

COMPARATIVE STUDY OF BIOGAS PRODUCTION FROM COW DUNG, CHICKEN DROPPINGS AND CYMBOPOGON CITRATUS AS ALTERNATIVE ENERGY SOURCES IN NIGERIA

BY

Meshach Ileanwa Alfa
B. Eng. (ABU, 2008), PGDEducation (UniMaid, 2010)

DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL ENGINEERING,
AHMADU BELLO UNIVERSITY, ZARIA NIGERIA

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M.Sc/ENG/2027/2009-10

A THESIS PRESENTED TO THE DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL ENGINEERING AHMADU BELLO UNIVERSITY, ZARIA NIGERIA IN PARTIAL FULFILMENT OF THE REQUIRMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN WATER RESOURCES AND ENVIRONMENTAL ENGINEERING

DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL ENGINEERING,
AHMADU BELLO UNIVERSITY, ZARIA
NIGERIA

JANUARY, 2013

DECLARATION

I declare that the work in the thesis entitled "Comparative Study of Biogas Production from Cow dung, Chicken droppings and *Cymbopogon citratus* as alternative Energy sources in Nigeria" was written by me and that it is a record of my findings. It has not, either in part or whole, been submitted by me or anybody for this or any other degree or qualification at this or any other University.

The information derived from literature has been duly acknowledged in the text and a list of references provided.

_____ _____

Meshach Ileanwa Alfa Date

CERTIFICATION

This Thesis entitled "Comparative Study of Biogas Production from Cow dung, Chicken droppings and *Cymbopogon citratus* as alternative Energy Sources in Nigeria" by Meshach Ileanwa Alfa meets the regulations governing the award of the degree of Master of Science in Water Resources and Environmental Engineering of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

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Dean, Postgraduate School

DEDICATION

Again to my late foster mother, Madam Otini Achor whose earnest desire was to see me get to the Zenith of my academic endeavour and to my late father, Pa Alfa Joel Emakoji who left me an eternal legacy of considering others better than myself.

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My greatest gratitude goes to the Almighty God, my Glory and the 'Lifter up' of my head, my Source, my Inspiration, my sufficiency whose grace made this a reality. Daddy, I reaffirm my eternal allegiance to you and will never relent in the execution of your mandate upon my life as the Holy Spirit continues to work in and through me until the kingdoms of this world become the Kingdom of our God and of His Christ.

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ABSTRACT

This study was carried out to produce biogas from Cow dung, Chicken droppings and *Cymbopogon citratus* as well as the respective co-digestion of Cow dung and Chicken droppings with *Cymbopogon citratus*. 25 litre digesters and gas collection systems were designed and fabricated using locally available materials. The digesters were used to digest cow dung, chicken droppings and *Cymbopogon citratus* respectively as single substrates as well as to co-digest cow dung and chicken droppings respectively with *Cymbopogon citratus*. The respective feed materials were collected locally. They were pre-fermented, digested and analysed in accordance with standard methods. For the single substrates, the total volume of gas produced were 0.191m^3 (0.032 m^3/kg), 0.211m^3 (0.035m^3/kg) and 0.125 m^3 (0.021 m^3/kg) (before scrubbing) and 0.125m^3 (0.021m^3/kg), 0.130m^3 (0.022 m^3/kg), 0.090 m^3 (0.015 m^3/kg) (after scrubbing) for cow dung, chicken droppings and lemon grass respectively. For the co-digested substrates, Cow dung + Lemon grass produced 0.146m^3 (0.024 m^3/kg) before scrubbing and 0.100m^3 (0.017m^3/kg) after scrubbing while Chicken droppings + Lemon grass produced 0.193m^3 (0.032 m^3/kg) before scrubbing and 0.127m^3 (0.0.021m^3/kg) after scrubbing. The average ambient temperatures during the study were within the mesophilic range (20-40^oC). The pH values were stable and always in the optimal range between 6.5-8.0. The reductions in total solid were 75.3 %, 60.1%, 98.2%, 61.9% and 35% for cow dung, chicken droppings, lemon grass, cow dung + lemon grass and chicken droppings + lemon grass respectively. The total coliform contents of the residue were 2.00 x10^7 CFU/100ml, 6.00 x 10^7 CFU/100ml, 1.00 x 10^7 CFU/100ml and 1.00 x 10^7 CFU/100ml for cow dung, chicken droppings, cow dung + Lemon grass, and chicken droppings + Lemon grass respectively with 95%, 70%, 95% and 99% reduction in each case. Pathogens such as *Salmonella spp* and *Klebsiella sp.* were still present in the residue although *E.Coli* and *Shigella sp.* were removed. The estimated methane contents of the gas from cow dung, chicken droppings, Lemon grass, Cow dung + Lemon grass and Chicken droppings + Lemon grass were 65.59%, 61.71%, 71.95%, 68.53% and 66% respectively. The cooking rates for water were 0.079L/min, 0.070L/min, 0.067L/min, 0.064L/min and 0.060L/min for unscrubbed lemon grass, cow dung + lemon grass, chicken droppings + lemon grass, cow dung and chicken droppings respectively while those for scrubbed lemon grass, cow dung + lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings were 0.12L/min, 0.10L/min, 0.091L/min, 0.085L/min and 0.079L/min respectively. The rice cooking rates were 0.0038kg/min, 0.0034kg/min, 0.0033kg/min, 0.0031kg/min, and 0.0030kg/min for unscrubbed lemon grass, cow dung+ lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings respectively while those for scrubbed lemon grass, cow dung+ lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings were 0.0055kg/min, 0.0048kg/min, 0.0045kg/min, 0.0041kg/min and 0.0039kg/min respectively.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Environmental pollution is one of the most serious problems facing humanity and all other living things today. Economic growth and heavy consumption of natural resources are responsible for the global warming, acid rain and the destruction of the ozone layer (Thakur, 2006).

