

EFFECTS OF ADDITIVES ON BIOGAS PRODUCTION FROM COW DUNG AND CHICKEN DROPPING MIXED WITH *DIGITARIA SMUTS II*

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DECLARATION

I declare that the work in the dissertation entitled "Effects of Additives on Biogas Production from Using Cow Dung and Chicken Droppings Mixed with *Digitaria Smuts II*" was written by me and that it is a record of my findings under the supervision of Engr. Dr S. B. Igboro and Dr E. M. Shu'aibu-Imodagbe. It has not, either in part or whole, been submitted by me or anybody for this or any other degree or qualification at this or any other University. The information derived from literature has been duly acknowledged in the text and a list of references provided.

Rabiu Musa

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CERTIFICATION

This dissertation entitled “Effects of Additives on Biogas Production from Cow Dung and Chicken Droppings Mixed with *Digitaria Smuts II*” by Rabiu Musa meets the regulations governing the award of the degree of Master of Science in Environmental Engineering of Ahmadu Bello University, Zaria.

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DEDICATION

I dedicate this work to my loving family for their immeasurable support.

ACKNOWLEDGMENTS

I thank the Almighty Allah for sparing my life and giving me the opportunity to be educated.

My profound goes gratitude to my parents for their support and constant prayers to make sure that I am successful. My dearly beloved siblings, Hajiya Safiya Musa, Hajiya Sadiya Musa, Tanimu Musa, Muktar Musa, Fatima Musa, Rukayya Musa, Engr. Auwal Musa, and Rahma Musa who were all with me to this very moment, I call them my pillars for their immense support.

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ABSTRACT

This study was carried out to examine the effects of Single Super Phosphate with Wood ash on the production of biogas from Cow Dung and Chicken Droppings mixed with *Digitaria Smuts II*. An existing digester design was adopted (3 in 1 floating drums) and fabricated using locally available materials to digest Cow Dung from Kawo Abattoir, Chicken Droppings from Salma Farms and *Digitaria Smuts II* (Woolly Finger Grass) from NAPRI respectively. The study was carried out in eight (8) identical reactors to enable variation of the catalyst combination and were labelled A_1, B_1, C_1, D_1, A_2 B_2 C_2 and D_2. The research showed that using SSP and wood ash could reduce the lag phase in anaerobic digestion. The controls A_1 and A_2 had the longest lag phase of 7.5 and 8.9 days as compared to 5.5 and 7.9 days with (200gSSP/100gWood ash). At the end of the digestion period, there was significant difference in volume of biogas produced across the digesters which ranged from 0.0893m^3 (no additives) to 0.1188m^3 (200gSSP/100gwood ash) for cow dung, while that of chicken droppings mixed with grass is from 0.0647m^3 (no additives) to 0.1088m^3 (200gSSP/100gWood ash), indicating 20.6% and 40.6% increment respectively. The Modified Gompertz equation was applied to describe the cumulative biogas generation. The biogas production kinetic constants estimated by the linear regression method using the solver function in Microsoft Excel as well as other characteristics obtained for the eight digesters were 0.0037m^3/day 0.0036m^3/day 0.0045m^3/day, 0.0056m^3/day, 0.0025m^3/day, 0.0028m^3/day, 0.0031m^3/day, and 0.0046m^3/day for Biogas Production Rate and 0.0893m^3, 0.0841m^3, 0.0977m^3. 0.1188m^3, 0.0647m^3, 0.0737m^3, 0.0808m^3 and 0.108 8m^3 for Biogas Production Potential. The average temperatures of the digesters recorded were 35.20 ^{0}C, 35.30 ^{0}C, 35.17 ^{0}C, 35.18 ^{0}C 35.25 ^{0}C, 35.28 ^{0}C, 35.30 ^{0}C, and 35.40 ^{0}C respectively while the average ambient temperature observed during the study was 36 ^{0}C which were within the mesophilic range. The results obtain indicated that the additives used influenced biogas production.

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CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Environmental pollution is a major problem in the world today, it affect humans, animals and other forms of living organisms including plants. This pollution is mostly as a result of man activities, either in the process of producing his food, shelter, transportation, or the quest to improve his economy. Thakur (2006), stated that economic growth and heavy consumption of natural resources are responsible for global warming, acid rain and destruction of the ozone layer.

Energy is an essential tool for development. Africa and other developing countries are faced with energy challenge. Less than 10% of the population of 21 Sub-Sahara African countries have access to electricity, Mshandete and Parawira, (2009). These countries however produce tremendous amount of waste which if channeled towards energy production can meet the energy need of the region. In Nigeria for instance, aside from the large amount of waste and manure generation, Adaramola and Ovewola (2011) opined that, the country is endowed with huge resources of conventional energy resources (hydrocarbon) and reasonable amount of renewable energy resources (e.g. hydro, wind, solar and biomass).

The Organization of Petroleum Exporting Countries (OPEC) annual statistical bulletin 2009 in buttressing these facts revealed that Nigeria proven crude oil reserves and natural gas are 37.2 billion barrels and 5,292 trillion standard cubic meters, respectively. In addition, the estimated reserve of tar sands and proven reserves of coals are about 30 billion barrels of oil equivalent and 639 million tons (with inferred reserves of about 2.75 billion tons), respectively (Adaramola and

Oyewola, 2011). According to (Iwayemi, 2008), the region has biomass reserve of 144 million tons per year

Despite all these abundant energy resources, Nigerian Bureau of Statistics (NBS) revealed that, Nigeria as at 2006 had a total of about 28,900,492 households. 79.6% of these households still depend on wood fuel for cooking as at 2008. In some states like Adamawa, Nasarawa, Zamfara, and Sokoto, there is over 90% dependency on fuel wood (NBS, 2009).

Over dependency on fossil fuel in most part of the urban area is also a major problem, which often results in the accumulation of carbon dioxide in the atmosphere. As human development continues to increase and fossil fuels continue to be depleted, it is undeniable that sustainable, alternative energy sources must replace fossil fuels in order for society to maintain its quality of life (Igboro, 2011).

Energy is central to nearly every major challenge and opportunity the world faces today. Be it for jobs, security, climate change, food production or increasing incomes, access to energy for all is essential SDG (2015). Part of the United Nations Sustainable Development Goal is to harness the potential of other sources of energy other than fossil fuel which is clean and sustainable. Sustainable energy is opportunity, it transforms lives, economies and the planet. At the UN conference held in France, December 2015 on climate action, the following were revealed;

i. One in five people still lacks access to modern electricity

ii. Three billion people rely on wood coal, charcoal or wood fuel for cooking

iii. Energy is the dominant contributor to climate change, accounting for around 60 percent of total global greenhouse gas emissions

iv. Reducing the carbon intensity of energy is a key objective in long term climate goals.

There is a great deal of environmental pressure in many parts of the world to ascertain how livestock and poultry waste can best be handled. These wastes like cow dung and poultry droppings in the absence of appropriate disposal methods can cause adverse environmental and health problems such as pathogen contamination, greenhouse gases, air borne ammonia and odor. Anaerobic digestion has been considered as waste to energy technology, and is widely used in the treatment of different organic wastes, for example, organic fraction of municipal solid waste, sewage, sludge, food waste, animal manure among others. Anaerobic treatment comprises of decomposition of organic material in the absence of oxygen resulting in the production of methane, carbon dioxide, ammonia and traces of other gases.

Biogas refers to a mixture of different gasses produced by the breakdown of organic matter in the absence of oxygen. Agricultural waste, sewage, food waste, municipal waste, plant material and manure are some of the raw materials used to produce biogas. Biogas can be produced by anaerobic digestion with anaerobic bacteria, which digest material inside a closed system, or fermentation of biodegradable materials. Biogas is primarily methane (CH_4) and carbon dioxide (CO_2) and may have small amount of hydrogen sulphide (H_2S) and traces of other gasses. The gasses methane, hydrogen, and carbon monoxide can be combusted or oxidized with oxygen. This energy released allowed biogas to be used as a fuel for heating or in some cases are used to generate electricity. Typical composition of biogas are; Methane (CH_4) 50 – 75%, Carbon Dioxide (CO_2) 25 – 50%, Nitrogen (N_2) 0 – 10%, Hydrogen (H_2) 0 – 1%, Hydrogen Sulphide (H_2S) 0 – 3%, (www.lowimpact.org/factsheetbiogas.pdf, 2012).

Environmental quality has been largely affected as a result of petroleum base fuels. The detrimental consequences of the fossil based fuels and the depleting supplies of crude oil products have prompted and triggered the search for renewable alternative energy.

Biofuel should meet peculiar criteria such as providing net energy gain, positive favorable environmental effect and benefits, be economically cost effective and competitive.

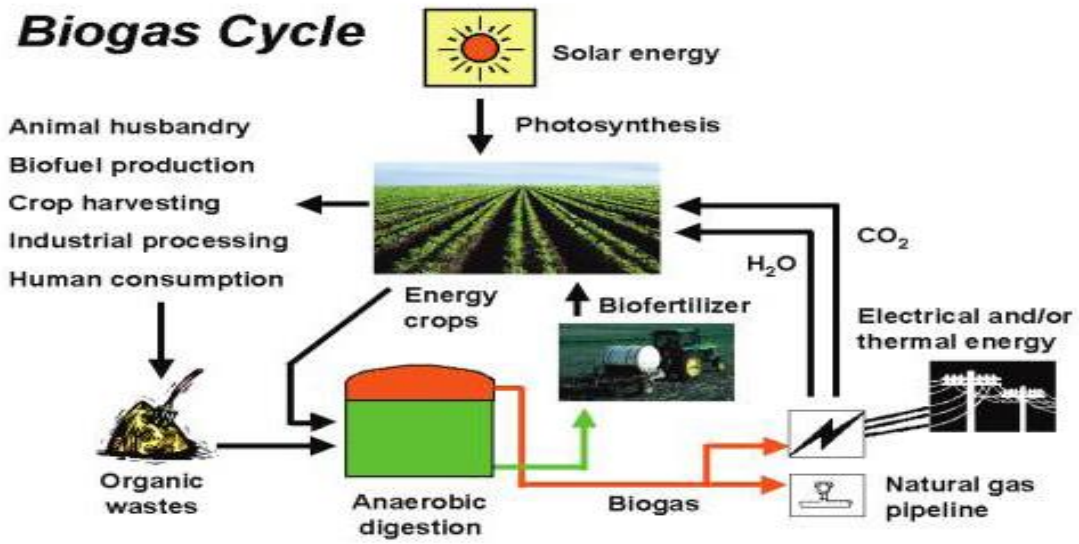


Fig. 1.1 Biogas Production from Organic Wastes (Igboro, 2011).

It is important to note that in biogas production, the substrates which are basically waste from municipalities helps in environmental cleanup, it produces lower CO_2 emissions compared to fossil fuels. The sources of Anaerobic Digestion can be classified as either industrial waste and waste water, Sewage sludge, Farm waste, Municipal solid waste, or Green waste. (Alfa, 2013).

Recently, large volume of cow dung and chicken dropping generated from feedlot and poultry farming increase annually, most of which are disposed into landfills or are applied to the land without treatment. Anaerobic digestion provides an alternative option for energy recovery and waste treatment.

Over the years, a lot of research has been made to produce gas from various bio degradable materials. In this study, the effect of catalyst on biogas production using cow dung and chicken droppings with grass will be assessed. The effectiveness of SSP (Single Super Phosphate) and Ash to accelerate the rate of digestion to produce biogas in batch operation will be determined.

1.2 Statement of Research Problem

In Nigeria, kerosene is one of the most commonly used fuel for lighting and cooking. The demand for this fuel is over whelming, yet it remains scarce and the price ridiculously high. As a result of this, larger percentage of the populace seek solutions to their energy needs from other sources which in most cases are detrimental to the environment. For instance, there was a 5.5% increase in the dependence on wood fuel for cooking between 2007 and 2008 (NBS, 2009). More so, 79.6% of the households depend on wood fuel for their cooking while kerosene, coal, gas and electricity come behind from distant 18.51%, 1.1%, 0.6% and 0.2% respectively (NBS, 2009).

Over the years, so many researchers have worked on biogas production from various biodegradable materials. It is therefore necessary to research on methods to make the production process faster by enhancing the rate of digestion through addition of additives.

Also, the excessive waste generated from various farms across the country if not properly handled can cause adverse environmental and health issues. Cow dung and chicken droppings are such waste if channeled towards biogas production instead of the current habit of using them for landfills or as fertilizer without pretreatment can help in environmental cleanup.

1.3 Justification

Mshandete and Parawira (2009) stated that Nigeria has been estimated to produce 227,500 tons of cow waste daily, since 1 kg of fresh cow waste produce about $0.03m^3$ biogas, then Nigeria can potentially produce about 6.8 million m^3 of biogas every day from cow waste only. A recent study that assessed Nigeria's minimum biogas potentials from solid waste and animal manure reveals that in 1999, Nigeria's biogas potential represent a total of $1.382x10^9m^3$ of biogas/year or an annual equivalent of 4.81million barrels of crude oil (Ojolo *et al., 2007*).

On the issue of Municipal Solid Waste (MSW) however, one can imagine the quantity produced by population of over 140milllion (Census, 2006). With population growth, industrialization and urbanization, MSW is now a serious problem in the country. Biogas production may therefore be a profitable means of reducing or even eliminating the menace and nuisance of urban solid waste in Nigeria. Presently, MSW are primary used for landfills in most part of the country.

With the rapidly increasing waste generation threatening to prevent humans from carrying out their activities for lack of space, the society is therefore faced with the choice to either allow this biomass waste to continue polluting the environment; methane and carbon dioxide production to

continue to increase global warming or boldly take the initiative of converting the biomass into alternative energy (Igboro, 2011).

Aside using organic manure to produce biogas, this study will also focus on effects of locally available additives (Single Super Phosphate and Wood Ash) on production of the gas. This can go a long way in reducing the dependency on kerosene and other oil based sources of fuel, which are presently expensive and scarce to access by the so called urban dwellers, talk more of the marginal small and medium scale farmers residing in rural areas. By using appropriate additives, more volume of gas can be obtained and retention time can also be reduced. Research like these are a key to ensuring cleaner and safer environment through sustainable energy production and better wealth creation.

1.4 Aim and Objectives

The research aims at determining the effect of Single Super Phosphate and Wood ash on biogas production using cow dung and chicken droppings with grass (*Digitaria Smuts II*).

Specific objectives of the study are;

a. To determine the possibility of reducing retention time of the substrate in biogas production
b. To compare the volume of gas produced with and without additives
c. To study the kinetics of biogas production and the cumulative biogas generation using the modified Gompertz equation.
d. To assess and establish the most feasible local environment parameters for optimum performance of the anaerobic digesters.

1.5 Limitation of the Studies

This study is limited to Cow Dung from Kawo Abattoir, Chicken Droppings from Salma Farms, Dan kande Village along Kaduna - Zaria road, fertilizer (single super phosphate) from Kawo market Kaduna with Wood ash and *Digitaria Smuts II* (Wooly Finger Grass) National Animal Protection and Research Institute, NAPRI. The digesters used were designed by late Dr. Sani Mu'azu, department of Biological Sciences, Ahmadu Bello University, Zaria.

CHAPTER TWO

LITERATURE REVIEW

2.1 History of Anaerobic Digestion

Historical evidence indicates that the anaerobic digestion process is one of the oldest technologies (Monnet, 2003). Very old sources indicate that using wastewater and so-called renewable resources for energy supply is not new, but were already known before the birth of Christ (Deublein and Steinhauser, 2008). The Assyrians used it to heat bath water in the 10th century but was historically insignificant, before reappearing in 17th century, when it was observed that decaying organic matter produced flammable gases, again used to heat water (Mahony and O'Flaherty 2002).

The idea that rotten vegetable matter gives off flammable gas has been understood since the Ancient Persians. The first sewage plant was built in Bombay in 1895, when the gas produced was used to light up street lamps (Monnet, 2003). The use of farm manure to generate methane was again developed in Bombay in the 1930s. It was only developed for use by Indian villagers by KVIC (Khadi and Villages Industries Commission) in the early 1960. This design which used a floating steel gas drum formed the basis of an ongoing Indian government outreach program to provide villagers with cooking fuel. China started the same program in the 1960s and claimed that 5million plants had been built by the early 1980s. The design was based on a septic tank. Similar designs were developed by various groups in India and formed the basis of an effective program in Nepal, which is now called BSP (Biogas Sector Partnership). The programs in India, China and Nepal have developed steadily (Maramba, 1978). Interest in Europe has also revived more recently.

China is one of the countries in the world where the use of biogas started at a very early stage (Ahmadu, 2009). In 1920, Mr. Luo Guorui built a biogas digester called "Chinese Guorui Natural Gas store", which was the first hydraulic digester in China, (Ahmadu, 2009). This marked the beginning of rural biogas systems development in China (Fulford, 2011). In 1978, 7 million plants were built, but only 3 million were working. In 2009, about 17 million biogas plants which mainly use underground masonry plants of size 4 to 10 m^3 but less than 50% success was recorded (Fulford, 2011).

In Indonesia, fixed dome type biogas plants of 18m^3 capacity with biogas purification plant have been constructed across communities. Efforts are on to develop the technology to the level of gas bottling and electricity generation, (Widodo and Hendriadi, 2005).

In Africa, efforts are being made to reduce excessive use of wood fuel and biogas technology is being adopted all over the continent. In Rwanda for instance, Kigali Institute of Science and Technology has built sewage systems for overcrowded prisons (10,000 people) using underground masonry plants with 100 m^3 volume, linked to make 1,400 m^3. This development saved 50% of wood for cooking (Fulford, 2011).

In 2006, Biogas Technology West Africa Ltd won the Ashden Award by building sewage systems for hospitals, schools, colleges, etc using underground masonry dome systems of 60 to 160 m^3 volume. The water recovered was used to flush the toilets while gas was collected and used for cooking (Fulford, 2011).

In Nigeria, research into biogas technology and its practical application is on-going, though, has not really received the deserved attention. The Sokoto Energy Research Centre, Usman Danfodio University, Sokoto, has carried out a number of pilot projects on construction of household size digesters. In addition to this the centre has constructed biogas digester plants of 20m^3 capacity at

these locations: NAPRI-Zaria, Zaria prisons, Kiri-kiri Prisons-Lagos, May flower School-Ikene, Ogun State, Ojokoro-Lagos and Maiduguri (Mshandete and Parawira, 2009).

There is a new African initiative to increase the number of biogas plants that was launched in 2007. Ukpabi (2008) stated that the goal of this initiative is to provide 2 million households by 2020 with biogas digesters. However, the number of biogas plants currently in Africa is unknown with most units installed in Tanzania (around 4,000) (Ocwieja, 2010). It has also been estimated that only 60% of these plants have remained in operation (Van-Nes and Nhete, 2007). Ocwieja (2010) opined that the following are some of the reasons responsible for failure or unsatisfactory performance of these biogas systems

i. Mistakes made during the planning stages.
ii. Lack of interest and understanding by the community
iii. Construction faults.
iv. Insufficient maintenance on the system.
v. Misconception of benefits of the system.
vi. Lack of training for new owners on the system, and
vii. Budgeting errors

2.2 Concept of Anaerobic Digestion

Anaerobic digestion is the controlled degradation of organic waste in the absence of oxygen and in the presence of anaerobic micro-organisms (Ojolo *et al.,* 2007). Simplified Process of Biogas Production is shown figure 2.1.

