic microorganisms like methanogens could have been inhibited by acidic condition because of sensitive to acid concentration (Chugh *et al*., 1999; Rittmann and McCarty, 2001).

The acidic conditions observed in this experiment might have also affected the amount of biogas generated. According to Nguyen (2004), the degradation of protein through the release of ammonia has a buffering capacity.

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In which as digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8. Once the methane production is stabilized, the pH stays between 7.2 and 8.2. In the experiment conducted, the waste composition showed very low protein proportion and this could have also accounted for the low pH recorded.

5.3.2 Conductivity

A conductivity of 6.37 µS/cm of the 12 L dilution was the highest average with the 8 L dilution recording the lowest conductivity of 4.55 µS/cm. Conductivity with respect to the various dilutions did not show any specific trend but varied widely. Generally, however, there was high conductivity in all the dilutions resulting probably from the different ionic compositions or amount of salts used in preparation of some of the feedstock. Moreover it could have also resulted from the contamination from varying impurities in waste containers and salts from detergent normally used in washing eating bowls or even the pipe borne water used. Thus the hydrolytic leachate was neither salt-free, ion-free, or impurity-free because according to Michaud (1991), the purer the liquid, the lower the conductivity.

5.3.3 HRT

In the experiment conducted, the HRT decreased with increasing dilution. The 8 L dilution recorded the highest HRT of 1.5±0 and the 20 L dilution recorded the lowest HRT of 0.6±0. Probably the lower the HRT the lower the biogas production rate as the 20 L dilution recorded the highest biogas whereas the 8 L recorded the lowest biogas production.

This notwithstanding, according to Climenhaga and Banks (2008), it is impossible to predict the effect of HRT on anaerobic treatment systems, since it depends on reactor configuration, type of feed and characteristics, organic loading rate, type of biomass and method used to evaluate performance.

5.4 BOD Removal in the Methanogenic Reactor

The average BOD increased as the dilutions increased probably because the dilutions enhanced solubilization and consequently degradation. Microbial degradation increased as the unstable organic components were available to the microbes. BOD of the hydrolytic leachate was generally higher than that of the buffered hydrolytic leachate. The average BOD of the methanogenic effluent was relatively lower because the methanogens extracted the unstable organic component delivered into the methanogenic reactor at higher rates. As the microbes fed on the biodegradable material, biogas was released as a result. In general, the assertions that may be made include the fact that a high BOD indicates a high content of easily degradable, organic material in the sample and a low BOD indicates a low volume of organic materials, substances which are difficult to break down or other measuring problems (Perley *et al.*, 1992).

The 12 L dilution recorded the highest percentage BOD removal of 9.90±0.28% and the 8 L dilution recorded the lowest percentage BOD removal of 2.28±0.16%. Although the 12 L dilution achieved the highest percentage BOD removal it nevertheless, recorded a biogas production rate of 0.52±0.14 L/kg TS which was relatively smaller than that of the 15 L and 20 L. Meanwhile the 20 L dilution which recorded the highest biogas production rate of 4.5±1.59 L/kg TS recorded as low as 4.06±0.07% BOD removal.

This is probably due to the fact that the BOD removed during the 20 L dilution was of highest quality in that it was highly degradable and had higher biogas potential.

5.5 Biogas Production in the Methanogenic Reactor

An increasing biogas production was realised with increasing dilutions and increasing percentage degradation. The highest biogas production of 8.91±3.15 L/day was achieved at the 20 L dilution and the lowest biogas production of 0.65±1.36 L/day was recorded by the 8 L dilution.

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The 20 L dilution achieved the highest biogas production rate of 4.5±1.59 L of biogas per kilogram of TS whereas the 8 L dilution recorded a biogas production rate of 0.21±0.09 L of biogas per kilogram TS. The high biogas production potential of the 20 L dilutions is probably the result of its corresponding higher biodegradability and higher BOD removal efficiency which was efficiently converted to biogas.

And according to Bernal *et al.* (1992), biogas yield is directly proportional to the process efficiency. However, it is also important to note that a low biogas yield does not necessarily indicate a deficient performance but it is simply due to a low biodegradability of the substrate used. The observation of Bernal *et al.* (1992) suggest that digestion of waste with high biodegradability like market waste may pose a problem due to the complex reaction involved in digestion especially that acidogenesis can produce more acids than methanogenesis can convert at higher temperature. The ultimate yield of biogas depends on the composition and biodegradability of the waste feedstock. But the rate of production will depend on the population of bacteria and archaea, their growth conditions and the temperature of the system (Veeken *et al.*, 2000; Madigan *et al.*,2003).

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATIONS

This chapter presents the conclusion and recommendations of the research work.

6.1 Conclusion

The 20 L dilution recorded the highest percentage degradation and the 8 L dilution recorded the lowest percentage degradation. Percentage waste degradation generally increased with increasing dilution.

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Biogas production increased with increasing percentage degradation.

The highest biogas production of 8.91±3.15 L/day was achieved at the 20 L dilution and the lowest biogas production of 0.65±1.36 L/day was recorded by the 8 L dilution.

The 20 litres dilution recorded the highest average biogas production rate of 4.5±1.59 litres of biogas per kilogram of total solids whereas the 8 litres dilution recorded the lowest of 0.2±0.09 litres of biogas per kilogram of total solids.