In Africa, water pollution and access to energy resources present challenges to human health, environmental health, and economic development. According to Mshandete and Parawira (2009), less than 10% of the population of 21 sub-Saharan African countries, have access to electricity. The need for alternative renewable energy sources from locally available resources cannot be over emphasised. Appropriate and economically feasible technologies that combine solid waste and wastewater treatment and energy production can simultaneously protect the surrounding water resources and enhance energy availability.

Abubakar (1990) noted that over the centuries, various sources of energy have been used by man in order to meet his basic life essentials. Man has utilized energy in modifying and manipulating land, water, plant and animals to obtain food, clothing and shelter.

Energy is a basic tool for development. Developing countries like Nigeria face added dilemmas regarding environmental protection due to their heavy dependency on biomass and fossil fuel. Adaramola and Oyewola, (2011) opined that Nigeria is endowed with huge resources of conventional energy resources (crude oil, tar sands, natural gas and coal) as

well as reasonable amount of renewable energy resources (e.g. hydro, solar, wind and biomass).

The Organization of Petroleum Exporting Countries (OPEC) annual statistical bulletin 2009 in buttressing these facts revealed that Nigeria proven crude oil reserves and natural gas are 37.2 billion barrels and 5,292 trillion standard cubic meters, respectively. In addition, the estimated reserve of tar sands and proven reserves of coals are about 30 billion barrels of oil equivalent and 639 million tonnes (with inferred reserves of about 2.75 billion tonnes), respectively (Adaramola and Oyewola, 2011). These fossil fuel reserves are more than adequate to fuel much of Sub-Saharan Africa energy demand for several decades. Coal reserves are also substantial at 2.75 billion metric tonnes. Also, a large amount of renewable energy resources including hydro electricity, solar, wind and biomass energy are present. Hydro resources are estimated at 14,750 Megawatts. Solar radiation is estimated at 3.5-7.0 Kilowatt-hour/m^2 per day, wind energy 2.0-4.0 m/s, wind energy at 150,000 Terra Joule per year and biomass at 144 million tonnes per year (Iwayemi, 2008).

Most of the developing nations are facing serious shortage of fuels, the most commonly used fuel being wood fuel. According to Nepalese 2001 population census, 65 percent of 4.17 million Nepalese households are using fuel wood for cooking purposes. As a result, 5.4 million tons of fuel wood is being burnt annually (Karki, *et al*, 2005). The case in Nigeria is not different.