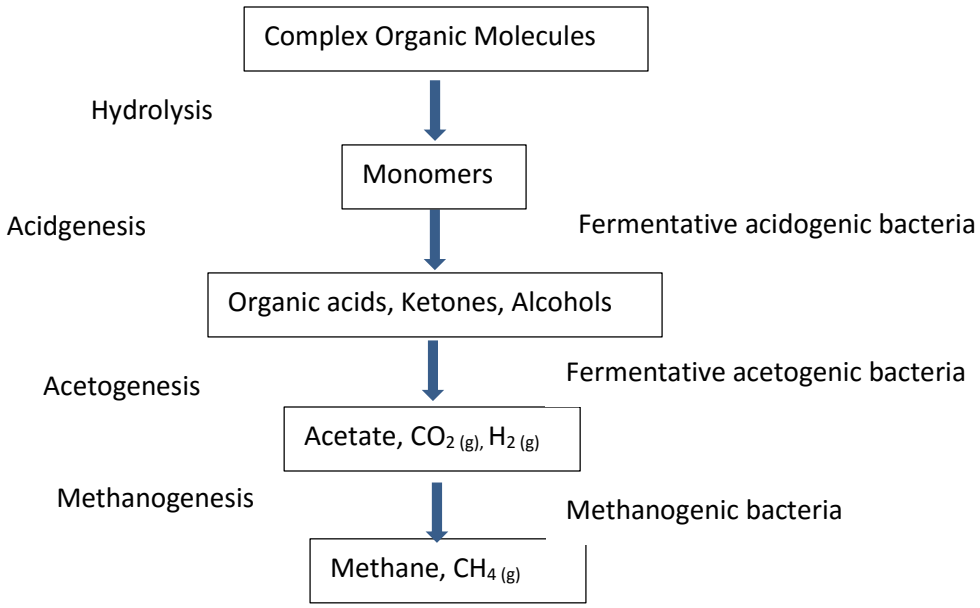


Fig 2.1 Schematic illustrations of the Anaerobic Digestion Process for Biogas Synthesis, (Omolola, 2011)

Anaerobic digestion can be used either to treat biodegradable wastes or produce saleable products such as heat/electricity, soil amendment among others. The most valuable use of anaerobic digestion is to combine both waste management and the use of the bi-products. It is unlikely that anaerobic digestion will be a viable treatment without using the biogas and the digestate. Anaerobic digestion can be further divided into four stages: pre-treatment, digestion, gas upgrading and digestate treatment. The level of pre-treatment depends on the type of feedstock, for example, manures need to be mixed whereas municipal solid wastes (MSW) are sorted and shredded (Monnet, 2003).

The digestion stage takes place in the digester. There are different types of digesters with different temperature and mixing devices. The digestion can be either dry or wet depending on the solid content. This implies that the feedstock can be mixed with water and other appropriate liquid wastes such as sludge or re-circulated liquid from digester effluent (Monnet, 2003).

The final stage which is the upgrading of the biogas is necessary because it may contain impurities that can damage boilers or engines depending on the area of gas application. Hydrogen sulphide and water vapour need to be removed for boilers and combined heat and power units. Removal of carbon dioxide will be required if the gas is to be used as natural gas or vehicle fuel (Monnet, 2003).

2.2.1 Solid Organic Wastes

Solid organic waste has become a social and environmental problem, as a result of an increase in public health concerns and depleted soil resources (Khalid *et al*., 2011). At present, worldwide municipal solid waste generation is about two billion tons per year, which is predicted to increase to 3 billion tons by 2025 (Charles *et al.,* 2009). The "3Rs" (reduce, reuse and recycle) principle aim to encourage the transaction of waste management practice towards a more environmentally friendly and economical direction, to generate the minimum amount of waste, while extracting the maximum uses and benefits from it (EPA, 2013).

Lignocellulosic biomass mainly consists of cellulose, hemicellulose, and lignin. The polysaccharides components (cellulose and hemicellulose) can be converted by different microbial consortia to various types of fuel, such as ethanol, butanol and biogas (Jewell *et al.,* 1993; Zheng *et al.,* 2014). The energy produced from lignocellulosic biomass is believed to be renewable, locally available and "carbon neutral" (Karthikeyan and Visvanathan, 2013; Weiland, 2010).

Cow dung in Nigeria is fast becoming difficult to manage. It has been estimated that Nigeria produces about 227,500 tons of fresh animal wastes daily. Since 1 kg of fresh animal waste produce about 0.03 m^3 biogas, then Nigeria can potentially produce about 6.8 million m^3 of biogas every day from animal waste only (Mshandete and Parawira, 2009). A recent study that assessed Nigeria's biogas potentials (minimum value) from solid waste and livestock excrements revealed

that in 1999, Nigeria's biogas potential represents a total of $1.382x10^9$ m^3 of biogas/year or an annual equivalent of 4.81 million barrels of crude oil (Ojolo *et al*, 2007).

2.2.2 Biochemical Processes in Anaerobic Digestion

Anaerobic digestion is a process in which anaerobic microorganisms digest organic materials in the absence of oxygen. The organic matter are broken down into its simpler chemical components under anaerobic conditions, with the production of methane and carbon dioxide under ideal conditions. The biogas produced in anaerobic digestion plant usually contains small amount of hydrogen sulphide (H_2S) and ammonia (NH_3), as well as trace amount of other gases (Monnet, 2003). Anaerobic Digestion can be used to process any carbon-containing material, including food, paper, sewage, yard trimmings and solid waste, with varying degrees of degradation. The Organic Fraction of Municipal Solid Waste (OFMSW), for example, is a complex substrate that requires an intricate series of metabolic reactions to be degraded (Mata-Alvarez, 2003).

The full process of anaerobic digestion occurs in the following four stages (Igboro, 2011);

i. hydrolysis, in which complex molecules are broken down to constituent monomers;
ii. acidogenesis, in which acids are formed;
iii. acetogenesis, or the production of acetate; and
iv. methanogenesis, the stage in which methane is produced from either acetate or hydrogen.

Mata-Alvarez *et al.* (2003) noted that digestion is not complete until the substrate has undergone all of these stages, each of which has a physiologically unique bacteria population that requires disparate environmental conditions.

Hydrolysis:

In the first stage, complex organic materials are broken down into their constituent parts in a process known as hydrolysis. The result is soluble monomers: Proteins are converted to amino acids; fats to fatty acids, glycerol and triglycerides; complex carbohydrates such as polysaccharides, cellulose, lignin, starch and fiber are converted to simple sugars, such as glucose. Fermentative bacteria are responsible for the creation of monomers, which are then available to the next group of bacteria. Hydrolysis is catalyzed by enzymes excreted from the bacteria, such as cellulase, protease, and lipase. If the feedstock is complex, the hydrolytic phase is relatively slow. This is especially true for raw cellulolytic waste, which contains lignin (Mata-Alvarez *et al.*, 2003). For this reason, woody waste is not an ideal feedstock for the Anaerobic Digestion process. Carbohydrates, on the other hand, are known to be more rapidly converted via hydrolysis to simple sugars and subsequently fermented to volatile fatty acids (Mata-Alvarez *et al.*, 2003).

An approximate chemical formula for the mixture of organic waste is $C_6H_{10}O_4$. A hydrolysis reaction where organic waste is broken down into a simple sugar, in this case glucose can be represented by the following: (Themelis and Verma, 2004, Igboro, 2011).

$$C_6H_{10}O_4 + 2H_2O = C_6H_{12}O_6 + 2H_2 \qquad (2.1)$$

Acidogenesis:

Hydrolysis is immediately followed by the acid-forming phase of acidogenesis. In this process, acidogenic bacteria turn the products of hydrolysis into simple organic compounds, mostly short chain (volatile) acids (e.g., propionic, formic, lactic, butyric, or succinic acids), ketones (e.g., ethanol, methanol, glycerol, Acetone) and alcohols. The specific concentrations of products

formed in this stage vary with the type of bacteria as well as with culture conditions, such as temperature and pH (Ostream, 2004).

Typical reactions in the acid-forming stages is shown in equation (2.2). The equation expresses how glucose is converted to ethanol.

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \qquad (2.2)$$

Acetogenesis:

The next stage of acetogenesis is often considered with acidogenesis to be part of a single acid forming stage. Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are reduced through these pathways. Acetogenesis occurs through carbohydrate fermentation, in which acetate is the main product, and other metabolic processes (Themelis and Verma, 2004). The result is a combination of acetate, CO_2, and H_2. The role of hydrogen as an intermediary is of critical importance to Anaerobic Digestion reactions. Long chain fatty acids, formed from the hydrolysis of lipids are oxidized to acetate or propionate and hydrogen gas is formed. Under standard conditions, the presence of hydrogen in the solution inhibits the oxidation. The reaction only proceeds if the hydrogen partial pressure is low enough to thermodynamically allow the conversion (Mata-Alvarez *et al*, 2003). The presence of Hydrogen Scavenging Bacteria (HMBs) that consume hydrogen, thus lowering the partial pressure, is necessary to ensure thermodynamic feasibility and thus the conversion of all the acids. Concentration of hydrogen, measured by partial pressure, is an indicator of the health of a digester (Mata-Alvarez *et al*, 2003).

For example, the free energy value of the reaction that converts propionate to acetate, shown in equation (2.4), is +76.1kJ, so that this reaction is thermodynamically impractical. When acetate and hydrogen are consumed by bacteria, however, the free energy becomes negative. In general,

for reactions producing H_2, it is necessary for hydrogen to have a low partial pressure for the reaction to proceed.

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \quad (2.3)$$

Other important reactions in the acetogenic stage involve the conversion of glucose (equation 2.5), ethanol (equation 2.6) and bicarbonate (equation 2.7) to acetate.

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (2.4)$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+ \quad (2.5)$$

$$2HCO_3^- + 4H_2 + H^+ \leftrightarrow CH_3COO^- + 4H_2O \quad (2.6)$$

The transition of the substrate from organic material to organic acids in the acid forming stages causes the pH of the system to drop. This is beneficial for the acidogenic and acetogenic bacteria that prefer a slightly acidic environment, with a pH of 4.5 to 5.5, and are less sensitive to changes in the incoming feed stream. On the other hand, this drop in pH is problematic for the bacteria involved in the next stage of methanogenesis (Igboro, 2011).

Methanogenesis:

Finally, in the last stage methane is produced by bacteria called methane formers (also known as methanogens). The methanogenic anaerobic bacteria involved in this stage, known as methanogenesis or methane fermentation, are the same fastidious bacteria that occur naturally in deep sediments or in the rumen of herbivores (Igboro, 2011). They carry out methane formation either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digesters results in that the acetate reaction

is the primary producer of methane (Monnet, 2003). The methanogenic bacteria include *methanobacterium, methanobacillus, methanococcus and methanosarcina*. Methanogens can also be divided into two groups: acetate and H_2/CO_2 consumers. *Methanosarcina spp*. and *methanothrix spp.* (also, methanosaeta) are considered to be important in anaerobic digestion both as acetate and H_2/CO_2 consumers. The methanogenesis reactions can be expressed as follows:

$$\underset{\text{(Acetic acid)}}{CH_3COOH} \rightarrow \underset{\text{(Methane)}}{CH_4} + \underset{\text{(Carbon dioxide)}}{CO_2} \quad (2.7)$$

$$\underset{\text{(Ethanol)}}{2CH_3CH_aOH} + \underset{\text{(Carbon dioxide)}}{CO_2} \rightarrow \underset{\text{(Methane)}}{CH_4} + \underset{\text{(Acetic acid)}}{2CH_3COOH} \quad (2.8)$$

$$\underset{\text{(Carbon dioxide)}}{CO_2} + \underset{\text{(Hydrogen)}}{4H_2} \rightarrow \underset{\text{(Methane)}}{CH4} + \underset{\text{(Water)}}{2H_2O} \quad (2.9)$$

Equations 2.8-2.10 show that many products, bye products and intermediates are produced in the process of anaerobic digestion of organic wastes before the final product (methane) is produced (Verma, 2002).

Igboro (2011) noted that, methanogens are very sensitive to changes and prefer a neutral to slightly alkaline environment. If the pH is allowed to fall below 6, methanogenic bacteria cannot survive. Methanogenesis is the rate-controlling portion of the process because methanogens have a much slower growth rate than acidogens.

Although anaerobic digestion can be considered to take place in these four stages, all processes occur simultaneously and synergistically, since the first group has to perform its metabolic action before the next can take over, and so forth (Alfa, 2012).

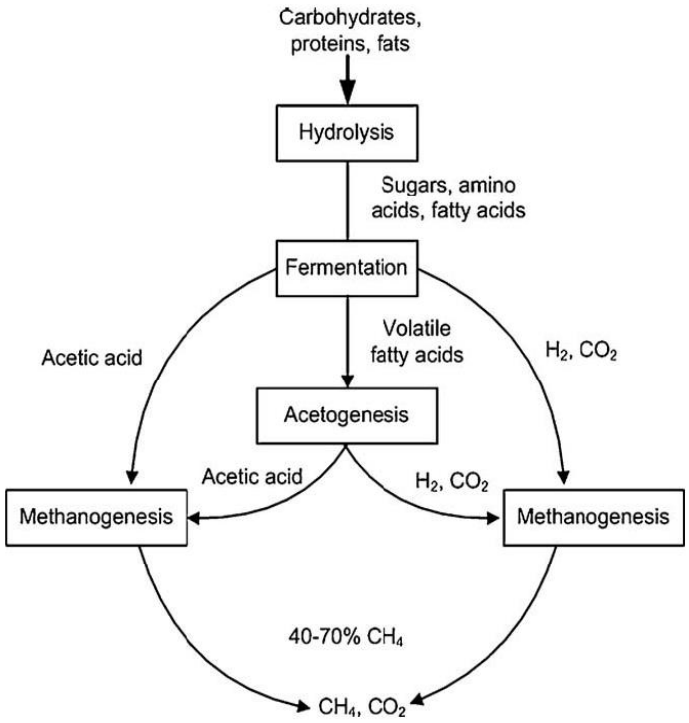


Fig. 2.2 Process flow during anaerobic digestion. (Li *et al*., 2011)

Figure 2.2 shows the schematic representation of stages of Anaerobic Digestion.

2.2.3 Factors Affecting Anaerobic Digestion Process

The complete process of anaerobic digestion requires a complex interaction of several varieties of bacteria that must be in equilibrium in order for the digester to remain stable. Changes in environmental conditions can disturb the equilibrium and result in the buildup of intermediaries that may inhibit the overall process or shut it down altogether. It is crucial for the manager to use design control technologies to continually monitor and adjust the environment to prevent this. Several factors within the digester affect the physical environment and therefore the rate of digestion and biogas production. Thus, the following parameters must be monitored and maintained within acceptable ranges: pH, temperature, C/N ratio, retention time, organic loading rate (OLR), bacterial competition, nutrient content, the presence of toxicants and solids content.

According to Igboro (2011), the important parameters in which failure to follow can cause digester failure or low gas production are;

Total solid content

Anaerobic digestion processes can be classified according to the total solids (TS) content of the slurry in the digester reactor. Low solids systems (LS) contain less than 10 % TS, medium solids (MS) contain about 15%-20%, and high solids (HS) processes range from 22% to 40% (Verma, 2002, Monnet, 2003). When the total solid content is increased, the volume of the digester decreases, due to low water requirements (Monnet, 2003).

Carbon/Nitrogen ratio in digester feedstock

The Carbon/Nitrogen Ratio (C/N) is a measure of the relative amounts of organic carbon and nitrogen present in the feedstock. This ratio may either be monitored explicitly or managers may simply keep track of the types of waste entering the facility, knowing the relative make-up of each. For example, proteins such as meats are high in nitrogen while paper products contribute relatively more carbon. If a feedstock is high in carbon, manure can also be added to increase nitrogen. As with composting, the optimum C/N ratio is within 20-30, with most sources citing 25 as the ideal level. A low C/N ratio, or too much nitrogen, can cause ammonia to accumulate which would lead to pH values above 8.5. Additionally, the quality of the compost is lessened with high ammonia production. A high C/N ratio will lead to a rapid consumption of nitrogen by the *methanogenic* bacteria and lower gas production rates (Gas Technology, 2003).

Temperature

There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic and thermophilic ranges. The mesophilic range is between

20°C-40°C and the optimum temperature is considered to be 30°C-35°C. The thermophilic temperature range is between 50°C-65°C (Verma, 2002). It has been observed that higher temperatures in the thermophilic range reduce the required retention time (Verma, 2002).

The optimum temperature of digestion may vary depending on feedstock composition and type of digester, but in most anaerobic digestion processes, it should be maintained relatively constant to sustain the gas production rate (Monnet, 2003).

pH

The pH values of the input mixture play very important role in methane formation. The acidic condition is not favourable for methanogenic process. The optimum biogas production is achieved when the pH value of input mixture in the digester is between 6 and 7. The pH in a biogas digester is also a function of the retention time. In the initial period of fermentation, as large amounts of organic acids are produced by acid forming bacteria, the pH inside the digester can decrease to below 5. This inhibits or even stops the digestion or fermentation process. Methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6.0 (Karki *et al.*, 2005).

Retention Time:

Karki *et al.* (2005) outlined the following approximate values of retention time:

i. Liquid cow manure: 20-30 days
ii. Liquid pig manure: 15-25 days
iii. Liquid chicken manure: 20-40 days
iv. Animal manure mixed with plant material: 50-80 days

Retention time (also detention time) is the average duration of time a sample remains in the digester. In a cow-dung plant, the detention time is calculated by dividing the total volume of the digester by the volume of slurry added daily. Usually, for a cow-dung plant a detention time of 40

to 60 days is required depending upon the temperature. Thus, the fermenting pit should have a volume of from 40 to 60 times the slurry added daily. But for a night-soil digester, a longer detention time (70 to 90 days) is needed in order to kill the pathogens present in human faeces (Alfa, 2013).

If the retention time is too short, the bacteria in the digester are "washed out" faster than they can reproduce, so that the fermentation practically comes to a standstill. This problem rarely occurs in agricultural biogas systems. Moreover, the required retention time for completion of the anaerobic digestion reactions varies with differing technologies, process temperature, and waste composition. The retention time for wastes treated in mesophilic digester range from 10 to 40 days (Verma, 2002).

Volatile Solids (VS)/Organic Loading Rate (OLR)

Volatile Solids (VS) represents the organic matter in a sample which is measured as solid content minus ash content, as obtained by complete combustion of the feed wastes. Volatile Solid comprises the biodegradable volatile solid (BVS) fraction and the refractory volatile solid (RVS). High volatile solid content with low RVS is more suitable for anaerobic digestion (Monnet, 2003, Verma, 2002).