6.2 Recommendations

The following recommendations are made:

- A single stage digester system may be set up as a control to compare the gas production rate with the double-stage digester system designed with the specifications used in this project work and subjected to the same conditions.

- A comparison could also be made by varying the amount of kitchen waste fed into the reactor with constant amount of water for dilution if it could produce more biogas.

- Extra buffering substances or alkaline/basic solution such as NaOH or KOH, limestones, gravels, bicarbonates etc. could be added to the water used as a buffer to find out if it could increase the pH level to the optimum for anaerobic digestion.

- Kitchen waste taken from the canteens and restaurants should be specifically incorporated with proteins foods to increase the amino acids and thereby release ammonia that serves as a buffering substance

- The proportions of pineapple peelings and wood shavings for improving the structure should be varied to see if it would affect the degradation potential and gas production rate.

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APPENDICES

APPENDIX A

Summary Statistics Of The Physico-Chemical Parameters Measured For The Samples During The 8 Litres Dilution

Parameter	Sample/days	1	2	3	4	5	6	7	8	9	10	Mean	SD	Variance
pH	HL *	2.98	3.05	3.13	2.99	3.05	2.95	3.21	3.04	3.14	2.96	3.05	0.09	0.01
	HL **	3.05	3.16	3.17	3.19	3.40	3.30	3.46	3.50	3.57	3.60	3.34	0.19	0.04
	HL	3.02	3.11	3.15	3.09	3.23	3.13	3.34	3.27	3.36	3.28	3.20	0.11	0.01
	BS *	3.94	3.95	3.97	3.99	3.87	3.99	4.01	3.74	3.70	3.06	3.82	0.29	0.08
	BS **	3.75	3.72	3.96	3.98	3.99	4.02	3.80	3.87	4.05	4.20	3.93	0.15	0.02
	BS	3.85	3.84	3.97	3.99	3.93	4.01	3.91	3.81	3.88	3.63	3.88	0.11	0.01
	MO *	3.92	3.92	3.93	3.93	3.94	3.78	3.85	3.45	3.09	3.04	3.69	0.36	0.13
	MO **	3.44	3.10	3.94	3.92	3.80	3.85	3.88	3.94	3.93	3.97	3.78	0.28	0.08
	MO	3.68	3.51	3.94	3.93	3.87	3.82	3.87	3.70	3.51	3.51	3.73	0.18	0.03
Conductivity, µS/cm	HL*	3.63	4.82	5.34	6.46	6.05	3.82	5.12	1.98	4.18	4.07	4.55	1.30	1.70
	HL**	4.19	4.06	3.64	4.84	5.11	1.99	5.33	3.81	6.45	6.02	4.54	1.29	1.68
	HL	3.91	4.44	4.49	5.65	5.58	2.91	5.23	2.90	5.32	5.05	4.55	1.02	1.05
	BS*	3.20	3.23	3.24	3.27	3.31	2.81	1.91	1.45	1.56	1.77	2.58	0.80	0.64
	BS**	1.56	1.78	3.22	3.25	1.93	1.45	3.25	2.79	3.29	3.31	2.58	0.80	0.64
	BS	2.38	2.51	3.23	3.26	2.62	2.13	2.58	2.12	2.43	2.54	2.58	0.39	0.15
	MO*	2.89	3.36	3.36	3.47	3.48	2.85	4.00	1.51	1.80	1.83	2.86	0.85	0.73
	MO**	1.79	1.82	2.89	3.35	4.00	1.50	3.37	2.85	3.48	3.47	2.85	0.86	0.74
	MO	2.34	2.59	3.13	3.41	3.74	2.18	3.69	2.18	2.64	2.65	2.85	0.60	0.35
BOD, mg/l	HL*	5475	8212	10950	10875	10837	10800	15300	17550	18675	19800	12847.40	4737.47	22443613.38
	HL**	6660	9992	13320	13665	13837	14010	15495	16237	16608	16980	13680.40	3204.87	10271197.16
	HL	6068	9102	12135	12270	12337	12405	15398	16894	17642	18390	13263.90	3889.23	15126135.32
	MO*	5400	8100	10800	10725	10687	10650	11625	12112	12356	12600	10505.50	2203.20	4854077.39
	MO**	5616	8424	11233	11516	11658	11800	11825	11837	11843	11850	10760.20	2088.49	4361782.62
	MO	5508	8262	11017	11121	11173	11225	11725	11975	12100	12225	10632.85	2123.69	4510076.78
	BS*	5325	7987	10650	10500	10425	10350	12675	13837	14418	15000	11116.70	2996.48	8978905.34
	BS**	5375	8062	10750	11245	11492	11740	11869	11933	11965	11998	10642.90	2197.53	4829148.10
	BS	5350	8025	10700	10873	10959	11045	12272	12885	13192	13499	10879.80	2515.74	6328945.07
Biogas, L/day	Gas Reading*	0.20	0.35	0.40	0.41	0.45	0.80	0.70	0.70	0.95	1.10	0.61	0.29	0.08
	Gas Reading**	0.28	0.35	0.45	0.50	0.45	0.90	0.85	0.90	1.00	1.20	0.69	0.32	0.10
	Mean volume	0.24	0.35	0.43	0.46	0.45	0.85	0.78	0.80	0.98	1.15	0.65	0.30	0.09
Biogas, L/kg TS		0.08	0.11	0.13	0.14	0.14	0.27	0.25	0.26	0.31	0.37	0.20	0.09	0.0086
Time(GMT)	Clock reading		7:00	9:00	11:00	13:00	15:00	17:00	19:00	21:00	23:00			