The Social statistics presented by the Nigeria Bureau of Statistics (NBS) reveal that, Nigeria as at 2006 had a total of about 28,900,492 households. 79.6% of these households still depended on Wood fuel for cooking as at 2008 (NBS, 2009). In some states like

Adamawa, Nassarawa, Zamfara, Sokoto etc, the percentage of households depending on wood fuel for cooking is over 90 (NBS, 2009). Even though sizeable proportions of urban and semi-urban dwellers use fuel wood, the majority of users of this fuel are rural dwellers, who constitute between 60-75% of the population in Nigeria (Ahmadu, 2009). With the recent hike in the pump price of Kerosene in Nigeria, the dependence on fuel wood for domestic cooking has significantly increased. The Figure 1.1 shows the percentage distribution of Nigerian households by the type of fuel used for cooking as at 2008.

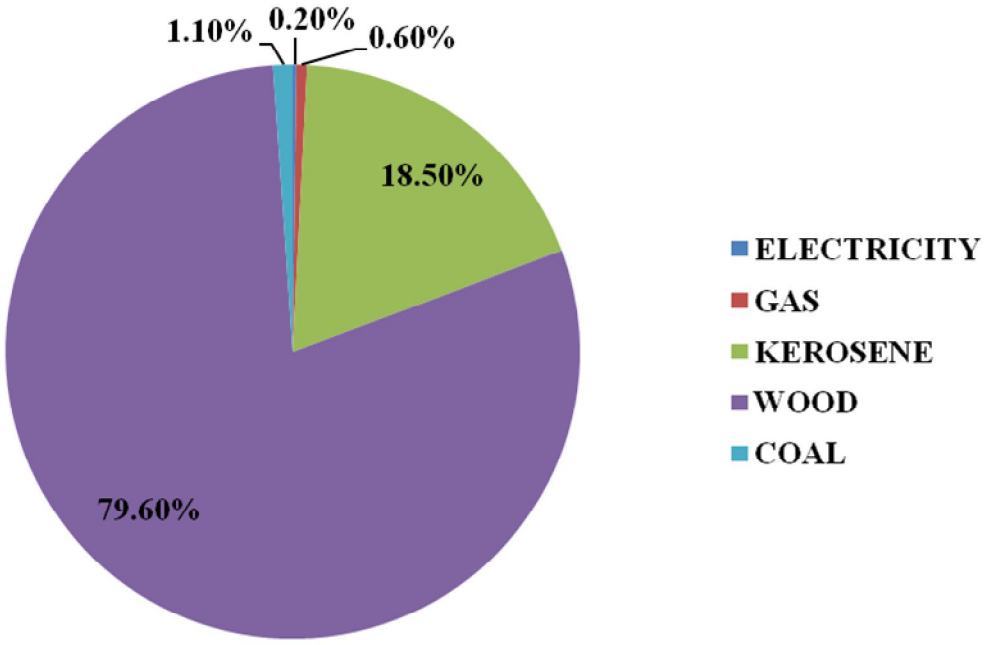


Fig 1.1: Percentage Distributions of Households by Type of Fuel for Cooking as at 2008 (NBS, 2009)

The main challenge of the present world is to harness the energy source which is environment friendly and ecologically balanced. This need has forced the world to search for other alternate source of energy. But unfortunately the new alternative energy sources like the solar, hydro, wind etc. require huge economical investment and technical power to operate, which seem to be very difficult for the developing countries like Nigeria. In the

present moment biogas energy can be one and only reliable, easily available and economically feasible source of alternative and renewable source which can be managed by locally available sources and simple technology for these rural villages.

A biogas plant or latrine when successful is an appropriate and sustainable method to deal with human or animal waste. This system produces two extremely useful products from the waste: biogas and slurry. Using biogas for cooking and lighting reduces the strain on the environment by decreasing the use of biomass and the production of green house gases (as methane that is produced normally from manure is now captured and used). The biogas system also provides a barrier protecting ground water from contamination from untreated waste (Ocwieja, 2010).

To save the environment from further deterioration and also supplement the energy needs of the rural populace, a strategy incorporating local resources and new technology as biogas technology can be effectively utilized (Ahmadu, 2009). More so, with the declining quantity of fossil fuels it is critical today to focus on sustained economic use of existing limited resources and on identifying new technologies and renewable resources, e.g., biomass, for future energy supply (Deublein and Steinhauser, 2008).

