PRODUCTION OF BIOGAS FROM CO-DIGESTION OF COW DUNG, HORSE DUNG AND CHICKEN FEATHER

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DECLARATION

I declare that the work in this dissertation entitled "**PRODUCTION OF BIOGAS FROM CO-DIGESTION OF COW DUNG, HORSE DUNG AND CHICKEN FEATHER."** has been carried out by me in the Department of Water Resources and Environmental Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other Institution.

Aliyu ISHAQ

P13EGWR8007	**Signature**	**Date**

CERTIFICATION

This dissertation entitle **"PRODUCTION OF BIOGAS FROM CO-DIGESTION OF COW DUNG, HORSE DUNG AND CHICKEN FEATHER "** by **Aliyu ISHAQ** meets the regulations governing the award of master of science degree in Water Resources and Environmental Engineering, of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This dissertation is dedicated to Almighty **Allah (S.W.A),** the most compassionate, and the most merciful, who in his infinite mercies gave me the grace and wisdom to complete my programme of study safely and my parents Engr. Ishaq Abubakar Danladi and Safiya Magaji Ishaq as well as my late step mother Hajiya Maryam Tanimu Ishaq, who care much about me in my entire endeavor, may her gentle soul rest perfectly in peace. I give Almighty Allah the glory.

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ABSTRACT

There is a great deal of environmental pressure in many parts of the country to ascertain how organic waste can best be handled in the absence of appropriate disposal methods can cause adverse environmental and health problems. Anaerobic digestion has been considered as waste-to-energy technology, and is widely used in the treatment of different organic wastes. The study was carried out for biogas production from co-digestion of cow dung, horse dung and chicken feather in producing biogas through anaerobic co-digestion with chicken feathers. This is achieved by constructing twelve (12) local digesters and gas collection systems mounted at the premises of Department of Water Resources and Environmental Engineering, Ahmadu Bello University Zaria. The digesters were used to digest the mixture of cow dung (CD), horse dung (HD) and chicken feathers (CF) at different percentage ratios for a period of thirty seven (37) days retention time until the biogas reduced significantly. Inflammability test was conducted to determine the quality of biogas produced. Proximate analysis such as nitrates, sulphates, carbon to nitrogen ratio and phosphates were determined before and after anaerobic digestion to rank the substrates in order of their biogas production capacity. The total volumes of the gas produced were 2.51E-01m^3, 1.71E-01m^3,1.38E-01m^3, 1.33E-01m^3,1.04E-01m^3, 9.43E-02m^3, 9.43E-02m^3, 5.30E-02m^3, 3.59E-02m^3, 5.93E-02m^3, 3.59E-02m^3 and 3.04E-04m^3 for 25%CD-75%HD, 100%CD, 50%CD-50%HD, 100%HD, 75%CD-25%HD, 75%CD-25%CF, 75%HD-25%CF, 50%HD-50%CF, 25%HD-75%CF, 50%CD-50%CF, 25%CD-75%CF and 100%CF respectively. These implied that the mix ratio of 25%CD-75%HD produced highest biogas production. The results of carbon to nitrogen ratio for anaerobic digestion were determined at optimum range of 20:1 to 30:1. The nitrates, sulphates and phosphates determined shown an increase after digestion for the cow dung, horse dung and chicken feather with percentage values of 15.1%, 9.7% and 3.2% respectively, which could be a good source of biofertilizer. The average temperatures of the digesters recorded in the morning, afternoon and evening range from 26°C-43°C under mesophilic condition, and the average ambient temperature observed during the study was 34°C, the pH values of the media in all the substrates digested were found almost in the optimal limits of methanogenic bacteria of 6.0-7.4. The modified Gompertz equation was used to adequately describe the cumulative biogas production from these digesters and also to assess the kinetics of the biodegradation process. It was observed that the rates of substrate biodegradability were obtained. The constants were determined using the nonlinear regression approach with the aid of the solver function of the Microsoft Excel tool pack. Biogas production was found to be feasible from the other wastes, but CF was regarded as failed digester as it does not produce significant amount of biogas because of inhibiting factor such as high keratin content. The inflammability test conducted during anaerobic digestion was found to be efficient. Biogas productions from organic wastes are having prospects in contributing towards solving the national energy crisis of most countries.

Keywords: Cow Dung, Horse Dung, Chicken feathers, Anaerobic Digestion, Gompertz model

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LIST OF ACRONYMS AND ABBREVIATIONS

Symbols	Descriptions
AAS	Atomic Absorption Spectroscopy
AD	Anaerobic Digestion
BCR	Biogas Consumption Rate
BMP	Biochemical Methane Potential
BPC	Biogas Production Capacity
CD	Cow dung
CF	Chicken Feather
CHP	Combined Heat and Power
cm^3	Cubic Centimeter
C:N	Carbon to Nitrogen Ratio
e.g.	For Example
etc	Etcetera
et al	And Others
FTIR	Fourier Transform Infrared spectro
kg	kilogram
g	Grams
GHGs	Greenhouse Gas
HMBs	Hydrogen Scavenging Bacteria
HD	Horse dung
HRT	Hydraulic Retention Time
i.e.	That is
IT	Inflammability Test
Kg	Kilograms
KWh	Kilowatt-hour(s).
L	Litre

LS	Low solids systems
m	Metre
mm:	Millilitre
M^3	Cubic Metre
M^2	Square Metre
MS	Medium Solids
MSW	Management Systems in World
NGOs	Non-Governmental Organizations
NRCS	Natural Resources Conservative Service
OFMSW	Organic Fraction of Municipal SolidWaste
PVC	Polyvinyl Chloride
SCFA	Short Chain Fatty Acids
SRT	Solid Retention Time
TS	Total Solid
WWPTs	Waste Water Treatment Plants
VFA	Volatile Fatty Acids
VS	Volatile Solid
%	Percentage

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Biogas is a clean, environmentally friendly and renewable form of energy generated when micro-organisms degrade organic materials in an oxygen free environment. The formation of biogas can occur either in natural environment or controlled conditions in constructed biogas plants, so called anaerobic digestion (AD). Swamps, marshes, river beds, rumen of herbivore animal are some of the areas where biogas is formed naturally. The same microbial activities are achieved in both natural and controlled conditions. The feedstock for biogas production in constructed plants is more or less any organic fractions from household organic waste to dedicated energy crops like maize (Lantz *et al*., 2007). The potential feedstock for the production of biogas include; municipal solid waste, industrial organic waste, garden waste, agricultural waste (manure and crop residue), energy crops, cellulose rich biomass, algae and seaweed (water based), by-products of ethanol and bio diesel production (Lantz *et al*., 2007).

Inadequate energy supply and environmental pollutions are serious problems confronting Nigeria with high population growth rate, access to adequate energy and healthy environmental demands for a diversification of sources of energy supply, if Nigeria is to achieve any meaningful growth and development, biogas generation from anaerobic digestion of readily available wastes could contribute to solving these problems. From the global perspective, the over- dependence on fossil fuels as primary source of energy has resulted in climate change, many environmental destruction and related human health problems (Budiyono *et al*., 2010). The joint challenge of global pollution and depletion of fossil fuels is driving intense research into alternative renewable energy sources, among which is the biogas. Biogas is produced by the

anaerobic digestion (AD) of organic waste through the synergistic metabolic activities of consortia of hydrolytic, acidinogenic, acetogenic and methanogenic bacteria on organic materials (Yebo *et al*., 2011).

Currently, AD is used to treat more than 10% of organic wastes for the generation of energy in several European countries (Baere, 2000). Nigeria can do likewise. The industrial viability of this process requires a suitable combination of physical and chemical process parameters and a low- cost substrate, hence the need for process optimization. Attempts have been made to improve biogas production using mixed co-substrates (Dalhat *et al*., 2015). Anaerobic co-digestion of a simulated organic fraction of municipal solid wastes and fats of animal and vegetable origin has been reported (Fernandez *et al*., 2005). A substrate of kitchen waste with cow manure has been used to achieve a yield increase of 44% (Rongpin *et al*., 2009). Kaparaju and Rintala (2005) have examined the co-digestion of pig manure, potato tuber and its industrial by-products. The co-digestion of fruit and vegetable wastes, cattle slurry and chicken manure or sewage sludge for biogas production has also been studied (Ritz *et al*., 2007; Gomez *et al*., 2006). The best combination of various substrates for optimal yield remains a big problem despite the enormous number of potential substrates. It is worthy of note that the technical and economical feasibility of an industrial anaerobic digestion plant depends on how much methane is yielded and the purity and on the composition and process variables (temperature, retention time and pH).

These performances are often not available in literature; thus this could entail an increase of the risk of investments due to excessive uncertainties in the design phase. Although the anaerobic digestion of animal manures has been extensively researched and demonstrated, however, based on investment returns from energy production, the economics of diary digesters are not favorable due to the relatively low biodegradability

and biogas yield of diary manure as compared to many other types of organic wastes such as food waste. One of the approaches for improving the economics of diary digesters is to increase their biogas production rate by co-digesting the manure with more degradable waste such as food wastes as long as such wastes are available in the vicinity (Hamed and Ruihong, 2010). Co-digestion of different materials may enhance the anaerobic digestion process due to better carbon and nitrogen balance (Mshandete *et al*., 2004; Parawira *et al*., 2004). According to Mata-Alvarez *et al*., (2000). Co-digestion i.e digestion of more than one substrate in the same digester can establish positive synergism and the added nutrients can support microbial growth.

The process of fermentation in bio-digesters results in transformation of organically bound carbon into gaseous carbon dioxide and methane. The anaerobic environment and extended retention time also inhibit the growth of most pathogenic organisms and prevent the survival of intestinal parasites. It is therefore to be expected that both the chemical and biological parameters of livestock excreta will be improved upon by passage through bio-digesters.

The prospect of this technology is bright in developing countries like Nigeria. This is because Nigeria is an energy resource rich country in terms of both fossil fuels (such as crude oil, natural gas, coal), and renewable energy resources like solar, wind and biomass (Mshandete and Parawira, 2009). The technology can be utilized to provide energy for households, rural communities, farms and industries.

Anaerobic digestion (AD) is a highly promising technology for converting biomass waste into vast quantities of biogas (methane and carbon dioxide), which may directly be used as an energy source or converted to hydrogen.

Since biogas is a mixture of methane (also known as marsh gas or natural gas, CH_4) and carbon dioxide, it is a renewable fuel produced from waste treatment. Anaerobic digestion is basically a simple process carried out in a number of steps that can use almost any organic material as a substrate. It occurs in digestive systems, marshes, rubbish dumps, septic tanks and the Arctic Tundra (Ola, 2008). The process does not require large expenditures of energy, as it is biologically driven by a mixed culture of bacteria in the absence of oxygen. Biogas is considered to be carbon neutral because all of the carbon released during combustion has been recently taken from the atmosphere through photosynthesis, unlike fossil fuels that have stored carbon for millions of years (Ryank *et al*, 2008). Thus biogas is a sustainable alternative to natural gas. Since anaerobic digestion only releases carbon to the gas phase, the other nutrients (nitrogen, phosphorus, and micronutrients) remain in the effluent, which makes it a high quality organic fertilizer and soil amendment wastes (Igboro, 2011). Fig 1.1 shows the biogas cycle.

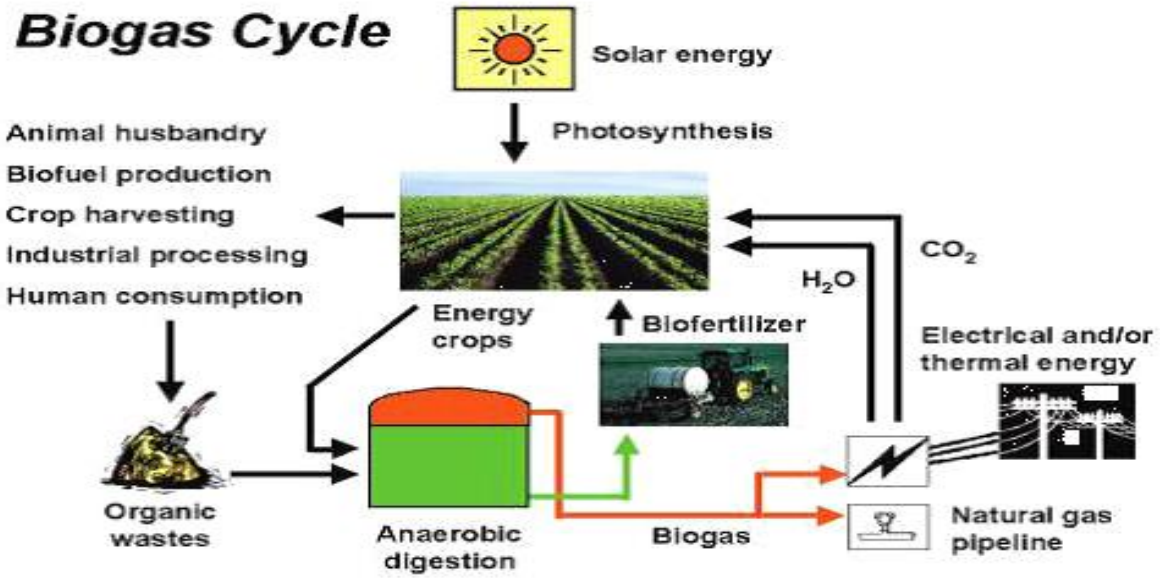


Fig. 1.1: Biogas from organic wastes (Igboro, 2011).

Several kinetic models have been developed for describing the degradation of organic matter for biogas production based on kinetics of the growth of microorganisms. These existing models vary with respect to their objectives and complexity. Because the growth rate of microorganisms is dependent on the quantity and the composition of the substrate, a lot of existing models are precisely adapted to special substrates or a small number of substrates; it therefore becomes very difficult or even impossible to apply the models' processes using different substrates without experimental results (Mandy and Roland, 2008)

1.2 Statement of Research Problem

The economy of the world in general and Nigeria in particular is dependent on fossil fuels such as natural gas and petroleum which are non-renewable. This has led to a rapid depletion of their reserves. Moreover, exploiting, processing and combusting of these fossil fuels pose a serious threat to the natural environment.

Disposal of chicken feather is wasteful as feather keratin is rich in useful amino acids and generates greenhouse gases (Salminen and Rintala, 2002). Efforts have been made to develop more attractive alternatives. For example, feathers have been used in agricultural production as an animal protein supplement after cooking under high pressure and temperature (Odetallah *et al.*, 2003) or as slow-releasing nitrogen fertilizer in agriculture (Choi and Nelson, 1996).

The control and inactivation of chicken prions from cattle carcasses during processing have been major public and animal health concerns (Hill *et al*., 1997). This research intends to investigate the possibility of utilizing this feather for energy production by co-digesting it with cow dung and horse dung.

Presently in Nigeria, management and disposal of animal waste have been of serious challenge to government, institutions and households as there are just few or no designed landfills for disposal of such waste.

1.3 Justification of Study

To meet energy demands and solve the problems of climate change and environmental pollution, alternative, low-emission energy technologies have to be developed urgently, Such as biogas via anaerobic digestion. Energy is a basic need for productivity and economic development of any nation. The energy crisis in Nigeria has been on the increase over the years as citizens have very limited access to energy. This research intends to contribute to solving this energy crisis through detailed investigation on the possibility of renewable energy generation from chicken feather, horse manure and cow dung

Biogas production via anaerobic digestion seems to be a right technology that could contribute to solving the above listed problems. The amount of feather waste and poultry manure generated in Nigeria and world over are becoming enormous as feathers are composed of over 90% keratin mostly as β-keratin (Sawyer *et al*., 2000) that is hard to degrade by commonly known proteases due to the presence of extensive disulfide bonds and cross-linkages. Traditionally, feathers are incinerated or disposed at waste disposal sites (Saliminen and Rintala, 2002). Application of biogas technology successfully, can reduces the volume of wastes to be disposed off by other disposal ways as incineration, landfill, direct burning or by open dumping of refuse which eliminate negative impacts associated with these ways as: smoke, dust, leachate forming and gases emissions.

Anaerobic digestion of poultry feather is a promising alternative for the treatment of feathers, even as recent studies have shown that keratin-hydrolyzing bacteria and keratinase enzyme mixtures digest prions responsible for transmissible spongiform encephalopathy or prion diseases including bovine spongiform encephalopathies (BSE), Furthermore, the ever increasing prices of petroleum products globally, has made kerosene, which is the most commonly used fuel for cooking and lighting unaffordable in Nigeria, especially the rural dwellers, (Ahmadu, 2009). In addition, Majority of the biogas kinetic models in literature are more applicable to simple substrates such as wastewater with a low load of organic substances, This therefore necessitates the need for the deliberate development of kinetic models that can suitably describe the production of biogas from these chosen local substrates. Cow dung and horse dung are readily available in the ancient city of Zaria because of the high availability of these animals for consumption.

1.4 Aim and Objectives of the Study

The aim of this research is to produce biogas from co-digestion of cow dung, horse dung and chicken feathers.

The specific objectives of this research are:

i. To develop simplified anaerobic digesters for biogas production by adopting existing design.
ii. To utilize the developed digesters for the anaerobic digestion of Cow dung, Horse dung and Chicken feathers.
iii. To examine the effect of Chicken feather on the biogas production from Cow dung and Horse dung via co-digestion.

iv. To estimate the maximum biogas potential for each substrate combination using the modified Gompertz model.

v. To determine the physicochemical characteristics of each substrates. Such as Nitrates, Sulphates, Phosphates and Carbon to Nitrogen ratio.

vi. To assess and establish the most feasible local environmental parameters for optimum performance of the anaerobic digesters.

1.5 Scope of study

This shall involve the collection of the chosen substrates for this research from the available sites. Cow dung and Horse dung from Zaria city, Chicken feather from Tudun Wada central market, Zaria local government area of Kaduna state. The research shall be a laboratory scale study.

CHAPTER TWO

LITERATURE REVIEW

2.1 HISTORY OF ANAEROBIC DIGESTION TECHNOLOGIES

Biogas originates from bacteria during the process of bio-degradation of organic materials under anaerobic (without air) conditions. The natural generation of biogas is an important part of the biogeochemical carbon cycle. Methanogens (methane-producing bacteria) are the last link in the chain of micro-organisms that degrade organic materials and return the decomposed products to the environment. It is in this step of the bio-geothermal carbon cycle that biogas, a source of renewable energy, is generated (Salmina *et al*., 2008).

It has been known from several centuries that combustible gas is generated when organic waste is allowed to rot in huge piles. For example in the seventeenth century, Van Helmont recorded that decaying organic material produced flammable gases. In 1776, Volta resolved that there was a direct connection between how much organic material was used and how much gas the material produced. That this combustible gas is methane was established by the work conducted independently by John Dalton and Humphrey Davy during 1804–1808, the formation of methane during the decomposition of organic matter was through a microbiological process (Salmina *et al*., 2008). Omelianski, in the 1990s, isolated microbes responsible for the release of hydrogen, acetic acid, and butyric acid during methane fermentation of cellulose. He also reported that methane perhaps formed due to micro-organism-mediated reaction between hydrogen and carbon dioxide (McCarty et al. 1992). Later, in 1995, he also reported that fermentation of complex materials occurs through oxidation-reduction reactions to form hydrogen, carbon dioxide, and acetic acid. He demonstrated that hydrogen then reacts with carbon dioxide to form methane. He also assumed that acetic

acid through decarboxylation forms methane. This assumption remained highly controversial for decades but is now known to be essentially correct (McCarty *et al*., 1992).

Shortly after the Second World War, there was a substantial growth in the biogas industry, particularly in Germany, Britain and France, and the technology also gradually found its way into agriculture with energy production as the main purpose. At the end of the 1950s, development nearly stopped, however, due to the cheapness of the fossil fuels oil and gas. The interest in biogas was not reawakened until the mid-1970s following the oil crisis in 1973. The Danish state initiated a research and development programme with the aim of testing and constructing different types of biogas plants using animal manure as the main source of biomass. In addition, around 20 communal biogas plants of various sizes have been constructed to treat manure, slurry in particular, from a number of livestock farms, these biogas plants also take in large amounts of organic waste from the food industry and slaughter houses, whereby the energy from the waste is extracted and the nutrients recycled to the agricultural sector (McCarty *et al*., 1992).

A number of developing countries use biogas extensively. In India and China alone, there are more than one million small, simple plants, each treating waste (sewage, animal manure, crop residues, etc.) from a single household. The plants are dug into the ground and are unheated. The biogas is used in the housekeeping for cooking and the digested biomass is used as a fertilizer (Peter *et al*., 2009).

2.1.1 Current Status of Biogas in Africa

Unlike U.S.A., Canada, many European and Asian countries like China, India, Japan e.t.c., biogas production and usage in Africa is still in the embryonic stage. Though

Africa has lots of biomass with high biogas yielding potential, these substrates have been put to little or no use, in terms of biogas production. The promotion efforts of various international organizations and foreign aid agencies to African countries have in the recent time stimulated interest in biogas technology. Though presently small scale biogas plants can be found within the African continent, just very few are working. Large-scale anaerobic digestion in Africa is still in infancy, even in the face of surplus potential substrates (Mshandete and Parawira, 2009).

2.1.2 Current Status of Biogas in Nigeria

Nigeria like many other sub-Saharan African countries has in abundance potential substrates for economical production of biogas. However, at the moment, there is no known documented data to show that there exists any operational biogas plant in Nigeria. It has been a case of laboratory researches in some Nigerian Universities Examples are; Usman Danfodio University Sokoto (Dangogo and Fernado, 1996), Obafemi Awolowo University, Ile-Ife (Adeoti, 1998) as can be obtained in (Mshandete and Parawira, 2009). However, recent energy policies and pronouncements tend to reflect a resolution from government to support biogas research and development.

Table 2.1 shows that as of 2005 the number of biogas plants in Africa was small with only a few countries making an effort to increase access to biogas technology 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. The reasons for failure or unsatisfactory performance of these biogas systems can often be found in the mistakes

made during the planning stages. Other reasons for failures include lack of interest and understanding by the community, construction faults, insufficient maintenance on the system, misconception of benefits of the system, lack of training new owners on the system, and budgeting errors (Ocwieja, 2010; Alfa *et al.*,2013).

Table 2.1: African Countries with Biogas Producing Units

Country	Number of small/medium ($100\ m^3$)	Number of large digesters ($>100\ m^3$)	Region
Botswana	Several	1	Southern Africa
Burkina Faso	>30	-	West Africa
Burundi	>279	-	East Africa
Egypt	Several	Few	NorthAfrica
Ethiopia	Several	>1	East Africa
Ghana	Several	-	West Africa
Cote D'Ivoire	Several	1	West Africa
Kenya	>500	-	East Africa
Lesotho	40	-	Southern Africa
Malawi	-	1	Southern Africa
Morocco	Several	-	Africa
	Few	-	

Nigeria	Several	Few/Several	North Africa
Rwanda	Several	-	West Africa
Senegal	>200	-	East Africa
Sudan	Several	Several	West Africa
South Africa	Several	-	North Africa
Swaziland	>1000	1	Southern Africa
Tanzania	>40	-	Southern Africa
Tunisia	Few	-	East Africa
Uganda	Few	-	North Africa
Zambia	>100	1	East Africa
Zimbabwe			

Source: Mshandete and Parawira (2009), Ocwieja (2010)

2.2 Current Energy Consumption

EIA estimates that in 2011 Nigeria's primary energy consumption was about 4.3 Quadrillion Btu (111,000 kilotons of oil equivalent) of this, traditional biomass and waste accounted for 83% of total energy consumption. This high percent represents the use of biomass to meet off-the-grid cooking heating and cooking needs, mainly in rural areas. Nigeria has vast natural gas, coal and renewable energy resources that could be used for domestic electricity generation, yet lacks policies to harness resources and develop new (and improve current) electricity infrastructure. Previous Researches have

shown that if the available biomass could be utilized a high amount of energy can be generated as shown in Figure 2.1.