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Temperature oC	HR*		25.4	26.5	28.8	29.8	30.5	29.4	28.6	27.9	26.8	28.19	1.68	2.82
	HR**		25.9	26.6	28.7	29.9	30.2	29.8	28.6	27.8	26.7	28.24	1.59	2.51
	HR		25.7	26.6	28.8	29.9	30.4	29.6	28.6	27.9	26.8	28.22	1.63	2.65
	HL*		25.6	25.4	27.8	29.8	29.6	29.5	27.7	27.9	26.4	27.74	1.68	2.84
	HL**		25.7	25.5	27.6	29.7	29.4	29.5	27.8	27.8	26.4	27.71	1.61	2.59
	HL		25.7	25.5	27.7	29.8	29.5	29.5	27.8	27.9	26.4	27.73	1.65	2.71
	BS*		26.4	26.6	27.2	29.3	29.4	29.6	28.5	27.6	27.2	27.98	1.25	1.55
	BS**		26.6	26.4	27.5	29.4	29.5	29.4	28.6	27.7	27.3	28.04	1.22	1.48
	BS		26.5	26.5	27.4	29.4	29.5	29.5	28.6	27.7	27.3	28.01	1.23	1.51
	MO*		25.7	26.6	28.6	29.2	29.7	29.9	27.7	29.1	27.5	28.22	1.44	2.08
	MO**		25.8	26.7	28.8	29.3	29.8	29.8	27.9	28.8	27.6	28.28	1.39	1.93
	MO		25.8	26.7	28.7	29.3	29.8	29.9	27.8	29.0	27.6	28.25	1.41	2.00

***** Experiment 1; ** Experiment 2. NB Samples with no asterix represents means of experiments 1 and 2.

KNUST

APPENDIX B

Summary Statistics Of The Physico-Chemical Parameters Measured For The Samples During The 10 Litres Dilution

Parameter	Sample/days	1	2	3	4	5	6	7	8	9	10	Mean	SD	Variance
pH	HL *	3.5	3.59	3.66	3.43	3.41	3.42	3.36	3.45	3.52	3.6	3.49	0.10	0.01
	HL **	3.71	3.63	3.57	3.56	3.71	3.65	3.82	3.89	3.89	3.91	3.73	0.13	0.02
	HL	3.61	3.61	3.62	3.50	3.56	3.54	3.59	3.67	3.71	3.76	3.61	0.08	0.01
	BS *	3.87	3.92	3.98	4.08	4.15	4.1	4.11	4.17	4.29	4.34	4.10	0.15	0.02
	BS **	3.7	3.67	3.71	3.67	3.85	3.7	3.83	3.89	4	4.12	3.81	0.15	0.02
	BS	3.79	3.80	3.85	3.88	4.00	3.90	3.97	4.03	4.15	4.23	3.96	0.15	0.02
	MO *	3.95	4.02	4.13	4.09	4.06	3.82	3.87	4.08	4.19	4.29	4.05	0.14	0.02
	MO **	3.75	3.73	3.79	3.86	3.98	3.91	4.07	4.17	4.16	4.17	3.96	0.18	0.03
	MO	3.85	3.88	3.96	3.98	4.02	3.87	3.97	4.13	4.18	4.23	4.00	0.13	0.02
Conductivity, µS/cm	HL*	3.38	3.47	3.32	3.97	3.8	3.8	3.94	4.12	4.18	4.37	3.84	0.35	0.12
	HL**	5.6	6.23	7.3	7.08	6.37	5.82	5.65	5.8	5.82	5.79	6.15	0.60	0.36
	HL	4.49	4.85	5.31	5.53	5.09	4.81	4.80	4.96	5.00	5.08	4.99	0.29	0.08
	BS*	2.99	2.99	2.97	3.08	3.02	3.2	3.25	3.26	3.31	3.32	3.14	0.14	0.02
	BS**	4.57	5.21	6.03	4.8	4.58	4.22	4.62	4.71	4.71	4.73	4.82	0.49	0.24
	BS	3.78	4.10	4.50	3.94	3.80	3.71	3.94	3.99	4.01	4.03	3.98	0.22	0.05
	MO*	2.87	2.93	2.85	3.08	3.1	3.27	3.33	3.35	3.36	3.4	3.15	0.22	0.05
	MO**	5.2	5.08	5.78	5.23	5.08	4.96	5.06	5.08	5.11	5.09	5.17	0.23	0.05
	MO	4.04	4.01	4.32	4.16	4.09	4.12	4.20	4.22	4.24	4.25	4.16	0.10	0.01
BOD, mg/l	HL*	1095	1642	2190	3435	4057	4680	9840	12420	13710	15000	6806.90	5370.28	28839931.88
	HL**	6600	9900	13200	13500	13650	13800	14900	15450	15725	16000	13272.50	2929.13	8579784.72
	HL	3848	5771	7695	8468	8854	9240	12370	13935	14718	15500	10039.70	3928.27	15431279.01
	MO*	1095	1640	2190	3405	4012	4620	6710	7755	8277	8800	4850.40	2859.07	8174260.71
	MO**	6000	9000	12000	12300	12450	12600	12610	12605	12602	12600	11476.70	2220.48	4930511.12
	MO	3548	5320	7095	7853	8231	8610	9660	10180	10440	10700	8163.55	2327.49	5417230.30
	BS*	1110	1665	2220	3390	3975	4560	6880	8040	8620	9200	4966.00	3006.07	9036432.22
	BS**	4500	6750	9000	10800	11700	12600	15300	16650	17325	18000	12262.50	4605.33	21209062.50
	BS	2805	4208	5610	7095	7838	8580	11090	12345	12973	13600	8614.25	3786.01	14333873.68
Biogas, L/day	Gas Reading*	0.3	0.4	0.5	0.65	0.85	1.15	0.95	1.05	1.1	0.9	0.79	0.30	0.09
	Gas Reading**	0.4	0.51	0.6	0.25	0.95	0.55	0.85	1.1	0.9	0.7	0.68	0.27	0.07
	Mean biogas	0.35	0.46	0.55	0.45	0.90	0.85	0.90	1.08	1.00	0.80	0.73	0.26	0.07
Biogas, L/kg TS		0.13	0.17	0.21	0.17	0.34	0.32	0.34	0.41	0.38	0.30	0.28	0.10	0.0097
Time(GMT)	Clock reading	7:00	9:00	11:00	13:00	15:00	17:00	19:00	21:00	23:00	7:00			
Temperature oC	HR*	25.9	26.4	28.7	29.9	30.6	29.4	28.7	27.7	26.9	25.9	28.24	1.62	2.63
	HR**	25.8	26.8	28.6	30.1	30.5	29.7	28.8	27.9	26.8	25.8	28.33	1.63	2.66