Organic loading rate is a measure of the biological conversion capacity of the anaerobic digestion system. Feeding the system above its sustainable OLR results in low biogas yield due to accumulation of inhibiting substances in the digester slurry (i.e. fatty acids) under such circumstances, the feeding rate of the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failure due to overloading. OLR is expressed in kg Chemical Oxygen Demand (COD) or Volatile solids (VS)

per cubic meter of reactor. It is linked with retention time for any particular feedstock and anaerobic reactor volume (Monnet, 2003).

Mixing Anaerobic Digester Content

Mixing within the digester improves the contact between the micro-organisms and substrate and improves bacterial population's ability to obtain nutrients. Mixing also prevents the formation of scum and the development of temperature gradients within the digester. However, excessive mixing can disrupt the micro-organisms and therefore slow mixing is preferred (Monnet, 2003).

In case of co-digestion, the different feedstock should be mixed before entering the digester to ensure a sufficient homogeneity (Monet, 2003).

A well agitated substrate can, leaving other parameters constant, increase biogas production by 50% (Kossman *et al*, 2000).

Dilution and Consistency of Inputs

Before feeding the digester, the excreta such as fresh cattle dung has to be mixed thoroughly with water. For proper solubilization of organic materials, the ratio between solid and water should be 1:1 on unit volume basis (i.e. same volume of water for a given volume of solid) when the domestic wastes are used. The dilution should be made to maintain the total solids (TS) from 5 to 10 percent. If the slurry mixture is too diluted, the solid particles can precipitate at the bottom of the digester and if it is too thick, the flow of gas can be impeded. In both cases, gas production will be less than optimum value (Alfa, 2013).

Inhibition and Toxicity

Mineral ions, heavy metals and the detergents used in livestock husbandry are some of the toxic materials that inhibit the normal growth of pathogens in the digester. Small quantity of mineral

ions (e.g. sodium, potassium, calcium, magnesium, ammonium and sulphur) also stimulates the growth of bacteria, while very heavy concentration of these ions will have toxic effect (Karki *et al*, 2005).

2.2.4 End Products of Anaerobic Digestion.

Anaerobic digestion is a cost effective way to manage biodegradable waste because it produces biogas and digestate. The use or sale of both can provide great financial incomes. However, in order to obtain the maximum value from these products, further processing may be necessary (Monnet, 2003). The components of the biogas depend on the process of digestion, but are predominately methane and carbon dioxide (Igboro, 2011).

The solid is a humus-like stable, organic material, the quality and subsequent use of which is determined by the characteristics of the feedstock to the anaerobic digestion process. The liquid contains soluble materials, including dissolved organic compounds (Igboro, 2011).

Many European communities are recently embracing the anaerobic digestion as waste management application following the strict environmental regulations of abatement of greenhouse gases. Anaerobic digestion technology is a proven energy yielding and odor removal process applicable in converting organic and biological content of waste into biogas and other residual by-products which can be further reprocessed for secondary applications. (Omolola, 2007).

Unique in its features, anaerobic digestion not only mitigates pollution problems but also is a cost effective reliable technique solution for dependable fuel, electric and heat generations for cleaner and healthier environments.

2.3 Biogas

Bacteria degradation of organic matter in the absence of oxygen known as Anaerobic Digestion generates biogas. The anaerobic digestion is an effective proven technology for handling and treating biological wastes and effluents which is used to generate heat and electricity, which is an effective means to clean our environment.

2.3.1 Key Drivers for biogas production

The major influential key factors for search of alternative renewable fuel are;

a. Oil Independence
b. Reduced Emissions
c. Rural Development and Value Added Agriculture

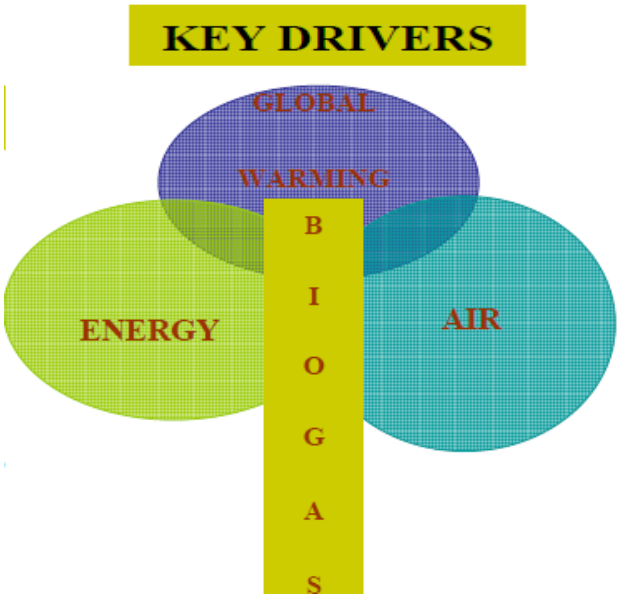


Fig. 2.3 Key drivers of biogas Production (Omolola, 2007).

Figure 2.3 shows the three key importance of biogas which can simply be put as reducing global warming through reduction of CO_2 emission resulting from clean energy. In addition, the process helps in improving air quality.

2.3.2 Biogas Composition

Biogas is the mixture of gas produced by methanogenic bacteria while acting upon bio degradable materials in an anaerobic condition. This gas is primarily composed of 50 to 70% methane (CH_4) and 30 to 40% carbon dioxide (CO_2), with smaller amounts of hydrohen sulphide (H_2S) and ammonia (NH_3). Trace amounts of hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), saturated or halogenated carbohydrates and oxygen (O_2) are occasionally present in the biogas. Usually the mixed gas is saturated with water vapour and may contain dust particles (Monnet, 2003). Methane is virtually odorless and colorless. It burns with a smokeless clear blue flame and is nontoxic.

However the main constituents of biogas are CH_4 and CO_2 gases. Biogas burns very well when the CH_4 content is more than 50%. Therefore, biogas can be used as a substitute for kerosene, charcoal, and firewood for cooking and lighting. This saves time and money and above all it conserves the natural resources such as cutting trees to get firewood (Fumen and Igboro, 2010).

The composition of biogas is different from that of natural gas but it is quite similar to landfill gas which often contains significant amounts of halogenated compounds and occasionally oxygen content when too much air is sucked during the collection on the landfill. The calorific value is 36.14 MJ/m^3 for natural gas and 21.48 MJ/m^3 for biogas (Monnet, 2003, Hullu, 2008). The methane content and hence the calorific value is higher with longer digestion process. The methane content falls to as little as 50% if retention time is short.

The first gas from a newly filled biogas plant contains too little methane. The gas formed in the first three to five days must therefore be discharged unused. The methane content depends on the digestion temperature. Low digestion temperatures give high methane content, but less gas is then produced (Sasse, 1988). The methane content also depends on the feed material. Some typical values of methane content for different feed materials (in %) are; Cattle manure 65, Poultry manure

60, Pig manure 52, Farmyard manure 55, Straw 59, Grass 70, Leaves 58, Kitchen waste 50, Algae 63, and Water hyacinths 60 respectively (Sasse, 1988). Biogas is somewhat lighter than air and has an ignition temperature of approximately 700°C (diesel oil 350°C; petrol and propane about 500°C). The temperature of the flame is 870°C (Sasse, 1988).

2.3.3 Advantages and disadvantages of biogas

Advantages

i. Renewable Source of Energy;

Biogas is considered to be a renewable source of energy. Since is often produce from materials that form sewage and waste products, the only time it will be depleted is when we stop producing waste.

ii. Non Polluting:

It is also considered to be non-polluting in nature. The production of biogas does not require oxygen, which means resources are conserved by not using any further fuel.

iii. Reduces Landfills:

It also uses up waste material found in landfills, dump sites and even farms across the country, allowing for decreased soil and water pollution.

iv. Cheaper Technology:

Application for biogas are increasing as the technology to utilize it gets better. It can be used to produce electricity and for the purpose of heating as well. Production can be carried out through many small plants or one large plant.

v. Jobs Creation:

Large number of jobs can be created through biogas technologies, especially in the rural areas.

vi. Little Capital Investment:

Biogas are relatively easy to set up and require little capital investment on a small scale basis. Farms can easily produce sufficient gas for its use from wastes generate by livestock, poultry and or crops.

vii. Reduces Greenhouse Effect:

It also reduces the greenhouse effect by utilizing the gases being produced in landfills as forms of energy. It recycles most forms of biodegradable waste and works on simple forms of technology.

Disadvantages

i. Contains Impurities:

Biogas contains a number of impurities even after refining process have been put in place. When compressed for use as fuel, these can become corrosive to the metal part of an engine.

ii. Not Attractive on Large Scale:

The process of using biogas on large scale is not economically viable and is difficult to enhance the efficiency of biogas systems.

iii. Little Technology Advancement:

Little new technology has been introduced for streaming the process and making it more cost effective. As a result, large scale industrial biogas production is still not on the energy map. Although it could solve the energy issues being faced by countries all over the world, very few investors are willing to put in the startup capital.

iv. Unstable:

It is also somewhat unstable, making it prone to explosions if the methane comes in contact with oxygen and become flammable in nature.

2.3.4 Uses of Biogas

Like any other fuel, biogas can be used for household and industrial purposes; the main prerequisite being the availability of especially designed biogas burners or modified consumers appliances (Alfa, 2013). Possible use of biogas as energy source is shown in figure 2.4.

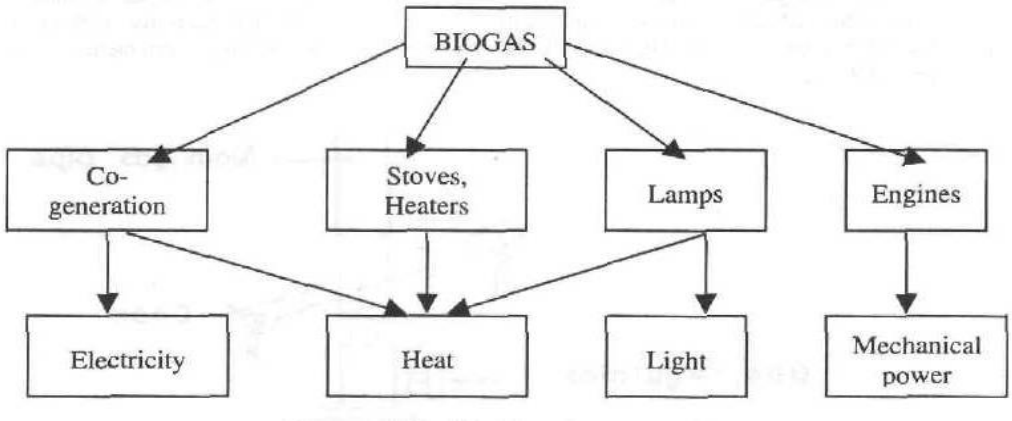


Fig 2.4 Possible Uses of Biogas (Karki *et al.*, 2005).

Uses of biogas according to (Alfa, 2013), are;

i. Cooking

Cooking is by far the most important use of biogas in the developing world. Biogas burners or stoves for domestic cooking work satisfactorily under a water pressure of 75 to 85 mm. The stoves may be single or double varying in capacity from 0.22 to 1.10 m^3 gas consumption per hour.

ii. Lighting

Biogas can be used for lighting in non-electrified rural areas. Special types of gauze mantle lamps consuming 0.07 to 0.14 m^3 of gas per hour are used for household lighting.

iii. Refrigeration

Biogas can be used for absorption type refrigerating machines operating on ammonia and water, and equipped with automatic thermo-siphon. Since biogas is only the refrigerator's external source of heat, the burner itself has to be modified. Refrigerators that are run with kerosene flame could be adapted to run on biogas.

iv. Biogas-fueled engines

Biogas can be used to operate four stroke diesel and spark ignition engines. Biogas engines are generally suitable for powering vehicles like tractors and light duty trucks as has been successfully experimented in China. When biogas is used to fuel such engines, it may be necessary to reduce the hydrogen sulphide content if it is more than 2 percent. Using biogas to fuel vehicles is not so much of an attractive proposition as it would require carrying huge gas tanks on the vehicle.

One of the uses of biogas, which has wide application in Nepal, is to fuel engines to run irrigation pumps. A dual-fuel engine is available in India, which will run on a mixture of biogas and diesel (80% biogas and 20% diesel).

v. Electricity generation

Generating electricity is a much more efficient use of biogas than using it for gas light. From energy utilization point of view, it is more economical to use biogas to generate electricity for lighting. In this process, the gas consumption is about 0.75 m^3 per kW hour with which 25 40-watt lamps can be lighted for one hour, whereas the same volume of biogas can serve only seven lamps for one hour (Karki *et al.*, 2005).

Small internal combustion engines with generator can be used to produce electricity in the rural areas with clustered dwellings. Biodigesters can be used to treat municipal waste and generate

electricity (Karki *et al.*, 2005). One of the options to utilize biogas is to produce electricity using a gas engine or gas turbine.

Other benefits of biogas include; (Igboro, 2011)

1. Improvement of hygienic conditions through reduction of pathogens, worm eggs and flies;
2. Environmental advantages through protection of soil, water, air and woody vegetation;
3. Reduction of workload, mainly for women, in firewood collection and cooking.
4. Micro-economic benefits through energy and fertilizer substitution, additional income sources and increasing yields of animal husbandry and agriculture;
5. Macro-economical benefits through decentralized energy generation and import substitution.

Thus, biogas technology can substantially contribute to conservation and development, if the concrete conditions are favourable (Igboro, 2011).

2.3.5 Effects of Biogas System

Biogas technology if properly harnessed will greatly impact positively on the socioeconomic life of rural dwellers, aside the fact that is a source of clean energy.

The use of energy and manure can lead to better environment, health, and other socio-economic gains (Shrestha, 2010; Igboro, 2011).

Biogas technology is best suited to convert the organic waste from agriculture, livestock, industries, municipalities and other human activities into energy and manure (Alfa, 2011).

2.3.6 Upgrading Biogas

Biogas can be used for all appliances designed for natural gas, subject to some further upgrading, as not all gas appliances require gas with the same quality standards. For instance, when used for heating in boilers, it is preferable to remove the hydrogen sulphide because it forms sulphurous

acid in the condensate which is highly corrosive. It is also recommended to condense the water vapour in the raw gas because water vapour can cause problems in the gas nozzles. Removal of water vapour will also remove hydrogen sulphide (Monnet, 2003).

a. Carbon dioxide removal:

Removal of carbon dioxide enhances the energy of the gas either to reach vehicle fuel standard or natural quality gas. At the present, four different methods are used commercially to achieve this (Monnet, 2003, Hullu, 2008). They are:

i. Water scrubbing
ii. Polyethylene glycol scrubbing
iii. Carbon molecular sieves
iv. Membrane separation

b. Hydrogen Sulphide Removal:

Hydrogen sulphide must be removed in order to avoid corrosion. The most common methods for hydrogen sulphide removal are (Muche, *et al*., 1985; Monnet, 2003; Hullu, 2008):

i. Lime scrubbing;
ii. Air/oxygen dosing to digester biogas;
iii. Iron chloride dosing to digester slurry;
iv. Iron oxide;
v. Activated carbon;
vi. Water scrubbing and
vii. NaOH scrubbing

Biological desulphurization of biogas can be performed by micro-organisms. Most of the sulphide-oxidizing micro-organisms belong to the family of *Thiobacillus* and it is essential to add stoichiometric amounts of oxygen to the biogas (Monnet, 2003).

2.4 Digestate

Anaerobic digestion can be seen as a method to treat the organic wastes but, in order to extract the maximum recovery value from these wastes, the digester should have a useful purpose and benefit should be derived from its production (Monnet, 2003).

Anaerobic digestion draws up carbon, hydrogen and oxygen from the feedstock. Meanwhile, essential plant nutrients (nitrogen (N), phosphorus (P) and potassium (K)) remain largely in the digestate. Its main advantage is that it has a high nutrient content. The availability of nutrients is higher in digestate than in untreated organic waste. For instance, digestate has 25% more accessible NH4-N (inorganic nitrogen) and a higher pH value than untreated liquid manure (Monnet, 2003). More so, it reduces the odour nuisance by about 80%.

(Mata- Alvarez *et al.* 2003) noted that the quality and composition of the dewatered solid depend on the feedstock and the digestion process. Additionally, even if digestion were allowed to proceed for long time periods, a maximum of only about 70% of the total organics are available for degradation.

(Monnet, 2003) noted that the dewatering separates the digestate into two fractions: the fibre and the liquor. He further stated that, because the fibre is bulky and contains a low level of plant nutrients, it can be used as a soil conditioner and as low grade fertilizer. In addition, further processing of the fibre such as through composting can produce a good quality compost.

The liquor (liquid effluent) on the other hand contains a large proportion of nutrients and can be used as a fertilizer. The high water content of the liquor facilitates its application through

conventional irrigation methods. Furthermore, consideration has to be given to the application time so that nitrogen which is readily available after digestion is taken by the crop and not leached into soil and subsequently groundwater. Nonetheless, it has advantages over raw manure applications, as the ammonia uptake by plants is higher than for organic nitrogen (Monnet, 2003).

The use of fibre and liquor from anaerobic digestion has led to improved fertilizer utilization and therefore less chemical consumption in cropping systems. In other to obtain high quality product, with a higher value, the digestate, can be processed into compost. It would ensure a complete breakdown of the organic components as well as fixing the mineral nitrogen onto humus-like fraction which would reduce nitrogen loss. As an additive to composting process, it provides a good source of nitrogen for speeding up the process. At same time, it enriches the compost in phosphorus and micro nutrients like magnesium (Mg) and iron (Fe). The water content of the digestate is also interesting for moisture management in the composting process (Monnet, 2003).

According to Mata- Alvarez et al. (2003) the safety of the digestate, measured by the concentration of pathogens present, is of great concern to end users. Pathogen destruction can be guaranteed at thermophilic temperatures with a high SRT (solid retention time). A sufficient degree of pathogen destruction can also occur at mesophilic temperatures and at lower SRT. In general, the lower the SRT, the more biologically active the solid will be. If solid digestion has occurred for at least 15 days, most of the organics would have been degraded and the resulting solid is stable. If anaerobic digestion is being used strictly to reduce the volume of the waste before going to landfill, then biological activity, measured by BOD, of the digestate should be reduced as much as possible. If, on the other hand, the digestate will be used as a soil amendment, a biologically active solid is beneficial.