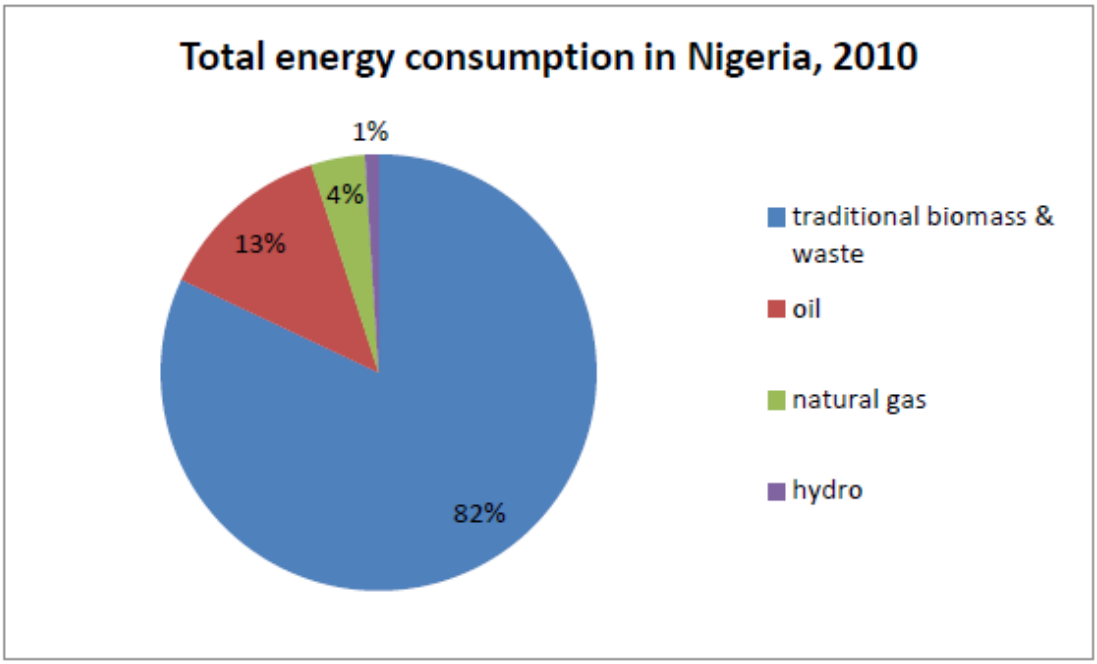


Figure 2.1Total Energy Consumption in Nigeria 2010

2.2.1 Energy situation in Nigeria

The country is located between longitude 8°E and latitude 10°N, and has two major seasons, wet and dry. The seasonality makes water availability at the different hydropower stations variable, leading to an intermittent supply at times of low water levels. Also, the thermal power stations have been bedeviled by lack of adequate supplies of natural gas from the various Niger Delta gas wells, thereby making continuous energy production from these installations difficult. This has left Nigerians at the mercy of private, alternative power generation through the use of diesel and petrol generators

2.3 Feasibility of Using Biogas Technology in Nigeria

Nigeria being a tropical country receives abundant solar radiation of the order 600-850kj/cm^3throughout the year. The average annual temperature is about 38° which is favorable for biogas production. In Nigeria, pastoral farming method and large numbers of livestock are reared. The number of animal per 100 persons has been reported to be in the range of 20-100, the population of animals and the quantity of wastes obtained from them in the country is given in Table 2.2 below. (Zuru *et al.*, 1998)

Table 2.2: Animal Population in Nigeria and the Production of Animal Waste

Animals	Number of heads (Million)	Waste production (Tons/days)
Cattle	10.90	100,000
Pigs	0.88	2,000
Goat and Sheep	30.00	60,000
Horses and Asses	1.00	4,000
Poultry birds	85.00	8,500
Total	127.78	174,500

(Zuru *et al*., 1998)

The same author reported that 227,500 tons (103,194,000kg) of animals waste would be obtained in 1982. If all this waste was used for biogas production, Nigeria would have obtained about 6.825 million m^3 of gas every day which is equivalent to 3,900m^3 of petroleum. A combination of 10% human excreta with 30% animal waste, plus 10% straw and grass, and 50% water has been reported to be used in biogas production in China (Zuru *et al*., 1998).

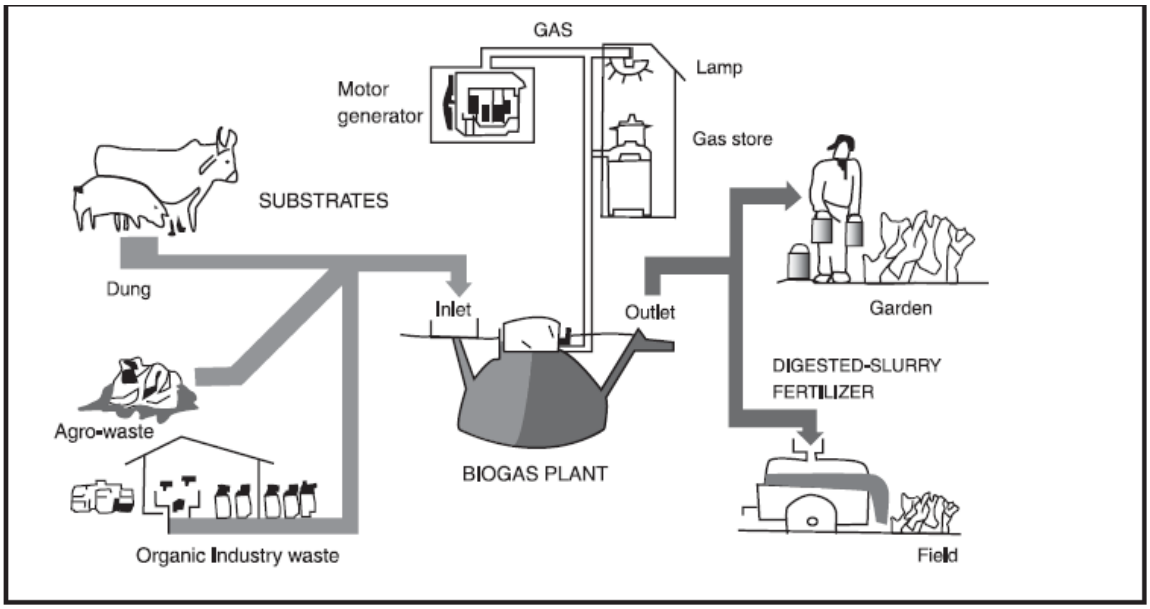
Furthermore, a lot of crops waste and grasses are available in the country. It has been reported that the grass growth rate in Nigeria is about 110 - 140g/m/ day. These grasses and farm wastes could be used for biogas production (Zuru *et al*., 1998).

Our cities are also filled with waste which is useful in biogas generation. It is estimated that the per-capita generation of refuse by urban dwellers may be as high as 2kg/day which can yield biogas at a rate of 0.46 m^3/kg volatile soils (Zuru *et al*., 1998).

Finally, Zuru *et al.*, (1998) realizes that, the majority of the people live in the rural areas, where animal and plant wastes are easily obtained and access to sources of energy like electricity is denied. He concluded that, biogas technology using both family and community size digesters could be used to solve the energy problems of the rural community (Dalhat, 2016).

2.4 Biogas Utilization

The historical evidence of biogas utilization shows independent developments in various developing and industrialized countries. Normally, the biogas produced by a digester can be used as, the same way as any other combustible gas. It is possible that further treatment or conditioning is necessary, for example, to reduce the hydrogen-sulfide content in the gas. When biogas is mixed with air at a ratio of 1:20 a highly explosive gas forms; therefore, leaking gas pipes in enclosed spaces poses a hazard. The schematic diagrams of biogas utilization are shown in Figure 2.2.



Source: GTZ Biogas Basics.

Figure 2.2 Typical biogas configurations

2.5.1 The Costs of Biogas Technology

An obvious obstacle to the large-scale introduction of biogas technology is the fact that the poorer strata of rural populations often cannot afford the investment cost for a biogas plant. This is despite the fact that biogas systems have proven economically viable investments in many cases. Efforts have to be made to reduce construction cost but also to develop credit and other financing systems. A larger numbers of biogas operators ensure that, apart from the private user, the society as a whole can benefit from biogas. Financial support from the government can be seen as an investment to reduce future costs, incurred through the importation of petrol products and inorganic fertilizers, through increasing costs for health and hygiene and through natural resource degradation (Zuru *et al*., 1998).

2.6. Fuel and Fertilizer

In developing countries, there is a direct link between the problems of fertilization and progressive deforestation due to high demand for firewood. In many rural areas, most of

the inhabitants are dependent on dung and organic residue as fuel for cooking and heating. Such is the case, for example, in the treeless regions of India (Ganges plains, central highlands), Nepal and other countries of Asia, as well as in the Andes Mountains of South America and wide expanses of the African Continent. According to data published by the FAO, 78 million tons of cow dung and 39 million tons of phytogenic waste were burned in India alone in 1970. That amounts to approximately 35% of India's total noncommercial/nonconventional energy consumption. The burning of dung and plant residue is a considerable waste of plant nutrients. Farmers in developing countries are in dire need of fertilizer for maintaining cropland productivity. Nonetheless, many small farmers continue to burn potentially valuable fertilizers, even though they cannot afford to buy chemical fertilizers. At the same time, the amount of technically available nitrogen, potassium and phosphorous in the form of organic materials is around eight times as high as the quantity of chemical fertilizers actually consumed in developing countries. Especially for small farmers, biogas technology is a suitable tool for making maximum use of scarce resources: After extraction of the energy content of dung and other organic waste material, the resulting sludge is still a good fertilizer, soil quality as well as higher crop yields (Zuru *et al*., 1998).

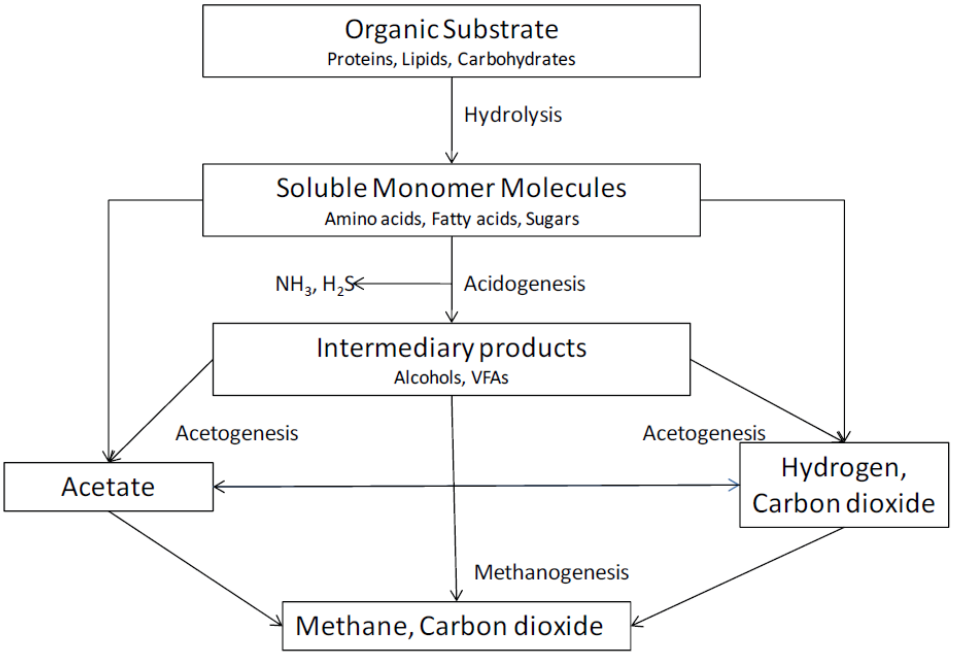
2.7 Public and Political Awareness

Popularization of biogas technology has to go hand in hand with the actual construction of plants in the field. Without the public awareness of biogas technology, its benefits and pitfalls, there will be no sufficient basis to disseminate biogas technology at grassroots level. At the same time, awareness within the government is essential. Since impacts and aspects of biogas technology concern so many different governmental institutions (e.g. agriculture, environment, energy, economics), it is necessary to

identify and include all responsible government departments in the dissemination and awareness-raising process.

2.8 Anaerobic Digestion

Anaerobic digestion is a natural process of complex microbial interactions that primarily converts organic carbon to methane and carbon dioxide. Anaerobic digesters are bioreactor systems that create favorable environments for anaerobic digestion. The type of bioreactor system used depends on the purpose at an industrial, communal, or household level. The main stages of anaerobic digestion are shown in figure 2.3



(Goteborge, 2012)

Figure 2.3 Four main stages in anaerobic fermentation of organic material.

2.8.1 Three Main Purposes of Anaerobic Digestion

The three main purposes of anaerobic digestion are decreasing volatile solids (VS) concentrations, generating methane for energy, and removing pathogens. First, anaerobic digestion can decrease the concentration of VS in wastes through a microbial community using organic materials as both their carbon and energy sources (Rittman

and McCarty, 2011). Shin *et al*. (2011) demonstrated how a community of Lactobacillus, Clostridium, and methanogens coexists and changes as some substrates are degraded and other substrates are generated throughout a batch anaerobic process. Second, anaerobic digestion generates biogas consisting of carbon dioxide, methane, hydrogen sulfide, and nitrogen gas. The methane can be used as a fuel source to provide energy. Rittman and McCarty (2011) state that methane has an approximate energy content of 36 MJ/m3, which is similar to the energy value of natural gas, 37 MJ/m3. This is likely due to the high methane content in natural gas. Third, anaerobic digestion can deactivate pathogens, The effectiveness of treatment depends on the operating conditions such as temperature, pH, hydraulic retention time (HRT), and solids retention time (SRT). It was found that removal of *Salmonella sp*. and *E. coli* increased with increasing solids retention time SRT. Certain pathogens, such as Ascaris, can also be affected by ammonium concentrations (Pecson and Nelson, 2005).

2.8.2 Anaerobic Digestion By-Products

The by-products of anaerobic digestion consist of gases, dissolved nutrients, and solid particulates. Aside from methane, the other primary constituent of biogas, carbon dioxide, is relatively harmless in its respective concentration. However, the concentrations of dissolved nutrients generated from the anaerobic digestion process can be environmentally detrimental and can vary greatly depending on the operating conditions and substrate. Digested swine waste typically has high concentrations of ammonium and phosphate (kossmann, 2004), whereas ions such as sulfides,10 magnesium, sodium, potassium, calcium, and bicarbonate can be present in high concentrations depending on the specific swine operation. Untreated total ammonium, total phosphate, and total sulfide at concentrations between 0.10-2.5 mg/L, 25-310 μg/L, and 2 μg/L, respectively, can present surface water quality problems, depending

on the pH, temperature, and sensitive species, anaerobic digester effluent can have concentrations two or three orders of magnitude greater than EPA surface water quality recommendation. The solids generated from the anaerobic digestion process consist of microbial biomass, undigested wastes, and recalcitrant material (Rittman and McCarty, 2001), such as cellulose from the pig's diet. These solids are better suited as soil amendments because of lowered pathogens while still containing essential N and P for plant growth (Kinney *et al*., 2006).

2.8.3 Biodegradability of digester feedstock

In general, most natural organic wastes can be digested; lignin is the major exception. In Developing Countries, the primary substrate is cattle dung, due to large cattle populations. This is a good substrate, since it is moderately degradable, and is well balanced nutritionally (C/N = 25:1). Swine and poultry manures produce even more biogas per unit weight, and at higher rates, with lower C:N ratio and higher risk of failure of digestion operations. Human wastes (night soil), as well, are high in nitrogen (C/N = 6), and can also be digested. Carbohydrate wastes could be added to raise the C/N ratio and provide more gas. Agricultural residues (e.g., wheat, rice straw) are usually readily available, but have high C/N ratios (over 40). They can only be digested in a mixture with manures and night soil. These wastes are usually partially biodegradable, and can be made more so by physical size reduction, and by pre-composting. However, problems can arise with these materials because they float in the digester and form hard scum on the surface. The high lignin content of this material, which is not degradable, gives the fibrous feature to the digested slurry, used after fermentation as a soil conditioner.

Plants, such as water hyacinth, duckweed, etc., can also be degraded easily, and give quite high gas yields. In these cases, digestion of these weeds can solve the problem

caused by excess weed growth in canals, while providing energy as well. Since their primary productivity is very high, the opportunity exists to create an "energy farm", by cultivating these weeds, perhaps in wastewater, which would also solve the problem of wastewater treatment. They absorb toxicants from the sewage and therefore the digested slurry obtained is limited in its uses.

Wastes generated in urban areas (garbage, organic domestic and industrial wastes) are in principle also amenable to anaerobic digestion. However, these feed stocks have not been thoroughly explored in Developing Countries.

Biomass is plant derived matter (Audu and Aluyor, 2012). It includes plants residues, animal manure, municipal solid wastes e.t.c. Methane production in an engineered anaerobic digestion (AD, or bio-methanation) system has been employed for more than a century to treat municipal sludge generated by municipal wastewater treatment plants (WWTPs), although the main objectives were to reduce pollution and to kill or eliminate pathogens present in the sludge.

As one of the few biotechnologies that can simultaneously produce bio-energy (as methane biogas), reduce environmental pollution and recycle nutrients, AD has recently received renewed attention to produce renewable energy. In fact, biomass wastes, such as animal manures and food processing wastes are ideal for AD because they contain large amounts of water and degradable organic substances such as starch and cellulose. Even the production of other bio-fuels (e.g., bio-ethanol and biodiesel) utilizes only a fraction of the biomass present in the feedstock, and additional energy as methane biogas can be harvested if the resulting wastes are subjected to bio-methanation. As estimated, the AD of bio-ethanol wastes and wastewaters can add approximately 30% more value to bio-ethanol production from corn (Audu and Aluyor, 2012).

In addition to producing renewable energy, the AD of biomass wastes-especially of animal manures and municipal sludge-reduces the emissions of greenhouse gases, nitrogen and odor, and intensifies nutrient recycling (mainly N and P), thus leading to sustainable agriculture and protecting the environment (Borjesson and Bergund, 2007; Clements *et al*., 2006).

For example, the USDA's Natural Resources Conservative Service (NRCS) provided financial assistance to help producers install more than 40 AD reactors in 2006. Recently, Audu and Aluyor (2012), in their study on the potentials of bio-energy and bio-fuels technology in Nigeria, found out that Nigeria has enough potential for biomass production. They further stated that through adequate funding and research, the biomass resources can be used to supply clean energy and materials in Nigeria.

2.8.4 Potential Feed stocks Used for Methane Biogas Production

Biomass wastes are the most common feed stocks of bio-methanation; reciprocally, bio-methanation is the most suitable and mature technology to harvest the otherwise wasted bio-energy from large amounts of biomass wastes. More importantly, biogas produced from biomass wastes is competitive in terms of both efficiency and cost with other bio-energy forms, including heat, synthesis gases, and ethanol (Chynoweth *et al.*, 2001).

Although methane biogas is being produced from millions of tons of organic wastes arising from municipal, industrial and agricultural sources (Chynoweth *et al*., 2001; Gunaseelan, 1997), tremendous amounts of biomass wastes suitable for bio-methanation are currently not subjected to AD. The main characteristics of different feed stocks pertinent to AD are summarized in Table 2.4

Table 2.4 Biochemical methane potential (BMP) of common feedstocks used in methane biogas production (Syed, 2009).

Feedstock	Characteristics	BMP(m^3 CH4 dry ton^{-1})	References
Energy crops			
Grass silage	Low-nitrogen, high-readily fermentable carbohydrates, low water content	390	Lehtomaki and Bjornsson, (2006)
Sugar beet	Low-nitrogen, high-readily fermentable carbohydrates, low water content	380	Lehtomaki and Bjornsson, (2006)
Willow	Low-nitrogen, high-readily fermentable carbohydrates, low water content	160	Lehtomaki and Bjornsson, (2006)
Food-processing wastes			
Brewery residues/wastes	Low-nitrogen, low-readily fermentable carbohydrates, high water content	147	Fountoulakis *et al.*, (2008)
Fresh fruit wastes	Low-nitrogen, low-readily fermentable carbohydrates, high water content	254-495	Gunaseelan, (2004)
Fresh vegetable wastes	Low-nitrogen, low-readily fermentable carbohydrates, high water content	228-454	Gunaseelan, (2004)
Olive oil wastewater	Low-nitrogen, low-readily fermentable carbohydrates, high lipids	108	Fountoulakis *et al.*, (2008)
Potato peels	Low-nitrogen, low-readily fermentable carbohydrates, low water content	454	Gunaseelan, (2004)
Slaughterhouse wastewater	High-nitrogen, high water content	297	Fountoulakis *et al.* (2008)
Stillage	High-nitrogen, low-readily fermentable carbohydrates, low	170-300	Wilkie *et al.*, (2000)

	water content		
Municipal sludge	High microbial biomass, low-readily fermentable carbohydrates, high water content	85-110,390	Angelidaki *et al*., (2000); Zupanc *et al*., (2008)
Municipal wastes(organic fraction)	Low-nitrogen, low-readily fermentable carbohydrates, low water content	300-550	Chanakya *et al*., (2007); Davidson *et al*., (2007b)
Crop residues			
Corn stover	Low-nitrogen, low-readily fermentable carbohydrates, low water content	250	Pfeiffer *et al*., (1979)
Oat straw	Low-nitrogen, low-readily fermentable carbohydrates, low water content	203	Lehtomaki *et al*.,*(*2007)
Wheat straw	Low-nitrogen, low-readily fermentable carbohydrates, low water content	161-241a	Moller *et al*., (2004)
Livestock manure			
Beef and dairy cattle manure	High-nitrogen, low-readily fermentable carbohydrates, high microbial biomass, high water content, may have inert material(e.g., sand)	148-250	Fujino *et al*., (2005); Moller *et al*., (2004)
Piggery manure	High-nitrogen, relatively low-readily fermentable carbohydrates, high microbial biomass, high water content.	275-356,450	Fujino *et al*., (2005); Moller *et al*., (2004)
Poultry manure	High-nitrogen, relatively low-readily fermentable carbohydrates, high microbial biomass, high water content.	460	Fujino *et al*., (2005)

2.9 Co-digestion

Co-digestion is an anaerobic treatment of a homogenous mixture of at least two different substrates, in order to improve the efficiency and efficacy of the anaerobic digestion process. It maximizes the methane production because of positive synergisms being established when balancing several parameters, such as macro- and micronutrients, C/N ratio, pH, and dry weight. Co-digestion also lowers the stress of the reactors, by diluting potential inhibitors and toxic components in any of the substrates. A co-digestion system is therefore often used to avoid inhibition, thus making the biogas plant more profitable

2.9.1 Co-digestion of Different Types of Feedstock

Different types of feedstock can vary widely in physical and chemical features that affect digestibility in AD reactors. The co-digestion of two different feed stocks that complement each other with respect to texture, carbohydrate content, moisture, nutrient balance or pH, can substantially increase methane yield and process stability due to synergisms. This is especially evident when carbohydrate-rich feed stocks are co-digested. For instance, when carbohydrate-rich food or food-processing wastes are digested alone, short chain fatty acids (SCFA) can form very rapidly and often accumulate, causing AD failure due to a lowered pH (Kim *et al.*, 2004). Likewise, when animal manures (which are rich in amino nitrogen) are digested alone, an operational disturbance often results due to the toxicity of high concentration of ammonia to methanogens. The co-digestion of animal manures and food wastes not only alleviates the problems associated with AD of either of these feed stocks alone, but also improves biogas yield. This is further exemplified by a pilot study conducted by Parawira *et al.*, (2008), who noted that the co-digestion of potato waste (C: N ration of 35) and beet leaf (C: N ratio of 14) increased the methane yield by 60%. Similarly, in a full-scale

mesophilic digester treating municipal sludge, a 10% increase in organic loading rate with OFMSW increase the methane yield by almost 60% (Zupancic *et al*., 2008), although co-digestion of certain feedstock represents an attractive technology, the location of digesters, the transportation of feed stocks and the additional equipment required to handle two or more feed stocks must be considered when a new co-digestion system is built. It is obvious that no single AD reactor is universally ideal or superior. Each AD design has certain advantages and disadvantages that make it appropriate for particular type (s) of feed stocks (kim *et al*., 2006). This means that, although comparisons of different AD reactors are of great interest to potential users, in reality such comparisons are difficult to make in a meaningful way. Even performance data from an existing AD digester can only be regarded as being broadly indicative of how a similar AD reactor might perform elsewhere, especially with respect to stability, the efficiency of organic removal, and biogas yield and quality. Therefore, studies using laboratory-scale and pilot-scale AD reactors are required to identify the most suitable technology for a specific feedstock or a mixture of feed stocks.

2.10. Process and Mechanism of Bio-Methanation

In anaerobic digestion, different groups of micro-organisms work in sequence at four different stages. Below illustrates the four main stages of anaerobic digestion of organic material. These are hydrolysis, acidogenesis, acetogenesis and methanogenesis (Jarvis, 2004).