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	HR	25.85	26.6	28.65	30	30.55	29.55	28.75	27.8	26.85	25.85	28.29	1.62	2.64
	HL*	25.5	25.3	27.9	29.9	29.3	29.5	27.6	27.8	26.2	25.5	27.67	1.72	2.94
	HL**	25.5	25.8	27.4	29.7	29.5	29.3	27.9	27.6	26.5	25.5	27.69	1.57	2.48
	HL	25.5	25.55	27.65	29.8	29.4	29.4	27.75	27.7	26.35	25.5	27.68	1.64	2.68
	BS*	26.5	26.4	27.1	29.4	29.1	29.6	28.7	27.5	27	26.5	27.92	1.28	1.63
	BS**	26.7	26.5	27.7	29.2	29.3	29.3	28.5	27.8	27.7	26.7	28.08	1.07	1.15
	BS	26.6	26.45	27.4	29.3	29.2	29.45	28.6	27.65	27.35	26.6	28.00	1.17	1.36
	MO*	25.6	26.5	28.7	29	29.9	29.7	27.5	29	27.4	25.6	28.14	1.48	2.18
	MO**	25.8	26.6	28.9	29.2	29.8	29.6	27.7	28.9	27.5	25.8	28.22	1.39	1.94
	MO	25.7	26.55	28.8	29.1	29.85	29.65	27.6	28.95	27.45	25.7	28.18	1.43	2.06

***** Experiment 1; ****** Experiment 2. NB Samples with no asterix represents means of experiments 1 and 2.

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APPENDIX C

Summary Statistics Of The Physico-Chemical Parameters Measured For The Samples During The 12 Litres Dilution