Biogas systems are highly friendly to the environment. In fact, the contribution of a methane molecule (CH_4) to the greenhouse effect is 21 times greater than that of a carbon dioxide molecule. Therefore burning methane, even though producing CO_2, reduces its impact on the environment. The digested slurry coming out of the plant is used for organic fertilizer production. Besides, Biodigesters can be used to treat municipal waste and

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

As well as being better for the climate, Anaerobic Digestion has other benefits over traditional waste management technologies. Plants can be small and low rise so may be situated in towns, reducing haulage distances and associated traffic pollutants. They are faster to build and to get planning permission for, as proposals are more acceptable to local residents than with other technologies. Anaerobic Digestion also produces less air and solid emissions than incineration, landfill and pyrolysis and gasification (Friends of the earth, 2007).

The process of fermentation in biodigesters 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 biodigesters (www.fao.org).

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.

Biogas is a flammable gas produced by the biological fermentation of organic materials such as agricultural waste, manure and industrial effluents in an anaerobic (oxygen deficient) environment to produce methane, carbon-dioxide and traces of hydrogen sulphide, (Ahmadu, 2009).

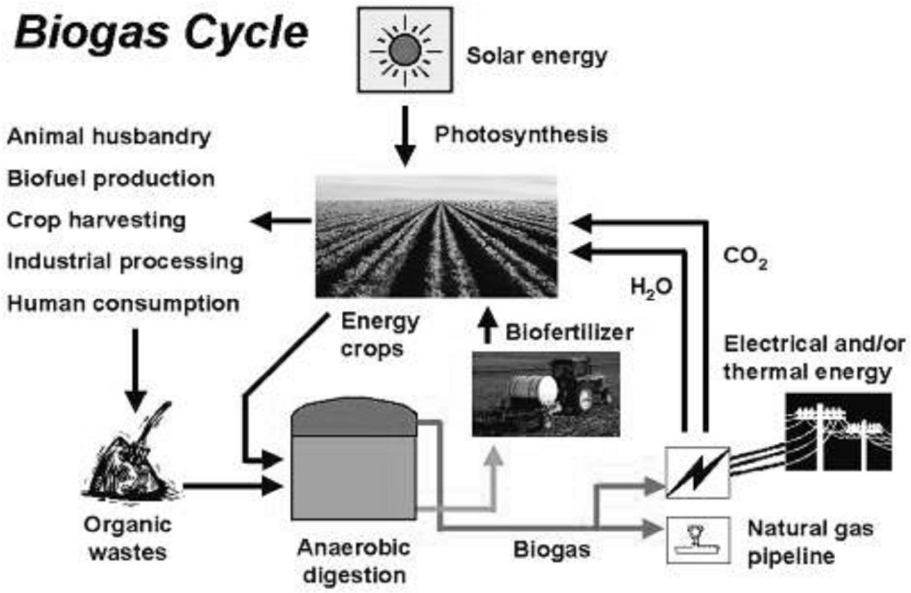


Fig. 1.2: Biogas from Organic Wastes (Igboro, 2011).

1.2 STATEMENT OF THE RESEARCH PROBLEM

Energy consumption in Nigeria has been increasing on a relatively high rate. On a global scale, Iwayemi (2008) opined that the Nigerian energy industry is probably one of the most inefficient in meeting the needs of its customers. This is most evident in the persistent disequilibrium in the markets for electricity and petroleum products, especially kerosene and diesel. The dismal energy service provision has adversely affected living standards of the population and exacerbated income and energy poverty in an economy where the majority of the people live on less than $2 a day.

Energy in form of electricity has been identified as an important element in achieving national development goals. It is an established fact that its availability in terms of sufficient quality and quantity at affordable prices will stimulate economic growth yet, the recent facts on the state of electricity in the country revealed that Nigeria currently generates an average of 4,500 Megawatts against a demand in excess of 25,000 MW (http://www.enownow.com/news). It therefore implies that the nation is meeting only 18% of her electricity need which is grossly inadequate.

The abundant hydrocarbon natural resource (crude oil and natural gas) in Nigeria is the mainstay of over 80% of revenues to the nation. This has not served as a catalyst for economic growth neither has it served as the major source of energy in the mix of energy supplies (Machunga-Disu and Machunga-Disu, 2012). Furthermore, the ever increasing prices of petroleum products globally, has made kerosene, which is the most commonly used fuel for cooking and lighting unaffordable to many, especially the rural dwellers, (Ahmadu, 2009). This therefore moves a larger percentage of the populace to seek solutions to their energy needs from other sources which in most cases are detrimental to the environment. For instance, there was a 5.5% increase in the dependence on wood fuel for cooking between 2007 and 2008 (NBS, 2009). More so, 79.6% of the households depend on wood fuel for their cooking while kerosene, coal, gas and electricity comes behind from distant 18.5%, 1.1%, 0.6% and 0.2% respectively (NBS, 2009).