The full process of anaerobic digestion occurs in the following four stages (Monnet, 2003, Verma, 2002, Igboro, 2011);

- Hydrolysis, in which complex molecules are broken down to constituent monomers;

- Acidogenesis, in which acids are formed;
- Acetogenesis, or the production of acetate; and
- Methanogenesis, the stage in which methane is produced from either acetate or hydrogen.

Hydrolysis

This step involves the enzyme-mediated alteration of insoluble organic compounds with high molecular mass, i.e. proteins, fats, lipids, and carbohydrate etc, into soluble organic components such as amino acids, fatty acids, monosaccharide, and other simple organic compounds (Yadvika *et al.*, 2004). The insoluble large molecules consist of many small molecules joined together by chemical bonds and thus need to be hydrolyzed before entering the bacterial cell. The hydrolysis step is carried out by several different anaerobic and facultative bacteria (Yadvika *et al*., 2004).

The hydrolytic activity is of significant importance in high organic waste and may become rate limiting. Some industrial operations overcome this limitation by the use of chemical reagents to enhance hydrolysis. The application of chemicals to enhance the first step has been found to result in a shorter digestion time and provide a higher methane yield (Monnet, 2003). The following conversions take place in hydrolysis/liquefaction reactions;

Lipids → Fatty Acids

Polysaccharides → Monosaccharides

Protein → Amino Acids

Nucleic Acids → Purines & Pyrimidines

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

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

Acidogenesis

In this stage, soluble compounds produced in the first stage are further degraded by a diversity of different facultative anaerobes through different fermentation processes. The fermentation results in the production of carbon dioxide, hydrogen gas, organic acids, alcohols, some organic-nitrogen compounds and some organic-sulphur compounds etc (Gerardi, 2003). The most important acid here is acetic acid as it is the principal organic acid used as a substrate material for the methane-forming organisms.

Typical reactions in the acid-forming stages are shown in equation (2.2) and (2.3). Equation (2.2) expresses how glucose is converted to ethanol, while equation (2.3) shows how glucose is transformed to propionate.

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

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2\ H_2O \quad (2.3)$$

Acetogenesis

In this stage, the other intermediate products and acids than acetate that were formed in the fermentation are further converted to acetic acid as well as carbon-dioxide and hydrogen by different anaerobic oxidation reaction involving so called acetogenic bacteria (Jarvis, 2004).

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.

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. 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 (Themelis and Verma, 2004)..

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.

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \qquad (2.4)$$

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.

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \qquad (2.5)$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+ \quad (2.6)$$

$$2HCO_3^- + 4H_2 + H^+ \leftrightarrow CH_3COO^- + 4H_2O \quad (2.7)$$

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

During this stage, methanogenic micro-organisms convert acetic acid, hydrogen and carbon dioxide to methane and carbon dioxide i.e. biogas. The remaining compounds like alcohols, organic-nitrogen compounds which methanogens cannot degrade will be accumulated in the digestate (Gerardi, 2003).

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_2C0_2 consumers. *Methanosarcina spp*. and *methanothrix spp.* (also, methanosaeta) are considered to be important in anaerobic digestion both as acetate and H_2C0_2consumers. The methanogenesis reactions can be expressed as follows:

$CH_3COOH \rightarrow CH_4 + CO_2$ (2.8)
(Acetic acid) (Methane) (Carbon dioxide)

$2CH_3CH_aOH + CO_2 \rightarrow CH_4 + 2CH_3COOH$ (2.9)
(Ethanol) (Carbon dioxide) (Methane) (Acetic acid)

$CO_2 + 4H_2 \rightarrow CH4 + 2H_2O$ (2.10)
(Carbon dioxide) (Hydrogen) (Methane) (Water)

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

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 (Igboro, 2011).

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.

More so, Monnet (2003) noted that some organic materials, such as lignin, remain effectively undigested, as of course do non-organic inclusions within the waste.

2.11. Struvite Precipitation

Struvite ($M_gNH4PO4 \cdot 6\mathbf{H_2}O$) is a mineral consisting of magnesium, ammonium, and phosphate, which commonly forms after anaerobic digestion on pipe walls and reactor vessels as scale. (Stratful *et al.*, 2001).The potential to form struvite depends on pH, magnesium concentration, and the presence of interferences. Struvite formation in anaerobic digesters and pipes can be very costly.

2.12 Operational Parameters for Biogas Production

The production of biogas is factored by many operational parameters. Some parameters that affect the production of biogas include temperature, pH, pre-treatment, particle size, agitation, rate of organic load, retention time etc. Any rapid change in these parameters can adversely affect the production of biogas (Yadvika *et al*., 2004).

2.12.1 Total solid content of anaerobic digesters

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). Monnet (2003) noted also that when the total solid content is increased, the volume of the digester decreases, due to low water requirements.

2.12.2 Carbon/Nitrogen ratio in digester feedstock

Nitrogen is essential for the growth of microorganisms. Lack of nitrogen leads to in sufficient utilization of the carbon source and consequently to insufficient growth. On the other hand, high nitrogen concentrations result in an increased ammonia production, subsequently inhibiting the methanogens. In order to maximize biogas production, an optimal C/N ratio is necessary. The optimum C/N ratio in a biogas digester ranges between 15 and 30; hence, mixing different substrates with low and high C/N ratios in a co-digestion process may be beneficial to acquire optimal nutritional conditions.

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 (Verma, 2002, Monnet, 2003).

The relationship between the amount of carbon and nitrogen present in organic materials is expressed in terms of the Carbon/Nitrogen (C/N) ratio. A suitable C/N ratio in a feed material plays an important role for the proper proliferation of the bacteria for the degradation process. C: N ratio ranging from 20 to 30 is considered optimum for anaerobic digestion. If the C:N ratio is very high, the nitrogen will be consumed rapidly by methanogens to meet their protein requirements and will no longer react on the left over carbon content of the material. As a result, gas production will be low. On the other hand, if the C: N ratio is very low; nitrogen will be liberated and accumulated in the form of ammonia (NH_3). NH_3 will increase the pH value of the content in the digester. A pH higher than 8.5 will have a toxics effects on methanogen population. Animal waste, particularly cattle dung, has an average C: N ratio of about 24.).

At the same time, the balance of carbon and nitrogen in a feed material is important. It is often suggested that an optimum C: N ratio is between 20:1 and 30:1. If there is too little nitrogen present, the bacteria will be unable to produce the enzymes which are needed to utilize the carbon. If there is too much nitrogen, then it can inhibit the growth of the bacteria through NH_3toxic concentration (Braun, 1992).

Table 2.5: .Carbon to nitrogen ratio of common composting materials

Material	C/N Ratio
Cattle manure	19:1
Cattle carcass	10:1
Corn sillage	40:1
Corn stalk	68:1
Dairy manure	20:1
Grass clippings	17:1
Horse manure	30:1
Leaves	54:1
Poultry carcass	4:1
Sawdust	42:1
Sheep manure	16:1
Swine manure	12:1
Turkey litter	16:1
Wheat straw	127:1
woodships	600:1

(Rynk *et al*., 2002)

2.12.3 Temperature

The biogas production process is highly influenced by the temperature inside the digester. In nature the formation of methane occurs at different range of temperatures; However, mesophilic and thermophilic temperature ranges are more favourable for anaerobes to be active (Yadvika *et al.*, 2004). In general, high temperature give a higher methane production rate and allows higher loading rates, thus decreasing the reactor volume needed for a specific material. The rate of bio-chemical processes with temperature. As a rule of thumb, the rate is doubled for every 10-degree rise in temperature within certain limits (Q10=2).This is also the case with the biogas process. In this situation there are, however, several types or strains of bacteria involved that have adapted to the different temperatures:

psychrophiles 0 – 20°C

mesophiles 15 – 45°C

thermophiles 40 – 65°C

Common to the bacteria is that they are very sensitive to changes in temperature. This sensitivity Increases with temperature. In practice, biogas plants are run at either a mesophilic level of around 37°C, where fluctuations of approx. ± 2°C are tolerated, or at a thermophilic level of around 52°C, where fluctuations of only approx. ± 0.5°C are tolerated.

Anaerobic digestion at thermophilic temperature also gives a better sanitation, i.e. killing of pathogens. However, thermophilic processes are more sensitive to high levels of ammonia, released from protein rich materials (Yadvika *et al*., 2004). Thermophilic processes are also more costly to heat compared to mesophilic processes (Demetriades,

2008). The digestion period in a mesophilic process usually needs comparably longer time, commonly between 20 and 30 days. In thermophilic temperature, however, gas can be produced in much less time comparing to mesophilic temperature. Digesters which process agricultural waste normally operate at mesophilic temperatures.

Methanogenic bacteria are more sensitive to changes in temperature than other organisms present in digesters. This is due to the faster growth rate of the other groups, such as the acetogens, which can achieve substantial catabolism even at low temperatures). All bacterial populations in digesters are fairly resistant to short-term temperature upsets, up to about two hours, and return rapidly to normal gas production rates when the temperature is restored. However, numerous or prolonged temperature drops can result in unbalanced populations, and lead to the low pH problems discussed above. Temperature variations can have adverse effects on mesophilic (35°C) digestion, or thermophilic (55°C) digestion. The temperature effect also depends significantly on the solids concentration of the fermentation. When high concentrations of organic loading were used (over 10%), the tolerance for changes of 5 - 10°C is much higher, and bacterial activity returns quickly when the temperature is raised again, Two distinct temperature regions for digestion have been noted: optimal digestion occurs at about 35°C (mesophilic range) and 55°C (thermophilic range), with decreased activity at around 45°C. This response to temperature may be due to effects on methanogenic bacteria, since these appear to exhibit similar optimal regions (Yadvika *et al*., 2004).

2.12.4 pH of the anaerobic digestion.

The substrate's acidity is measured by pH, which is an important parameter affecting the growth of microbes during anaerobic digestion (Yadvika *et al*., 2004). For optimal performance of the microbes, the pH within the digester should be kept in the range of 6.8 - 8.0. The pH value below or above this interval may restrain the process in the

reactor since micro-organisms and their enzymes are sensitive to pH deviation (Yadvika *et al*., 2004). There are also situations in anaerobic fermentation which can highly affect the pH in the digester. These include high amounts of volatile fatty acids, acetic acid, and impact on the pH in the reactor and might inhibit the activity of the microbes (Yadvika *et al*., 2004).

Acetate and fatty acids produced during digestion tend to lower the pH of digester liquor. However, the ion bicarbonate equilibrium of the carbon dioxide in the digester exerts substantial resistance to pH change. This resistance, known as buffer capacity, is quantified by the amount of strong acid (or alkali) added to the solution in order to bring about a change in pH. Thus the presence of bicarbonate helps prevent adverse effects on microorganisms (methanogens) which would result from low pH caused by excessive production of fatty acids during digestion. Proteins and other organic compounds, as well as bicarbonate, take a part in the buffering capacity and the resistance to changes in pH.

2.12.5 Particle size

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

2.12.6 Water content

Water is the vital element for micro-organisms' life and their activity. The movement of bacteria and activity of extra cellular enzyme etc are highly determined by the water content in the digester. Optimum moisture content has to be maintained in the digester and the water content should be kept in the range of 60-95 % (Demetriades, 2008). However, the optimum water content is likely to differ with different input materials depending up on the substrates chemical characteristics and bio-degradation rate (Nijaguna, 2002).

2.12.7 Agitation

The close contact between micro-organisms and the substrate material is important for an efficient digestion process. This can be achieved in a number of ways. For example, daily feeding of the substrate instead of long interval provides the desired mixing effect. Installation of certain mixing devices such as propeller, scraper, or piston is also a mechanism for stirring (Yadvika *et al*., 2004).

2.12.8 Organic loading rate

The rate at which substrate is supplied to the digester is referred to as organic loading rate and is usually expressed in terms of Kg volatile solids per m^3 per day. The gas production rate in the digester is highly dependent on the organic loading rate (Yadvika *et al*., 2004).

2.12.9 Hydraulic retention time (HRT)

The average time spent by the biomass inside a continuous biogas plant before it comes out from the digester is known as the hydraulic retention time, also abbreviated as HRT. The process of degradation requires at least 10-30 days in mesophilic condition, while in thermophilic environment HRT is usually shorter (Demetrides, 2008).

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.

For liquid manure undergoing fermentation in the mesophilic temperature range, Karki *et al*, (2005) outlined the following approximate values of retention time:

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

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) and Alfa *et al*., (2013).

2.12.10 Seeding

To start up a new anaerobic process, it is critical to use an inoculum of micro organisms to commence the fermentation process. The common seeding materials include digested sludge from a running biogas plant or material from well-rotted manure pit or cow manure slurry (Yadvika *et al*., 2004).

2.12.11 Biochemical oxygen demand (BOD)

According to Kruis (2007), the biochemical oxygen demand (BOD) of a given sample is the amount of 0_2, expressed in mg, consumed by microorganisms in 1 litre of a sample, when incubated in the dark at a fixed temperature for a fixed period of time. Qualitatively, microbial population must consist of microbes capable of attacking the organic matter present. If not available, such a population must be obtained in a preceding enrichment experiment which then furnishes suitable (acclimated) inoculation (seed) material. Quantitatively, the population must be large enough to overcome retardation in 0_2 consumption: below a certain limit the size of the inoculums has a great influence on the time-course of growth and 0_2consumption. In general, according to Igboro *et al*., (2014), the following assertions were made:

• A high BOD indicates a high content of easily degradable.

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

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

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

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

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

2.12.13 Organic loading rate (OLR)/ Volatile Solids (VS):

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).

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).

2.12.14 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).

2.12.15 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).

2.12.16 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.

2.13 Factors Affecting Microbial Activities in Anaerobic Digestion Process

According to Karki *et al.,* (2005), the following factors affect the microbial activities in an anaerobic digester.

Nature of Slurry: For proper solubilization of organic materials, the ratio between solid and water should be 1:1 when the domestic wastes are used.

Seeding or Bacterial Population: Acetogenic and methanogenic bacteria are naturally present in cow dung. However, their number is quite small. Acid forming bacteria proliferate fast and increase their number, while methanogenic bacteria develop very slowly. Therefore, for the initial reaction, small amount of sludge of another digester is generally used as seeding or inoculums. This sludge contains high concentration of acetogenic and methanogenic bacteria, which could enhance the process of anaerobic digestion of organic materials.

Nitrogen Concentration: Methane production is the activity of Carbon metabolism, thus excess amount of nitrogen inhibits the bacterial metabolism and lowers down the methane production.

2.14 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).

2.15 Characteristics of Biogas

Composition of biogas depends upon feed material also. Biogas is about 20% lighter than air, has an ignition temperature in range of 650 to 750 °C. An odourless & colourless gas that burns with blue flame similar to LPG gas. Its caloric value is 20 Mega Joules (MJ) /m3 and it usually burns with 60 % efficiency in a conventional biogas stove. This gas is useful as fuel to substitute firewood, cow dung, petrol, LPG, diesel, & electricity, depending on the nature of the task, and local supply conditions and constraints. Biogas digester systems provides a residue organic waste, after its anaerobic digestion (AD) that has superior nutrient qualities over normal organic fertilizer, as it is in the form of ammonia and can be used as manure. Anaerobic biogas digesters also function as waste disposal systems, particularly for human wastes, and can, therefore, prevent potential sources of environmental contamination and the spread of pathogens and disease causing bacteria. Biogas technology is particularly valuable in agricultural residual treatment of animal excreta and kitchen refuse (residuals), 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). Biogas is a gas produced by the anaerobic digestion of organic wastes. Its primary elements are about 60% methane (CH_4) and about 40% of carbon (IV) oxide (Momoh, 2012). Because methane (CH_4) is the primary fuel present in natural gas, the energy value of biogas is similar to natural gas. Biogas can be produced from the biodegradation of organic materials of biological origin (biomass) in anoxic environments, such as swamps, wetlands, sediments, and in the rumen of ruminants.

2.15.1 Composition of Biogas

The composition of biogas in (Table 2.6) 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). 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.

Table 2.6 shows composition of biogas

Substances	Symbol	Percentage (%)
Methane	CH_4	50 - 70
Carbon Dioxide	$C0_2$	30-40
Hydrogen	H_2	5- 10
Nitrogen	N_2	1-2
Water vapour	H_20	0.3
Hydrogen Sulphide	H_2S	Traces

Source: Shrestha (2010)

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 are as shown in Table 2.7

Table 2.7: Percentage Methane Content of Biogas from Different Feed Materials

Feed Material	Methane Content (%)
Cattle manure	65
Poultry manure	60
Pig manure	52
Farmyard manure	55
Straw	59
Grass	70
Leaves	58
Kitchen waste	50
Algae	63
Water hyacinths	67

(Sasse, 1988).

However, the main constituents of biogas are CH_2 and CO_2 gases. Biogas burns very well when the methane content is more than 50%. If the methane content is considerably below 50%, biogas is no longer combustible. 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 (Igboro, 2011).

2.15.2 Properties of biogas

i. Change in volume as a function of temperature and pressure.
ii. Change in calorific value as function of temperature, pressure and water vapour content.
iii. Change in water vapour as a function of temperature and pressure.

2.15.3 Factors affecting yield and production of biogas

Many factors affecting the fermentation process of organic substances under anaerobic condition are,

i. The quantity and nature of organic matter
ii. The temperature
iii. Acidity and alkanity (pH value) of substrate
iv. The flow and dilution of material

2.15.4 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 consumer appliances. Possible use of biogas as energy source is shown in Figure 2.4 below.

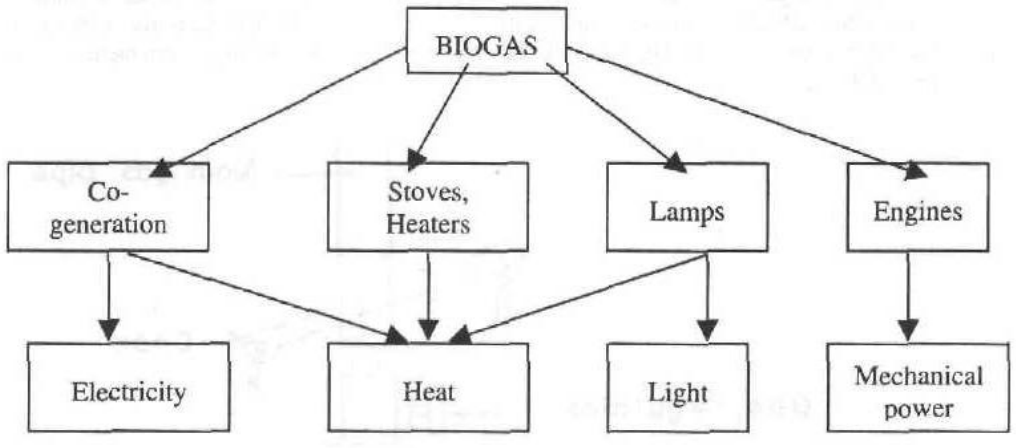


Figure 2.4: Possible Uses of Biogas (Karki *et al.*, 2005).

a) 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.

b) 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.

c) 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.

d) Biogas-fueled Engines: Biogas can be used to operate four stroke diesels 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). Alfa, (2013).

e) 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. Bio-digesters 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 as shown in Table 2.8

Table 2.8 shows the general features of biogas energy content

GENERAL FEATURES OF BIOGAS ENERGY CONTENT	**6-6.5 kWh/m^3**
Fuel Equivalent	0.6-0.65 l oil/m^3 biogas
Explosion Limits	6-12 % biogas in air
Ignition Temperature	650-750 °C
Critical Pressure	75-89 bar
Critical temperature	-82.5 °C
Normal Density	1.2 kg/m^3
Smell	Bad eggs

(Karki *et al.*, 2005).

2.15.5 Benefits of biogas technology

1) Production of energy.

ii. Transformation of organic wastes to very high quality fertilizer.

iii. Improvement of hygienic conditions through reduction of pathogens.

iv. Environmental advantages through protection of soil, water, air etc.

v. Micro-economical benefits by energy and fertilizer substitutes.

vi. Macro-economical benefits through decentralizes energy generation and environmental protection. (Igboro *et al.*, 2011).

2.15.6 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 sulpurous 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 hudrogen sulphide (Monnet, 2003).

A number of gas upgrading technologies have been developed for the treatment of natural gas, landfill gas etc. However, not all of them are recommended for the application with biogas either because of the price, environmental concerns or both (Alfa, 2013).

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:

b) Water scrubbing

c) Polyethylene glycol scrubbing

d) Carbon molecular sieves

e) Membrane separation

f) Hydrogen Sulphide Removal: Hydrogen sulphide must be removed in order to avoid corrosion. The most common methods for hydrogen sulphide removal are (Monnet, 2003, Hullu, 2008).

2.16 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% (Alfa, 2013).

The digestate leaving the chamber is a thick sludge with a moisture content of about 80%, close to the consistency of a milk shake. It is obvious that transporting this would be uneconomic. Therefore, digestate is normally dewatered. The solid is reduced to a liquid content of about 50% - 70% and the remaining water can be collected (Igboro, 2011).

Mara- 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 (Alfa, 2013).

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 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 fiber 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.

2.17 Biogas Systems

A biogas plant converts biodegradable waste to a useable gas under anaerobic conditions. This gas consists mainly of methane and carbon dioxide as well as other trace elements. Organic Material is added to the digester where under anaerobic conditions bacteria convert the material to two products which are biogas and slurry. The system consists of a digester, which provides an area for the material to be digested by bacteria in an environment devoid of oxygen. Material is added to the system via an inlet tube and the digested material is then removed from a separate opening (Ocwieja, 2010).

Ostream (2004) reported that the digestion efficiency and stability can vary significantly depending upon the type of digester used and the parameters of its operation. Digesters range in complexity from simple cylindrical cans with no moving parts to fully automated industrial facilities. The simplest, used in rural China and India, are easy to design and maintain, but require consistent monitoring and are less efficient. The most complex, on the other hand, are designed to automatically detect subtle changes in environmental conditions and warn operators, such as would occur with a change in the feedstock.

Design considerations for such facilities are capacity, vertical or horizontal orientation, batch or continuous flow total solids content, number of stages, mixing and pretreatment.

Also, Ostream (2004) suggested that multitude of digester varieties are designed to optimize the process for specific geographic locations, types of waste, and other considerations. Each of these can be modified to provide the desired degree of autonomy and complexity.

2.18.1 Capacity of Anaerobic Digesters

The capacity of a digester depends on the availability of feedstock. With vast agricultural and municipal solid wastes as the feedstock, farms, urban or populated suburban areas are the most likely choice. The capacity of a system may include simply organics or mixed waste, in which case a separate materials recovery facility would be placed on the front end of the system, such as at Arrow Bio in Israel or Canada Composting in Toronto (Igboro, 2011). As the systems have been proven to be reliable and economic, larger sizes have become more popular.

The Friesland plant in the Netherlands, for example, has a capacity of 230,000 metric tons per year (Ostream, 2004). For MSW management systems in the developed world, the smallest digester that is economic is about 50,000 tons per year (Igboro, 2011). Many plants under construction are close to 100,000 tons per year. The size of individual chambers ranges from 70 m^3 to 5000 m^3 (Themelis and Verma, 2004). Larger capacities are normally accommodated by the use of multiple chambers because incomplete mixing occurs when an individual chamber gets too large (Alfa, 2013).

2.19 Classification of Biogas Plants

There is a wide range of facility types, which differ in location, size, feedstock and process employed. The characteristics of the facility have to be carefully chosen in each specific case (Monnet, 2003).

A typical biogas plant consists of two main parts; a digester (where fermentation occurs) and a gas holder (where the gas produced is stored) (Ahmadu, 2009). Other parts include; an inlet mixing tank and an outlet tank. Various kinds of biogas plants, e.g. the Indian, Chinese, Taiwanese and Philippine plants are in use.

The classification of biogas plants is based on several criteria such as method of feeding the digester, orientation, geometry as well as the gas storage system.

2.19.1Classification based on method of feeding the digester:

There are two broad classifications of biogas systems on the basis of the method of feeding the digester with the feed materials. These are batch plants and the continuous plants. They are briefly discussed below.

Batch Plants: The biomass is fed in batches, with large time interval between two consecutive batches. One batch of biomass in feed is given sufficient retention time in the digester (30-50 days). After completion of the digestion, the residue is emptied and a fresh charge is fed.

Continuous Plants: The plant is fed and emptied continuously. They empty automatically through the over-flow whenever new material is fed in, therefore, the substrate must be fluid and homogenous (Alfa, 2013).