Parameter	Sample/days	1	2	3	4	5	6	7	8	9	10	Mean	SD	Variance
pH	HL *	3.19	3.08	3.03	3.07	3.16	3.11	3.54	3.51	3.49	3.50	3.27	0.21	0.05
	HL **	3.49	3.54	3.64	3.67	3.55	3.49	3.37	3.39	3.41	3.51	3.51	0.10	0.01
	mean	3.34	3.31	3.34	3.37	3.36	3.30	3.46	3.45	3.45	3.51	3.39	0.07	0.01
	BS *	3.54	3.24	3.23	3.22	3.25	3.18	3.60	3.62	3.60	3.57	3.41	0.19	0.04
	BS **	3.61	3.61	3.72	3.70	3.61	3.62	3.61	3.57	3.56	3.57	3.62	0.05	0.00
	mean	3.58	3.43	3.48	3.46	3.43	3.40	3.61	3.60	3.58	3.57	3.51	0.08	0.01
	MO *	3.32	3.17	3.17	3.17	3.20	3.13	3.56	3.51	3.54	3.55	3.33	0.19	0.03
	MO **	3.52	3.55	3.74	3.71	3.69	3.46	3.63	3.65	3.64	3.62	3.62	0.09	0.01
	Mean	3.42	3.36	3.46	3.44	3.45	3.30	3.60	3.58	3.59	3.59	3.48	0.11	0.01
Conductivity, µS/cm	HL*	7.28	7.37	7.02	6.91	6.7	6.32	6.29	7.55	6.45	7.7	6.96	0.51	0.26
	HL**	6.55	6.7	4.83	5.07	5.18	5.39	5.79	6.06	6.16	5.99	5.77	0.63	0.40
	HL	6.92	7.04	5.93	5.99	5.94	5.86	6.04	6.81	6.31	6.85	6.37	0.48	0.23
	BS*	4.53	5.13	5.1	5.62	5.66	5.45	5.77	4.95	4.58	5.43	5.22	0.44	0.19
	BS**	4.94	5.42	5.25	4.81	5	5.08	5.3	5.41	5.53	5.11	5.19	0.23	0.05
	BS	4.74	5.28	5.18	5.22	5.33	5.27	5.54	5.18	5.06	5.27	5.20	0.21	0.04
	MO*	6.35	6.19	6.27	6.12	5.57	5.73	5.65	6.8	5.83	6.63	6.11	0.42	0.17
	MO**	5.8	5.67	5	4.68	4.87	5.37	5.12	5.28	5.32	5.38	5.25	0.34	0.12
	MO	6.08	5.93	5.64	5.40	5.22	5.55	5.39	6.04	5.58	6.01	5.68	0.31	0.10
BOD, mg/l	HL*	7200	10800	14400	17400	18900	20400	20100	19950	19875	19800	16883	4605	21205563
	HL**	6600	9900	13200	16800	18600	20400	23100	24450	25125	25800	18398	6698	44867563
	HL	6900	10350	13800	17100	18750	20400	21600	22200	22500	22800	17640	5569	31011000
	BS*	10200	15300	20400	19200	18600	18000	15300	13950	13275	12600	15683	3286	10795563
	BS*	7500	10400	14200	16000	17500	18000	18750	19125	19312	19600	16039	4141	17149166
	BS	8850	12850	17300	17600	18050	18000	17025	16538	16294	16100	15861	2882	8304317
	MO*	6000	9000	12000	14700	16050	17400	17100	16950	16875	16800	14288	3984	15871563
	MO**	6000	9015	12020	14810	16200	17600	17100	16850	16725	16600	14292	3976	15810246
	MO	6000	9008	12010	14755	16125	17500	17100	16900	16800	16700	14290	3980	15836806
Biogas, L/day	Gas Reading*	0.7	0.95	1.14	0.86	1.8	1.15	1.9	1.1	0.85	1.65	1.21	0.42	0.18
	Gas Reading**	0.6	0.93	1.22	1.86	1.5	1.64	1.98	1.88	1.84	1.61	1.51	0.46	0.21
	Mean biogas	0.65	0.94	1.18	1.36	1.65	1.40	1.94	1.49	1.35	1.63	1.36	0.37	0.14
Biogas, L/kg TS		0.25	0.36	0.45	0.52	0.63	0.53	0.74	0.57	0.51	0.62	0.52	0.14	0.0196
Time(GMT)	Clock reading	7:00	9:00	11:00	13:00	15:00	17:00	19:00	21:00	23:00	7:00		0.24	0.06
Temperature oC	HR*	25.8	26.5	28.5	30.5	30.7	29.5	28.5	27.8	26.8	25.8	28.04	1.82	3.30
	HR**	25.5	26.7	28.5	31.2	30.8	29.9	28.8	27.9	26.9	25.5	28.17	2.05	4.19
	HR	25.65	26.6	28.5	30.85	30.75	29.7	28.65	27.85	26.85	25.65	28.11	1.93	3.72
	HL*	25	25.2	27.5	29.8	29.5	29.1	27.5	27.5	26.5	25	27.26	1.83	3.34
	HL**	25.1	25.3	27.5	29.5	29	29	28	27.5	26.8	25.1	27.28	1.67	2.79

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	HL	25.05	25.25	27.5	29.65	29.25	29.05	27.75	27.5	26.65	25.05	27.27	1.75	3.05
	BS*	26.3	26.5	27	29.3	29	29.5	28.5	27.4	27.2	26.3	27.70	1.26	1.59
	BS**	26.5	26.8	27.5	29	29.4	29.5	28.2	27.5	27.5	26.5	27.84	1.14	1.30
	BS	26.4	26.65	27.25	29.15	29.2	29.5	28.35	27.45	27.35	26.4	27.77	1.19	1.43
	MO*	25.5	26.2	28.8	29.1	30.1	29.5	27.2	28.9	27.5	25.5	27.83	1.69	2.85
	MO**	25.9	26.5	29	29	30	29.5	27.5	28.8	27.2	25.9	27.93	1.52	2.31
	MO	25.7	26.35	28.9	29.05	30.05	29.5	27.35	28.85	27.35	25.7	27.88	1.60	2.57

***** Experiment 1; ****** Experiment 2. NB Samples with no asterix represents means of experiments 1 and 2.

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APPENDIX D

Summary Statistics Of The Physico-Chemical Parameters Measured For The Samples During The 15 Litres Dilution