Poorly managed forests have to shoulder immense burden to meet the increasing demand for energy caused by both the rising population and the lack of development alternative energy resources. Wood fuel has been and still is the major source of fuel daily used by rural mass in Nigeria. This total dependence on wood fuel as the source of energy for

cooking has resulted in deterioration of the quality and quantity of forests and has posed a serious threat in maintaining ecological balance, thereby manifesting various problems like deforestation, flood, Global warming, soil erosion , landslides, climate change etc. Thus, an alternative energy source that would be affordable and environmentally friendly becomes necessary if the green forest must be preserved. Furthermore, there exist abundant evidence that climate change is a severe threat to socio-economic development and can substantially affect a nation's GDP, as it affects water, forest, sanitation, food security, industrial development, housing, energy, health and the very air we breathe (Machunga-Disu and Machunga-Disu, 2012). Thus, development of biogas technology is a suitable alternative energy source that would be affordable and environmentally friendly that would help preserve the green forest thus achieving the 7th mandate of the Millennium Development Goal on environmental sustainability.

Moreover, governments and industries are constantly on the lookout for technologies that will allow for more efficient and cost-effective waste treatment. In addition to meeting the dire need for waste treatment options to enhance a clean environment, alternative processing technologies, such as anaerobic digestion, offer some potential for recovery of value from organic wastes (i.e., waste to wealth) by producing biogas and soil-conditioning composts. Furthermore, with the enormous cattle population especially in the northern part of the country, millions of tonnes of dung released daily emit a lot of methane gas when exposed to the atmosphere, which is 320 times more harmful to human health than carbon dioxide (Thakur, 2006). In addition *Cymbopogon citratus* (Lemon grass) is a well known medicinal plant as due to its citral content (Tajidin et al., 2012). After it is boiled for medicinal purpose and the citral content is extracted, the remains of the grass become waste

and could constitute nuisance to the environment. There is therefore an urgent need for development of adequate means to recycle these wastes and generate wealth from them. Thus biogas technology could be an appropriate means for recycling organic waste thereby achieving the goal one of the Millennium Development Goals (MDGs) of eradicating extreme poverty (UN, 2005) via waste to wealth initiative. Thus the organic waste becomes a channel for wealth creation as they are harnessed as feed materials for the production of biogas as well as biofertilizers that would accrue from the digestate. It is for these reasons that researches like the present one are desirable to chart a course for sustainable energy production and utilization while a cleaner and safer environment is enhanced.

1.3 JUSTIFICATION OF STUDY

Kerosene and other oil based sources of fuel are scarce and costly to be easily available for small marginal and medium farmers residing in rural areas. Furthermore, frequent alarming hike in prices of imported oil and chemical fertilizer have serious economic threat to the rural poor. In this context, to reach the self-sufficiency in energy and fertilizer and to minimize the pressure on traditional biomass fuel, biogas technology has been the best alternative energy solution, which could be achieved through the active mobilization and economic utilization of local indigenous resources available in the country.

It has been estimated that Nigeria produces about 227,500 tonnes of fresh animal waste daily. Since 1 kg of fresh animal waste produce about 0.03 m^3 biogas, then Nigeria can potentially produce about 6.8 million m^3 of biogas every day from animal waste only (Mshandete and Parawira , 2009). A recent study that assessed Nigeria's biogas potentials (minimum value) from solid waste and livestock excrements revealed that in 1999,

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

In addition, 20 kg of municipal solid waste (MSW) per capita has been estimated to be generated in the country annually (Mshandete and Parawira , 2009). By the 2005 census figure of about 140.4 million inhabitants, the total generated MSW will be at least 2.81 million tonnes every year. With increasing urbanization and industrialization, the annual MSW generated will continue to increase.

Biogas production may therefore be a profitable means of reducing or even eliminating the menace and nuisance of urban wastes in many cities in Nigeria.

Moreover, the methane content of biogas depends to a significant extent on the nature of the feed material with succulent grass having the highest value of about 70% (Sasse, 1988).