2.5 Suitable Wastes For Anaerobic Digestion

Anaerobic digestion is suitable for the treating of a wide range of organic waste (Monnet, 2003). These include:

a. Agricultural materials such as liquid manure, energy crops and crop residues (Ley crops, maize, straw, sugar beet), silages (grass silage, maize silage), vegetable wastes
b. Industrial residues such as distillery wastes (Stillage), whey, and pomace.
c. Municipal wastes such as source separated solid organic wastes.
d. Municipal wastewaters and sewage treatment Plants
e. Animal manures and slaughtery wastes. (O. Jönsson, ENGVA 2001, Malmö)

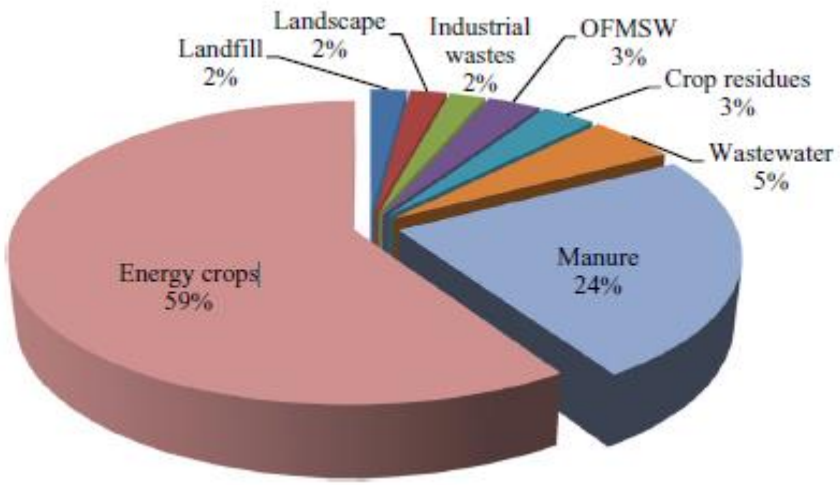


Fig. 2.5 Biogas potential of AD substrates from different sources (*Xu et al. 2015*)

2.5.1 Anaerobic Co-digestion

The anaerobic co-digestion is the simultaneous treatment of more than one substrate in the same digester. According to Mata-Alvarez (2003), the mixing of several wastes types has positive effects

on the anaerobic digestion process because it improves the methane yield, improves the process stability and achieves a better handling of the waste. In addition, such a system is economically more favourable as it combines different waste streams in one common treatment facility. To enhance biogas production and assist in municipal organic waste management, anaerobic digestion with the addition of co-substrates, i.e. co-digestion, has been considered an effective, low-cost, and commercially flexible approach to reduce process limitations and improve methane yields (Alatrise-Mondragon *et al.,* 2006). Anaerobic co-digestion process with the addition of low-cost municipal organic wastes could also be given consideration and as such, municipally available organic wastes including fats, oils and grease (FOG) and kitchen waste (KW), could be employed as the potential co-substrates (Cotrell, 2008) recorded a 50% increase in biogas generation at a full-scale digester using FOG as a co-substrate (Kabouris *et al*., 2008) also investigated FOG as a co-substrate and reported significantly higher methane generation. (Li *et al*., 2002; Gunaseelan, 2004; Carucci *et al*., 2005; Gómez *et al*., 2006; Labatut *et al*., 2010) evaluated food wastes as co-substrates and succeeded in enhancing methane yield production. However, the physical and chemical nature of organic wastes and inocula can vary considerably, and the organic waste loading rate to the anaerobic digesters is critical in pilot or full-scale applications (Gelegenis *et al*., 2007).

2.6 Modelling of Anaerobic Digestion Technology

Modelling means different things to different people. Different models can be used to provide different set of information. Models can generally be classified as optimization models and simulation models.

i. Optimization Models; These are the types of models which are built and run in order to give an idea of what combination of what can be used to have a certain desirable outcome.

ii. Simulation Models tells the outcome of a situation where you have given it a whole lots of pre-defined inputs.

2.6.1 Kinetics-based models

The Anaerobic Digestion modeling started in the early 1970s when the need for design and efficient operation of anaerobic systems became evident (Gavala *et al.,* 2003). Models that are based on reaction kinetics are one type of "white box" models which aim to accurately describe the chemical and biological processes occurring during AD process (Lauwers *et al.,* 2013).

Anaerobic Digestion Model No.1 (ADM1)

One of the most famous and comprehensive AD dynamic models is the Anaerobic Digestion Model No. 1 (ADM1) (Batstone *et al.,* 2002). Aiming to "be as widely applicable as possible for anaerobic process", ADM1 was developed to be a relatively general and comprehensive model, with 19 biochemical processes involved and the related coefficients reviewed. Developed based on the merits of many previous AD models, ADM1 has been verified and utilized as the basis for many following researches (Batstone *et al.,* 2006; Lee *et al.,* 2009).

2.6.2 Models for Solid State Anaerobic Digestion (SS-AD)

The three most cited types of models for SS-AD of OFMSW are discussed as follows. These models all assume spatial separation of acetogenesis and methanogenesis. However, they also have unique features based on their assumptions and focuses.

i. Two-particle model

A “two-particle” model was proposed for the SS-AD of OFMSW aiming to facilitate the process control and optimization (Kalyuzhnyi *et al.,* 2000). To describe the process which adds about 50% of methanogenic seed sludge to feedstocks for SS-AD, the model assumes two different types of organic materials in the digester: “seed particles” that have low biodegradability but high methanogenic activity, and “waste particles” that has high biodegradability and low methanogenic activities. All “seed particles” and “waste particles” are homogenous inside, and tightly attached to each other, while there is no exchanged of microbes between particles. The “waste” particles provide VFAs to “seed particles” by diffusion, thus no water flow exists (Fuqin Xu, 2014). The physical process of this concept was illustrated in Figure 2.6.

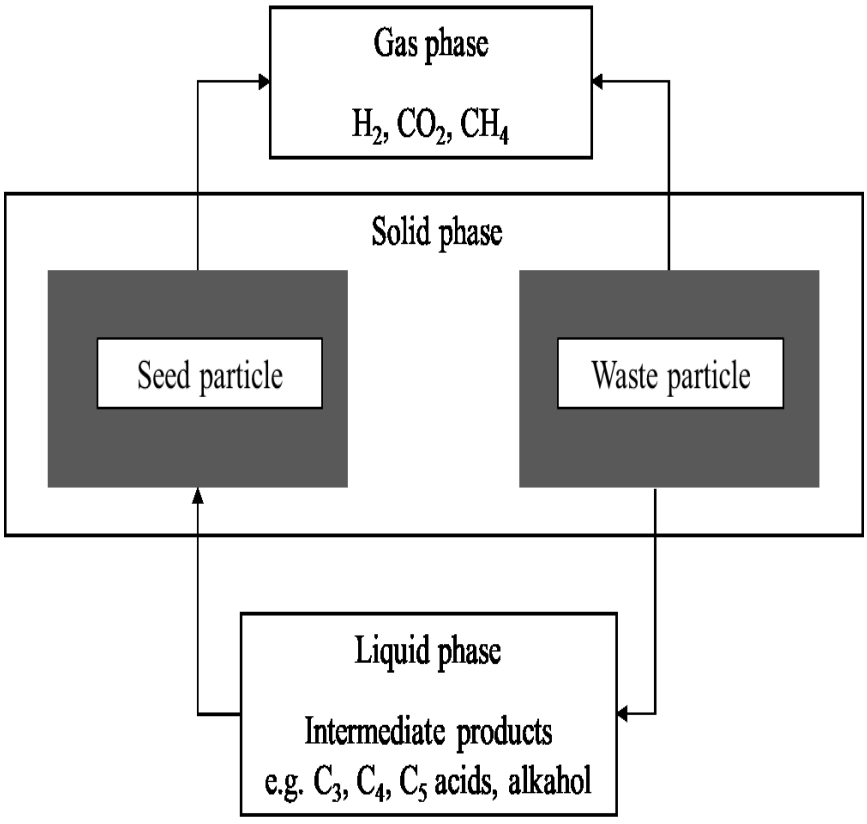


Fig. 2.6 Schematic representation of “two-particle” model of SS-AD Adapted from (Kalyuzhuyi *et al.,* 2000)

The physical process of this model was similar with many lab scale SS-AD system thus can provide good reference for future model development. However, the length of "seed" and "waste" particles are hard to measure or control in reality, and the effect of different TS content is not considered in this model.

ii. Reaction front model

Observing the phenomenon in landfill that the rapid acidogenesis from organic wastes does not cause significant pH change in some methanogenic zones, a hypothesis was proposed that methanogenic sites are protected from VFAs by mass-transfer resistant pockets formed by decomposed "lean" material (Martin, 2001).

Similar with the "two-particle" model, this hypothesis also depicted a spatial separation of acetogenesis and methanogenesis in distinct zones, and solutes diffused between zones was based on Fick's law. However, development was made based on "two particle" model by dividing the substrates into "rich zones" with easily digestible material and fast VFA production, and "lean" zones with relatively inert materials (Martin, 1999). The "lean" zone can form a thick buffering zone between "acid pocket" and methanogenic zones, and became a "reaction front" around "seed bodies" (methanogenic sites). The overall rate of waste stabilization was determined by the rate of the advance of this multi-zoned "reaction front", and mass transfer processes occur between these zones could be rate-limiting (Fuqin Xu, 2014).

iii. Distributed model

Considering the poor mass transfer and acid inhibition in engineered landfills and bioreactors, Vavilin et al. (2002, 2003, 2004) developed a series of models that consider the vertical mass transfer by leachate (1D distributed model) and horizontal mixing in cylinder reactor (2D distributed model). Vavilin's models also confirmed the importance of spatial separation of the

initial methanogenic centers from active acidogenic areas at high organic loading rates, and the simulation suggested that vigorous mixing and leachate recirculation can disperse the methanogenic centers and inhibit microbial growth (Vavilin and Angelidaki, 2005).

Compared with previous models, Vavilin *et al*. (2002) simplified the biological processes by dividing organic waste into food waste (easily degradable) and non-food waste (slower hydrolysis), and only acetate was used to represent VFAs, instead of including the reaction stoichiometry for the production of each VFA. This model also only focuses on hydrolysis and methanogenesis as two rate limiting steps (Ma *et al.*, 2013; Mata-Alvarez *et al.*, 2000).

2.6.3 Data-based models for SS-AD

Data-based models aim to predict process output based on previously obtained patterns of data, without with requirement of deep understanding of the underlying mechanisms of the process (Lauwers *et al.*, 2013). Several commonly used methods for process output (e.g. methane yield, methane content, VFA concentration and pH) prediction include multiple linear regression (Motte et al., 2013), partial least square regression (Appels *et al.*, 2011; Mottet *et al.*, 2010), logistic regression (Pommier *et al.*, 2007) and artificial neural network (Ozkaya *et al.*, 2007; Sinha *et al.*, 2002).

According to literature, the application of data-based models are generally focusing on two aspects: One is to predict the biochemical methane potential (BMP) or ultimate methane yield of certain feedstocks/or feedstock combinations based on their chemical compositions, where the experimental data were usually obtained under the same digestion conditions. Another is using fixed types of feedstock and analyze system output under different process parameters, such as hydraulic retention time (HRT), organic loading rate (OLR) and alkalinity (Angelidaki et al., 2009;

Raposo *et al.*, 2012). However, currently, limited study were found to predict the actual methane yield of new feedstocks under different process parameters, especially for SS-AD.

This part of review aimed to introduce several commonly used data-based models for system output prediction and process optimization. The models were classified into statistical models and artificial neural networks (ANN) models. The conditions, limitations and examples of the application of each method were discussed.

Statistical models

1. Simple linear regression

Simple linear regression is one of the most basic statistical methods that correlate a single explanatory variable to a single response variable. Some AD research found high correlation between explanatory variables and response variables, where a simple linear regression may be able to predict 80% to 99% of the variations (Gunaseelan, 2007; Liew *et al.,* 2012a; Schievano *et al.,* 2008). Simple linear regression is also used to identify the influential parameters within a system.

When operating at the same conditions, the methane yield of a digester is believed to be highly correlated with feedstock characteristics, such as volatile solids (VS), cellulose, hemicellulos and lignin content (Buffiere *et al.,* 2006). In SS-AD of lignocellulosic biomass, linear relationship was found between lignin content and methane yield of with an R square ranging from 0.59 to 0.95 (Brown *et al.,* 2012; Liew *et al.,* 2012b; Tong, 1990). Enzymatic digestibility of lignocellulosic feedstocks has also been correlated with methane yield with an R square ranging from 0.8641 to 0.9884 (Brown *et al.,* 2012; Liew *et al.,* 2012b).

2. Multiple linear regression (MLR)

Although in some AD processes a single parameter can be dominant, in most cases, AD is a complicated process where one variable cannot result in satisfactory fit, and thus multiple linear regression with more variables is required (Gunaseelan, 2009). Generally, when the parameters are few in number, are not significantly redundant (collinear), and have a well-understood relationship to the responses, MLR can be a good method to turn data into information (Tobias, 1995). Analyzing AD process using MLR can help to select the significant variables, and thus achieve the needed monitoring and prediction accuracy with reduced labor work in terms of time and laboratory analyses (Schievano *et al.*, 2008).

MLR models were also used to predict methane yield of a fixed substrate under different processing parameters in SS-AD. A quadratic MLR model were developed to predict methane yield and VFA production in SS-AD of wheat straw based on operating parameters, including inoculation ratio, total solid (TS) and particle size, and interactions of operating parameters, substrate/microbe ratio-TS (Motte *et al.*, 2013). Among these five parameters, the TS content has the major influence on methane yield, particularly because of the high values of its linear coefficient (-30.2) and its interaction coefficients with size and S/X ratio (+19.1 and -12.7, respectively). These three coefficients represent 56% of the model description (27%, 17% and 12% for TS, TS-Size and S/X-TS, respectively). The positive and negative coefficients were used to suggest the positive or negative relations of the parameter with the response variables.

3. Principal component regression (PCR)

In MLR, when the number of factors gets too large (for example, greater than the number of observations), it is likely to get a model that fits the sampled data perfectly but will fail to predict new data well. This phenomenon is called over-fitting (Tobias, 1995). In such cases, although there are many manifest factors, there may be only a few underlying or latent factors that account for

most of the variation in the response. Projection to latent structures has been shown to be a powerful linear regression technique for problems where the data is noisy and highly correlated or when there are only a limited number of observations compared with the number of variables (Baffi *et al.*, 1999b). However, these methods may not be helpful with screening out significant factors that affect the response, nor helpful with understanding the underlying relationship between the variables. So, when prediction is the goal and there is no practical need to limit the number of measured factors, regression with latent factors might be a useful tool (Baffi *et al.*, 1999a).

Principal component regression (PCR) is one of the methods that are commonly used to overcome the multicollinearity problem. PCR is a regression analysis technique that is based on principal component analysis (PCA). PCA is a statistical procedure that uses an orthogonal transformation to convert a set of possibly correlated variables into a new set of linearly uncorrelated variables called principal components (PCs). The number of principal components is less than or equal to the number of original variables. This transformation is defined in such a way that the first PC has the largest possible variance (that is, accounts for as much of the variability in the data as possible), and each succeeding component in turn has the highest variance possible under the constraint that it is orthogonal to (i.e., uncorrelated with) the preceding components. PCs are guaranteed to be independent if the data set is jointly normally distributed. PCR is regression analysis that uses the PCs that generated from PCA as regressors to obtain the response variables. PCR can achieve a dimension reduction in data analysis and exclude some of the low-variance principal components in the regression step, since usually only 2 or 3 major principal components are significant to be used for the regression. This can be particularly useful in settings with high-dimensional covariates. Through appropriate selection of the PCs used for regression, PCR can lead to efficient prediction of the outcome based on the assumed model.

One example of PCR used in AD the anaerobic digestion of alfalfa silage with recirculation of process liquid (Nordberg *et al.,* 2007). PCR model was first constructed using three PCs generated from 23 variables, then the variables were reduced based on prior knowledge of digestion process, and then the highly correlated and insignificant variables were reduced based on correlation matrix and weighted coefficients of regression. A second model using 3 PCs obtained from 7 variables was found to explained 76% of the variance of the response variables, which was nearly as well as the original model using all 23 measured input variables (explain 77% of variance). PCR using seven variables, including OLR, SRT, pH, alkalinity, ammonia, total VFA and isocapronate can reach an R2 between 0.85 to 0.93 for all six response variables, where total VFA and soluable COD strongly correlated with some dependent variables, such as methane yield (R2 = 0.81 and 0.79) and conversion efficiency of cellulose and hemicellulose (R2 =0.87-0.92).

2.6.4 Artificial neural network (ANN)

Artificial neural network (ANN) has been attracting great interest as a predictive tool in environmental problems particularly for biological water and wastewater treatment processes (Hamed *et al.,* 2004; Mahanty *et al*., 2013; Sinha *et al.,* 2002). Current published study usually apply ANN for the prediction of AD system output under different operating parameters using the same feedstock, probably because the influence of operating parameters on AD performance is usually complicated, non-linear, highly redundant and interact with each other, while ANN with sigmoid layer and a linear output layer are capable of dealing with these problems (Ozkaya *et al*., 2007).

It is usually recommended to have 5-10 individual experimental data per weight during the learning of neural network, where number of weights is equal to m(n + k) with n the number of input neurons, m the number of hidden neurons neurons, and k the number of output neurons.

However, ANN modelling with insufficient/fewer experimental data, particularly, in context of time and resource-intensive biological studies is generally accepted by many researchers for pattern recognition, impact analysis, and for comparison with other mechanistic models (Mahanty *et al.*, 2013).

ANN models have been widely adopted to analyze online data for system control (Guwy *et al.*, 1997; Ozkaya *et al.,* 2007; Wilcox *et al.,* 1995). More applications were found for wastewater treatment using different process, (Parthiban and Parthiban 2011), (Ozkaya *et al*., 2007), (Sinha *et al*., 2002), while landfill process can also be monitored using leachate and landfill gas data with ANN analysis (Ozkaya *et al*., 2007). The input variables for online monitoring are usually parameter can be acquired easily and fast by sensors or other fast methods, such as pH, alkalinity, conductivity, COD, sulfate, chloride, temperature, gas production rate and methane content Ozkaya *et al* (2007), or controlled process parameters such as organic loading rate (OLR) and hydraulic retention time (HTM) (Sinha *et al*.., 2002).

The specific methane yield of different industrial sludges of paper, chemical, petrochemical, automobile, and food industries and their interactions during co-digestion were assessed by both artificial neural network (ANN) and statistical regression models (Mahanty *et al*., 2013). ANN models were found to be superior to the regression models because the ANN models generally provided a more robust tool for prediction in that the prediction error varied slightly, and smoothly, over the range of data sizes used in training and testing. However, the application of ANN requires sufficient data for model training, data with less noise, and the involvement of important parameters to improve the predictive capability of the model.

2.6.5 Gompertz Kinetic Modeling

Recently, some authors have made prediction of biogas production potential using modified Gompertz model (Budiyono *et al*., 2010), (Adiga *et al*., 2012), (Patil *et al.,* 2012) and first order kinetic model (Raposo *et al*., 2009), (Kafle *et al*., 2012). Modified Gompertz model was developed by (Zwietering *et al*., 1990) to predict bacterial growth. By assumptions that biogas production rate had correspondence to methanogenic bacterial growth rate in digester. Both of them, modified Gompertz model and first order kinetic model, give different result in predicted biogas production. According to (Kafle *et al*., 2012), the prediction of biogas yield using modified Gompertz model (fitting error 0.7-13.7%) was more accurate than first order kinetic (fitting error 9.2-37.1%). In other hand, (Raposo *et al*., 2009) reported that first order kinetic could be used to predict biogas yield with good fitting error (10% or less). The different results may be caused by kind of substrates, where (Kafle *et al*., 2012) used fish industry waste and (Raposo *et al*., 2009) used sunflower oil cake (SuOC). Based on information above, the accuracy of biogas yield prediction in model is depended on substrates that are used as feedstock. That means, using of modified Gompertz and first order kinetic in making kinetic of biogas yield production must be aware of the substrates used to get the best accurate prediction.