2.19.2 Classification Based on Orientation of Anaerobic Digesters:

The selection of a horizontally or vertically oriented tank depends on how material is intended to flow through the system. Vertical tanks are predominately gravity driven forcing the material to flow generally downward, though the exact path can vary depending on interior boundaries in the chamber. In some cases, material is pumped into the bottom of the tank and removed from the top, causing general upward flow that is further mixed by a lesser, downward, gravity driven flow. While vertical tanks have a smaller footprint, this implies that stratification occurs over a smaller cross-sectional area, which in turn is harder to prevent. Ostream (1999) cited in Igboro (2011) noted that horizontal tanks minimize the area over which the substrate can settle, but require greater space. It may take less input to mix a horizontal tank because the direction of settling is perpendicular to the direction of propagation (Alfa, 2013).

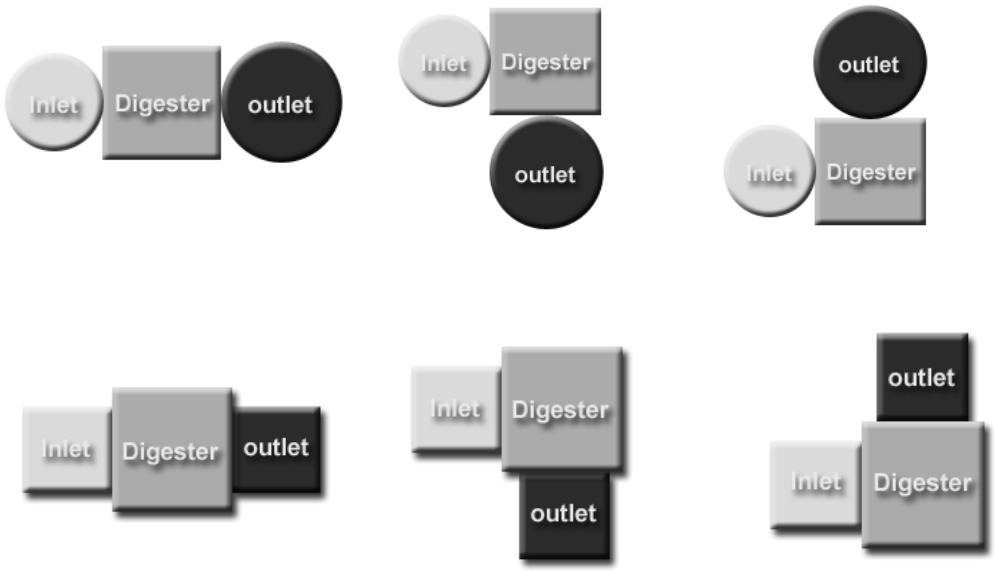


Figure 2.5: Design of Biogas Systems According to Orientations of Inlet and Outlet

2.19.3 Classification Based on Geometrical Shapes of Anaerobic Digesters:

Biogas digesters can be constructed in various geometrical shapes: vertical cylindrical, spherical, rectangular, square, pipe-shaped, oval, spindle-shaped, elliptical, arch, oblate, etc.

2.19.4 Classification Based on Buried Positions of Anaerobic Digesters

Buried anaerobic digesters concerns a system for biogas and fertilizer production from organic wastes. It is composed with a buried curve equipped with a manual agitation system, with a system for biogas storage (gazometer) and a sludge bed. Feedstocks are loaded into the digester all at once. Following loading there is a set period of time for digestion to occur. Following this time period, the digester is manually emptied and reloaded. In a Buried Positions digester, feedstocks are constantly fed into the digester and digested material is continuously removed which can be erected in either of the following ways as shown in Fig 2.6a-c

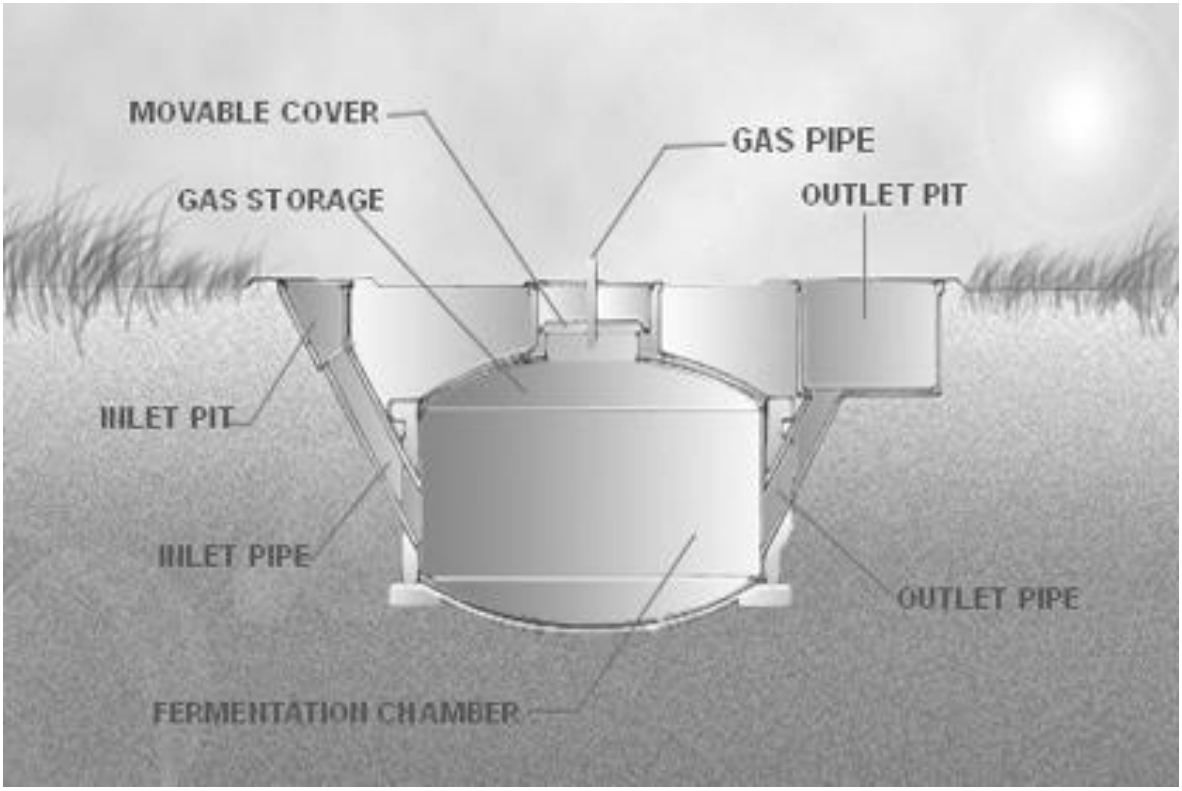


Figure 2.6(a): Underground digester

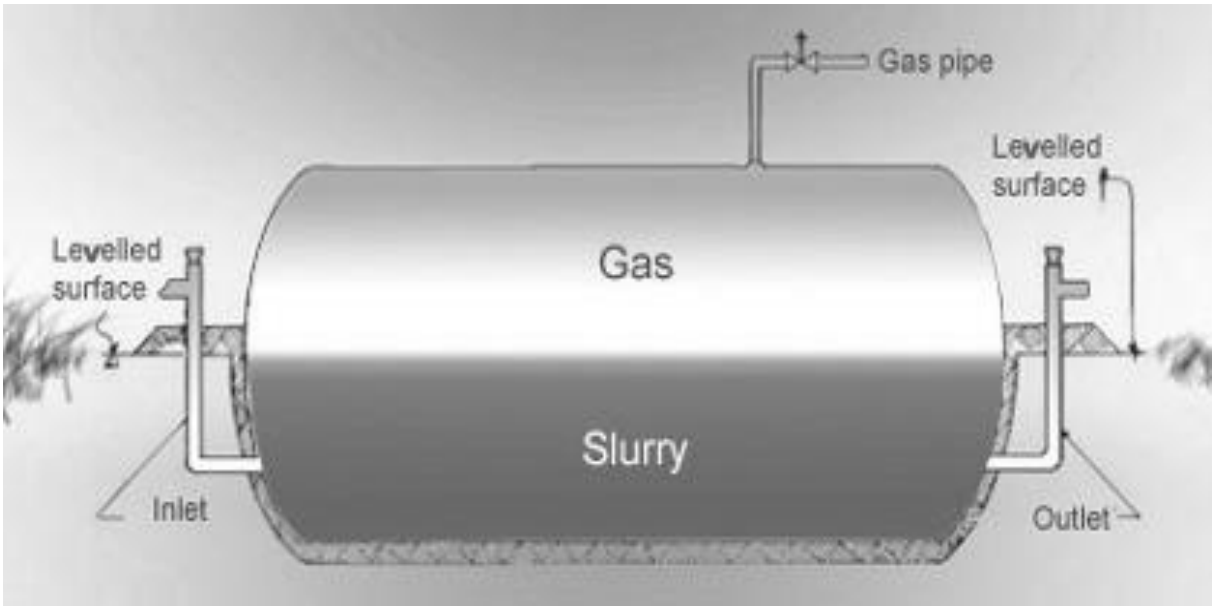


Figure 2.6(b): Semi-Buried digester

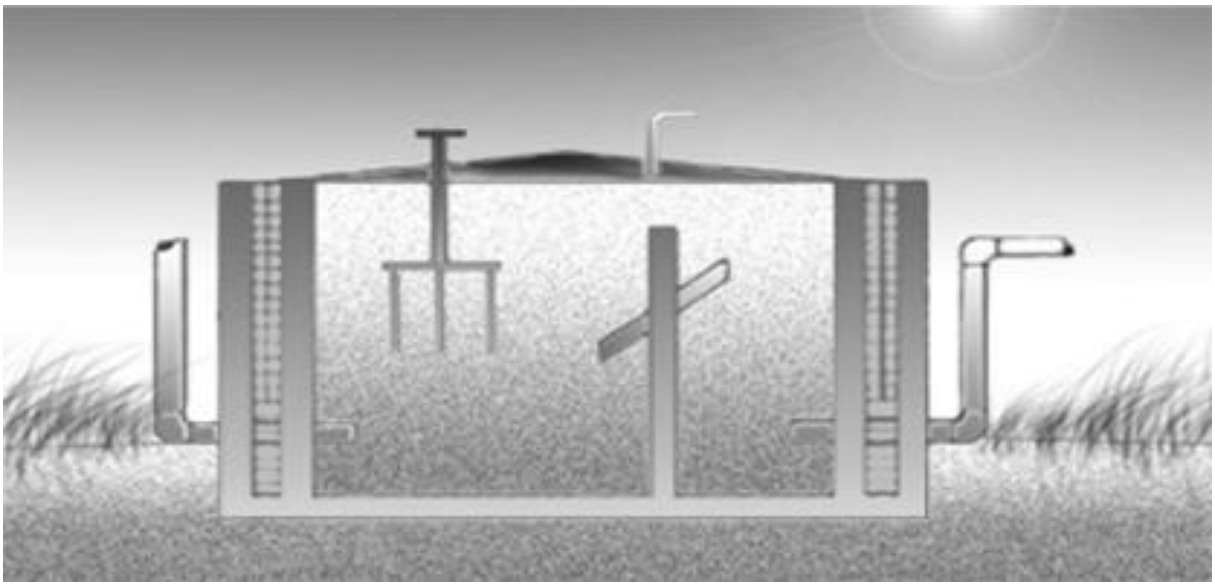


Figure 2.6(c): Ground digester. (Alfa, 2013)

2.19.5 Staged Digesters

The first digestion facilities were simple, single chamber designs where every stage, i.e. hydrolysis through methanogenesis, occurred in the same volume. This approach is still the most often used in modern designs (Igboro, 2011). Some recent designs, however, take advantage of the fact that the biochemical pathways of digestion occur in phases, each one optimized under distinct environmental conditions. The design physically separates the bacteria populations according to these stages; usually they consist of two

stages, though some have as many as eight. Davis and Cornwell (1998) noted that in a single stage digester, all of the bacteria exist in the same volume and the environmental conditions are kept at equilibrium. These parameters are not necessarily optimal for any bacteria, but are acceptable to all. The most crucial parameter is the pH, which must always be kept close to neutral in order to ensure the survival of the methanogens. A pH that is lower than 5.5, in which acidogens thrive, is fatal to methanogens. Once in operation, these digesters are simpler to operate than multi-stage digesters because the equilibrium is fairly stable (Alfa, 2013).

In a multiple stage digester, the substrate is transported to sequential chambers where progressive stages of anaerobic digestion occur according to prescribed timing (Davis and Cornwell, 1998). Each chamber maintains environmental conditions most favorable to the bacteria present. If two tanks are used, the first tank allows hydrolysis, acidogenesis and acetagenesis to occur while the second optimizes methanogenesis. The first tank is mixed and heated to a uniform temperature and fed continuously. The pH is allowed to fall. The residence time in this chamber is anywhere from 10-15 days (Davis and Cornwell, 1998). The second tank must maintain a higher pH and provide capacity for gas collection or storage. In more complex multiple stage digesters, up to eight tanks are used, with each tank having a unique purpose and living environment (Davis and Cornwell, 1998).

There have not been studies on the optimal number of tanks. Two-stage digesters can be more efficient because the microorganisms have separate nutrient needs, growth capacities, and abilities to cope with environmental stress. The need to construct multiple tanks, however, may offset the cost savings incurred by reduced retention time. Additionally, the BOD is higher at the conclusion of a multiple stage digester, and total solids can be as high as 12,000 mg/L (Davis and Cornwell, 1998).

2.20 Feedstock and Feedstock Pretreatment

Feedstock: The identification of feedstock substrate for an economically feasible biogas production in Nigeria, to include water lettuce, water hyacinth, dung, cassava leaves and processing waste, urban refuse, solid (including industrial) waste, agricultural residues and sewage have been made (Akinbami *et al.*, 1996), Many other raw materials available in Nigeria have been critically assessed for their possible use in biogas production : They include refuse and sewage generated in urban areas, agricultural residues and manure. It was concluded that poultry manure generated in Nigerian homes and in commercial poultry farms could be economically feasible substrates for biogas production. The potential to utilize poultry, cow and kitchen wastes for biogas production was demonstrated by other workers including.

Alkan-Ozkaynak and Karthikayan (2011), investigated production of biogas from co-digestion of banana and plantain peels using a 10 L laboratory scale anaerobic digester. The highest volume of biogas was obtained when the banana and plantain peels were in equal proportions as feedstock. More so, Igboro (2011) compared the biogas from cow dung from abattoir and the National Animal Production Institute, Zaria, with the abattoir waste generating the highest volume of gas. Igboro *et al*., (2011) also designed a biogas stove burner which was effectively tested with the biogas produced from cow dung and other feed materials. It appears that some groundwork for biogas research and development have been initiated in Nigeria.

2.20.1 Feedstock pretreatment:

There are a variety of pretreatment processes that are chosen based on the characteristics of the incoming waste and the effects they have on digestion. Separation technologies for metals, glass and plastics are usually necessary and similar to those

used in material recovery facilities (Igboro, 2011). This section will focus on pretreatment processes unique to the anaerobic digestion process.

The pre-treatment of feedstock for anaerobi digestion involves:

Removing the non-biodegradadble materials, which are not affected by digestion and take up unnecessary space;

Providing a uniform small particle size feedstock for efficient digestion;

Protecting the downstream plant from components that may cause physical damage and removing materials which may decrease the quality of the digestate (Monnet, 2003).

While pre-treatment process for manure is most of the time limited to grit removal or mixing with other organic wastes, it can be more complex with farm residues and municipal solid wastes. Pre-treatment for the later can be achieved either by source separation or by mechanical means (Monnet, 2003).

The following pre-treatment methods are in use:

Manual sorting, which can be used to remove contrary materials such as batteries, large items, bricks, stones and other inorganics.

Rotating trommels or other type of screen to remove oversize items.

Hammermill for size reduction of the waste.

A hydropulper (Monnet, 2003).

Cluff, (2003) noted that diluting the waste with water allows the bacteria to move more freely inside the digester. Sometimes the recovery of recyclable materials is done simultaneously with preparation of the organic suspension.

Karki *et al*., (2005) reported that larger vegetable and fruit pieces for anaerobic digestion were cut into smaller ones of size less than or equal to 20-50 mm to allow faster biodegradation after which the prepared material was then put into a polythene drum for a period of 20 to 40 days for pre-fermentation during which it was agitated periodically.

2.21 Environmental and Health Impacts

Animal wastes can deposit excess nutrients into the environment via surface runoff or as leachate (water contaminated with manure) from improper manure storage and land application. This can negatively impact water quality and subject landowners to investigation, its therefore encouraged to use best management practices and develop a nutrient management plan. Nutrient management plans describe the farm's manure production, soil fertility, and recommended manure application and removal rates.

2.21.1 The Environmental and Economical use of Compost

The economic importance of the digested slurry is becoming more acceptable in recent times as a source of plant nutrients. The organic residues after anaerobic digestion have superior nutrient qualities over the cattle dung, this aspect of biogas technology may, in fact, be more important than the gas produced. Digester effluent acts as a soil conditioner and good source of inorganic nutrients. Provide slow-release plant nutrients, it improves filth, increases water-holding capacity, lessens wind and water erosion, improves aeration, promotes the growth of beneficial organisms, maintains soil fertility, Prevent plant disease, Increase nutritional content in plants, and Produce tastier fruits and vegetables. Unlike chemical fertilizers that provide short term results yet, in the long term, damage the soil by affecting its pH, changing the kinds of microorganisms (such as *mycorrhizal*) that provide plants with natural immunity to diseases. The soil suffers from lack of aeration and the elimination of naturally occurring fertilizers as

wonderful creatures such as Earthworms are being eliminated by chemical fertilizers, undermined ground water, and more importantly our health, Chinese workers report that digested biomass increases agricultural productivity by as much as 30% over farmyard manure, on an equivalent basis, the total nitrogen for dairy manure increased from 5.2 % to 6.9 % of the solids during digestion found increases from 3.7 % to 3.9 % of the solids. The use of biogas digested slurry in conjunction with the chemical fertilizers as an integrated nutrient management strategy may help in reducing the problems related to the use of chemical fertilizers (Sasse *et al.,* 1991).

An experiment was carried out in Fisheries Research Complex of the Punjab Agricultural University Ludhiana, India to study the effect of biogas slurry on survival and growth of common carp. The study concluded that growth rates of fish in terms of weight were 3.54 times higher in biogas slurry treated tanks than in the control. Bio slurry provides to be a better input for fish pond than raw cow dung since the growth rate of common carp in raw cow dung treated tanks was only 1.18 to 1.24 times higher than the control. There was 100% survival of fish in ponds fed with digested biogas slurry as compared to only 93 percent survival rate in ponds fed with raw cow dung (Sasse *et al.,* 1991).

The composted manure has advantage over fresh, non-composted manure despite by the fact that, the fresh, non-composted manure will generally have a higher N content than composted manure. However, the use of composted manure will contribute more to the organic matter content of the soil. Fresh manure is high in soluble forms of N, which can lead to salt build-up and leaching losses if over applied. Fresh manure may contain high amounts of viable weed seeds, which can lead to weed problems. In addition, various pathogens such as *E. coli* may be present in fresh manure and can cause illness to individuals eating fresh produce unless proper precautions are taken.

The National Organic Standards Final Rule (USDA, 1990) in pages 45-46 and section 205.203) states that "Raw animal manure must either be composted, applied to land used for a crop not intended for human consumption, or incorporated into the soil at least 90 days before harvesting an edible product that does not come into contact with the soil or soil particles and at least 120 days before harvesting an edible product that does come into contact with the soil or soil particles.

2.22 A Review of Existing Mathematical Models for Biogas Production

Models for describing process to produce biogas are required to undertake the following:

i) Facilitate the understanding of the process

ii) Design new or enhance old biogas plants

iii) Compare and select appropriate substrates and substrates mixtures

iv) Compare and select appropriate process steps and components

v) Optimize the operation of biogas plants

vi) For an ecological and economic analysis

A lot of models have been developed within the last decades for describing the processes of biogas production from the degradation of substrates, predicting biogas production rate and digesters stability.

2.22.1 Biogas Production Models with Reaction Kinetics using modified Gompertz equation.

The kinetics of biogas production involves three fundamental processes:

i) Growth of microorganisms

ii) Substrates degradation

iii) Products Formation

2.22.2 Modified Gompertz equation

Modified form of the Gompertz equation which is commonly used to simulate the cumulative biogas production (zwietering *et al*.,2010). The modified Gompertz equation can be presented as follows:

$$y=A\exp\{-\exp[\frac{\mu_m e}{A}(\lambda - T) + 1]\} \quad (2.11)$$

Where, P is the cumulative of the specific biogas production (ml/gm), A is the biogas production potential (ml/gm), U is the maximum biogas production rate (ml/gm/day), λ is the lag phase period or the minimum time required to produce biogas (day). Analysis of the experimental data was performed in MS-excel using the solver feature by non-linear regression.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

The materials used for this research are cow dung, horse dung, chicken feather, chemicals, as well as the apparatus and instruments used for measurements as described below

3.1.1 Chemicals Used

The chemicals utilized for various purposes in the work are given in Table 3.1:

Table 3.1: List of Chemicals and Reagents

S/n	Chemicals	Manufacturers	Grade (% Purity)
1	Ammonium fluoride, NH_4F	Eagle Scientific Company Ltd	Extra Pure
2	Ammonium molybdate, (HN4)6MO_{24}. 4H_2O	Reidel-Pahaen	83
3	Ammonium sulphate, NH_4SO_4	British Drug House	
4	Boric acid, H_3BO_3	May & Baker	99.5
5	Boric acid indicator	May & Baker	
6	Hydrochloric acid, HCl	British Drug House	36
7	Molybdenum phosphate, $M0_3 0_{16} P_4$	Reidel-Pahaen	
8	Potassium chloride, KCl	May & Baker	
9	Potassium hydroxide, KHO	Merck	85
10	Sodium hydroxide, Na0H	Gillard Chemical Company	
11	Tetra oxosulphate (VI) acid, H_2SO_4	May & Baker etc.	

3.1.2 Instruments/ Apparatus

The instruments and apparatus used in this work are described below.

1. Instruments

The major instruments used in this work are shown in table 3.1 below:

Table 3.2: List of Instruments

S/No.	Instruments	Manufacturer
1	Hatch Spectrophotometer	Jenway Ltd England
2	Furnace (0-1200°C)	Dubuque Iowa, USA
3	Oven (0-200°C)	Philip Harris Ltd England
4	Kjeldahl apparatus	Heraeus-witmana W.G
5	12 digesters with gas collection system	Locally Fabricated
6	pH meter model pHS-2S	Shanghai jinyke rex, china
7	057748 united inventory database Milling machine	kera made in Holland
8	Filter cloth	
9	Conical flasks	
	Beakers and Pipettes	

2. Apparatus:

Laboratory glass wares were used in the preparation of solutions. However, the biogas digester and collection system was fabricated as described below:

3.1.3. The Construction of laboratory scale Biogas system

Twelve (12) biogas digester and collection system were locally fabricated and used in the digestion of three chosen substrates and its co-digestion under the study. These digesters were similar in design by (Alfa *et al.,* 2013) and were operated simultaneously to ensure fair basis for comparison of results.

3.1.4. Material and tools Used:

1. 12 digesters with gas collection system

2. PVC Pipe (3/4)^{II}

3. Waterproof sacks

4. Funnel

5. Tyre Tube

6. PVC glue and araldite adhesive

7. Soldering Iron

8. Black Paint, coaltar and Brush

9. A Saw, Screwdriver, File, Meter, and scissors

10. Bowl inflator

11. Plastic Buckets

12. Electronic weighing balance

13. A portion of land was acquired within the Department of Water Resources and Environmental Engineering on which the set up was installed as shown in plate 3.1.

Plate 3.2. Setup of biogas plant

3.2 Methods

The methods followed to achieve the stated objectives for this research objectives are discussed in the sections below.

3.2.1 Method of development of anaerobic digestion

A laboratory scale anaerobic digester and gas collection system designed previously by Alfa (2013) was adopted. The design was a modification of Ajoy Karki's (2002) biogas model. The modified design fit into the purpose of this study and was adopted without any alteration or modification.

3.2.2 Design of pilot scale anaerobic digesters

The design theory adopted for this study combines the (Alfa, 2013) comparative production and utilization of biogas for cooking, using cow dung, chicken droppings, *Cymbopogon citrates* (lemon grass) as well as the respective co-digestion of cow dung and chicken droppings with *Cymbopogon citratus* (lemon grass) and Ajoy Karki's kitchen waste Biogas model (Karki, 2002) and the separate floating gas holder system. The cylindrical shape was adopted to enhance better mixing. The separate gas holder system was incorporated into this design to allow for ease of measurement of gas volume at atmospheric pressure. The succeeding sections give details of the principles and design consideration for the digester type adopted (Alfa, 2013).