Most of the previous biogas researches in Nigeria used animal dung and kitchen wastes as feedstock substrates while the use of succulent plants for biogas production have been limited to water lettuce, water hyacinth, cassava leaves and *Eupatorium odoratum* (Akinbami et al., 1996, 2001; Okagbue, 1988; Ubalua, 2008, Odeyemi 1981). These plants are mostly found in the riverine regions of the country. There is no record of any research on the potential of *Cymbopogon citratus* (Lemon grass) which is more widely distributed in Nigeria than the other plants previously tested. *Cymbopogon citratus* popularly known as Lemon grass belong to the family *Grami-neae* and the genus *Cymbopogon* (Akhila, 2012). It is native of the warm temperate and tropical regions of the old world. Lemon grass can tolerate a wide range of soils and climatic conditions (Sugumaran et al., 2005). Since *Cymbopogon citratus* is not as widely available as the animal wastes, co-digesting it with animal dung would provide a good synergy for improved gas production. Thus, the animal

waste provides the high volume while the quality of the resultant gas is optimized by the *Cymbopogon citratus.*

With the rapidly increasing waste generation threatening to prevent humans from carrying out their activities for lack of space, the society is therefore faced with the choice to either allow this biomass waste to continue polluting the environment; methane and carbon dioxide production, to continue to increase global warming or boldly take the initiative of converting the biomass into alternative energy (Igboro, 2011).

The study therefore explores means of converting this and other organic waste to energy as a very attractive option for adequate treatment that will enhance environmental sustainability, which is one of the eight Millennium Development Goals set by the UN.

It is therefore necessary in moving towards a sustainable energy society. While converting waste into energy is especially appealing conceptually, there is still much to be done before the technology becomes commonplace. Also, the research is necessary in order to optimize the technologies, build confidence in their effectiveness, and prepare them for the market (Igboro, 2011). This will require significant efforts in outreach. Policy makers, farmers, engineers, the business community and the rural community need to know about issues of sustainable development which confront us and biogas utilization would just be the panacea for our energy problem.

1.4 AIM AND OBJECTIVES OF STUDY

The research aims at the comparative production and utilization of biogas for cooking, using cow dung, chicken droppings, *Cymbopogon citratus* (lemon grass) as well as the

respective co-digestion of cow dung and chicken droppings with *Cymbopogon citratus* (lemon grass).

The study has the following specific objectives:

i. To design and construct biogas digester plants that would operate under existing weather conditions;
ii. To utilize the biogas digesters so constructed for the digestion of cow dung, chicken droppings and lemon grass;
iii. Optimisation of the anaerobic digestion of cow dung and chicken droppings for maximum energy production via co digestion of each with lemon grass;
iv. To establish the technical performance of the anaerobic digestion of cow dung, chicken droppings and lemon grass as well as their co-digestions with lemon grass respectively as biomass feed material.
v. To study and determine the most feasible local environmental conditions to optimally operate the developed biogas facilities.
vi. To upgrade the biogas via scrubbing of impurities and test for the heating efficiency before and after scrubbing.

1.5 SCOPE OF THE STUDY

This study is limited to cow dung from Zango abattoir, chicken droppings from the poultry section (deep litter) in the National Animal Production Research Institute (NAPRI), Shika, Zaria as well as *Cymbopogon citratus* (Lemon grass) sourced locally from Area BZ staff quarters, Ahmadu Bello University main campus, Samaru-Zaria.

CHAPTER TWO

LITERATURE REVIEW

2.1 HISTORICAL DEVELOPMENT OF ANAEROBIC DIGESTION TECHNOLOGIES

Historical evidence indicates that the anaerobic digestion process is one of the oldest technologies (Monnet, 2003). Very old sources indicate that using wastewater and so-called renewable resources for the energy supply is not new, but were already known before the birth of Christ (Deublein and Steinhauser, 2008).

The first allusion to animal manure comes from Humphrey Davy, who reported early in the nineteenth century the presence of this combustible gas in fermenting farmyard manure. Davy is known for the invention of the miner's safety lamp (Maramba, 1978).