Parameter	Sample/days	1	2	3	4	5	6	7	8	9	10	Mean	SD	Variance
pH	HL *	3.25	3.19	3.69	3.41	3.44	3.35	3.49	3.45	3.52	3.55	3.43	0.15	0.02
	HL **	3.57	3.50	3.61	3.71	3.78	3.72	3.80	3.86	3.90	3.99	3.74	0.15	0.02
	HL	3.41	3.35	3.65	3.56	3.61	3.54	3.65	3.66	3.71	3.77	3.59	0.13	0.02
	BS *	3.76	3.67	4.13	3.94	3.88	3.62	3.93	3.80	3.81	3.88	3.84	0.15	0.02
	BS **	3.59	3.62	3.65	3.76	3.87	3.79	3.85	3.88	3.94	3.96	3.79	0.13	0.02
	BS	3.68	3.65	3.89	3.85	3.88	3.71	3.89	3.84	3.88	3.92	3.82	0.10	0.01
	MO *	3.78	3.68	4.14	3.93	3.94	3.89	3.76	3.82	3.92	3.97	3.88	0.13	0.02
	MO **	3.65	3.66	3.68	3.89	3.95	3.92	3.97	3.98	3.98	3.99	3.87	0.14	0.02
	MO	3.72	3.67	3.91	3.91	3.95	3.91	3.87	3.90	3.95	3.98	3.88	0.10	0.01
Conductivity, µS/cm	HL*	4.91	5.64	5.71	5.81	6.11	4.98	5.38	4.08	5.08	5.15	5.29	0.58	0.34
	HL**	5.96	6.24	6.83	6.65	6.03	5.88	5.84	5.82	5.77	5.88	6.09	0.37	0.14
	HL	5.44	5.94	6.27	6.23	6.07	5.43	5.61	4.95	5.43	5.52	5.69	0.42	0.18
	BS*	4.59	4.68	4.62	4.14	3.95	4.39	3.95	3.73	3.78	4.09	4.19	0.35	0.13
	BS**	5.31	5.61	6.00	6.23	5.05	4.88	5.04	5.22	5.55	5.32	5.42	0.43	0.19
	BS	4.95	5.15	5.31	5.19	4.50	4.64	4.50	4.48	4.67	4.71	4.81	0.31	0.10
	MO*	4.21	4.78	4.66	4.37	3.92	4.43	4.76	3.75	3.83	4.97	4.37	0.43	0.19
	MO**	5.53	5.38	5.86	5.61	5.31	4.97	4.29	5.35	5.82	5.36	5.35	0.45	0.21
	MO	4.87	5.08	5.26	4.99	4.62	4.70	4.53	4.55	4.83	5.17	4.86	0.26	0.07
BOD, mg/l	HL*	7680	11520	14375	18450	21500	23550	24420	25860	26580	27300	20123.50	6854.83	46988700.28
	HL**	9250	12375	14500	16525	20030	22550	23500	24600	25300	25650	19428.00	5894.28	34742534.44
	HL	8465	11948	14438	17488	20765	23050	23960	25230	25940	26475	19775.75	6366.42	40531290.35
	BS*	6900	10255	13800	16200	17350	18600	19950	21200	21860	22500	16861.50	5175.67	26787533.61
	BS**	8700	11900	13600	14950	16820	20600	21500	22800	23150	24300	17832.00	5392.74	29081684.44
	BS	7800	11078	13700	15575	17085	19600	20725	22000	22505	23400	17346.75	5252.96	27593572.29
	MO*	6700	10060	13425	15950	17240	18200	19570	20730	21305	21700	16488.00	5034.92	25350412.22
	MO**	8000	10675	11900	12450	14230	18010	19300	21740	22360	23950	16261.50	5535.21	30638555.83
	MO	7350	10368	12663	14200	15735	18105	19435	21235	21833	22825	16374.75	5204.98	27091829.79
Biogas, L/day	Gas Reading*	6.15	4.25	4.55	7.25	8.20	8.52	8.95	9.00	8.95	6.80	7.26	1.80	3.23
	Gas Reading**	5.35	5.80	5.95	6.75	9.10	8.98	8.50	8.95	8.50	7.99	7.59	1.47	2.17
	Mean biogas	5.75	5.03	5.25	7.00	8.65	8.75	8.73	8.98	8.73	7.40	7.42	1.58	2.50
Biogas, L/kg TS		2.29	2.0	2.09	2.79	3.44	3.49	3.48	3.54	3.48	2.95	2.96	0.63	0.3939
Time(GMT)	Clock reading		7:00	9:00	11:00	13:00	15:00	17:00	19:00	21:00	23:00			
Temperature oC	HR*		25.70	26.80	28.90	29.50	30.30	29.70	28.60	27.80	26.90	28.24	1.54	2.38
	HR**		25.80	26.90	28.80	29.60	30.00	29.60	28.80	27.90	26.80	28.24	1.47	2.17

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	HR		25.75	26.85	28.85	29.55	30.15	29.65	28.70	27.85	26.85	28.24	1.51	2.27
	HL*		25.20	25.60	27.70	29.80	29.40	29.60	27.80	27.90	26.20	27.69	1.73	2.98
	HL**		25.40	25.60	27.60	29.60	29.30	29.50	27.60	27.90	26.10	27.62	1.65	2.71
	HL		25.30	25.60	27.65	29.70	29.35	29.55	27.70	27.90	26.15	27.66	1.69	2.84
	BS*		26.50	26.50	27.30	29.40	29.40	29.70	28.50	27.50	27.30	28.01	1.26	1.60
	BS**		26.40	26.60	27.30	29.50	29.60	29.70	28.70	27.40	27.30	28.06	1.32	1.75
	BS		26.45	26.55	27.30	29.45	29.50	29.70	28.60	27.45	27.30	28.03	1.29	1.67
	MO*		25.80	26.20	28.00	29.30	29.90	29.70	27.80	29.00	27.70	28.16	1.47	2.15
	MO**		25.80	26.40	28.20	29.50	29.80	29.70	27.70	28.90	27.60	28.18	1.44	2.07
	MO		25.80	26.30	28.10	29.40	29.85	29.70	27.75	28.95	27.65	28.17	1.45	2.11

***** Experiment 1; ** Experiment 2. NB Samples with no asterix represents means of experiments 1 and 2.

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APPENDIX E

Summary Statistics Of The Physico-Chemical Parameters Measured For The Samples During The 20 Litres Dilution