The digester is a separate component, with the gas holder (inverted drum) floating in a separate water jacket.

The theory behind the design is simply "downward delivery and upward displacement". The slurry on fermenting in the digester produces gas. This gas is delivered to the bottom of the water jacket via a pipe; the pipe extends above the surface of the water level (water seal) in the water jacket. The 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, thus the gas is collected and transferred to the kitchen where it is used for cooking. Figure 3.1 shows a schematic view of the plant set up.

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

i) It's a simple design and construction with high tolerance to construction flaws and defects.

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

iii) It is space conservative as it requires minimal space for the set up

iv) The cost of construction is affordable.

v) Low maintenance and adapted to the habits and perceptions of the intended users.

vi) Collecting the gas outside the digester reduces pressure in the digester

vii) 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 the position of the drum.

viii) There's superior sealing of the substrate, no risk of spillage of slurry into the gas holder, thus very hygienic.

ix) Gas holder can easily be protected from rust by painting regularly, thus facilitating gas tightness. (Ahmadu, 2009).

3.3 Construction of Biogas Digestion plant.

Biogas plants were constructed to digest the three substrates at different percentage ratios for the study which were similar in the design of Alfa, (2013), and would be operated simultaneously to ensure fair basis for comparison of results.

3.3.1 Material Selection

As a general rule, the selection of all the materials would be based on: Cost-effectiveness, availability and durability.

3.3.2 Materials for Digester Construction

The material used for the digester is a mild-steel drum meeting the calculated dimensions. It was selected to meet the following requirements:

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 entering into the digester.

Good tensile strength and ease of rolling by machine to required design geometry.

3.3.3 Materials for gas holder and water jacket

The material used for the gas holder is a thin sheet metal while that for water jacket is a mild-steel sheet metal painted aluminum colour to prevent corrosion and provide reflective surface. It was selected to meet the following requirements:

a) Relatively cheap.
b) Provides reflective surface thereby minimizing heat buildup inside the gas holder and within the water seal.
c) Good tensile strength and easy to roll by machine to required design geometry.

d) Provides gas tightness to store biogas

3.3.4 Materials for gas pipe

The materials used for the gas pipe are; galvanized steel pipe, which was used inside the water jacket, and flexible plastic pipe which was used from the digester outlet to the galvanized pipe inlet at the bottom of the water jacket.

Both have the same diameter. Galvanized steel pipe was selected based on its resistance to corrosion and rigidity, flexible plastic pipe was selected based on its resistance to corrosion and flexibility.

3.3.5 Fabrication of Parts

Having selected the materials to be used, machining of component parts was carried out using the appropriate machine tools and hand tools at the laboratory of the Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria.

3.4 Selection of the Substrates used for the Research

The substrates for this research are Horse dung (HD), Cow dung (CD), and Chicken feather (CF). The methodology comprised collection of substrates, preparation of substrates and the anaerobic digestion of the substrates in batch mode. Twelve (12) local digesters were fabricated for the digestion of the chosen substrates

3.4.1 Collection of Substrates

In order to accomplish this research, three kinds of organic waste substances were collected from Zaria city and utilized for biogas production and model study experiments. These substrates are Horse dung (HD), Cow dung (CD), and Chicken feather (CF).

3.4.2 Preparation of Chicken Feather Substrate

Freshly plucked chicken feathers of about 50 kg was collected from the poultry slaughter house of Zaria city market, and then washed with tap water to remove sand and other particles. The washed chicken feathers were placed in dryer boxes at 230^0C. After drying, the feathers were grinded using a hammer mill to a very small particle size of about 4mm.a laboratory analyses was conducted such as the Carbon nitrogen ratio, nitrate, sulphate and phosphate using standard procedures as outlined in (Kjeldahl

method). The analysis was conducted at National Research Institute for Chemical Technology Zaria (NARICT).

3.4.3 Preparation of Horse Manure, cow dung

Cow dung and Horse manure of about 30 kg was collected from Zaria city And divided into five (5) samples of 6kg each and neatly stored in six different polyethene bags labeled PM1, PM2, PM3, PM4 and PM5, Laboratory analyses of the substrate was carried out to determine the physicochemical characteristics of the substrates such as the Carbon nitrogen ratio, Nitrate, sulphate and phosphate using standard procedures as outlined in Kjeldahl method .The analysis was conducted at National Research Institute for Chemical Technology Zaria (NARICT).

3.5 Process Description for Anaerobic Digestion of Cow dung, Chicken feather and Horse dung

A set of batch reactors fabricated as shown in Appendix I were used as digesters labeled 1-12. Each digester contained organic waste and its co-digestion at different percentage ratios (ranging from 0%, 25%, 50%, 75%, 100% which is equivalent to 0kg, 1.5kg, 3kg, 4.5k, 6kg respectively). Digester one (D1) contained 100%CD, Digester two (D2) contained 75%CD-25%HD, Digester three (D3) contained 50%CD-50%HD, Digester four (D4) contained 25%CD-75%HD, Digester five (D5) contained 100%HD,Digester six (D6) contained 100%CF, Digester seven (D7) contained 75%CD-25%CF, Digester Eight (D8) contained 50%CD-50%CF, Digester nine (D9) contained 25%CD-75%CF, Digester ten (D10) contained 75%HD-25%CF,Digester Eleven (D11) contained 50%CD-50%CF, Digester twelve (D12) contained 25%HD-75%CF. Different percentage ratios of the chosen substrates as mentioned above were mixed with water to form slurry in the ratio 1:1 by volume which were separately introduced into each digester through an inlet pipe of 50mm at the top of the digester tank. The slurry was

allowed to occupy three quarter of the digester space leaving a clear height of about 0.0625m as space for the gas production. The inflow was directed downward to cause the solids to accumulate at the bottom of the tank where after digestion they can be easily removed. Before feeding the reactors, the flexible plastic pipe connecting the gas outlet from the reactor to the gas holder was disconnected, such that the gas outlet from the reactor was left open. This was done to prevent negative pressure build up in the reactor. The gas was collected from the digester through a 15mm diameter flexible host connected from the digester to the bottom of the gas collection system. The collected gas is allowed to pass through water and slaked lime respectively as scrubbers. (owamah *et al.*, 2014, Alfa *et al.*, 2013).

The biogas production was measured with the aid of the rule attached to the gas holder and the measurement of gas production was done daily until the retention time was achieved.

3.6 Measurement of Physico-Chemical Parameters of Feedstock and Residue

3.6.1 Determination of Nitrate, Sulphate, Phosphate and Carbon to Nitrogen ratio.

The experiment was conducted using Kjeldahl method. Nitrogen and Sulphate were determined using a spectrophotometer (HACHLANGEDR 2800) and a modified Nessler method (No. 8038) adopted by HACH. Phosphorus was also determined using same spectrophotometer coupled with Phosphate Reagent Powder Pillow Test (method 8048). The full details of the procedures have been previously described in (Dalhat *et al.*, 2014).

3.7 Measurement of Operational Parameters

3.7.1 Temperature of the digesters

The research was carried out under mesophilic temperature and it was measured to determine the feedstock influence on the temperature and consequently, the metabolism of the bacteria. 2/1 $^{\circ}$C Thermometers (made in England) were used to measure the temperature of the digester and that of Samaru (Ahmadu Bello University Zaria). The digester temperatures were taken three times daily, morning, afternoon and evening. i.e. 8am, 2pm and 6pm respectively while the ambient Samaru temperature was recorded at 2pm daily.

3.7.2 pH of the slurry

This was measured to determine the feedstock influence on the acidity/alkalinity and consequently because it gives the intensity of acidic or basic character at a given temperature. The metabolism of the bacteria. Samples were analysed at ambient temperature with a pH meter model pHS-2S, (SHANGHAI JINYKE REX, CHINA). The pH analysis was carried out twice in a week throughout the period of study.

3.8 Inflammability Test for the Biogas Produced

The Inflammability test for the biogas produced was carried out in order to know the quality of the biogas produced from each and every biomass. This is manifested in their biogas consumption rate. Therefore, the less the biogas consumption rate the more the quality is the gas and vice versa.

This test was carried out with the aid of Bunsen burner which is connected to the biogas holder.

3.8 ANALYSIS OF THE CUMMULATIVE BIOGAS PRODUCTION WITH THE MODIFIED GOMPERTZ MODEL

The scope of the model study in this research was restricted to the studying of the cumulative biogas production using the modified gompertz equation. Thus, modified gompertz equation was used to model cumulative biogas production from cow dung, horse dung and chicken feather.

The equation (3.1) shows modified gompertz equation.

$$y=A\exp\{-\exp[\frac{\mu_m e}{A}(\lambda - T) + 1]\} \qquad (3.1)$$

Where:

Y (t) = cumulative biogas produced (m^3) at any time (t)

A = biogas production potential (m^3)

λ= Lag phase period (days), which is the min time taken to produce biogas or time taken for bacterial to acclimatize to the environment.

t = cumulative time for biogas production (days) and

e = mathematical constant (2.718282)

μ = maximum biogas production rate

(Matheri *et al.*, 2015; Yusuf *et al*., 2011; Alfa *et al.*, 2016)

The constants *A*, μ_m and λ were determined using the non linear regression approach with the aid of the solver function of the Microsoft excel tool pack.

The modified gompertz equation has been extensively used by researchers to study the cumulative/methane production as well as bacteria growth in both biogas and biogas production studies (Budiyo *et al*., 2010).

3.8.1 Procedure to fit the data in to solver equation

(1) Solver menu was selected under the tools icon.

(2) A new pop up window appeared

(3) A target cell was labeled by typing $G: $4

(4) "Equal to " the min function was selected to minimize the value in cell G4

(5) In the labeled box, the cells were changed to G1: G3

(6) Solver values was varied for A, C and K to minimize the sum of Chi Squared.

(7) A box appeared to choose solve or cancel

(8) Solve option was clicked on the menu and initial values were altered to fit the data

(9) A new pop up appeared asking if to keep the values or revert to the original values, and keep solver solution was selected.

(10) A, C and K values were inserted in cells G1:G3

(11) A graph of column B against Column C was plotted, and two curves were matched very closely. But if they do not, then a better guesses for A, C and K should be selected to start with.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

Twelve (12) number pilot scale anaerobic digesters were developed and were utilized for the digestion of the three substrates both as single and co-digested substrates in this study. The experimental results obtained during the monitoring period in the study were presented in tables and graphs and were analyzed using statistical methods as presented and discussed in subsequent sections.

4.2 Development of pilot scale anaerobic digester

Table 4.1 shows the summary of the parameters of the digesters and gas collection system developed by Alfa (2013) and adopted for this study.

Table 4.1: Summary of Dimensions for Anaerobic Digester and Gas collection System

Design of Digester	**Design of Gas holder**	**Design of Gas pipe**	**Design of Water Jacket**
Operating volume $V_o = 2.0 \times 10^{-3} m^3$ Total volume, $V_T = 2.5 \times 10^{-3} m^3$ Digester height, $h_d = 0.50m = 50cm$ Digester diameter, $d_d = 0.25m = 25cm$	Total gas holder volume, $V_g = 1.21 \times 10^{-3} m^3$ Gas holder height, $h_g = 0.25m = 25cm$ Digester diameter, $d_g = 0.25m = 25cm$	Length of pip = 1m Diameter of pipe = 0.0127m (1/2 inch)	Water jacket height, hj = 0.25m = 25cm Water jacket diameter, dj = 0.27m = 27cm

Source: Alfa, (2013).

4.3 Measurement of gas production for the three substrates digested alone and with its co-digestion.

The study of biogas production from Cow dung, Horse dung and their mixtures was conducted in digesters labeled 1–12 as shown in appendices. Biogas production was monitored and measured until biogas production reduced significantly. The modified Gomperzt equation was then used to fit the cumulative daily biogas production which was observed to adequately describe the biogas production from these substrates.

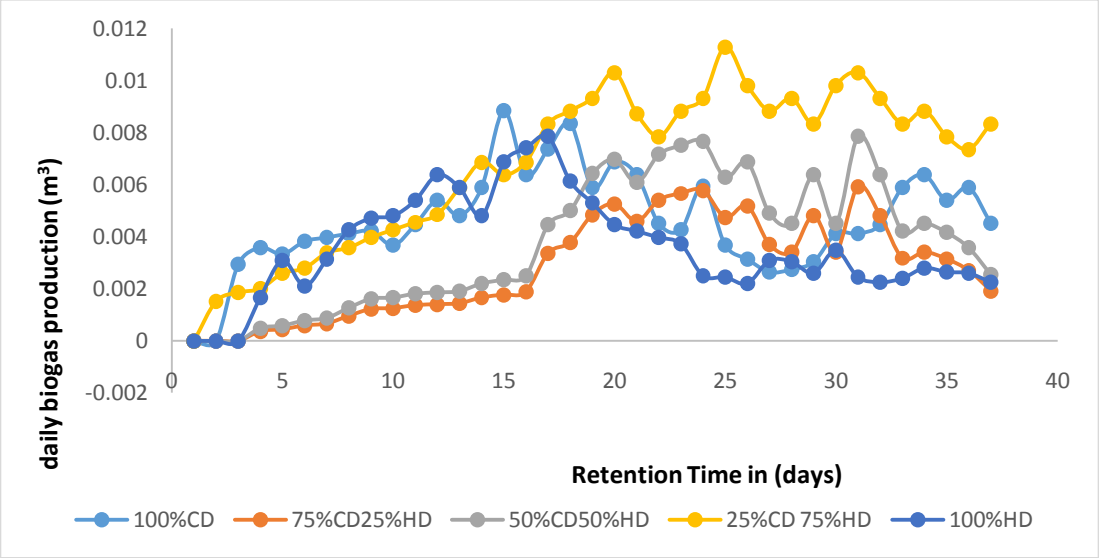


Fig 4.1: Daily biogas production of cow dung and Horse dung at different percentage ratios.

Figure 4.1 shows the daily biogas production from the various combinations of cow dung and horse dung at varying percentage ratios. At the end of 37-days retention period the biogas production rate reduces, it was observed that digester with (25% CD-75% HD) produced the highest biogas production potential, followed by 100% CD, 100% HD, 50% CD-50%HD and 75% HD-25% CD produced the least biogas. This is due to adequate balance between the carbon to nitrogen ratio, which lies between the optimum of 20:1–30:1 (Marchaim, 1992) and the lignin content. Also, the time taken for the bacteria to acclimatize was the fastest in the digester 25%CD-75%HD, which may be attributed again to the optimum level of carbon to nitrogen ratio of substrate in

this digester and possible presence of sufficient bacteria population in the cow manure used as the co-substrate which confirmed previous studies of (Yusuf *et al*., 2011).

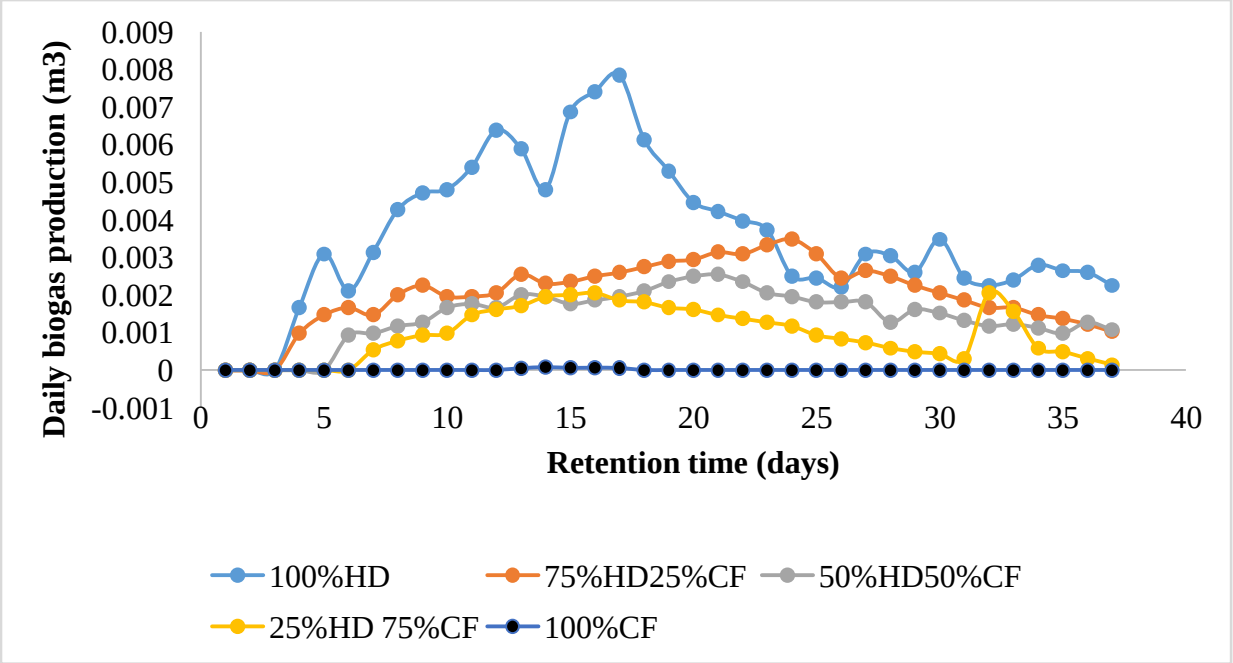


Fig 4.2: Relationship between Horse dung digested alone and its co-digestion with Chicken feather

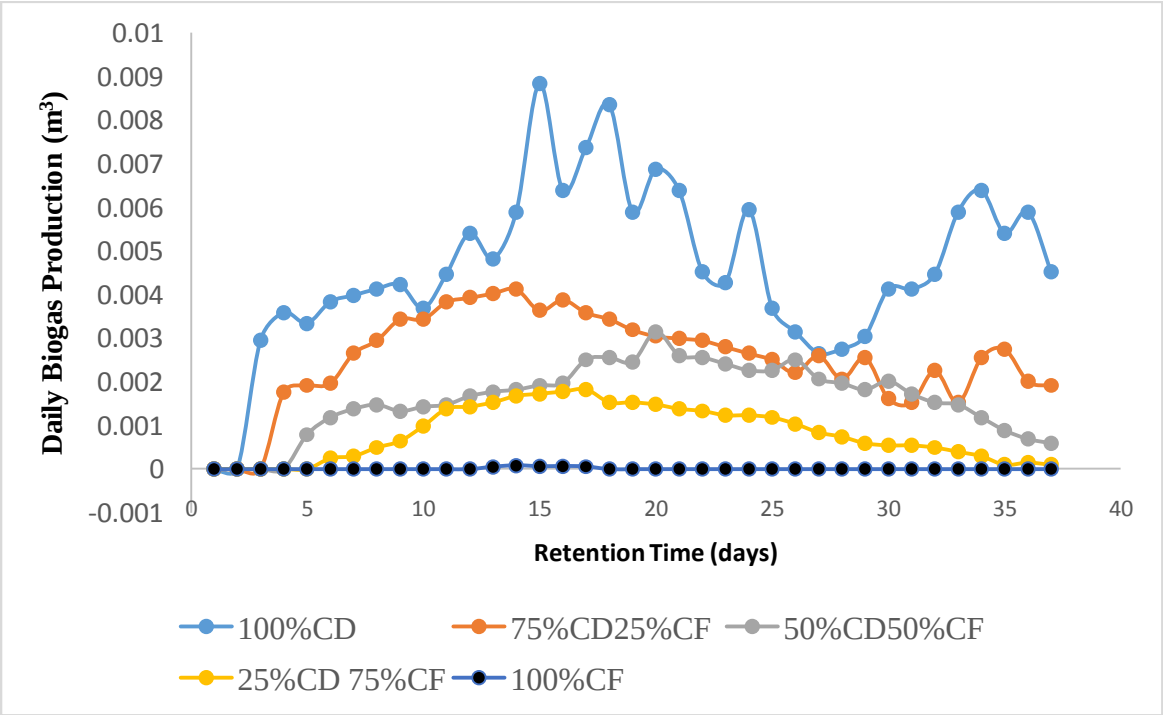


Fig 4.3: Daily biogas production of cow dung digested alone and its co-digestion with chicken feather at different percentage ratios.

Figure 4.2-4.3 shows a daily gas production of CD, HD and CF and their respective co-digestion at different percentage rations. It was observed that HD and CD produced significant biogas compared with CF as shown in fig 4.7. CF was regarded as failed digester because of its inability to produce tangible biogas.

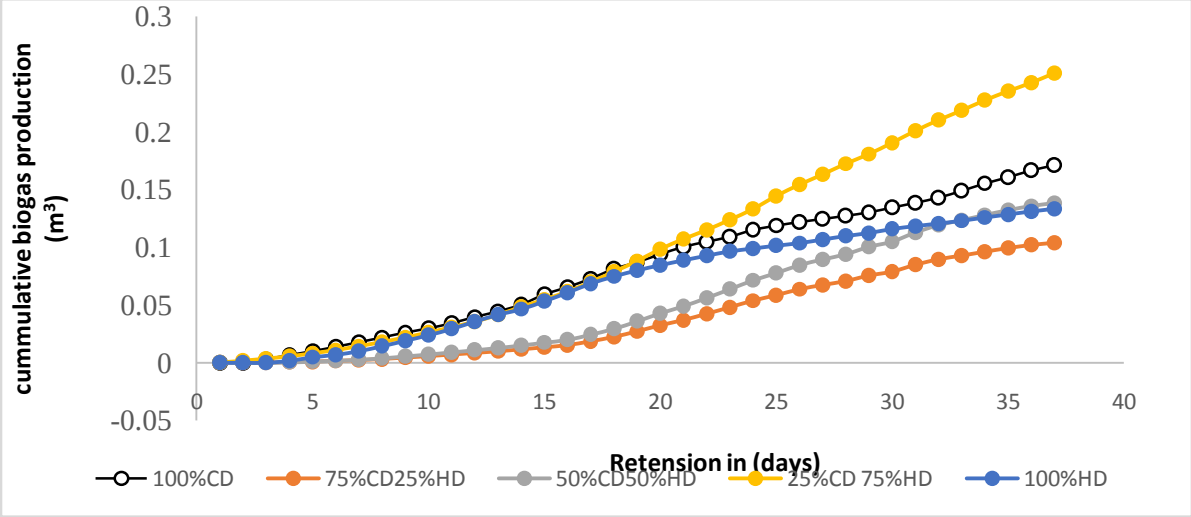


Figure 4.4: Cumulative relationships between horse dung and cow dung at different percentage ratios.

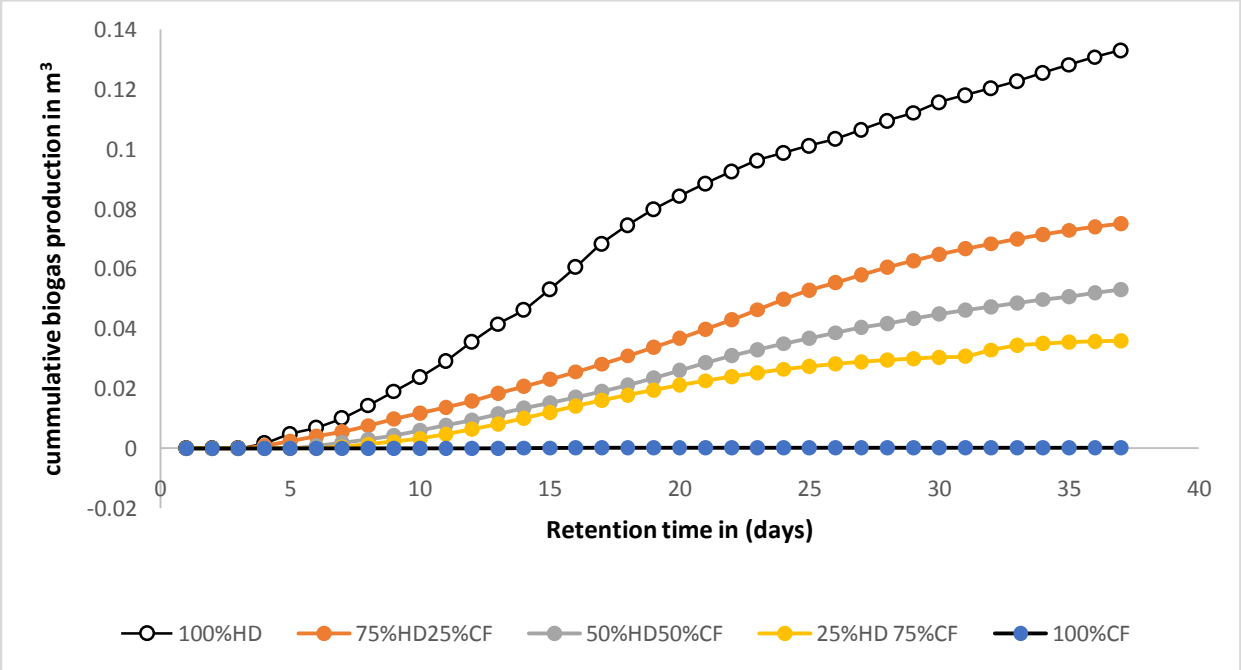


Figure 4.5: Cumulative relationships of horse dung digested alone and its co-digestion with chicken feather at different percentage ratios.