In this study, authors compared kinetic model of biogas production from vinasse obtained using modified Gompertz and using first order kinetic model. (Sumardiono *et al*., 2013) investigated the effect of pH control and COD/N ratio to biogas production. (Budiyono *et al*., 2013) studied the influence of initial pH and pH control to biogas production.

An overview of the models used in literature to describe microbial inactivation was done by (Xiong, Xie *et al.,* 1999). Those models describe linear and non-linear curves, with lag and/or tailing phases. Among non-linear models, the Gompertz equation and its modified forms have been

successfully applied to describe inactivation of Listeria monocytogenes at isothermal conditions (Bhaduri *et al. (*1991), (Linton, Carter *et al.*, 1995), (Xiong *et al*. 1999).

2.7 Digester Considerations

2.7.1 Digester:

Operating Volume:

The operating volume of the digester is the volume of slurry in the digester Ahmadu (2009).

The operating volume of the digester (V_o) is determined on the basis of the chosen retention time (RT) and Quantity of Substrate (Q_s) (Mu'azu, 2010), and is given as;

$$V_o = Q_s \times RT \qquad (2.1)$$

The retention time is the interval of time during which the biomass is allowed to decompose in the digester. The retention time, in turn, is determined by the chosen digester temperature and the amount of biomass resource available. Retention time should amount to at least 30 days for a simple plant (Kossmann *et al*. 2001).

Quantity of Substrate (Q_s) = Biomass (B) + Water (W) (cm^3)

The ratio of Biomass to Water is 1:9

Total Volume:

The total volume of the digester (V_T) should be greater than the operating volume. This is to give room for the biogas produced and the rise of the slurry during fermentation. The operating volume of the digester must not exceed 90% of the total volume of the digester (Ahmadu, 2009). The total volume is thus given as:

$$V_T = V_o / 0.9 \quad (2.2)$$

Digester dimensions:

This depends on the geometric shape of the digester. In this case a cylindrical digester is used, hence the chosen geometry is;

$$V_T = \pi r^2_d h_d \quad (2.3)$$

Where V_T = Total volume of digester

r_d = radius of digester

h_d = height of digester

Digester Temperature:

The digester is designed to operate within the mesophilic temperature range (20-40^{o}C). This can be achieved by natural heating from the sun. The digesters were set up in an open field. This allows for direct heating by sun, the desired temperature is achievable as a result.

2.7.2 Gas Holder:

The gas holder floats in the water jacket over the reactor. The radius of the gas holder is given as;

$$r_g = r_r + C \quad (2.4)$$

Where r_g = radius of gas holder

r_r = radius of reactor

C = clearance

Gas holder volume (V_g):

According to (Kossmann *et al*., 2001) the size of the gas holder, i.e. the gas holder volume (V_g) depends on the relative rates of gas generation and gas consumption (Ahmadu, 2009). The gas holder should:

- Cover the peak consumption rate for the period of maximum consumption
- Hold the gas produced during the longest Zero consumption period

Gas holder dimensions:

Having determined the volume of the gas holder, a desired ratio for the dimensions can be adopted depending on the geometric shape of the design. For a cylindrical gas holder,

$$V_g = \pi r^2_g h_g \qquad (2.5)$$

Where,

V_g = volume of gas holder `

r_g = radius of gas holder

h_g = height of gas holder (Mu'azu, 2010)

2.7.3 Water jacket:

The water jacket holds the water in which the digester is placed and gas holder floats. The radius is a little larger than the gas holder.

$$r_j = r_g + c \qquad (2.6)$$

Where, r_j = radius of water jacket

r_g = radius of gas holder

c = clearance

The height of the water jacket should be equal to the height of the gas holder, therefore:

$$h_j = h_g \quad (2.7)$$

Where,

h_j = height of water jacket

h_g = height of gas holder

Volume of water jacket (V_j) is given by;

$$V_j = \pi \ r_j^2 h_j \quad (2.8)$$

Where;

r_j = radius of water jacket

h_j = height of water jacket

2.7.4 Force on Gas Holder

The force on the gas holder is given as:

$$F_g = P_g \text{ x } A_g \quad (2.9)$$

Where;

P_g = Pressure in gas holder

A_g = Cross-sectional area of gas holder (Ahmadu, 2009)

2.7.5 Gas Pipe Diameter:

The gas pipe diameter is selected based on the flow rate of biogas through the pipe and the distance between the gas holder and burner. (i.e. length of pipe required). The values can be checked from standard tables to determine the required pipe diameter (Mu'azu, 2010).

Also according to (Mu'azu, 2010), to calculate the quantity of substrate in the digester, the following formular is applied; Qs = Cs x V (2.10)

Where Qs = Quantity of Substrate

Cs = Concentration of Substrate within the range 5-10%

V = Volume of container.

7.5% Average Concentration was adopted (Cs).

Therefore, Cs = 7.5/100 = 0.075

The volume of digester is given by

$V = \pi r^2 h$ (2.11)

Where, V = volume of container

r = radius of container

h = height of container

$V = 3.142 \times (11)^2 \times 51$

$= 19389.2\text{cm}^3$

The volume of container, $V = 19389.2\text{cm}^3$

2.8 Techniques for Enhancing Biogas Production

Different methods used to enhance biogas production can be classified into the following categories:

i. Use of additives

ii. Recycling of slurry and slurry filtrate

iii. Variation in operational parameters like temperature, retention time and particle size of the substrate

iv. Use of fixed film/ bio filters.

2.8.1 Use of additives

Some attempts have been made in the past to increase gas production by stimulating the microbial activities using various biological and chemical additives under different operating condition. These additives are either organic or inorganic.

Organic Additives

Additives under this category includes; different plants, weeds, crop residues, microbial cultures, among others, (Gunaseelan, 1987). Which are available naturally in the surroundings. As such, generally these are of less significance in terms of their use in the habitat, however if used as additives in biogas plant could improve its performance significantly. The suitability of an additive is expected to be strongly dependent on the type of substrate.

Powdered leaves of some plants and legumes (like *Gulmohar, Leucacena leucocephala, Acacia auriculiformis, Dalbergia sisoo and Eucalyptus tereticonius*) have been found to stimulate biogas production between 18% and 40% SPOBD, China, (1979); (Chowdhry *et al*. 1994). Increase in biogas production due to certain additives appears to be due to adsorption of the substrate on the surface of the additives. This can lead to high-localized substrate concentration and a more favourable environment for growth of microbes (Chandra and Gupta 1997).The additives also help to maintain favourable conditions for rapid gas production in the reactor, such as pH, inhibition/promotion of acetogenesis and methanogenesis for the best yield. Alkali treated (1% NaOH for 7 days) plant residues (lantana, wheat straw, apple leaf litter and peach leaf litter) when used as a supplement to cattle dung resulted in almost twofold increase in biogas and CH_4 production (Dar and Tandon, 1987). Partially decomposed ageratum produced 43% and *Euphorbia tirucalli L*. produced 14% more gas as compared to pure cattle dung (Kalia and Kanwar 1989); (Rajasekaran *et al*. 1989). (Trujillo *et al.* 1993) found that the addition of the tomato-plant wastes to the rabbit wastes in proportion higher than 40% improved the methane production. Crop residues like maize stalks, rice straw, cotton stalks, wheat straw and water hyacinth each enriched with partially digested cattle dung enhanced gas production in the range of 10– 80% (El Shinnawi *et al.,* 1989); (Somayaji and Khanna, 1994). (Babu *et al*., 1994) observed improvement in biomethanation of mango processing wastes by several folds by the addition of extracts of seeds of Nirmali, common bean, black gram, guar and guargum at the rate of 1500ppm. Mixture of Pistia stratiotes and cowdung (1:1) gave a biogas yield of 0.62 $m^3/(m^3$ day) (CH_4 ¼76.8%, HRT¼15 days) (Zennaki *et al*. 1998). Recently (Sharma, 2002) observed an increase of 40–80% in biogas production on addition of 1% onion storage waste (OSW) to cattle dung in a 400-l floating drum biogas reactor.

Inorganic Additives

Several inorganic additives that improve gas production have also been reported. (Shimizu, 1992) claimed that higher concentration of bacteria could be retained in the digester by the addition of metal cations since cations increase the density of the bacteria, which are capable of aggregating by themselves. (Wong and Cheung, 1995) found that the plant with a higher content of heavy metals (Cr, Cu, Ni and Zn) had a higher CH_4 yield than the control. The addition of iron salts at various concentrations [$FeSO_4$ (50 mM), $FeCl_3$ (70 lM)] have been found to enhance gas production rate (Wodzinski *et al*. 1983); (Patel *et al*., 1993); (Rao and Seenayya 1994); (Clark and Hillman, 1995).Nickel ions (2.5 and 5 ppm) enhanced biogas up to 54% due to the activity of Ni-dependent metallo-enzymes involved in biogas production (Geeta *et al*. 1990). Single super phosphate (SSP) used in digesting rice straw in batch fermenters yielded 8-11% increase of biogas (Bardiya and Gaur 1997).

Certain adsorbents are also reported to improve gas production for example (Madamwar and Mithal 1986) obtained a maximum enhancement of over 150% with higher CH_4 content (65% CH_4) on addition of 10 g/l commercial pectin. According to (Kumar *et al.,* 1987), commercial charcoal Darco G-60 resulted in 17% and 34.7% increase in biogas in batch and semi continuous fermenters, respectively. Also, the locally produced wood charcoal (16% enhancement in biogas) was found as good as the commercial charcoal in batch digesters. (Patel *et al.*, 1992) found a trend of enhanced gas production with high CH_4 content and lower effluent BOD and COD with increasing doses of different adsorbents (gelatin, polyvinyl alcohol, powdered activated charcoal, pectin, kaolin, silica gel, aluminium powder, bentonite and tale powder) on anaerobic digestion of water-hyacinth-cattle dung. They observed (Patel and Madamwar 1994) a twofold increase in gas production on addition of 4 g/L silica gel, with CH_4 content of 72.8% as compared to control

(62%).Process stability increased with increasing levels of silica gel, indicating that volatile acids were consumed at a faster rate in the presence of an adsorbent.

Using Ca and Mg salts as energy supplements, CH4 production was enhanced and foaming was avoided Mathiesen (1989). Dhawale (1996) found 25–35% enhancement in anaerobic digestion of manure by the addition of Eosin blue dye at 0.1lM concentration. (Gaddy, 1994) found a new method for improving the performance of anaerobic digestion of solid substrate. It involved the addition of at least 1-chelating agent (preferably 1–100 l M, especially 10 l M) 1:2 diaminocyclohexane- N, N, tetraacetic acid, EDTA, citric acid or nitrilotriacetic acid (NTA)) and at least one nutrient (preferably 1–5000 l M (10 l M)) of iron, sulfide, selenium or nickel, especially $FeSO_4$, $FeCl_2$, SeO_2 or $NiCl_2$) to a solid substrate for solubilizing solid nutrients to enhance bacterial growth. Methane production can be increased or smaller digesters can be used to achieve the same methane production. Faster startup, greater stability and more rapid recovery from upsets were possible by using this new method.

2.8.2 Single Super Phosphate and Wood ash

Single Superphosphate (SSP) is mineral fertilizer which contain phosphorus and sulphur. It is produced by reacting phosphate rock with sulphuric acid.

Phosphate Rock + Sulphuric Acid -> Single Superphosphate.

SSP is one of the cheapest forms of phosphate, it is 2-5mm granules and off white in colour. It provides balance of P, S and Ca that mimics pasture growth requirements. The ratio of phosphorus and sulphur suits many crop and pasture needs, and are readily available.

Wood Ash is the residue powder left after the combustion of wood. It is a good source of potash.





Plate 2.1: Single Superphosphate and Wood ash

2.9 Safety Considerations in Handling Biogas Plant

2.9.1 Fire/Explosion

Methane, which makes up from 0% to 80% of biogas, forms explosive mixtures in air, the lower explosive limit being 5% methane and the upper limit 15% methane. Biogas mixtures containing more than 50 % methane are combustible, while lower percentages may support, or fuel, combustion. With this in mind no naked flames should be used in the vicinity of a digester and electrical equipment must be of suitable quality, normally "explosion proof". Other sources of sparks are any iron or steel tools or other items, power tools (particularly comutators and brushes), normal electrical switches, mobile phones and static electricity.

It was reported that four people were killed and several others injured when a biogas plant exploded at Aluva in Ernakulam on 26th August, 2009.

If conducting a flammability test, take a small sample well away from the main digester, or incorporate a flame trap in the supply line, which must be of suitable length (minimum 20m).

Furthermore, (Monnet, 2003) revealed that while applying air/oxygen directly into the biogas digester as a method of desulphurisation, measures of safety have to be taken to avoid overdosing of air because biogas in air is explosive in the range of 6 to 12% depending on the methane content.

2.9.2 Disease

As Anaerobic Digestion relies on a mixed population of bacteria of largely unknown origin, but often including animal wastes, to carry out the waste treatment process, care should be taking to avoid contact with the digester contents and to wash thoroughly after working around the digester (and particularly before eating or drinking). This also helps to minimise the spread of odours which may accompany the digestion process. The digestion process does reduce the number of pathogenic (disease causing) bacteria, particularly at higher operating temperatures, but the biological nature of the process need to be kept in mind.

2.9.3 Asphyxiation

Biogas consists mainly of CH_4 and CO_2, with low levels of H_2S and other gases. Each of these components has its own problems, as well as displacing oxygen.

CH_4 - lighter than air (will collect in roof spaces etc), explosive (see section 2.8.1 above).

CO_2 - heavier than air (will collect in sumps etc), slightly elevated levels affect respiration rate, higher levels displace oxygen as well.

H_2S - (rotten egg gas) destroys olefactory (smelling) tissues and lungs, becomes odourless as the level increases to dangerous and fatal. More details, an actual case and detection equipment are available.

Adequate ventilation, suitable precautions and adequate protective equipment will minimize the dangers associated with biogas, making it a good servant rather than a bad master.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

The following materials (equipment, glassware) were used in this study

i. Shovel: was used to pack the waste material into sacks
ii. Sacks: were used to convey dung and chicken droppings to site
iii. Protective gloves: were worn to protect the hands from contamination
iv. Nose mask: was used to prevent inhalation of particulate and odor.
v. Pestle and Mortar: were used to pound the waste and single super phosphate for better mixing
vi. Sieve: the single super phosphate was sieved to get a fine sample (0.2mm)
vii. Stirrer (wooden stick): to stir the mixture of waste and water to form slurry
viii. Spring Balance: was used to measure weight of samples before mixing in the various digesters
ix. Gallenhamph Weight balance, Mettler P160: was used to measure weight of catalyst
x. Plastic bucket was used to fetch water
xi. Boiling ring (heater) for heating the water before mixing
xii. Thermometers: (2/1 ^{0}C made in England): was used to obtain daily temperature of the digester as well as the ambient temperatures for Samaru, Zaria.
xiii. pH meter model pHS-2S, (SHANGHAI JINYKE REX, CHINA) was used to measure pH of slurry before and after the digestion period.
xiv. Flat bottom flask: was used for scrubbing of biogas

xv. Burner: was used to flame the gas produced.

While the feed materials used were;

i. Cow dung from Kawo abattoir, collected around September 2015
ii. Chicken droppings from Salma farms, Dan kande village around September 2015
iii. Digitaria Smuts II (wooly finger grass) from NAPRI, Zaria collected July 2015

3.2 The Pilot Scale Anaerobic Digesters

Cylindrical shaped digesters made from aluminum were used for this work. The cylindrical shape adopted was to enhance better mixing. The Anaerobic Digester consist of the reactor, height 51cm and diameter 22cm, water seal height 55cm and 27cm diameter and gas collector 24cm diameter and height 55cm with calibrations as shown in figure 3.1.

The digester was placed into a water jacket, with the gas holder (inverted drum) floating in the same water jacket.

The theory behind the digester is simply "downward delivery and upward displacement". The slurry on fermenting in the digester produces gas. This gas displaces the gas holder (upward) and gets trapped between the gas holder and the water seal. The displacement of the gas holder is dependent on the pressure and volume of the gas produced. The main constituents of this gas, methane and CO_2 are only sparingly soluble in water, (Alfa, 2013). The gas can then be collected via a pipe connected from the top of the gas holder or transferred to the cooking device (e.g burner).

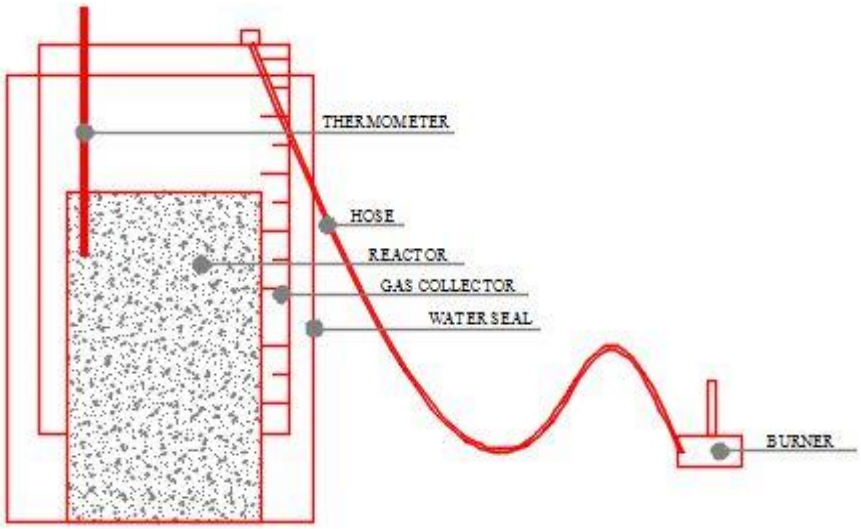


Fig. 3.1: Schematic Diagram of the Digester

The adoption of this digester was necessitated by the following objectives:

i. It's simple to design and has high tolerance to construction flaws and defects.

ii. It's suitable for small scale study of anaerobic digestion.

iii. It does not require too much space to set up

iv. Low fabrication cost.

v. Cheap and easy to maintain.

vi. Gas is produced at steady/constant pressure, as weight of gas holder balances the pressure in the gas holder; volume of gas produced is immediately recognizable by position of the calibrated gas holder.

vii. No risk of spillage of slurry into the gas holder, thus very hygienic.

viii. The system can easily be protected from rust by painting regularly, thus facilitating gas tightness, (Ahmadu, 2009).



Plate 3.1: Plant Setup for the Production of Biogas

3.3 Material Selection

As a general rule, the selection of all the materials was based on the following;

1. Cost-effectiveness
2. Availability and
3. Durability.

3.3.1 Materials for Digester Construction:

The material used for the setup in plate 3.1 was aluminum. It was selected to meet the following requirements:

i. Good tensile strength, ductile and ease of rolling by machine to required design geometry (malleability).

ii. Water/gas tightness: Water tightness in order to prevent seepage and the resultant threat to soil and ground water quality. Gas tightness to ensure proper containment of the entire biogas yield and prevent air from entering into the digester.

iii. High resistance to corrosion

iv. Relatively cheap.

v. Provides reflective surface thereby minimizing heat buildup inside the gas holder and within the water seal

vi. Provides gas tightness to store biogas

3.3.2 Materials for gas pipe:

Flexible plastic pipe was used to transfer the gas produced from gas holder to burner.