Parameter	Sample/days	1	2	3	4	5	6	7	8	9	10	Mean	SD	Variance
pH	HL *	3.51	3.52	4.22	4.04	4.03	3.91	3.97	4.06	4.09	3.95	3.93	0.23	0.06
	HL **	3.62	3.57	4.05	4.05	4.04	3.98	3.98	4.02	3.89	4.10	3.93	0.19	0.03
	HL	3.57	3.55	4.14	4.05	4.04	3.95	3.98	4.04	3.99	4.03	3.93	0.20	0.04
	BS *	3.58	3.58	4.29	4.08	4.09	4.04	4.05	4.05	4.11	3.99	3.99	0.23	0.05
	BS **	3.68	3.73	3.66	3.88	4.09	4.08	4.06	4.06	3.97	3.98	3.92	0.17	0.03
	BS	3.63	3.66	3.98	3.98	4.09	4.06	4.06	4.06	4.04	3.99	3.96	0.17	0.03
	MO *	3.64	3.63	4.35	4.12	4.11	4.09	4.04	4.10	4.04	3.99	4.01	0.22	0.05
	MO **	3.74	3.79	3.71	4.03	4.02	4.03	3.95	3.90	4.07	3.98	3.92	0.13	0.02
	MO	3.69	3.71	4.03	4.08	4.07	4.06	4.00	4.00	4.06	3.99	3.97	0.15	0.02
Conductivity, µS/cm	HL*	6.18	6.45	6.08	5.15	6.17	6.14	5.64	6.17	5.98	6.22	6.02	0.37	0.14
	HL**	6.32	6.25	6.35	6.21	5.68	5.93	6.03	5.84	5.74	5.95	6.03	0.24	0.06
	HL	6.25	6.35	6.22	5.68	5.93	6.04	5.84	6.01	5.86	6.09	6.03	0.21	0.04
	BS*	5.97	6.12	5.99	5.01	5.39	5.97	5.99	6.01	5.99	5.89	5.83	0.35	0.12
	BS**	6.05	6.01	6.06	6.03	5.52	4.95	5.46	5.73	5.86	5.92	5.76	0.36	0.13
	BS	6.01	6.07	6.03	5.52	5.46	5.46	5.73	5.87	5.93	5.91	5.80	0.24	0.06
	MO*	5.51	6.20	5.95	5.26	5.35	6.00	5.51	5.99	5.83	5.90	5.75	0.32	0.10
	MO**	5.86	5.68	5.94	5.98	5.60	4.98	5.49	5.50	5.74	5.87	5.66	0.30	0.09
	MO	5.69	5.94	5.95	5.62	5.48	5.49	5.50	5.75	5.79	5.89	5.71	0.18	0.03
BOD, mg/l	HL*	9900	14850	19800	23550	25425	27300	31050	32925	33862	34800	25346.20	8422.39	70936694.40
	HL**	10250	15375	20500	23525	25030	26550	30250	33600	34770	35950	25580.00	8488.86	72060672.22
	HL	10075	15113	20150	23538	25228	26925	30650	33263	34316	35375	25463.25	8448.66	71379775.40
	BS*	8400	12600	16800	20700	22640	24600	28500	30450	31420	32400	22851.00	8249.76	68058498.89
	BS**	8600	12900	17200	18950	19820	20700	24100	28800	31155	33500	21572.50	7930.54	62893484.72
	BS	8500	12750	17000	19825	21230	22650	26300	29625	31288	32950	22211.80	8034.02	64545555.73
	MO*	8100	12150	16200	20100	22000	24000	27900	29850	30820	31800	22292.00	8171.05	66766084.44
	MO**	8450	12670	16900	18455	19230	20010	22500	25740	28360	30990	20330.50	6900.05	47610713.61
	MO	8275	12410	16550	19278	20615	22005	25200	27795	29590	31395	21311.30	7485.74	56036314.68
Biogas, L/day	Gas Reading*	6.50	2.20	4.70	11.80	11.21	15.20	8.10	12.30	7.80	9.20	8.90	3.88	15.03
	Gas Reading**	7.70	5.80	4.20	8.70	12.80	11.50	10.50	11.80	8.30	7.90	8.92	2.74	7.50
	Mean Biogas	7.10	4.00	4.45	10.25	12.01	13.35	9.30	12.05	8.05	8.55	8.91	3.15	9.92
Biogas, L/kg TS		3.58	2.02	2.25	5.18	6.06	6.74	4.70	6.09	4.07	4.32	4.5	1.54	2.5287
Time(GMT)	Clock reading		0.29	0.38	0.46	0.54	0.63	0.71	0.79	0.88	0.96			
Temperature oC	HR*		25.90	26.90	29.10	29.70	29.90	29.90	28.80	27.90	27.10	28.36	1.47	2.16
	HR**		25.80	26.70	28.90	29.60	30.10	29.80	28.90	27.90	26.90	28.29	1.53	2.35