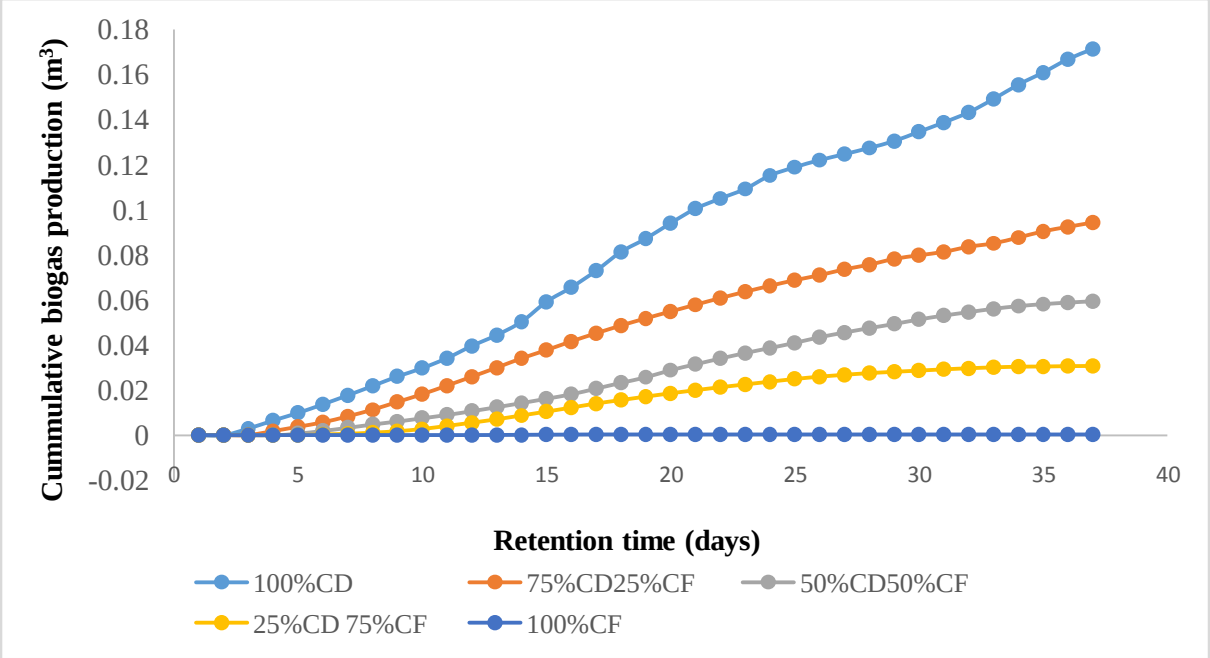


Figure 4.6: Cumulative biogas production potential of cow dung digested alone and its co-digestion with chicken feather at different percentage ratios.

CD and HD alone showed a cumulative increase in biogas yield as shown in fig 4.5-4.6 above, but when prepared chicken feather was mixed at different percentage ratios for CD and HD, the biogas production reduced gradually as the percentage of chicken feather increases. Chicken feather has an inhibiting factor and this could be attributed to the long chain fatty acid which showed lower methane yield (Salminen *et al.*, 2003).

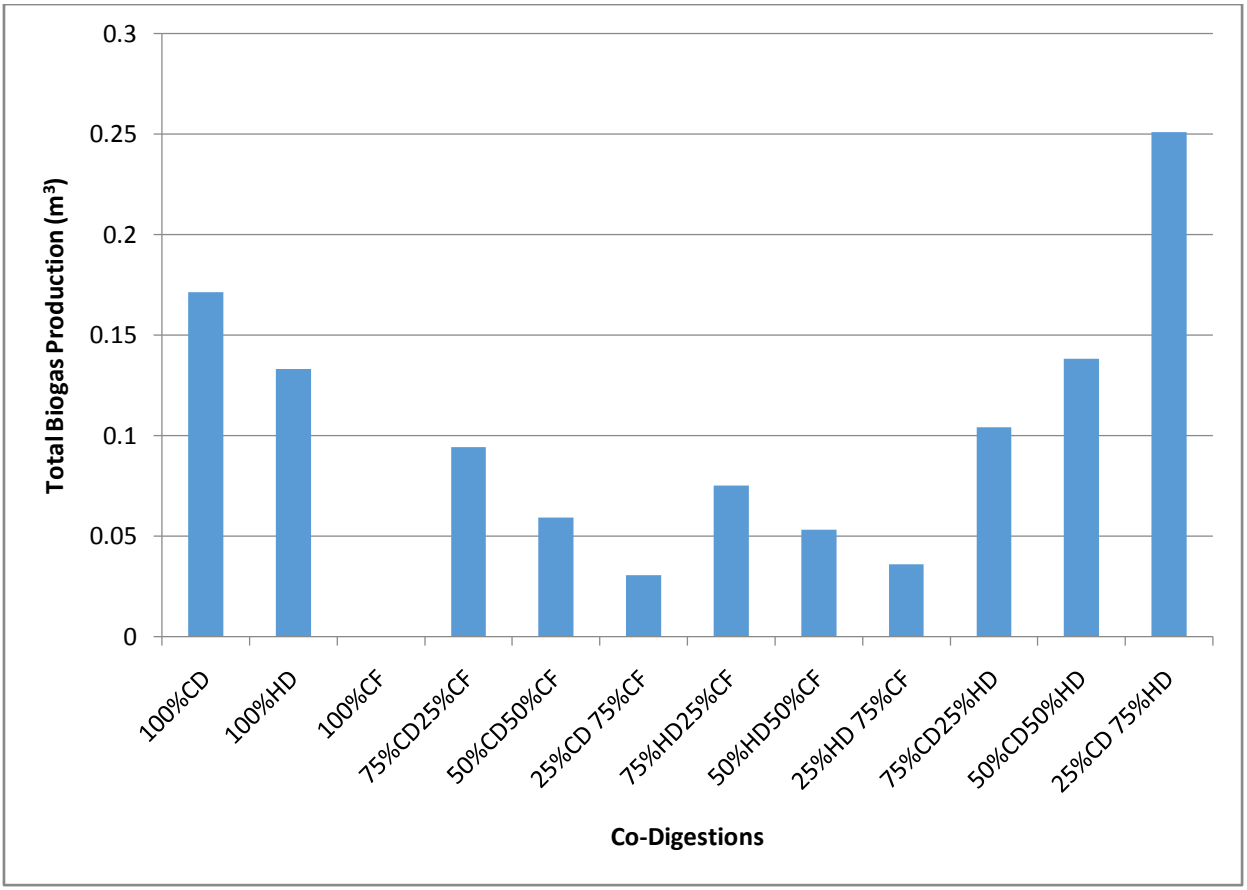


Figure 4.7: Comparison of total biogas production from the substrates at different percentage ratios.

Figure 4.7: Shows the fluctuation in the quantity of gas produced from each substrate possibly due to variation in environmental conditions. Figure 4.4 shows that gas production in cow dung, and its co-digestion with horse dung started on the second, third and fourth day as 25%CD-75%HD, 75%CD- 25%HD and 100%CD respectively. Those of the chicken feather and its co-digestion with horse and cow dung began on the fifth day while that of chicken feather was recorded after 14days of feeding and it was considered as failed digester because of inability to produce any significant biogas as shown in appendix I. The co-digestion of 25%CD-75%HD had the highest average daily gas production of 0.006782m^3/day. 100%CD, 50%CD-50%HD and 75%CD-25%HD produced Average daily biogas production 0f 0.004627m^3/day, 0.003732m^3/day and 0.002548m^3/day respectively. And the respective co-digestion of

100%HD, 75%CD-25%CF, 75%HD-25%CF, 50%CD-50%CF,50%HD-50%CF 25%HD-75%CF, 25%CD-75%CF and 100%CF recorded average daily gas production of 0.003598 m^3/day, 0.002548 m^3/day, 0.002032 m^3/day, 0.001603 m^3/day, 0.001433 m^3/day, 0.00097 m^3/day, 0.000827m^3/day and 0.00000823 m^3/day. These fast rates of production are comparative with the results of previous studies reported by Yusuf *et al.,* (2011).

A total of 0.250938m^3 of biogas was produced from the 25%CD-75%HD during the retention period of 37days while 100%CD, 100%HD and 100% CF were respectively produced a total volume of biogas of 0.1711875m^3, 0.133129m^3 and 0.000304m^3. The co-digestion of 50%CD-50%HD, 75%CD-25%HD, 75%CD-25%CF, 75%HD-25%CF, 50%CD-50%CF 50%HD-50%CF, 25%HD-75%CF and 25%CD-75%CF respectively produced 0.138089m^3, 0.10416m^3 0.094286m^3, 0.075183m^3, 0.059321m^3, 0.053036m^3, 0.035883m^3 and 0.030594m^3.

The higher biogas production from 25%CD-75%HD could also be attributed to the high content of carbon, oxygen, hydrogen, nitrogen, sulfur, phosphorous, potassium, calcium, magnesium and a number of trace elements. The reason for choosing these percentage ratios is to balance between the foods to bacteria. If food less or more the needs amount, the production may be decreasing. However, if the case is reversed this makes the substrate insufficient to improve bacteria activity and thus reduce methane production. This result is in agreement with those obtained by (Faiza *et al.*, 2014).

From the results above it was observed that cow dung and horse dung alone produced the high biogas yield and this could be attributed to multiplication of microbial organism within the methanogenesis stage, the chicken feather digested alone did not produce biogas, the traced quantity of biogas of biogas produced from the chicken

digested alone may not be methane, as this happens with the first few days and stop when the percentage of chicken feather in the co-digestion with horse dung and cow dung was gradually increased as shown in figures above. There was a steady reduction in the biogas production. It could be inferred that, the chicken feather was either neutral in the digestion process or had inhibiting effects (keratin content) in the process. This assertion could be validated from the result of cow dung and horse dung digested singly as well as co digested with each other at various percentage combinations.

However, (Salminen *et al*., 2003) shows that chicken feathers produced low methane yield, when subjected to pretreatments and enzymatic (commercial alkaline endopeptidase) there would be an increase of methane yield by 37 to 50%. Chemical such as sodium hydroxide improved methane yield by 5 to 32% by breaking down the disulfide bonds, thus, opening up the keratin structure and the sulphur content liberated as hydrogen sulphide H_2S. Therefore anaerobic digestion of chicken feather appears promising possibility because of the high methane yield and nitrogen content.

4.3.1 Comparison of biogas produced from different percentage of HD combined with CF as well as estimated volume of gas produced in the 100%HD digested.

Figure 4.8a shows the total biogas produced from horse dung co-digested with chicken feather and estimated biogas from horse dung alone at different percentages. The estimated biogas was obtained by multiplying the volume of biogas obtained from 100%HD digestion by 75%, 50% and 25% respectively, which were in turn combined 75%HD-25%CF, 50%HD-50%CF, 25%HD-75%CF respectively.

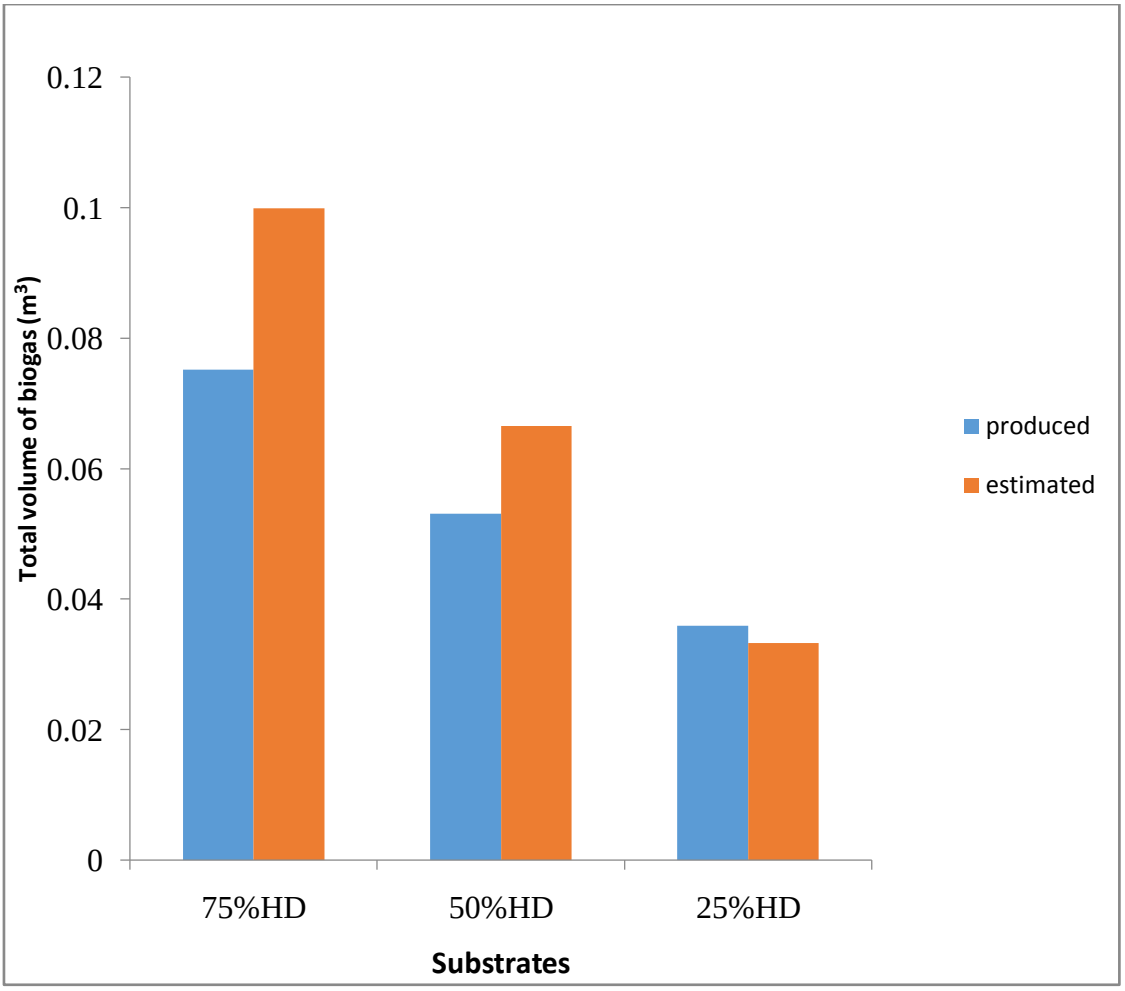


Fig 4.8a: Comparison of the Total volume Biogas produced from HD and CF at different percentage ratios and estimated from HD alone.

It can be observed from figure 4.8a that the volume estimated is higher than the volume of biogas produced which shows there is a probably inhibiting effect of chicken feather of biogas production from horse dung.

4.3.2. Comparison of biogas produced from different percentage of CD combined with CF as well as estimated volume of gas produced in the 100%CD Digested.

Figure 4.8b shows the total biogas produced from cow dung co-digested with chicken feather and estimated biogas from cow dung alone at different percentages. The estimated biogas was obtained by multiplying the volume of biogas obtained from 100% CD digestion by 75%, 50% and 25% respectively, which were in turn combined 75% CD-25% CF, 50% CD-50% CF, 25%CD-75%CF respectively.

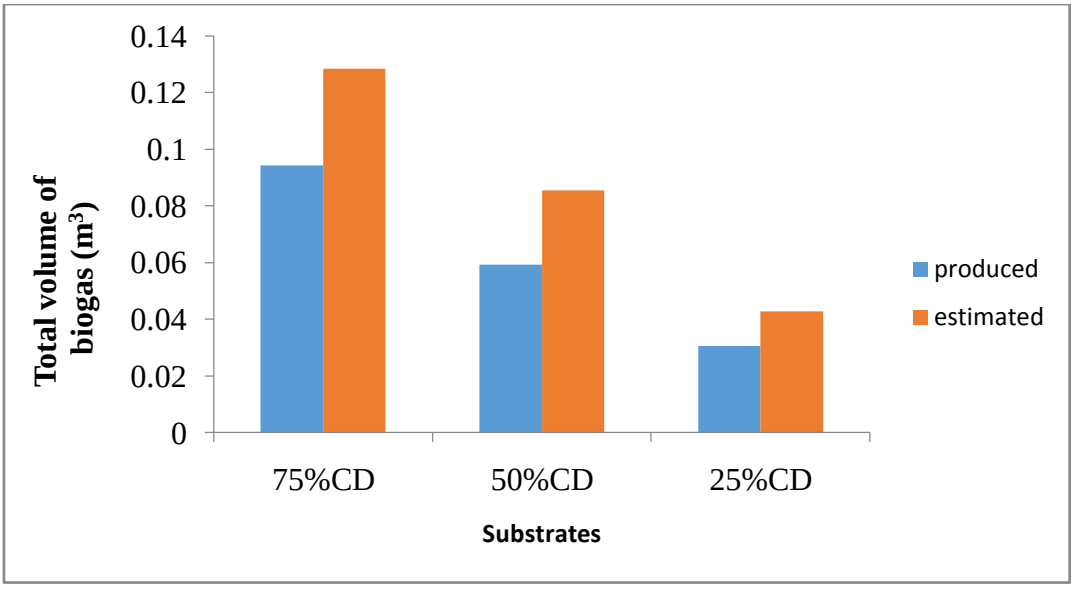


Fig 4.8b: Comparison of the Total volume Biogas produced from CD and CF at different percentage ratios and estimated from CD alone.

It can be observed from Figure 4.8b the volume estimated is higher than the volume of biogas produced which shows there is a probably inhibiting effect of chicken feather of biogas production from Cow dung.

In addition figures 4.8a-4.8b was observed as the chicken feather increases, the biogas production potential reduces. This is due to keratin content on chicken that inhibits the rate of production and also affect the microbial activities in the respective digesters. This can be subjected for further investigation.

4.3.3 Inflammability test

When the biogas and air mixtures reaches the burner ports and burnt, it formed a pilot heat, which is blue cone shaped. The cone shaped blue flame produced is as a result of laminar flow in a cylindrical mixing tube which shows the quality of a gas, which agrees the previous studies of Fulford, (1996).

4.4 ANALYSIS OF THE CUMMULATIVE BIOGAS PRODUCTION WITH THE MODIFIED GOMPERTZ MODEL

The study of biogas production from cow dung, horse dung and chicken feather and their mixtures was conducted in digesters labeled 1–12 as shown in Fig 1. Biogas production was monitored and measured until biogas production reduced significantly. The modified Gomperzt equation was then used to fit the cumulative daily biogas production which was observed to adequately describe the biogas production from these substrates.

Figures 4.9 to 4.11 show the results of the fitting of the cumulative biogas production in the Modified Gompertz equation for the respective substrates combinations.

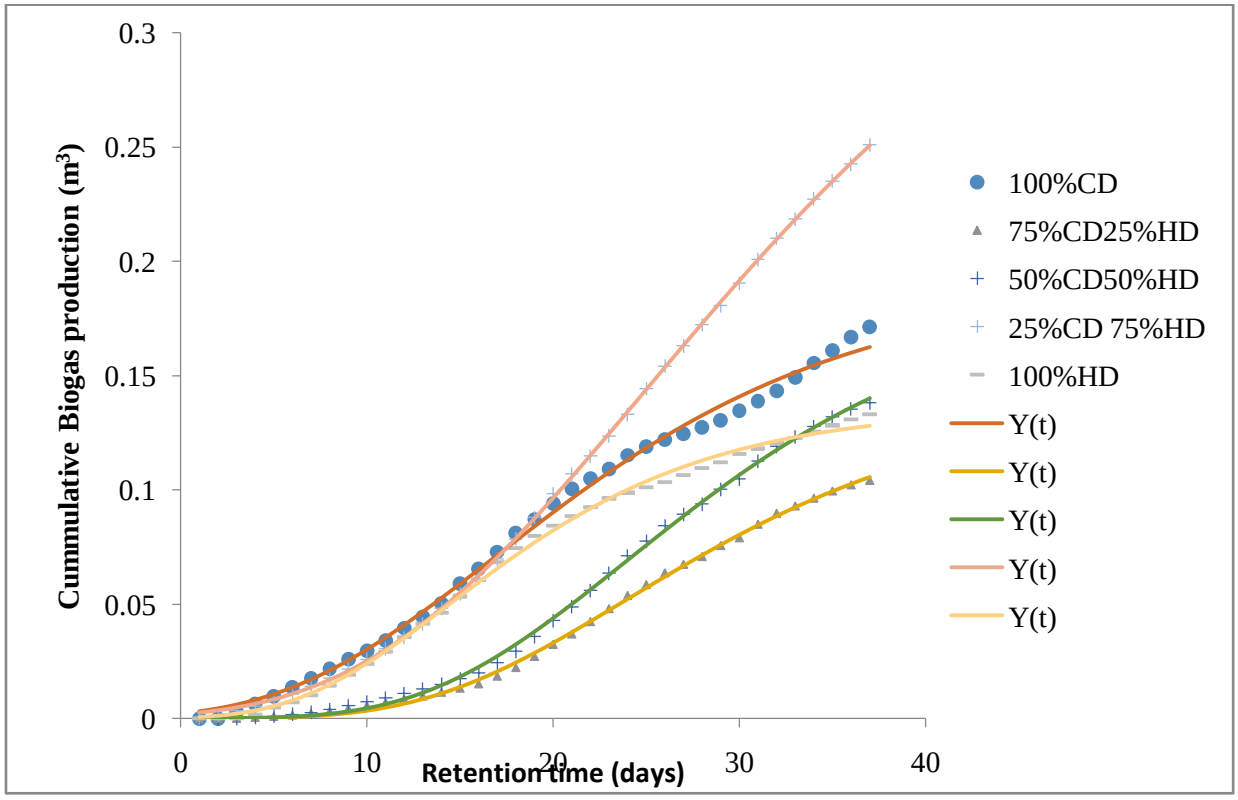


Fig 4.9: Gompertz Fitting of Cumulative Biogas Production from cow dung and horse dung.