3.4 Bio reactor Considerations

The digester, gas holder, water jacket and pipe diameter (volume and dimensions) were obtained using methods described by (Ahmadu, 2009), (Mu'azu, 2010) and (Alfa *et al.,* 2014) in previous studies.

3.5 Procedure for Anaerobic Digestion of Cow Dung and Chicken Droppings with *Digitaria Smuts II* (Wooly Finger Grass)

3.5.1 Method of Biomass Collection and Slurry Preparation

The digester setup is made of three drums of different diameter (gas collector, reactor and water seal), fitted to one another (Mu'azu, 2010). The primary structure consists of aluminum sheet

which is strong enough to withstand the weight and pressures of the contained slurry. The aluminum sheet is selected because of its high resistance to corrosion. The edges and corner were sealed with glue and ash then painted to prevent leakages. The tank is air tight and is clearly placed above the ground level and outside the shed where it is exposed to the sunlight for partial heating.

Eight kinds of waste were introduced simultaneously into the respective digesters for a period of thirty two days during the study, these wastes include;

i. 1.5kg of Cow Dung from Kawo Abattoir (A_1)

ii. 1.5kg of Cow Dung and 100gSSP/50gAsh (B_1)

iii. 1.5kg of Cow Dung and 150gSSP/75gAsh (C_1)

iv. 1.5kg of Cow Dung and 200gSSP/100gAsh (D_1)

v. 0.4kg Chicken Droppings from Salma Farms with 1.2kg *Digitaria Smuts II* (Wooly Finger Grass) from NAPRI (A_2)

vi. 0.4kg Chicken Droppings with 1.2 Grass and 100gSSP/50gAsh (B_2)

vii. 0.4kg Chicken Droppings with 1.2kg Grass and 150gSSP/75gAsh (C_2)

viii. 0.4kg Chicken Droppings with 1.2kg Grass and 200gSSP/100gAsh (D_2)

Cow dung, chicken droppings and *Digitaria Smuts II* (Wooly finger grass) were the biomass resources used as feed materials in this research with Single Super Phosphate and wood Ash as the additives. Cow Dung was obtained from Kawo Abattoir Kaduna, while the Chicken droppings were gotten from Salma Farms, Dan Kande village along Kaduna Zaria road. They were both dried for a period of 3 weeks. *Digitaria Smuts II* (Wooly Finger Grass) was also obtained from NAPRI (National Animal Protection and Research Institute) Zaria and dried for

forty days. The dried feed materials (Cow Dung and Chicken Droppings) were then pounded to enhance mixing. Single Super Phosphate obtained from Kawo market Kaduna was also pounded using mortar and pestle then sieved and Ash collected from burnt wood used for cooking were taking together with the wastes materials to the research site.

Fresh dung (1kg) from Zango Abattoir, Zaria was used as inoculum in all the substrates digested in this study.

To calculate the quantity of substrate in each digester, the approach of (Mu'azu, 2010) in previous studies was adopted.

$$Qs = Cs\ x\ V$$

Where Qs = Quantity of Substrate

$Cs =$ Concentration

$V =$ Volume

Qs = 0.075 × 19389.2

= 1454.19g

= 1.5kg

1.5kg of Cow Dung was measured using spring balance and poured into reactor A_1 (Control).

1.5kg of Cow Dung was measured using spring balance and poured into reactor B_1, 100gSSP/50gAsh (2:1) was also measured using Gallenhamph Weight balance and added into the reactor.

Same quantity of Cow Dung (1.5kg) was measured into digesters C_1 and D_1 with 150gSSP/75gAsh and 200gSSP/100gAsh respectively.

While for the chicken droppings with grass *(Digitaria Smuts)*, grass Chicken Droppings ratio was (3:1). That is 1.2kg grass and 0.4kg chicken droppings.

1.2kg grass with 0.4kg chicken droppings was measured into the remaining four digesters (A_2, B_2, C_2, and D_2). A_2 being the control, while 100gSSP/50gAsh, 150gSSP/75gAsh and 200gSSP/100gAsh was added into digesters B_2, C_2 and D_2 respectively.

There after 1kg of slaughter house waste (inoculum) with warm water was added to about 90% capacity and stirred continuously for about 30s. The clear space above (10% of the reactor) is for fermentation and gas production. The initial pH and temperatures were measured and recorded using pH meter and thermometer respectively. The reactors were put into the water seals, gas collectors were inverted over the reactor into the water seal. Water is then added into the various water seals.

3.6 Monitoring and Measurement of Gas Production for the Eight Substrate

The reactors were monitored for the 32- day retention time and measurement taken for biogas production

The gas holders were calibrated to enable the reading of daily gas production of the eight substrates in the anaerobic digesters. The daily gas production measurement was done just before sun set. The produced biogas was measured by adopting the method previously described by (Alfa *et al.*, 2014).

3.7 Monitoring of Operational Parameters

In order to study and determine the most feasible local environmental conditions to optimally operate the developed biogas facilities, various physical and chemical parameters were monitored to check the status of the digester. Monitoring of the plant was carried out every day between 8am and 6pm and was done three times a day. Readings were taken to record biogas and ambient temperatures. Below are the physic-chemical parameters monitored, reasons why and the instruments used for the monitoring.

3.7.1 Temperature

It was measured to determine the feedstock influence on the temperature and consequently, the metabolism of the bacteria. 2/1 ^{0}C Thermometers (made in England) were used to measure the temperature of the digester and the ambient. The digester and ambient temperatures were taken three times daily, i. e. 8am, 1pm and 6pm respectively.

3.7.2 pH

This was measured twice, before digestion and after digestion. It gives the intensity of acidic or basic character at a given temperature. It was measured to determine the initial and final acidity/alkalinity. Samples were analyzed at ambient temperature with a pH meter model pHS-2S, (SHANGHAI JINYKE REX, CHINA).

3.8 Preparation of Saturated Wood Ash

2000g of ash was collected from burnt wood, which was dissolved in 8litres of water and kept for 24hours. The mixture was sieved to remove undissolved particles, the result serves as the saturated

wood ash. It is suitable for removing H_2S and other impurities from biogas (Mu'azu, 2010).This method was completely adopted from Mu'azu.

3.9 Polishing of Biogas Produced

The biogases produced were in turn passed through water and saturated wood ash to remove hydrogen sulphide and carbon dioxide respectively, this is aimed at obtaining clean methane (Mu'azu, 2010). A clear blue flame was achieved which is an evidence of high methane concentration.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

Pilot scale anaerobic digesters were fabricated for the digestion of the eight substrates in this study. The experimental results obtained during the monitoring period of the study were tabulated and analyzed using statistical methods. They are presented in tables, graphs, and bar charts, and discussed as follows.

4.1.1 Production of Biogas from Cow Dung

Fig 4.1 shows the daily gas production from cow dung and the different concentration of the additives.

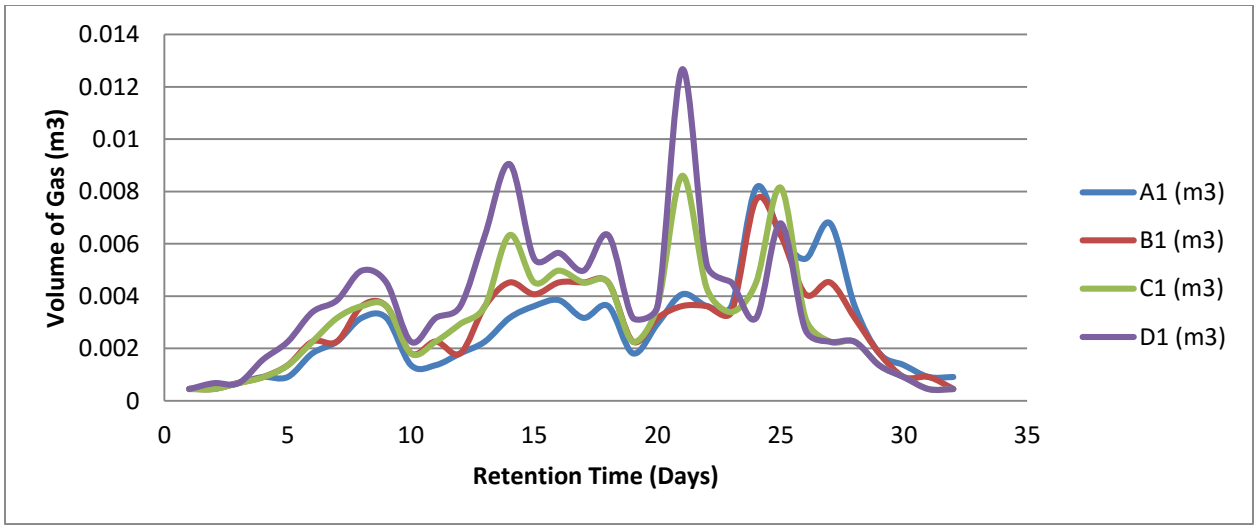


Fig. 4.1 Daily Gas Production of Cow Dung (m^3)

The peaks in Figure 4.1 indicates the fluctuation in the volume of gas produced from each substrate. The fluctuation signifies possible variation in environmental conditions which affects

the microbial activities in the system. Figure 4.1 shows that gas production in all the substrate started within the first week of setup. On the 8th day, the gas produced were burnt but a clear blue flame was not achieved indicating the presence of excess carbon dioxide (CO_2). From Fig. 4.1, D_1 contained more additives (200gSSP and 100gAsh) which resulted in higher gas production followed by C_1 (150gSSP and 75gAsh) then B_1 (100gSSP and 50gAsh). The control A_1 has a lower gas production at the early stage but produces more gas just before the final days of digestion. Biogas production was higher in the second and third week. Gas production dropped significantly during the fourth week as seen.

4.1.2 Production of Biogas from Chicken Droppings mixed with Digitaria Smuts II (Wooly Finger Grass)

Fig 4.2 shows the daily gas production from chicken droppings mixed with grass and the different ratio of additives.

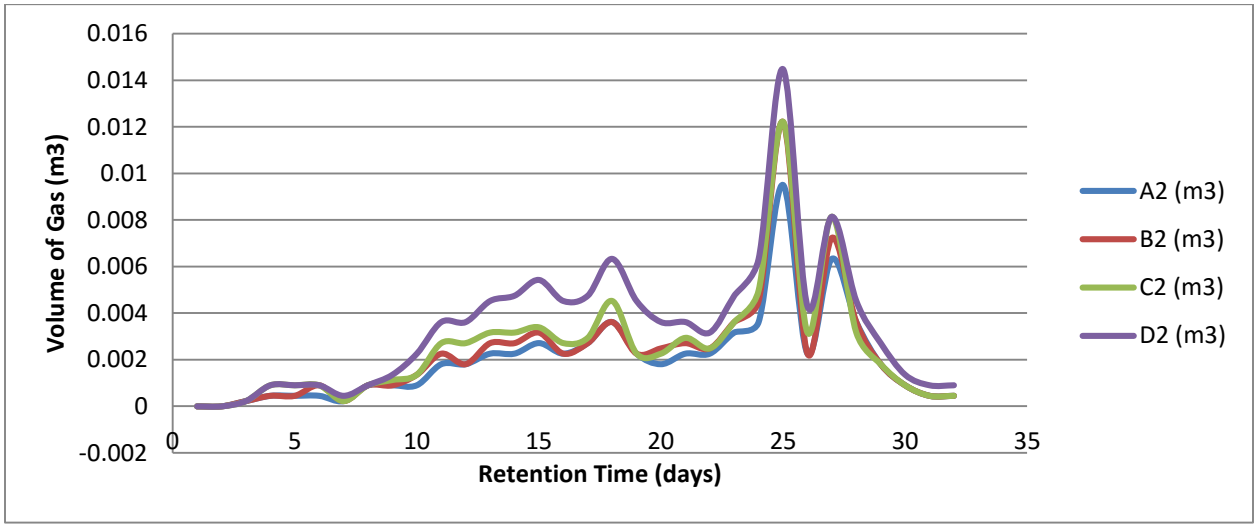


Fig. 4.2 Daily Gas Production of Chicken droppings mixed with Grass (m^3)

On the other hand, the peaks in fig. 4.2 shows daily fluctuation of biogas produced using chicken droppings with *digitaria smuts II.* Again, the set up with more percentage of single superphosphate and wood ash produced more gas while there were no significant difference in the other three setup. Gas production was highest on the 26th day for all the set up. Biogas production was very low in the first week of setup. As the feedstock matures over the days, gas production increases. The gas was perfectly producing even at the final week of setup.

For the first week, combustion was very poor for all the setup which improved during the second week with a reddish blue flame. Clear blue flame was achieved during the third and forth week respectively.

4.1.3 Cumulative Biogas Production

Finally, figure 4.3 shows the cumulative biogas production for the control and the different ratio of additive. 1 being the control, while 2, 3, and 4 variations in concentration of additives (i.e, 100gSSP/50gAsh, 150gSSP/75gAsh and 200gSSP/100gAsh). The blue bar indicates cow dung while red is chicken droppings with grass.

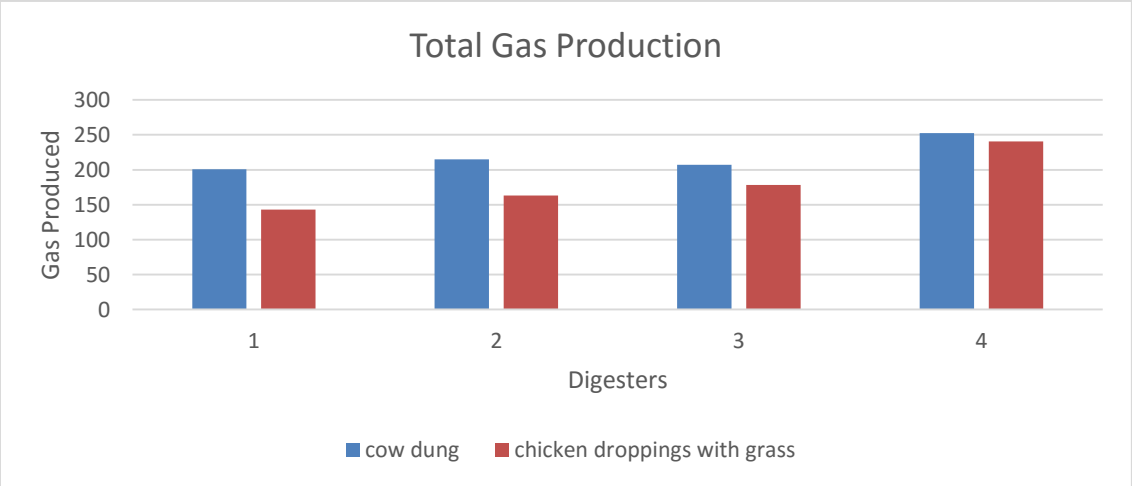


Fig. 4.3 Cumulative Biogas Production

4.2 Monitoring of Operational Parameters

The pH for each of the eight substrate were measured before and after digestion. The daily temperatures were adequately monitored also to determine the daily temperature of the reaction, in addition to the daily ambient temperature. The following results were obtained.

1. *pH Before and After Digestion.*

pH of the eight feedstock were measured immediately after preparation. The pH values of the cow dung were slightly neutral while that of chicken droppings and its co-digestion with *Digitaria Smuts II* were acidic. It was also observed that the acidity increased slightly with increase in catalyst ratio. (200gSSP/100gWoodash > 150gSSP/75gWoodash > 100gSSP/50GWoodash), as shown in Table 4.1.

Tab. 4.1 pH of the Feedstock Before and After Digestion

Feedstock pH	**A_1**	**B_1**	**C_1**	**D_1**	**A_2**	**B_2**	**C_2**	**D_2**
Before Digestion	7.0	6.9	6.8	6.7	5.9	5.5	5.2	5.2
After Digestion	6.7	6.7	6.5	6.5	7.0	6.7	6.7	6.9

From the table, A_1, B_1, C_1, and D_1 containing cow dung and different ratio of additives had a slight drop in pH, while for A_2, B_2, C_2, and D_2 containing chicken droppings mixed with grass increases across the digesters after the digestion period. The results shows that, acidity increases slightly with increase in additive. Also, chicken dropping are generally more acidic than cow dung. After digestion, the pH across the reactors were near neutral (7.0).

2. *Digester Temperature during Biogas Production*

Appendix III shows the digester temperatures for the eight substrates observed at a point of observation within the digesters. The temperature were recorded three times daily using a

thermometer. And appendix IV shows the corresponding ambient samaru temperature for the thirty two (32) days retention time and the daily average temperature.

Figure 4.3 and 4.4 shows that the temperatures within the digesters fluctuated optimally between 25^{o}C and 40^{o}C which conforms to the mesophilic range. The foregoing show that the digesters operated within the mesophilic temperature range; and that it is possible to install digesters that will operate within this range in Samaru. This agrees with the findings of previous studies (Igboro, 2011 and Alfa, 2013). Since all the digesters were operated simultaneously, the temperature across them were the same as shown in figures 4.4 and 4.5.