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	HR		25.85	26.80	29.00	29.65	30.00	29.85	28.85	27.90	27.00	28.32	1.50	2.25
	HL*		25.50	25.70	27.80	29.90	29.60	29.70	27.90	27.90	26.40	27.82	1.69	2.87
	HL**		25.60	25.80	27.70	29.70	29.50	29.60	27.80	27.80	26.50	27.78	1.59	2.53
	HL		25.55	25.75	27.75	29.80	29.55	29.65	27.85	27.85	26.45	27.80	1.64	2.70
	BS*		26.70	26.70	27.50	29.60	29.60	29.80	28.80	27.60	27.50	28.20	1.26	1.59
	BS**		26.60	26.70	27.30	29.70	29.70	29.70	28.90	27.50	27.40	28.17	1.32	1.75
	BS		26.65	26.70	27.40	29.65	29.65	29.75	28.85	27.55	27.45	28.18	1.29	1.66
	MO*		25.70	26.40	28.30	29.40	29.80	29.80	27.70	29.20	27.50	28.20	1.49	2.23
	MO**		25.90	26.50	28.10	29.50	29.70	29.60	27.70	29.00	27.70	28.19	1.38	1.90
	MO		25.80	26.45	28.20	29.45	29.75	29.70	27.70	29.10	27.60	28.19	1.43	2.06

***** Experiment 1; ** Experiment 2. NB Samples with no asterix represents means of experiments 1 and 2.

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APPENDIX F

Summary Statistics of Parameters Measured for Feedstock placed into Hydrolytic Reactor During the 8 Litres Dilution

	M_b (kg)	M_a (kg)	$M.C_b$ (%)	$M.C_a$ (%)	TS_b (%)	TS_a (%)	TS_b (kg)	TS_a (kg)	%degradation	HRT (days)
Expt 1	10	9.4	64.7	66	35.3	34	3.5	3.2	9.6	1.5
Expt 2	10	9.3	65.4	67	34.6	33	3.5	3.1	11.3	1.5
Mean	10	9.4	65.1	66.5	35	33.5	3.5	3.1	10.5	1.5
SD	0	0.1	0.5	0.7	0.5	0.7	0	0.1	1.2	0

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APPENDIX G

Summary Statistics of Parameters Measured for Feedstock placed into Hydrolytic Reactor During the 10 Litres Dilution

	M_b (kg)	M_a (kg)	$M.C_b$ (%)	$M.C_a$ (%)	TS_b (%)	TS_a (%)	TS_b (kg)	TS_a (kg)	%degradation	HRT (days)
Expt 1	10	9.1	65.5	72.4	34.5	27.6	3.5	2.5	27.3	1.2
Expt 2	10	9.2	62.7	70	37.3	30	3.7	2.8	26	1.2
Mean	10	9.2	64.1	71.2	35.9	28.8	3.6	2.6	26.7	1.2
SD	0	0.1	2	1.7	2	1.7	0.2	0.2	0.9	0

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APPENDIX H

Summary Statistics of Parameters Measured for Feedstock placed into Hydrolytic Reactor During the 12 Litres Dilution

	M_b (kg)	M_a (kg)	$M.C_b$ (%)	$M.C_a$ (%)	TS_b (%)	TS_a (%)	TS_b (kg)	TS_a (kg)	%degradation	HRT (days)
Expt 1	10	9.7	61.3	77.9	38.7	22.1	3.9	2.1	44.7	1.0
Expt 2	10	8.7	63	74.8	37	25.2	3.7	2.2	40.8	1.0
Mean	10	9.2	62.2	76.4	37.9	23.7	3.8	2.2	42.8	1.0
SD	0	0.7	1.2	2.2	1.2	2.2	0.1	0	2.8	0

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APPENDIX I

Summary Statistics of Parameters Measured for Feedstock placed into Hydrolytic Reactor During the 15 Litres Dilution

	M_b (kg)	M_a (kg)	$M.C_b$ (%)	$M.C_a$ (%)	TS_b (%)	TS_a (%)	TS_b (kg)	TS_a (kg)	%degradation	HRT (days)
Expt 1	10	8.8	75	82	25	18	2.5	1.6	36.8	0.8
Expt 2	10	8.5	74	80	26	20	2.6	1.7	34.6	0.8
Mean	10	8.7	74.5	81	25.5	19	2.6	1.6	35.7	0.8
SD		0.2	0.7	1.4	0.7	1.4	0.1	0.1	1.6	

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APPENDIX J

Summary Statistics of Parameters Measured for Feedstock placed into Hydrolytic Reactor During the 20 Litres Dilution

	M_b (kg)	M_a (kg)	$M.C_b$ (%)	$M.C_a$ (%)	TS_b (%)	TS_a (%)	TS_b (kg)	TS_a (kg)	%degradation	HRT (days)
Expt 1	10	7.4	80	84.8	20	15.2	2	1.1	44	0.6
Expt 2	10	8.1	78	84	22	16	2.2	1.3	40.9	0.6
Mean	10	7.8	79	84.4	21	15.6	2.1	1.2	42.5	0.6
SD		0.5	1.4	0.6	1.4	0.6	0.1	0.1	2.2	

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APPENDIX K

Table showing Summary of Average Quantity of BOD produced with corresponding Percentage BOD Removal

Parameter/Dilution	**8 L/day**	**10 L/day**	**12 L/day**	**15 L/day**	**20 L/day**
BOD_5 of Buffered Hydrolytic Leachate /(mg/L)	10880 ± 2516	8614 ± 3786	15861 ±2882	17347 ±5253	22212 ±8034
BOD_5 of Methanogenic Effluent (mg/L)	10633 ±2124	8164 ±2327	14290 ± 3980	16375 ± 5205	21311 ± 7486
Percentage BOD removal (%)	2.28 ± 0.16	5.22 ± 0.39	9.90 ± 0.28	5.60 ± 0.01	4.06 ± 0.07

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