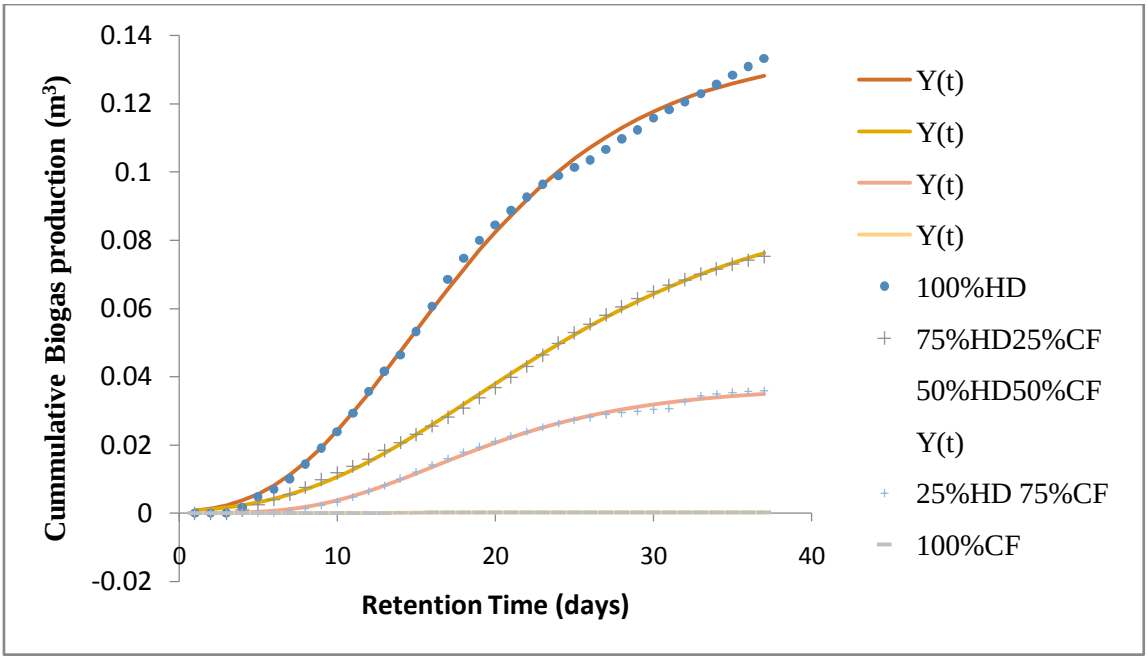


Fig 4.10: Gompertz cumulative biogas production from horse dung and chicken feathers

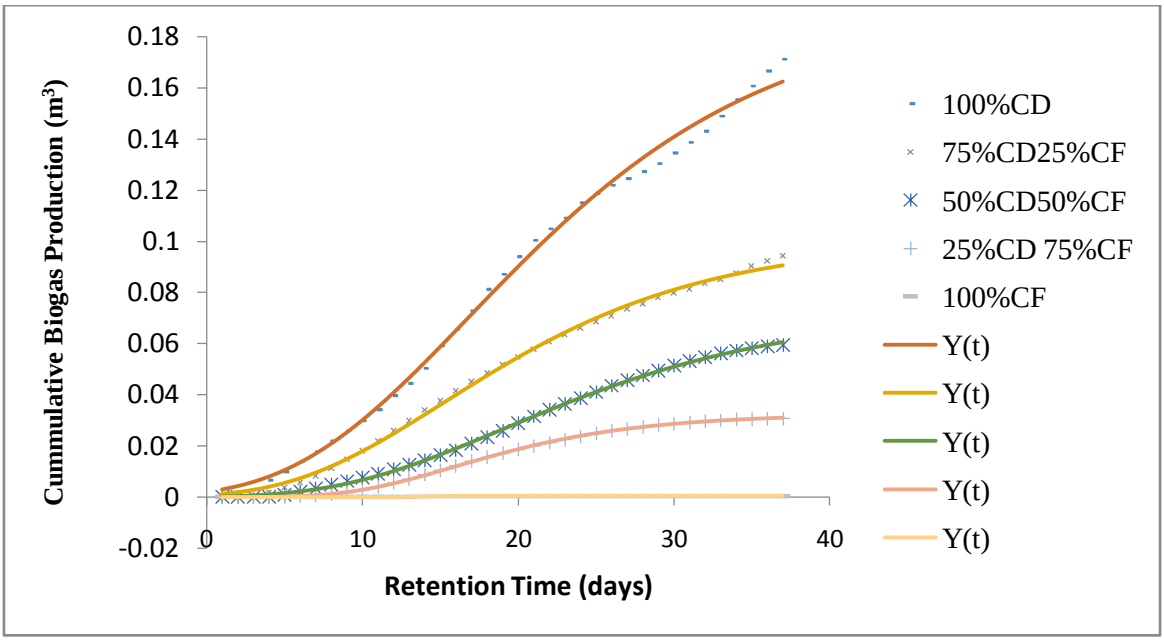


Fig 4.11: Gompertz cumulative biogas production from cow dung and chicken feather.

The biogas produced is a function of bacterial growth in batch digesters, modified Gompertz equation relates cumulative biogas production and the time of digestion through biogas yield potential (A), the maximum biogas production rate (μ) and the

duration of the lag phase (λ**).** To analytically quantify parameters of the reactors growth curve, a modified Gompertz equation was fitted to the cummulative biogas production data as shown in figures 4.9-4.11.

The estimated kinetic constants using non-linear regression and other characteristics of the digesters 1–12 are shown in Table 4.2

Table 4.2: Model Study with Modified Gompertz Equation using Solver Excel.

SUBSTRATES	TOTAL BIOGAS(m^3)	A (m^3)	μ(m^3/day)	λ(days)	SSE	R^2
100%CD	1.71E-01	1.71E-01	6.33E-03	5.72E+00	4.5E0-4	9.62E-01
75%CD25%CF	9.43E-02	9.43E-02	3.85E-03	5.63E+00	8.50E-05	9.93E-01
50%CD50%CF	5.93E-02	7.25E-02	2.54E-03	8.59E+00	1.03E-05	9.99E-01
25%CD75%CF	3.06E-02	3.06E-02	1.76E-03	9.22E+00	1.01E-06	1.00E+00
100%CF	3.04E-04	3.05E-04	7.04E-05	1.20E+01	2.82E-09	1.00E+00
100%HD	1.33E-01	1.36E-01	6.18E-03	6.34E+00	1.59E-04	9.86E-01
75%HD25%CF	7.52E-02	9.29E-02	3.02E-03	7.44E+00	2.35E-05	9.98E-01
50%HD50%CF	5.30E-02	6.07E-02	2.30E-03	8.58E+00	6.43E-06	1.00E+00
25%HD75%CF	3.59E-02	3.70E-02	1.86E-03	8.71E+00	1.74E-05	9.99E-01
75%CD25%HD	1.04E-01	1.41E-01	4.91E-03	1.34E+01	5.44E-05	9.98E-01
50%HD50%CD	1.38E-01	1.88E-01	6.52E-03	1.34E+01	9.55E-05	9.96E-01
25%CD75%HD	2.51E-01	3.92E-01	9.69E-03	1.02E+01	3.20E-05	9.98E-01

From table 4.2 it was observed 25% CD-75% HD had the highest biogas production potential (A) 0.3921663m^3 which confirmed the previous studies of (Yusuf *et al*., 2011), and at a maximum biogas production rate (μ) of 0.009692m^3/day with a lag phase (λ) of 10.15474 days. At 100%CD biogas production potential (A) of 0.1711875m^3 at a maximum biogas production rate (μ) 0.006326m3/day with a lag phase (λ) of 5.718365days. at 75%CD-25%CF biogas production potential (A) of 0.0942857m^3 at a maximum biogas production rate (μ) 0.003849m3/day with a lag phase (λ) of 5.629287days. At 50%CD-50%CF biogas production potential (A) of 00.0724784m^3 at a maximum biogas production rate (μ) 0.002537m3/day with a lag phase (λ) of 8.59421days. At 25%CD-75%CF biogas production potential (A) of

0.0305938m^3 at a maximum biogas production rate (μ) 0.00176m3/day with a lag phase (λ) of 9.216072days. At 100%CF biogas production potential (A) of 0.0003045m^3 at a maximum biogas production rate (μ) 7.04E-05m^3/day with a lag phase (λ) of 12days. At 100%HD biogas production potential (A) of 0.1362465m^3 at a maximum biogas production rate (μ) 0.006181m^3/day with a lag phase (λ) of 6.335297days. At 75%HD-25%CF biogas production potential (A) of 0.0929268m^3 at a maximum biogas production rate (μ) 0.003022m^3/day with a lag phase (λ) of 7.442253days. At 50%HD-50%CF biogas production potential (A) of 0.0606779m^3 at a maximum biogas production rate (μ) 0.002299m^3/day with a lag phase (λ) of 8.578214days. At 25%HD-75%CF biogas production potential (A) of 0.0370332m^3 at a maximum biogas production rate (μ) 0.001855m^3/day with a lag phase (λ) of 0.001855days. At 75%HD-25%CD biogas production potential (A) of 0.1414521m3 at a maximum biogas production rate (μ) 0.004914m3/day with a lag phase (λ) of 13.36749days. At 50% HD-50%CD biogas production potential (A) of 0.1875168m^3 at a maximum biogas production rate (μ) 0.006515m3/day with a lag phase (λ) of 13.36796 days.

From Table 4.2 the following observations were made.

1) The shortest lag phase was exhibited by digester (9) contained 25% CD-75% CF, 5.63days. While the largest lag phase (λ) was exhibited by digester (3) which contained 50% HD-50% CD, 13.36days. This suggests that digester (3) does not have the essential microbes to produce biogas early. However after that the yield became faster.
2) The biogas production rate (μ) for digester four (4) which contained 25% CD-75% HD is the highest with a value of 0.009692m^3/day and the lowest is digester six (6)

contained 100%CF with a value of 0.0000704m^3/day. This indicates that anaerobic digestion with 25%CD-75%HD was vital in enhancing the biogas production rate.

3) The biogas yield potential (A) is maximum in digester four (4) contained 25% CD-75% HD of 0.3921663m^3 and minimum (6) contained 100% CF of 0.0003045m^3.
4) Digester four (4) which contained 25%CD-75%HD produced the maximum amount of biogas of 0.2509375m^3 and the least amount of biogas was produced by digester six (6) which contained 100% CF.
5) From fig 4.9-4.11 it is clear that modified Gompertz equation fits well to all the experimental data.

Therefore, the model was able to fit the data set with a goodness of fit (R^2) close to 1 which shows the correlation between the model and the data fitting for biogas production potential.

4.4 Results of the Physiochemical Properties of the Substrates before and after Digestion.

The quantity of each parameters determined during the experimental analysis was computed in terms of the mass of substrates used in the analysis. The results obtained for the substrates such as Carbon to Nitrogen Ratio, Nitrate, Sulphate and Phosphate before and after digestions are shown in the Figure 4.12.

Carbon to nitrogen ratio is one of factor affecting the anaerobic process; it affects methane yield and production rates. It is often suggested that an optimum C/N ratio should be between 20:1 and 30:1.

Figure 4.12 shows the results of carbon to nitrogen ratios (C/N) for Cow dung, Horse dung and Chicken feathers respectively which is fairly in agreement with the optimum i.e. carbon to nitrogen ratio (C/N) of **20:1 to 30:1** as stated by Braun, (1992)

4.4.1 Carbon to Nitrogen (C: N) Ratio

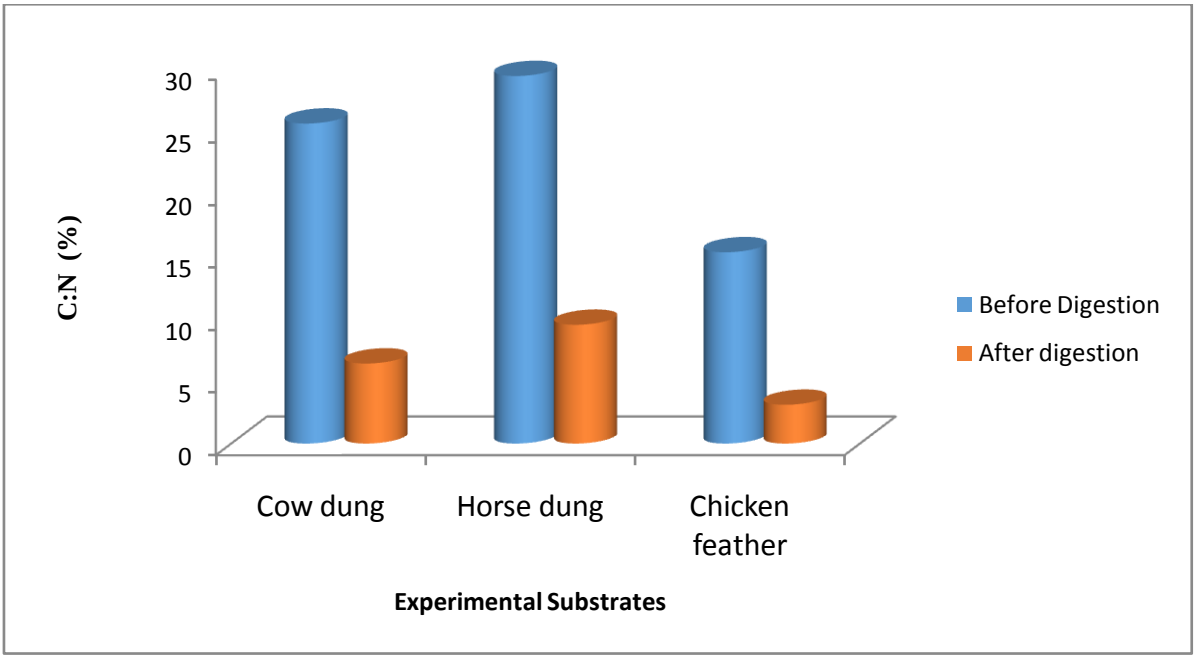


Figure 4.12: Shows Carbon to Nitrogen (C: N) Ratio of cow dung, horse dung and chicken feather before and after digestion.

4.4.2 Results of Sulphates Measurement before and after digestion

The Sulphates determined before and after digestion for the above chosen substrates are 1.2 mg/l, 7mg/l, 6.2mg/l, 2.4mg/l, 1.1mg/l, 0.9mg/l,6.7mg/l, 2.1mg/l, 3.4mg/l, 2.5 mg/l, 2.7mg/l and 2.1mg/l, 9.2mg/l, 7.4mg/l, 2.7mg/l, 7.5mg/l, 1.4mg/l, 1.6mg/l, 7.8mg/l, 2.7mg/l, 3.6mg/l, 3mg/l, 3.4mg/l.

Figure 4.13a shows the increase in sulphates before and after digestion and could be attributed for the conversion of sulfate to sulfide which requires a carbon source.

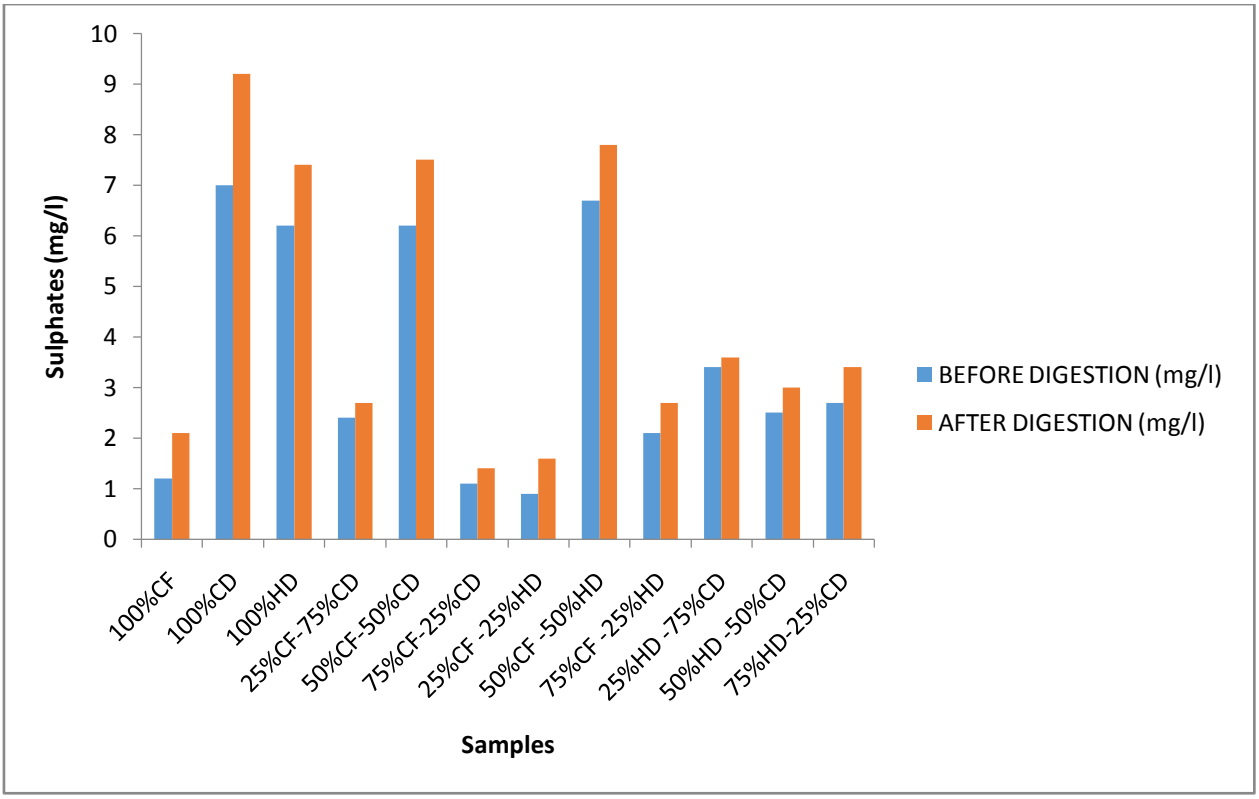


Fig 4.13a: Determination of Sulphates before and after digestion

4.4.2 Results of Phosphate Measurement before and after digestion

The Phosphates determined before and after digestion were 11.4mg/l, 4.8mg/l, 5.7mg/l, 0.7mg/l, 9.5mg/l,4.1mg/l, 3.4mg/l, 14.2mg/l, 10.5mg/l, 9.2mg/l, 8.7mg/l, 8.9mg/l and 12.2mg/l, 6.6mg/l, 7.2mg/l, 10.1mg/l,5.1mg/l, 4.7mg/l, 4.7mg/l, 15.3mg/l, 11.3mg/l, 10.1mg/l, 9.3mg/l and 10.3mg/l respectively.

Fig 4.2 shows that Cow dung, horse dung and chicken feather are not likely to contain significant concentration of calcium and magnesium, this is inferred the trophic characteristics of cow dung, horse dung and chicken feather as a result of the likely hood of phosphates concentration precipitation by calcium or magnesium is very low, this could be the reason for the increase in phosphate measured after digestion. This could be attributed due to high rate of activity as microbial activity indicated high biogas yield where calcium and magnesium are used by micro-organisms in their cellular metabolism.

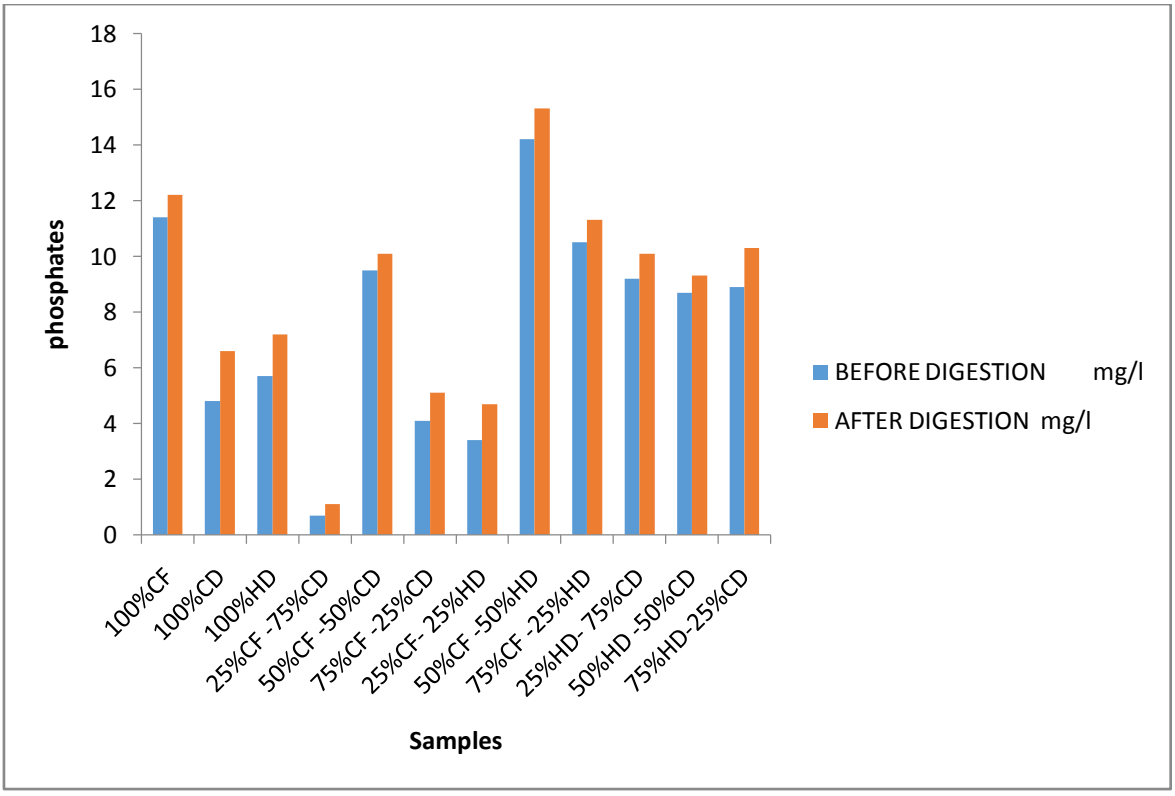


Fig 4.13b: Determination of phosphate before and after digestion

4.4.3 Results of Nitrate Measurement before and after digestion.

The nitrates determined before and after digestion were 0.1mg/l, 2.7mg/l, 0.6 mg/l, 0.11 mg/l, 0.13 mg/l, 0.01 mg/l, 0.16 mg/l, 0.14 mg/l, 0.11 mg/l, 1.4 mg/l, 1.5 mg/l, 1.7mg/l and 0.23mg/l, 3.2 mg/l, 0.9 mg/l, 0.18 mg/l, 0.19 mg/l, 0.07 mg/l, 0.25 mg/l, 0.31 mg/l, 0.34 mg/l, 2.7 mg/l, 3.2 mg/l, 4.1mg/l respectively.

Fig 4.13c shows an increase of nitrogen in the substrate can lead to excessive ammonia formation, resulting in toxic effects. Therefore, it is important that the proper amount of nitrogen be in the feedstock, to avoid either nutrient limitation (too little nitrogen) or ammonia toxicity (too much nitrogen). The composition of the organic matter added to a digestion system has an important role on the growth rate of the anaerobic bacteria and the production of biogas. Chicken feather has low nitrates at the beginning and could be the reason for low biogas production for its co digestions with cow dung and horse dung. In this research, animal wastes are evaluated for suitability for biogas

production (such as room temperature with no form of physical treatment). Cattle manure was established to have lower available volatile solids because ruminants extract much of the nutrients from the fodder and the leftover is rich in lignin complexes which were extensively exposed to enzyme action of the four chamber stomach of ruminants (Wilkie 2005). In previous researches the volatile solids content for cow dung and horse dung used were determined to be 58.7% and 87.5% respectively while the ambient room temperature ranged between 27–32°C.(Yusuf *et al.*, 2011)

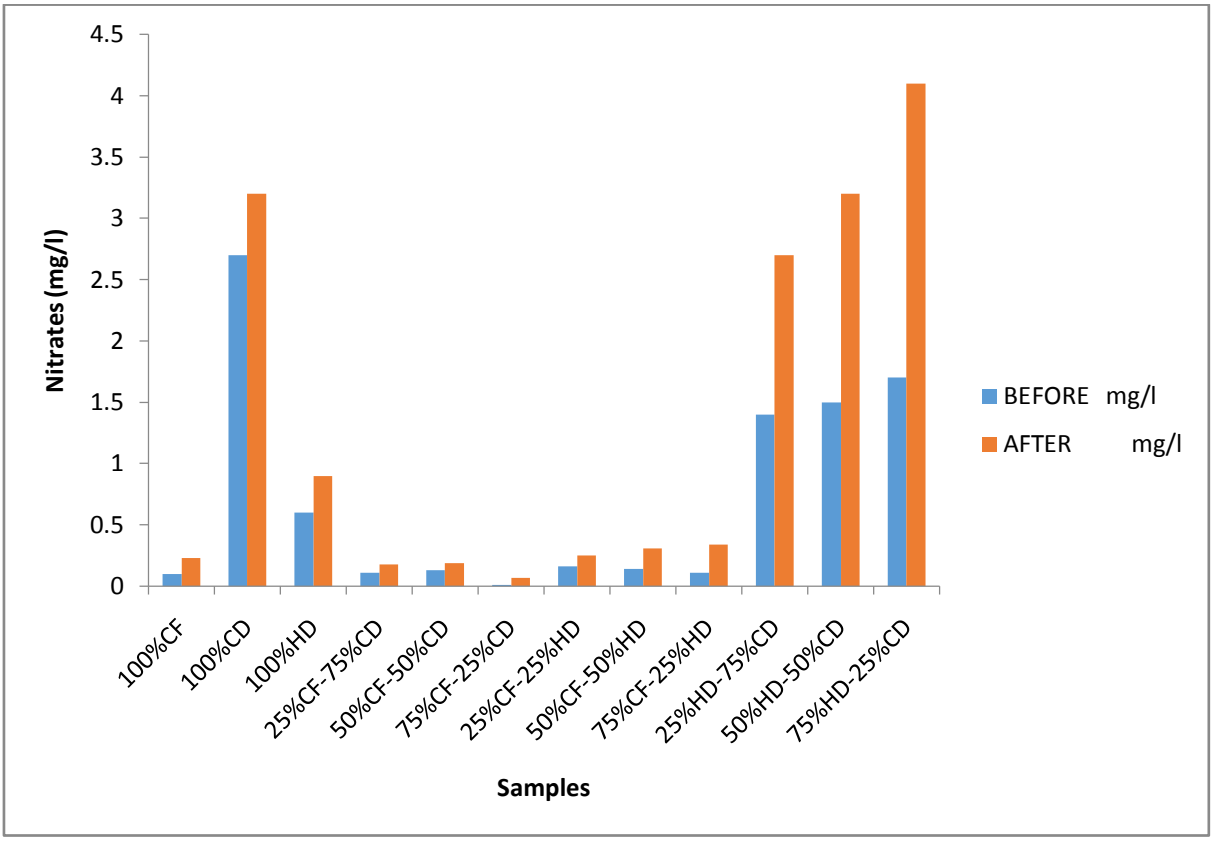


Fig 4.13c: Determination of nitrates before and after digestion

4.5 Ambient and Digester Temperature during Biogas Production

Table 4.2 shows the average digester temperatures for the three substrates observed in the morning afternoon and evening within the digesters, and the average ambient temperatures for Samaru during the digestion.