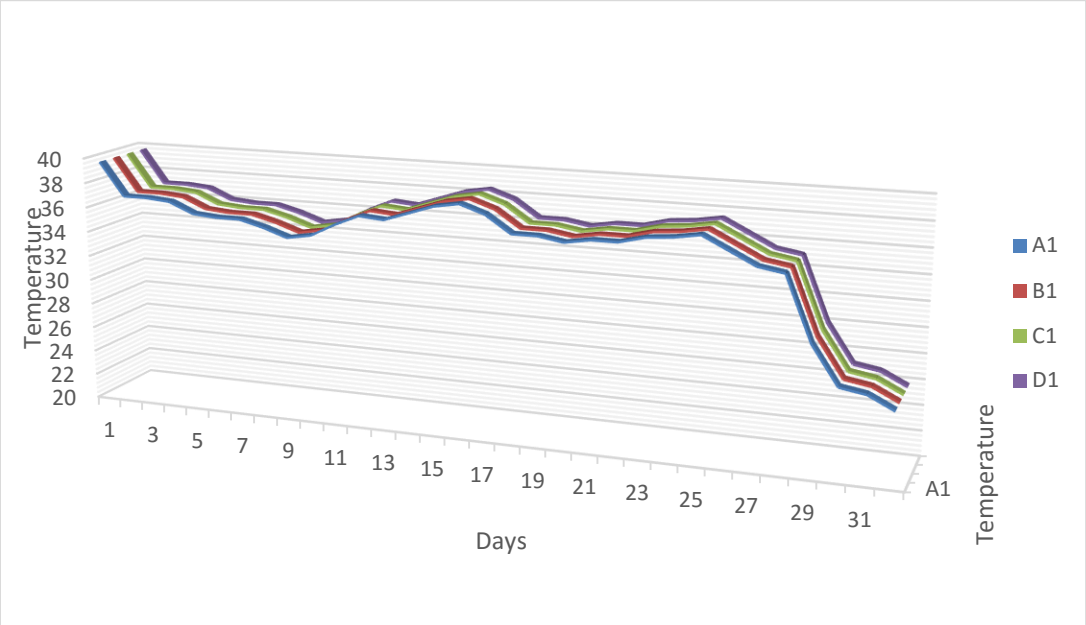


Fig. 4.4 Daily Digesters Temperature (Cow Dung)

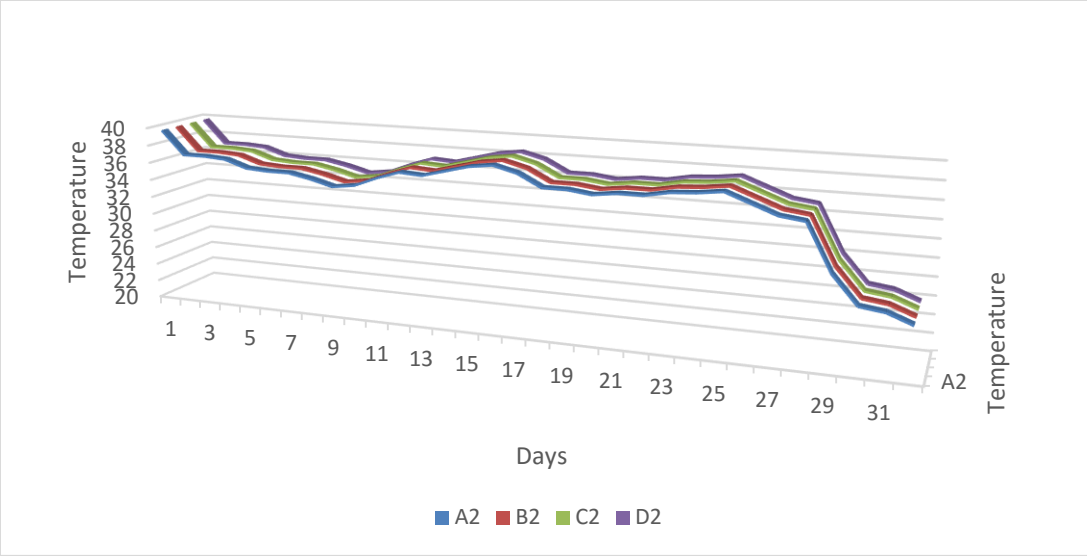


Fig. 4.5 Daily Digesters Temperature (Chicken Droppings with Grass)

3. *Average Ambient and Digesters Temperature during the Digestion Period*

Table 4.2 shows the average temperature for the 32 days retention time as well as the average ambient temperature of the entire period of digestion.

Tab. 4.2 Average Digesters and Ambient Temperature (ºC)

Average Temperature	**A_1**	**B_1**	**C_1**	**D_1**	**A_2**	**B_2**	**C_2**	**D_2**
Digester (ºC)	35.20	35.30	35.17	35.18	35.25	35.28	35.30	35.40
Ambient (ºC)	36.01							

Table 4.2 shows the average temperatures are within the mesophilic range, hence there wasn't any hindrance for biogas production from temperature.

4.3 Scrubbing of the Biogas

The gas produced were not collected for analysis, rather burnt directly after the daily readings has been recorded. However, Blue flame is an evidence of high methane concentration. In the early

stages of burning, pure blue flame was not achieved indicating the presence of CO_2 and H_2S according to previous literatures. The gas was passed through water and saturated wood ash respectively to achieve blue flame. Plate 4.1 and 4.2 shows the scrubbing/flaming of biogas.



Plate 4.1: Image of Scrubbing Process



Plate 4.2: Combustion

Plate 4.3 shows the researcher burning the produced gas



Plate 4.3 Researcher Burning Produced Biogas

Other plates of the research process are attached in appendices V and VI respectively.

4.4 Gompertz Kinetic Modeling

The Cumulative biogas generation was modelled using the modified Gompertz equation and the kinetics of biogas production studied. The Modified Gompertz Kinetic equation is as follows;

$$R = A\, exp\left[-exp\left[\frac{B \times e}{A}(\lambda - t) + 1\right]\right]$$

Where; R = Cumulative Biogas Produced (m^3) at any time (t)

A = Biogas Production Potential (m^3)

B = Biogas Production Rate (m^3/day)

λ = Lag phase (days), which is the minimum time taken to produce biogas or time taken for bacteria to acclimatize to the environment in days

t = time (days)

The Constant A, B and λ where determined using the linear regression approach with the aid of the solver function of the MS Excel Tool pack.

The gompertz equation was utilized by researchers to study the cumulative methane production in biogas production, for instance, (Zwietetring *et al.,* 1990), and (Lay *et al.,* 1996) applied this equation to study bacteria growth. (Budiyino *et al.* 2010) and (Momoh, 2011) also utilized this modified equation to describe biogas yield from cattle manure and co-digestion of horse manure and cow dung respectively.

Biogas production in the eight digesters were measured until production reduced significantly. The modified Gompertz equation was then used to fit the cumulative daily biogas production which

was observed to adequately describe the biogas production from these substrates. The estimated kinetic constants using linear regression and other characteristics of the digesters A_1 to D_2 are shown in table 4.3.

Tab. 4.3 Composition of Digesters and their Corresponding Kinetic Parameters

Digesters	Quantity of Substrate	Biogas Production Rate (m^3/day), B	Biogas Production Potential (m^3), A	λ, Lag Phase (Days)	R Square
A_1	1.5kg Cow dung	0.0037	0.0893	7.54	0.9695
B_1	1.5kg Cow dung and 100gSSP with 50gAsh	0.0036	0.0841	5.5	0.996
C_1	1.5kg Cow dung and 150gSSP with750gAsh	0.0045	0.0977	6.355	0.994
D_1	1.5kg Cow dung and 200gSSP with 100gAsh	0.0056	0.1188	5.875	0.9925
A_2	1.2kg Chicken droppings with 0.4g Grass	0.0025	0.0647	8.88	0.9973
B_2	1.2kg Chicken droppings with 0.4kg Grass and 100gSSP with 50gAsh	0.0028	0.0737	8.571	0.9969
C_2	1.2g Chicken droppings with 0.4kg Grass and 150gSSP with 75gAsh	0.0031	0.0808	7.935	0.9974
D_2	1.2kg Chicken droppings with 0.4kg Grass and 200gSSP with 100gAsh	0.0046	0.1088	8.565	0.9971

From the table, digesters D_1 and D_2 have the highest biogas production potential of 0.1188m^3 and 0.1088m^3 at a biogas production rate of 0.0056m^3/day and 0.0046m^3 day with a lag phase of 5.9days and 8.6days respectively. Digesters D_1 and D_2 contains more quantity of single super phosphate and wood ash which is an indication that they are a good source of catalyst to increase the volume of biogas production using cow dung and chicken droppings mixed with *digitaria smuts II.*

The modified Gompertz equation was observed to adequately describe biogas production with goodness of fit (R^2) as shown in table 4.3.

4.4.1 Experimental data Vs Modified Gompertz Kinetic Equation

Figures 4.5 and 4.6 shows the fit between experimental data obtained during the research and data obtained using the modified gompertz kinetic equation for all the substrate digested. It can be seen that the two fits perfectly from the initial stage, it however deflected towards the end probably due to sudden changes in environmental conditions.

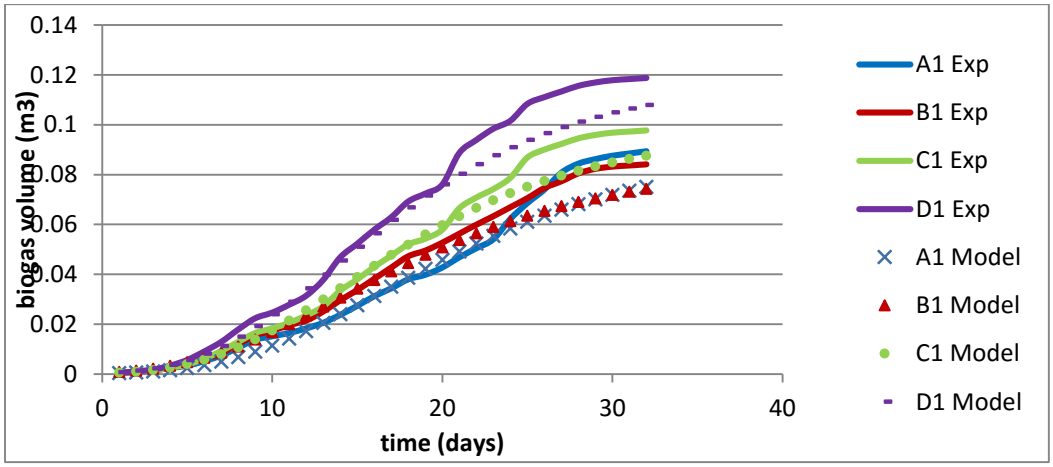


Fig. 4.6 Experimental data and Gompertz Kinetic Model for Cow dung

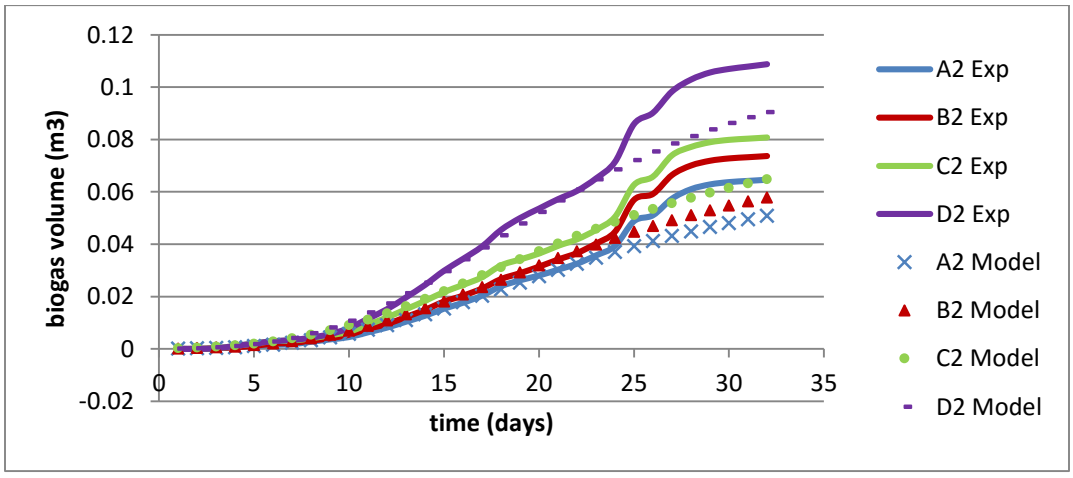


Fig. 4.7 Experimental data and Gompertz Kinetic Model for Chicken droppings with Grass

4.4.2 Biogas Production Potential and Maximum Biogas Production Rate

The biogas production potential and maximum biogas production rate/day for all the substrates digested is represented in figure 4.7 and 4.8, as determined by the modified gombertz equation. Digesters D1 and D2 with more additives has the higher potential as well as production rate.

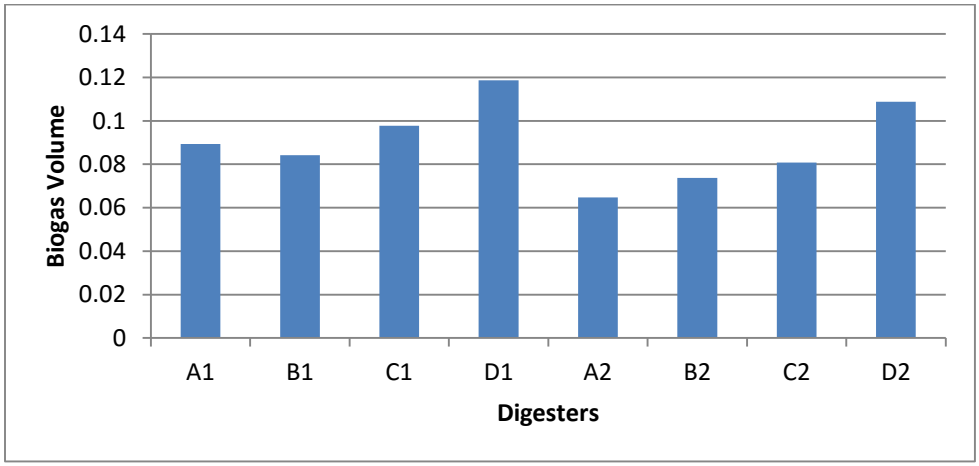


Fig. 4.8 Biogas Production Potential, A (m^3)

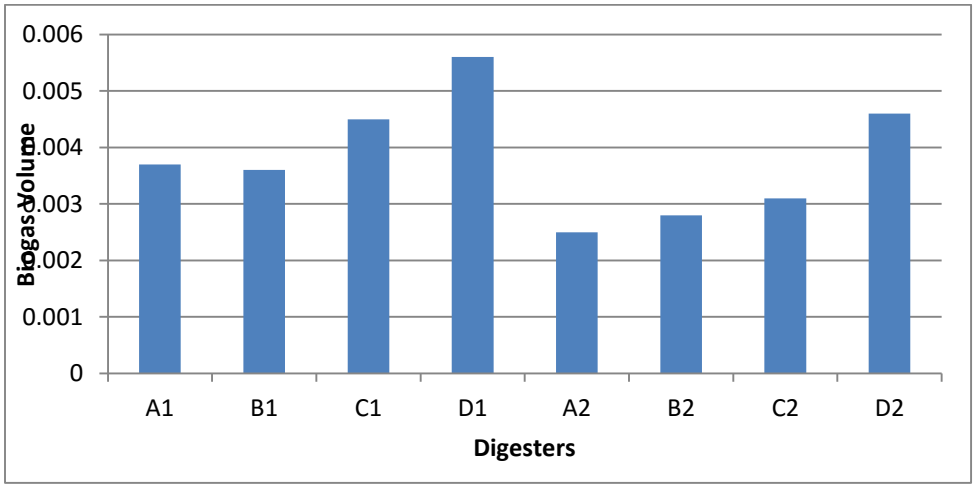


Fig. 4.9 Biogas Production Rate/Day, B (m^3)

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

- Single super phosphate and wood ash were used as the additives for this research work. Their quantity were varied in this form (100gSSP/50gAsh, 150gSSP/75gAsh and 200gSSP/100gAsh), and were tested using cow dung and chicken droppings with *Digitaria Smuts II* (Wooly Finger Grass).
- Single super phosphate and ash can be used to increase the volume of gas production using cow dung and chicken droppings with *Digitaria Smuts II.*
- There was increase in total gas production for the 32 days retention time for cow dung from $0.0906m^3$ (no additive) to $0.1141m^3$ (200gSSP/100gWood ash), while that of chicken droppings and its co-digestion with grass is from $0.0646m^3$ (no additive) to $0.1087m^3$ (200gSSP/100gWood ash). Indicating 20.6% and 40.6% increment respectively.
- The pH values recorded before and after digestion indicates that the plants operated well. The temperature inside the digesters were stable fluctuating around 35±1°C which is within the mesophilic range.
- Modified gompertz kinetic equation was used to adequately describe the cumulative of biogas produced with high goodness of fit R^2, which ranged from (0.970 to 0.997)
- In addition, the model was used to predict the biogas production potential for each substrate digested.
- Water and saturated wood ash were used to remove hydrogen sulphide and carbon dioxide. This was done to achieve clean blue flame which indicated the presence of methane.

5.1 Recommendations

- Bold step should be taken towards commercializing biogas production in Nigeria, the work done herein can serve as valuable tools towards achieving that.
- This technology should be encouraged in the rural areas where our forest resources are stretched due to over dependency on wood.
- The technology again can play a major role in achieving the United Nations Sustainable Development Goal of climate action.
- In the case of co-digestion of chicken droppings with *Digitaria Smuts II*, the grass should be pre fermented for two to three weeks before feeding it into digesters to attain maximum yield.

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APPENDIX I

Tab. 4.1 Daily Gas Holder Reading (cm)

Digesters	**A_1**	**B_1**	**C_1**	**D_1**	**A_2**	**B_2**	**C_2**	**D_2**
Date								
3rd/11/15	1	1	1	1	0	0	0	0
4th/11/15	1	1	1	1.5	0	0	0	0
5th/11/15	1.5	1.5	1.5	1.5	0.5	0.5	0.5	0.5
6th/11/15	2	2	2	3.5	1	1	2	2
7th/11/15	2	3	3	5	1	1	2	2
8th/11/15	4	5	5	7.5	1	2	2	2
9th/11/15	5	5	7	8.5	0.5	0.5	0.5	1
10th/11/15	7	8	8	11	2	2	2	2
11th/11/15	7	8	8	10	2	2	2.5	3
12th/11/15	3	4	4	5	2	3	3	5
13th/11/15	3	5	5	7	4	5	6	8
14th/11/15	4	4	6.5	8	4	4	6	8
15th/11/15	8	9	10	14	5	6	7	10
16th/11/15	9	14	14	20	5	6	7	10.5
17th/11/15	8	9	10	12	6	7	7.5	12
18th/11/15	8.5	10	11	12.5	5	5	6	10
19th/11/15	7	10	10	11	6	6	6.5	10.5
20th/11/15	8	10	10	14	8	8	10	14
21st/11/15	4	5	5	7	5	5	5	10
22nd/11/15	6.5	7	8	8	4	5.5	5	8
23rd/11/15	9	15	19	28	5	6	6.5	8
24th/11/15	8	8	9.5	11.5	5	5.5	5.5	7
25th/11/15	8	7.5	7.5	10	7	8	8	10.5
26th/11/15	18	14	10	7	8	10	11	14
27th/11/15	8	8	7	5	21	27	27	32
28th/11/15	11	9	7	6	5	5	7	9.5
29th/11/15	15	10	5	5	14	16	18	18
30th/11/15	8	7	5	5	8	8	7	10
1st/12/15	7	6	3	3	4	4	4	6
2nd/12/15	4	4	2	2	2	2	2	3
3rd/12/15	3	4	1	1	1	1	1	2
3rd/11/15	2	1	1	1	1	1	1	2

Using $V = 452.45\chi\,cm^3$, from equation (3.14)
Where, V = volume of biogas

χ = height of cylinder above water level.
Substituting for x in the equation above, volume of daily gas produced is shown in appendix II

APPENDIX II

Volume of Daily Biogas Produced (m^3)

Day	A1 (m3)	B1 (m3)	C1 (m3)	D1 (m3)	A2 (m3)	B2 (m3)	C2 (m3)	D2 (m3)
1	0.000452	0.000452	0.000452	0.000452	0	0	0	0
2	0.000452	0.000452	0.000452	0.000679	0	0	0	0
3	0.000679	0.000679	0.000679	0.000679	0.000226	0.000226	0.000226	0.000226
4	0.000905	0.000905	0.000905	0.001583	0.000452	0.000452	0.000905	0.000905
5	0.000905	0.001357	0.001357	0.002262	0.000452	0.000452	0.000905	0.000905
6	0.00181	0.002262	0.002262	0.003393	0.000452	0.000905	0.000905	0.000905
7	0.002262	0.002262	0.003167	0.003845	0.000226	0.000226	0.000226	0.000452
8	0.003167	0.003619	0.003619	0.004976	0.000905	0.000905	0.000905	0.000905
9	0.003167	0.003619	0.003619	0.004524	0.000905	0.000905	0.001131	0.001357
10	0.001357	0.00181	0.00181	0.002262	0.000905	0.001357	0.001357	0.002262
11	0.001357	0.002262	0.002262	0.003167	0.00181	0.002262	0.002714	0.003619
12	0.00181	0.00181	0.002941	0.003619	0.00181	0.00181	0.002714	0.003619
13	0.002262	0.003619	0.003619	0.006333	0.002262	0.002714	0.003167	0.004524
14	0.003167	0.004524	0.006333	0.009048	0.002262	0.002714	0.003167	0.00475
15	0.003619	0.004072	0.004524	0.005429	0.002714	0.003167	0.003393	0.005429
16	0.003845	0.004524	0.004976	0.005655	0.002262	0.002262	0.002714	0.004524
17	0.003167	0.004524	0.004524	0.004976	0.002714	0.002714	0.002941	0.00475
18	0.003619	0.004524	0.004524	0.006333	0.003619	0.003619	0.004524	0.006333
19	0.00181	0.002262	0.002262	0.003167	0.002262	0.002262	0.002262	0.004524
20	0.002941	0.003167	0.003619	0.003619	0.00181	0.002488	0.002262	0.003619
21	0.004072	0.003619	0.008595	0.012667	0.002262	0.002714	0.002941	0.003619
22	0.003619	0.003619	0.004298	0.005202	0.002262	0.002488	0.002488	0.003167
23	0.003619	0.003393	0.003393	0.004524	0.003167	0.003619	0.003619	0.00475
24	0.008143	0.007691	0.004524	0.003167	0.003619	0.004524	0.004976	0.006333
25	0.006333	0.006333	0.008143	0.006786	0.0095	0.012215	0.012215	0.014476
26	0.005429	0.004072	0.003167	0.002714	0.002262	0.002262	0.003167	0.004298
27	0.006786	0.004524	0.002262	0.002262	0.006333	0.007238	0.008143	0.008143
28	0.003619	0.003167	0.002262	0.002262	0.003619	0.003619	0.003167	0.004524
29	0.00181	0.00181	0.001357	0.001357	0.00181	0.00181	0.00181	0.002714
30	0.001357	0.000905	0.000905	0.000905	0.000905	0.000905	0.000905	0.001357
31	0.000905	0.000905	0.000452	0.000452	0.000452	0.000452	0.000452	0.000905
32	0.000905	0.000452	0.000452	0.000452	0.000452	0.000452	0.000452	0.000905

APPENDIX III

Table showing daily digester temperature reading for the eight digesters as recorded three times daily (8am, 1pm and 6pm).