Table 4.3 Average digester temperatures of the substrates for the respective co-digestion in °C

25%CD75%CF	50%CD50%CF	75%CD25%CF	25%HD75%CF	50%HD50%CF	75%HD25%CF	100% CD	100%HD	100%CF	25%CD75%HD	50%CD50%HD	75%CD25%HD
32.3±2.4	35.1±1.9	34.2±3.4	33.7±3.2	35.7±3.2	36.2±2.9	33.2±3.2	35.3±2.8	28.9±2.5	39.9±3.7	37.1±2.9	35.7±2.6

The average ambient temperature observed during the study was 34°C while the average digester temperatures of the substrates for the respective co-digestion are shown in the Table 4.3 The temperatures within the respective digesters fluctuated optimally between 25°C and 39°C which conforms to the mesophilic range, and it is possible to install digesters that will operate within this range in Samaru. This agrees with the findings of previous studies (Ahmadu, 2009, Igboro, 2011).

4.5.2 pH during the Digestion

Table 4.2 shows the pH of the digester contents monitored twice in a week (Mondays and Fridays only) during the digestion period.

Table 4.4: Substrate pH during the Retention Period

R. Time	25% CD75 %CF	50% CD50 %CF	75%CD 25%CF	25%HD 75%CF	50% HD 50% CF	75% HD 25% CF	100 % CD	100 %HD	100 %CF	25% CD 75% HD	50% CD 50% HD	75%CD 25%HD
1	6.24	6.36	5.78	5.8	6.74	6.84	5.74	6.61	5.7	6.4	6.3	5.86
5	6.32	6.5	6.43	5.92	6.81	6.9	6.2	6.71	6.0	6.53	6.5	6.27
10	6.7	6.6	6.61	6.23	6.84	7	6.4	6.83	6.3	6.73	6.58	6.49
15	6.8	6.71	6.73	6.31	6.86	7.12	6.7	6.98	6.1	6.92	6.76	6.57
20	6.8	6.61	6.74	6.47	6.64	6.84	6.97	7.01	6.0	7.2	6.83	6.76
25	6.82	6.7	6.81	6.59	6.13	6.81	7.15	7.13	5.7	7.3	6.91	6.83
30	6.81	6.71	6.1	6.56	6.04	6.72	7.2	7.2	5.4	7.41	7	6.84
35	6.64	6.71	6.46	6.27	6.58	6.89	6.62	6.92	5.3	6.93	6.68	6.51

Table 4.4 shows the pH values of the media in all the substrates digested, and were varied almost in the optimal limits of methanogenic bacteria (pH: 6.0 -7.4), all the

feedstock showed a general increase in pH with minimal fluctuation. This progressive increase in pH could account for steady rate of gas production which is in agreement with the studies carried out previously by Ahmadu (2009) and Igboro (2011), except for chicken feather which showed a downward trend. The pH fell from 6.5 to 5.2. This could be associated with the low gas production, which is in agreement with the studies carried out previously by Ahmadu (2009), Golueke (2002), Igboro (2011), which suggest low pH as a limiting factor for biogas production.

Methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6.0 (Karki *et al*, 2005).

Most microorganisms grow best under neutral pH conditions, since other pH values may adversely affect metabolism by altering the chemical equilibrium of enzymatic reactions, or by actually destroying the enzymes. The methanogenic group of organisms is the most pH sensitive. Low pH can cause the chain of biological reactions in digestion to cease

4.6 BILL OF ENGINEERING MEASUREMENT AND EVALUATION

Table 4.5 gives the detailed cost estimate of materials used in the fabrication of the pilot scale anaerobic digester plant.

Table 4.5: Cost Analysis for Construction of Anaerobic Digester

S/No	Component	Material	Unit	Quantity	Unit Rate (₦)	Amount (₦)
1	Digester Body	1 mm Mild steal sheet	m^2	$1^{1/2}$	3,500	5250
2	Slurry Inlet Pipe	ϕ60mm Mild Steel pipe	m.	0.5	900	500
3	Slurry Outlet Pipe	ϕ60mm Mild Steel pipe	m.	0.5	900	500
4	Gas Holder	Aluminium sheet	m^2	1	1500	1500
5	Water Jacket	1mm Mild steel	m^2	0.5	3500	1750
6	Gas Pipe	ϕ10mm galvanized steel pipe	m.	1	300	300
7	3/4 inch Hose	Plastic	Yard	6	250	1500
8	1/2 valve	Plastic	Nr	2	200	400
9	1/2x3/4 inches Bushing	Aluminum	Nr	1	120	120
10	Inflator key	Metallic	Nr	12	20	240
11	3/4 Clip	stainless steel	Nr	12	30	360
12	ABRO Silicon Sealant		Nr	2	700	1400
13	Coal tar					500
14	Black paints					500
15	Workmanship					2500
16	Transportation					300
17	miscellaneous					500
	Add 10% Contingency					**16620**
						1662
	Total					**18282:00**

The overall cost for producing one of the pilot scale Anaerobic Digester Plants used for this study is Eighteen Thousand Two Hundred and Eighty Two Naira (**₦18282:00**).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

From the results of the study conducted, the following conclusions are made:

1) The biogas digesters adopted based on the modified designed of Biogas model of Karki (2002) and Alfa (2013), fabricated using locally available materials worked efficiently as significant biogas production was achieved.
2) The biogas digester plants constructed in this study were used for the anaerobic digestion of cow dung, chicken feather and horse dung as well as co-digestion. It was observed that digester with (25%CD-75%HD) produced the highest biogas production potential (as observed in previous studies Yusuf *et al*., 2014) with A total of 0.251m^3 of biogas during the retention period of 37 days.
3) Anaerobic digestion of chicken feather is a challenge, because of the complex, rigid, and fibrous structure of keratin, and the main component of feathers. Under anaerobic conditions, chicken feather degrades poorly, which is the main obstacle for anaerobic digestion.
4) Application of the modified Gomperzt equation in studying the biogas production was able to predict the pattern of biogas production with time. It was observed that the maximum biogas production could be obtained from substrate in digester (25% cow dung and 75% horse dung) which was closely followed by substrate mixture containing (100% cow dung) and lastly by substrate mixture comprising (50% cow dung and 50% horse dung). Digesters with 100% CF classified as failed digester because of their inability to produce any measurable amount of biogas at the end of the digestion period.

5) The model was able to fit the data set with a goodness of fit (R^2) close to 1 which shows the correlation between the model and the data fitting for biogas production potential.
6) The parameters determined in the proximate analysis both before (fresh) and after (digested) anaerobic digestion of the biomass resources in case of Carbon to Nitrogen ratio, Sulphates, Nitrates and Phosphates were within the optimum range which enhanced biogas production potential.
7) The pH values in all the plants were very stable and always in the optimal range between 6.5-8.0, and also the temperature inside the digesters were stable fluctuating around 38±1°C which is within the mesophilic range.

5.2 RECOMMENDATIONS

1) Pre-treatments of chicken feather is required to increase methane yield such as the use of thermal pretreatment at 120°C for 10 min, enzymatic hydrolysis with an alkaline endopeptidase, calcium hydroxide ($Ca(OH)_2$) as well as a combination of these pretreatments and as suggested by previous studies.
2) The developed two-stage system for utilizing keratin-rich feather waste for biogas production, using a biological degradation step prior to the anaerobic digestion step, is an economically feasible and environmentally friendly alternative. One day long biological pretreatment by the recombinant *B. megaterium* strain resulted in a methane production
3) Comparative study of the substrates should be repeated at different percentage ratios in order to obtain optimum yield of biogas potential.
4) The Local, State and Federal Government should encourage the use of Biogas as alternative source of energy to ease the current price depletion suffering in the world fuel market.

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APPENDICES

Appendix I

NITRATE (mg/l)		
SAMPLE	BEFORE mg/l	AFTER mg/l
100%CF	0.1	0.23
100%CD	2.7	3.2
100%HD	0.6	0.9
25%CF 75%CD	0.11	0.18
50%CF 50%CD	0.13	0.19
75%CF 25%CD	0.01	0.07
25%CF 25%HD	0.16	0.25
50%CF 50%HD	0.14	0.31
75%CF 25%HD	0.11	0.34
25%HD 75%CD	1.4	2.7
50%HD 50%CD	1.5	3.2

Appendix II

PHOSPHATE (mg/l)		
SAMPLE	BEFORE DIGESTION mg/l	AFTER DIGESTION mg/l
100%CF	11.4	12.2
100%CD	4.8	6.6
100%HD	5.7	7.2
25%CF 75%CD	0.7	1.1
50%CF 50%CD	9.5	10.1
75%CF 25%CD	4.1	5.1
25%CF 25%HD	3.4	4.7
50%CF 50%HD	14.2	15.3
75%CF 25%HD	10.5	11.3
25%HD 75%CD	9.2	10.1
50%HD 50%CD	8.7	9.3

Appendix III

SULPHATE (mg/l)		
SAMPLE	BEFORE DIGESTION (mg/l)	AFTER DIGESTION (mg/l)
100%CF	1.2	2.1
100%CD	7	9.2
100%HD	6.2	7.4
25%CF 75%CD	2.4	2.7
50%CF 50%CD	6.2	7.5
75%CF 25%CD	1.1	1.4
25%CF 25%HD	0.9	1.6
50%CF 50%HD	6.7	7.8
75%CF 25%HD	2.1	2.7
25%HD 75%CD	3.4	3.6
50%HD 50%CD	2.5	3

Appendix IV

Shows the cumulative data of cow dung and horse dung at different percentage ratios

Retention Time	100%CD	75%CD25%HD	50%CD50%HD	25%CD 75%HD	100%HD
1	0	0	0	0	0
2	0	0	0	0.001522	0
3	0.002946	0	0	0.003388	0
4	0.006531	0.00037	0.000491	0.005402	0.00167
5	0.009871	0.000815	0.00108	0.008004	0.004763
6	0.013701	0.001408	0.001866	0.010804	0.006875
7	0.017679	0.002074	0.00275	0.014192	0.010018
8	0.021804	0.003037	0.004027	0.017777	0.01429
9	0.026027	0.00426	0.005647	0.021754	0.019004
10	0.02971	0.005519	0.007317	0.026027	0.023817
11	0.034179	0.00689	0.009134	0.030594	0.029219
12	0.03958	0.008298	0.011	0.035455	0.035603
13	0.044393	0.009742	0.012915	0.041348	0.041496
14	0.050286	0.011409	0.015125	0.048223	0.046308
15	0.059125	0.013187	0.017482	0.054607	0.053183
16	0.065509	0.015076	0.019987	0.061482	0.060598
17	0.072875	0.018447	0.024455	0.06983	0.068455
18	0.081223	0.022226	0.029464	0.07867	0.074594
19	0.087116	0.027078	0.035897	0.088	0.079897
20	0.093991	0.032338	0.042871	0.098313	0.084366
21	0.100375	0.036931	0.04896	0.107054	0.088589
22	0.104893	0.04234	0.056129	0.114911	0.092567
23	0.109165	0.048007	0.063643	0.12375	0.096299
24	0.115107	0.053786	0.071304	0.13308	0.098804
25	0.11879	0.058527	0.077589	0.144375	0.101259
26	0.121933	0.063713	0.084464	0.154196	0.103469
27	0.124585	0.067417	0.089375	0.163036	0.106563
28	0.127335	0.070825	0.093893	0.172366	0.109607
29	0.130379	0.075641	0.100277	0.180714	0.11221
30	0.134504	0.079049	0.104795	0.190536	0.115696
31	0.138629	0.084976	0.112652	0.200848	0.118152
32	0.143098	0.089791	0.119036	0.210179	0.120411
33	0.148991	0.092977	0.123259	0.218527	0.122817
34	0.155375	0.096385	0.127777	0.227366	0.125616
35	0.160777	0.099533	0.131951	0.235223	0.128268
36	0.16667	0.102238	0.135536	0.242589	0.130871
37	0.171188	0.104164	0.138089	0.250938	0.133129

Appendix V

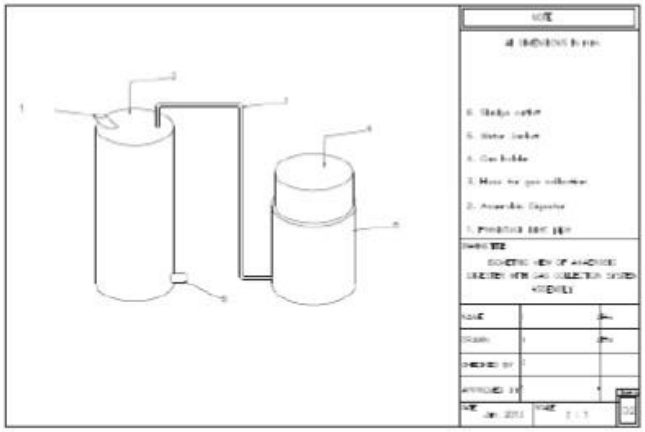
Shows the cumulative data of horse dung and chicken feather at different percentage ratios

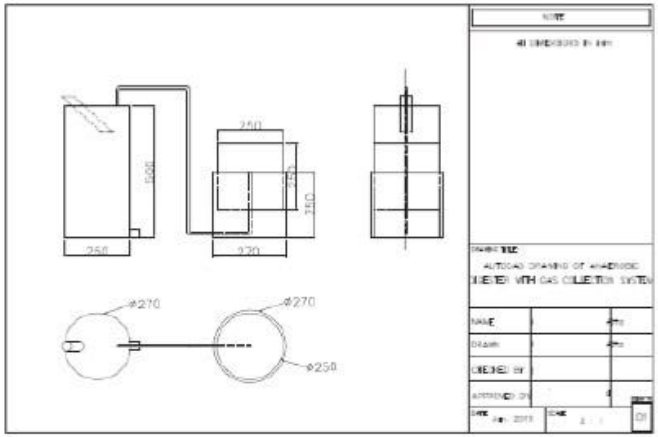
Retention Time	100%HD	75%HD25%CF	50%HD50%CF	25%HD 75%CF	100%CF
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0.00167	0.00098	0	0	0
5	0.00476	0.00246	0	0	0
6	0.00688	0.00413	0.00093	0	0
7	0.01002	0.0056	0.00192	0.00054	0
8	0.01429	0.00761	0.00309	0.00133	0
9	0.019	0.00987	0.00437	0.00226	0
10	0.02382	0.01183	0.00604	0.00324	0
11	0.02922	0.0138	0.00781	0.00471	0
12	0.0356	0.01586	0.00948	0.00633	0
13	0.0415	0.01842	0.01149	0.00805	4.9E-05
14	0.04631	0.02072	0.01346	0.01002	0.00013
15	0.05318	0.02308	0.01522	0.01203	0.00019
16	0.0606	0.02558	0.01709	0.01409	0.00025
17	0.06846	0.02819	0.01905	0.01596	0.0003
18	0.07459	0.03094	0.02117	0.01778	0.0003
19	0.0799	0.03383	0.02352	0.01945	0.0003
20	0.08437	0.03678	0.02603	0.02107	0.0003
21	0.08859	0.03992	0.02858	0.02254	0.0003
22	0.09257	0.04302	0.03094	0.02392	0.0003
23	0.0963	0.04636	0.033	0.02519	0.0003
24	0.0988	0.04984	0.03496	0.02637	0.0003
25	0.10126	0.05294	0.03678	0.0273	0.0003
26	0.10347	0.05539	0.0386	0.02814	0.0003
27	0.10656	0.05804	0.04042	0.02888	0.0003
28	0.10961	0.06055	0.04169	0.02946	0.0003
29	0.11221	0.06281	0.04331	0.02996	0.0003
30	0.1157	0.06487	0.04483	0.03039	0.0003
31	0.11815	0.06674	0.04616	0.03071	0.0003
32	0.12041	0.06841	0.04734	0.03277	0.0003
33	0.12282	0.07008	0.04857	0.03434	0.0003
34	0.12562	0.07155	0.0497	0.03493	0.0003
35	0.12827	0.07292	0.05068	0.03542	0.0003
36	0.13087	0.07415	0.05196	0.03574	0.0003
37	0.13313	0.07518	0.05304	0.03588	0.0003

Appendix VI

Shows the cumulative data of cow dung and chicken feather at different percentage ratios

Retention Time	100%CD	75%CD25%CF	50%CD50%CF	25%CD 75%CF	100%CF
1	0	0	0	0	0
2	0	0	0	0	0
3	0.00295	0	0	0	0
4	0.00653	0.00177	0	0	0
5	0.00987	0.00368	0.00079	0	0
6	0.0137	0.00565	0.00196	0.00025	0
7	0.01768	0.0083	0.00334	0.00054	0
8	0.0218	0.01125	0.00481	0.00103	0
9	0.02603	0.01468	0.00614	0.00167	0
10	0.02971	0.01812	0.00756	0.00265	0
11	0.03418	0.02195	0.00904	0.00403	0
12	0.03958	0.02588	0.01071	0.00545	0
13	0.04439	0.02991	0.01247	0.00697	4.9E-05
14	0.05029	0.03403	0.01429	0.00864	0.00013
15	0.05913	0.03767	0.01621	0.01036	0.00019
16	0.06551	0.04154	0.01817	0.01213	0.00025
17	0.07288	0.04513	0.02067	0.01395	0.0003
18	0.08122	0.04857	0.02323	0.01547	0.0003
19	0.08712	0.05176	0.02568	0.01699	0.0003
20	0.09399	0.0548	0.02883	0.01846	0.0003
21	0.10038	0.0578	0.03143	0.01984	0.0003
22	0.10489	0.06075	0.03398	0.02117	0.0003
23	0.10917	0.06354	0.03639	0.02239	0.0003
24	0.11511	0.0662	0.03865	0.02362	0.0003
25	0.11879	0.0687	0.04091	0.0248	0.0003
26	0.12193	0.07091	0.04341	0.02583	0.0003
27	0.12458	0.07351	0.04547	0.02667	0.0003
28	0.12733	0.07558	0.04744	0.0274	0.0003
29	0.13038	0.07813	0.04925	0.02799	0.0003
30	0.1345	0.07975	0.05127	0.02853	0.0003
31	0.13863	0.08127	0.05299	0.02907	0.0003
32	0.1431	0.08353	0.05451	0.02956	0.0003
33	0.14899	0.08505	0.05598	0.02996	0.0003
34	0.15538	0.08761	0.05716	0.03025	0.0003
35	0.16078	0.09036	0.05804	0.03035	0.0003
36	0.16667	0.09237	0.05873	0.0305	0.0003
37	0.17119	0.09429	0.05932	0.03059	0.0003

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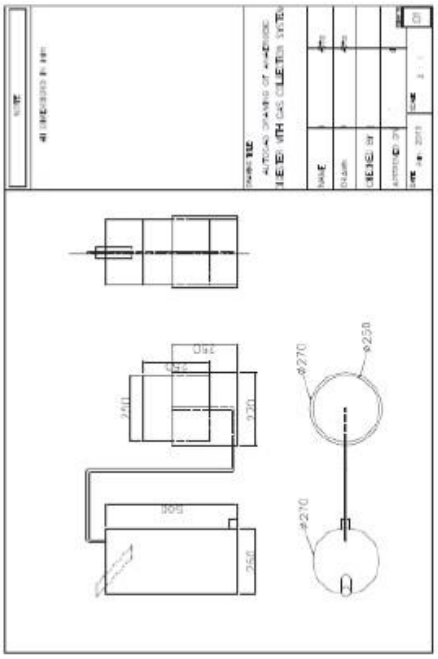

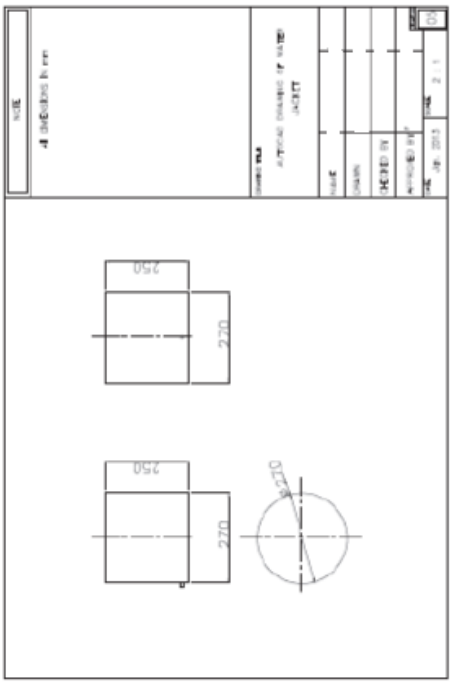

Plate 1: First day step up plant for biogas production.

Plate II: Early production of biogas

Plate III: Researcher is taking the readings of daily biogas production

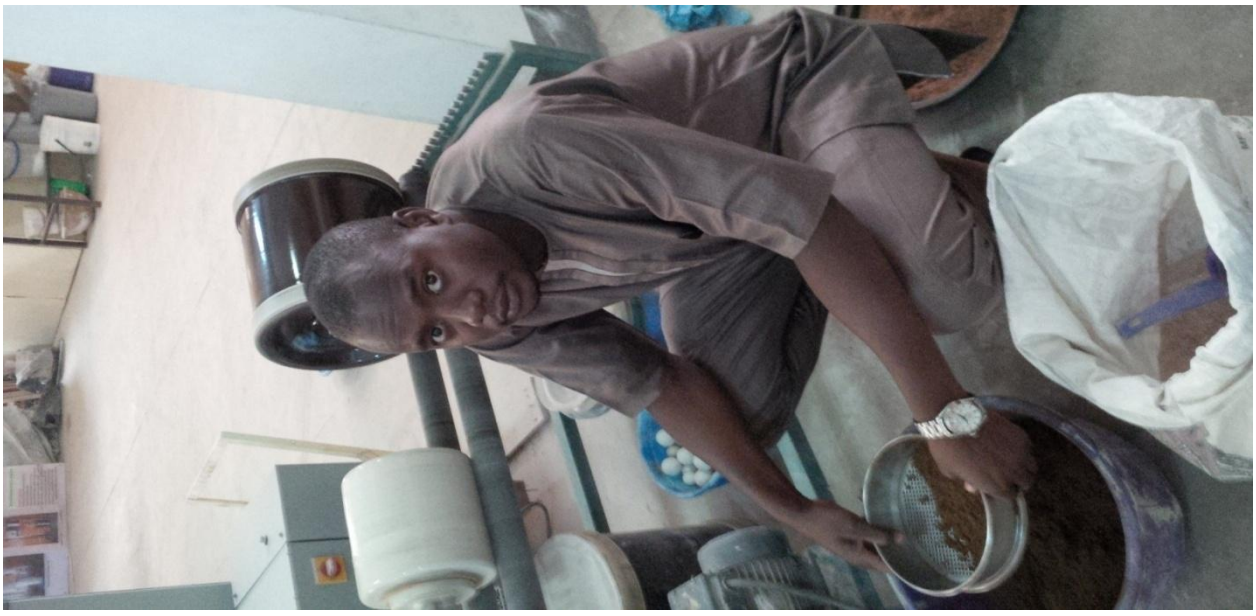

Plate IV: Sieving of substrates by the researcher after milling.

Plate V: Inflammability test by the researcher

Plate VI: Titration analysis for determining Nitrates, Sulphates and Phosphates

Plate VII: Mixing of the substrates