Digesters	**A_1**			**B_1**			**C_1**			**D_1**			**A_2**			**B_2**			**C_2**			**D_2**		
Date/Time	**8_{am}**	**1_{pm}**	**6_{pm}**	**8_{am}**	**1_{pm}**	**6_{pm}**	**8_{am}**	**1_{pm}**	**6_{pm}**	**8_{am}**	**1_{pm}**	**6_{pm}**	**8_{am}**	**1_{pm}**	**6_{pm}**	**8_{am}**	**1_{pm}**	**6_{pm}**	**8_{am}**	**1_{pm}**	**6_{pm}**	**8_{am}**	**1_{pm}**	**6_{pm}**
3rd/11/15	40	40	39	40	40	39.5	40	40	39	40	40	39	40	40	39	40	40	39	40	40	39.5	40	40	39
4th/11/15	35	38	37	35	39	37	35	39	37	35	39	37	35	39	37	35	39	37	35	39	37	35	39	37
5th/11/15	34	38	37	35	38	36.5	34.5	38	36.5	35	38	37	35	38	37	35	38	37.5	35	38	38	35	38	38
6th/11/15	34	37	37.5	34.5	37	37	34	37	37	34	37.5	37	35	37.5	37	35	37.5	38	35	37	38	35	38	37.5
7th/11/15	33	37	36	34	37	36	34	37	36	34	37	36	34	37	36	34	37	36	34	37	37	34	37	37
8th/11/15	33	37	36	33	37	36	33	36.5	36	33	37	37	33	37	37	33	37	37	33	37	37	33	37.5	37
9th/11/15	33	37	36	33	37	36	33	36	36	33	37	36	33	37.5	36	33	37	36.5	33	37	37	33	37.5	37
10th/11/15	33	37	35	33	37	36	33	37	36	33	37	36	33	37	36	33	37	36	33	37	36	33	37	36
11th/11/15	32	37	35	32	37	35	32	37	35	32	37	35	32	37	35	32	37	35	32	37	35	32	37	35
12th/11/15	33	37	36	32	37	36	32	37	36	32	37	36	32	37	36	32	37	36	32	37	36	32	37	36
13th/11/15	33	38	36	33	38	36	33	38	36	33	38	36	33	38	36	33	38	36	33	38	36	33	38	37
14th/11/15	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34.5	38	38
15th/11/15	34	38	37	35	38	37	35	38	37	35	38	37	35	38	37	35	38	37	35	38	37	35	38	37
16th/11/15	35	39	38	35	39	37	35	39	37	35	39	37	35	39	37	35	39	37	35	39	37	35	39	38
17th/11/15	35	40	38	36	40	38	36	40	38	36	40	36	36	40	36	36	40	38	36	40	38	36	40	38
18th/11/15	34	40	38	35	40	38	35	40	38	36	40	38	36	40	38	35	40	38	36	40	38	36	40	39
19th/11/15	35	39	38	35	39	38	35	39	38	35	39	38	35	39	38	35	39	38	35	39	38	35	40	38
20th/11/15	34	38	36.5	34	38	36.5	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37
21st/11/15	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37
22nd/11/15	34	37	37	34	37	37	34	37	37	34	37	37	34	37	37	34	37	37	34	37	37	34	37	37
23rd/11/15	35	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37
24th/11/15	35	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37
25th/11/15	35	38	37	35	38	37	35	38	37	35	38	37	35	38	37	35	38	37	35	38	37	35	38	37.5
26th/11/15	35.5	39	37	35	39	37	35	39	37	33	37	37	35	39	37	35	39	37	35	39	37	35	39	37
27th/11/15	35	39	38	35	39	38	35	39	38	35	39	38	35	39	38	35	39	38	35	39	38	35	39	38

28th/11/15	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37	34	38	37
29th/11/15	33	37	36	33	37	36	33	37	36	33	37	36	33	37	36	33	37	36	33	37	36	33	37	36
30th/11/15	31	37	35	31	37	35	31	37	35	31	37	35	31	38	35	31	38	36	31	38	36	31	38	36
1st/12/15	29	31	29.5	29	31	38	28.5	31	28	29	31	30	29	31	30	29	31	28.5	29	31	28	29	31	30
2nd/12/15	26	30	25	26	30	25	26	30	25	26	30	25	26	30	25	26	30	25	26	30	25	26	30	25
3rd/12/15	25	30	25	25	30	25	25	30	25	25	30	25	25	30	25	25	30	26	25	30	25	25	30	25
4th/12/15	24	29	24	25	24	24	29	24	24	24	29	24	24	24	29	29	24	24	29	24	24	24	29	24	24	24	29	24	24	24	29	24	24	24

APPENDIX IV

Ambient Samaru Temperature Sheet (ºC)

Date/Period	Morning	Afternoon	Night	Average
3rd/11/15	36	38	37	37
4th/11/15	36	39	37	37.33333
5th/11/15	36	38	37	37
6th/11/15	37	40	38	38.33333
7th/11/15	35	38	37	36.66667
8th/11/15	35	38	37	36.66667
9th/11/15	34	37	37	36
10th/11/15	35	38	37	36.66667
11th/11/15	33	37	35	35
12th/11/15	32	36	36	34.66667
13th/11/15	33	38	37	36
14th/11/15	34	38	37	36.33333
15th/11/15	35	39	38	37.33333
16th/11/15	37	40	38	38.33333
17th/11/15	37	41	38	38.66667
18th/11/15	37	41	38	38.66667
19th/11/15	37	41	38	38.66667
20th/11/15	37	39	38	38
21st/11/15	36	39	37	37.33333
22nd/11/15	36	39	37	37.33333
23rd/11/15	35	38	37	36.66667
24th/11/15	35	37	37	36.33333
25th/11/15	36	39	38	37.66667
26th/11/15	37	40	37.5	38.16667
27th/11/15	36	39	37	37.33333
28th/11/15	35	38	37	36.66667
29th/11/15	35	38	37	36.66667
30th/11/15	33	37	35	35
1st/12/15	30	34	29	31
2nd/12/15	28	34	30	30.66667
3rd/12/15	27	32	28	29

APPENDIX V



Plate 4.4 Pounding feed material



Plate 4.5 Mixing the feedstock



Plate 4.6 Adding Water into Water seal



Plate 4.7 Experimental Set Up

APPENDIX VI



Plate 4.8 Early Stage of Biogas Production



Plate 4.9 Researcher Taking the Reading of Biogas Production



Plate 4.10 Digesters at High Biogas Capacity

APPENDIX VII

Experimental Data and Modified Gompertz Kinetic Data for Cow dung.

Days	A1 Model	A1 Exp	B1 Model	B1 Exp	C1 Model	C1 Exp	D1 Model	D1 Exp
1	0.00030619	0.000452	0.00085642	0.000452	0.000480792	0.000452	0.00074015	0.000452
2	0.00056032	0.000905	0.00141719	0.000905	0.000898516	0.000905	0.00136345	0.001131
3	0.00096148	0.001583	0.00221897	0.001583	0.001560056	0.001583	0.00233369	0.00181
4	0.00155767	0.002488	0.00330747	0.002488	0.002538405	0.002488	0.00374424	0.003393
5	0.00239719	0.003393	0.00471855	0.003845	0.003900364	0.003845	0.00567523	0.005655
6	0.00352369	0.005202	0.0064741	0.006107	0.005697705	0.006107	0.00818224	0.009048
7	0.00497143	0.007464	0.00857963	0.008369	0.007960273	0.009274	0.01128873	0.012893
8	0.00676162	0.010631	0.01102381	0.011988	0.010692221	0.012893	0.01498310	0.017869
9	0.0089002	0.013798	0.01377979	0.015607	0.013871726	0.016512	0.01922054	0.022393
10	0.01137738	0.015155	0.01680791	0.017417	0.017453791	0.018322	0.02392853	0.024655
11	0.01416874	0.016512	0.02005917	0.019679	0.02137524	0.020584	0.02901477	0.027822
12	0.01723755	0.018322	0.02347905	0.021488	0.025560854	0.023524	0.03437571	0.031441
13	0.02053785	0.020584	0.02701108	0.025108	0.029929638	0.027143	0.03990484	0.037775
14	0.02401789	0.02375	0.03060001	0.029632	0.034400483	0.033477	0.04549949	0.046822
15	0.0276234	0.02737	0.03419422	0.033703	0.038896752	0.038001	0.05106602	0.052251
16	0.0313006	0.031215	0.03774753	0.038227	0.043349583	0.042977	0.05652322	0.057906
17	0.03499853	0.034382	0.04122023	0.042751	0.047699948	0.047501	0.06180402	0.062882
18	0.03867085	0.038001	0.04457958	0.047275	0.051899595	0.052025	0.06685590	0.069216
19	0.042277	0.03981	0.04779978	0.049537	0.055911113	0.054287	0.07164030	0.072382
20	0.0457828	0.042751	0.05086162	0.052703	0.059707344	0.057906	0.07613136	0.076001
21	0.04916058	0.046822	0.05375194	0.056322	0.063270385	0.066501	0.08031430	0.088668
22	0.05238903	0.050441	0.05646284	0.059942	0.066590349	0.070799	0.08418359	0.093871
23	0.05545272	0.054061	0.05899092	0.063335	0.069664048	0.074192	0.08774119	0.098395
24	0.05834149	0.062204	0.06133653	0.066954	0.072493692	0.078716	0.09099487	0.101561
25	0.06104979	0.068537	0.06350297	0.070573	0.075085687	0.086859	0.09395670	0.108347
26	0.06357594	0.073966	0.06549585	0.074644	0.077449552	0.090025	0.09664179	0.111062
27	0.06592145	0.080751	0.0673225	0.077359	0.079597001	0.092287	0.09906721	0.113324
28	0.06809035	0.084371	0.06899141	0.080525	0.081541166	0.094549	0.10125111	0.115585
29	0.07008864	0.08618	0.07051187	0.082335	0.083295971	0.095907	0.10321203	0.116943
30	0.07192375	0.087537	0.07189357	0.08324	0.084875633	0.096811	0.10496840	0.117847
31	0.0736041	0.088442	0.07314634	0.083692	0.086294286	0.097264	0.10653815	0.1183
32	0.07513873	0.089347	0.07427992	0.084144	0.087565693	0.097716	0.10793845	0.118752

APPENDIX VIII

Experimental Data and Modified Gompertz Kinetic Data for Co Digestion of Chicken Droppings with *Digitaria Smuts II* (Wooly Finger Grass).

Days	A2 Model	A2 Exp	B2 Model	B2 Exp	C2 Model	C2 Exp	D2 Model	D2 Exp
1	0.000128684	0	0.000194323	0	0.000296985	0	0.000166087	0
2	0.000239274	0	0.000347905	0	0.000517568	0	0.000335814	0
3	0.00041822	0.000226	0.000588292	0.000226	0.000853682	0.000226	0.000629022	0.000226
4	0.000691405	0.000679	0.000944827	0.000679	0.001339953	0.001131	0.001100627	0.001131
5	0.001087149	0.001131	0.001448549	0.001131	0.002011319	0.002036	0.00181232	0.002036
6	0.001633974	0.001583	0.002129679	0.002036	0.002899968	0.002941	0.002826923	0.002941
7	0.002358063	0.00181	0.003014951	0.002262	0.004032352	0.003167	0.004201753	0.003393
8	0.003280798	0.002714	0.004125165	0.003167	0.005426715	0.004072	0.005982195	0.004298
9	0.004416738	0.003619	0.005473298	0.004072	0.007091444	0.005202	0.008196581	0.005655
10	0.005772288	0.004524	0.007063391	0.005429	0.009024394	0.00656	0.010853146	0.007917
11	0.007345179	0.006333	0.008890269	0.007691	0.011213159	0.009274	0.013939316	0.011536
12	0.009124748	0.008143	0.010940049	0.0095	0.013636173	0.011988	0.017423175	0.015155
13	0.011092872	0.010405	0.013191288	0.012215	0.016264384	0.015155	0.021256625	0.019679
14	0.013225398	0.012667	0.015616556	0.014929	0.019063282	0.018322	0.025379584	0.024429
15	0.01549382	0.015381	0.018184236	0.018096	0.021995015	0.021715	0.029724592	0.029858
16	0.017867042	0.017643	0.020860346	0.020358	0.025020418	0.024429	0.034221264	0.034382
17	0.020313036	0.020358	0.023610244	0.023072	0.028100794	0.02737	0.038800193	0.039132
18	0.022800296	0.023977	0.026400088	0.026691	0.031199379	0.031893	0.043396088	0.045465
19	0.02529902	0.026239	0.029198023	0.028953	0.034282445	0.034155	0.047950042	0.049989
20	0.027781988	0.028048	0.031975046	0.031441	0.037320045	0.036417	0.052410967	0.053608
21	0.030225148	0.03031	0.034705583	0.034155	0.040286445	0.039358	0.056736295	0.057227
22	0.032607938	0.032572	0.037367789	0.036644	0.043160273	0.041846	0.060892075	0.060394
23	0.034913392	0.035739	0.03994364	0.040263	0.045924457	0.045465	0.064852618	0.065144
24	0.037128057	0.039358	0.042418836	0.044787	0.048566002	0.050441	0.068599833	0.071478
25	0.0392418	0.048858	0.044782586	0.057001	0.051075647	0.062656	0.072122371	0.085954
26	0.041247508	0.05112	0.047027298	0.059263	0.053447463	0.065823	0.075414677	0.090252
27	0.043140754	0.057453	0.049148222	0.066501	0.055678417	0.073966	0.078476034	0.098395
28	0.044919429	0.061073	0.051143071	0.07012	0.057767928	0.077132	0.081309634	0.102919
29	0.046583383	0.062882	0.053011643	0.07193	0.059717445	0.078942	0.083921736	0.105633
30	0.048134071	0.063787	0.054755453	0.072835	0.061530052	0.079847	0.086320906	0.10699
31	0.049574233	0.064239	0.056377397	0.073287	0.063210106	0.080299	0.088517362	0.107895
32	0.050907607	0.064692	0.057881446	0.073739	0.064762924	0.080751	0.090522424	0.1088

APPENDIX IX

Weekly and Total Gas Production

Digesters	**A_1**	**B_1**	**C_1**	**D_1**	**A_2**	**B_2**	**C_2**	**D_2**
Week 1								
	1	1	1	1	0	0	0	0
	1	1	1	1.5	0	0	0	0
	1.5	1.5	1.5	1.5	0.5	0.5	0.5	0.5
	2	2	2	3.5	1	1	2	2
	2	3	3	5	1	1	2	2
	4	5	5	7.5	1	2	2	2
	5	5	7	8.5	0.5	0.5	0.5	1
	7	8	8	11	2	2	2	2
Sub Total	**23.5**	**26.5**	**28.5**	**39.5**	**6**	**7**	**9**	**9.5**
Week 2								
	7	8	8	10	2	2	2.5	3
	3	4	4	5	2	3	3	5
	3	5	5	7	4	5	6	8
	4	4	6.5	8	4	4	6	8
	8	9	10	14	5	6	7	10
	9	14	14	20	5	6	7	10.5
	8	9	10	12	6	7	7.5	12
	8.5	10	11	12.5	5	5	6	10
Sub Total	**50.5**	**63**	**68.5**	**88.5**	**33**	**38**	**45**	**66.5**
Week 3								
	7	10	10	11	6	6	6.5	10.5
	8	10	10	14	8	8	10	14
	4	5	5	7	5	5	5	10
	6.5	7	8	8	4	5.5	5	8
	9	15	19	28	5	6	6.5	8
	8	8	9.5	11.5	5	5.5	5.5	7
	8	7.5	7.5	10	7	8	8	10.5
	18	14	10	7	8	10	11	14
Sub Total	**68.5**	**76.5**	**79**	**96.5**	**48**	**54**	**57.5**	**82**
Week 4								
	8	8	7	5	21	27	27	32
	11	9	7	6	5	5	7	9.5
	15	10	5	5	14	16	18	18
	8	7	5	5	8	8	7	10
	7	6	3	3	4	4	4	6
	4	4	2	2	2	2	2	3
	3	4	1	1	1	1	1	2
	2	1	1	1	1	1	1	2
Sub Total	**58**	**49**	**31**	**28**	**56**	**64**	**67**	**82.5**
Grand Total	**200.5**	**215**	**207**	**252.5**	**143**	**163**	**178.5**	**240.5**