However, the industrialization of anaerobic digestion began in 1859 with the first digestion plant in Bombay. By 1895, biogas was recovered from a sewage treatment facility and used to fuel street lamps in Exeter, England (Monnet, 2003). Research led by Buswell (Monnet, 2003) and others in the 1930s identified anaerobic bacteria and the conditions that promote methane production. As the understanding of the anaerobic digestion process and its benefits improved, more sophisticated equipments and operational techniques emerged. The result was the use of closed tank, heating and mixing systems to optimize anaerobic digestion.

In 1900 a methane (biogas) generating plant from human wastes was constructed in a leper asylum in Matunga, India (Maramba, 1978). This was the Homeless Lepers' Asylum, now known as the Acworth Leprosy Hospital in Wadals, India.

In the years around 1940, many municipal sewage treatment plants in the United States and elsewhere were already employing anaerobic "digestion" as part of the treatment of municipal waste, and thereby generating methane which was used to generate electricity for the plant. This indicated that for pollution control, the anaerobic digestion process is proven effective with additional benefits in the form of a supply of a useful gas (Maramba, 1978).

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

In India, Mumbai system gas was used in lights in 1897 while the gas was used in an engine in 1907. In 1951, the KVIC national programme developed floating drum design plants for individual farmers of volume 7 to 35 m^3 with cattle dung as feed stock (Fulford, 2011). More so, in 1961, PRAD (state sector) involved adapted Chinese dome design as "Janata" plant (4 to 10 m^3). In 1981, AFPRO (NGO sector) involved adapted Chinese dome design as Deenbhandu plant (2 to 8 m^3). As at 2009, 12 million plants built with less than 60% success rate. In 2005, ARTI won Ashden Award for a floating drum design made from

HDPE water tanks designed for urban families of volume 1 to 2 m^3 with food wastes as feed stock. In 2007 Biotech won Ashden Award for similar system, made from glass reinforced plastics on domestic, institutional and market scales (Maramba, 1978).

In Nepal, a demonstration plant in a school in 1955. In 1975, the Nepalese Government programme involved development and Consulting Services (Aid programme) and Agricultural Development Bank of Nepal in Biogas research development. In 1976 the Gobar Gas Company was set up to continue the programme as commercial operation. Pilot programme of 95 plants which used KVIC design with metal gas drums were set up. USAID funded R&D project also developed fixed dome design: cast-in-place with cattle dung used as feed stock for small farmers using 4 to 20 m^3 systems. In 1986, the programme was transferred to local management. With UNDP funding and Dutch (SNV) who provided subsidy, 189,122 plants built in 2009 with 98% success rate (Maramba, 1978).

In Kaunas – Lithuania, the Rokai pig farm biogas plant operates on a daily 60m^3 of manure from 11,000 pigs. The produced biogas is by co-generation converted into electricity and heat. About 1,200-3,600m^3 of biogas is produced per day and 2,400kwh of electricity per day (Maramba, 1978).

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

In Taiwan, more than 7,500 units of methane-generating device utilizing pig manure have been constructed, (Maramba, 1978).

In the United States, there has been considerable interest in the process of anaerobic digestion. Digesters are aimed at meeting energy production and waste treatment, especially with regard to animals in farms, allowing the manipulation of a material free of odours, (Maramba, 1978).

2.1.1 Biogas Projects in Africa

Biogas projects are on the rise throughout the world. They provide a method to produce methane used for cooking and lighting from the waste of animals and humans. In countries such as Nepal there is a large push to increase the number of biogas plants in the country. These projects usually use cow manure to produce the gas, but by making a small adjustment, a household latrine can be connected to a digester increasing gas production and providing an easy way to manage the human waste (Ocwieja, 2010).

In Rwanda, Kigali Institute of Science and Technology built sewage systems for overcrowded prisons (10,000 people) using underground masonry plants with 100 m^3 volume, linked to make 1,400 m^3. This development saved 50% of wood for cooking (Fulford, 2011).

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

In Nigeria, research into biogas technology and its practical application is on-going, though, has not really received the deserved attention. The Sokoto Energy Research Centre,

Usman Danfodio University, Sokoto, has carried out a number of pilot projects on construction of household size digesters. In addition to this the centre has constructed biogas digester plants of $20m^3$ capacity at these locations: NAPRI-Zaria, Zaria prisons, Kiri-kiri Prisons-Lagos, May flower School-Ikene, Ogun State, Ojokoro-Lagos and Maiduguri (Mshandete and Parawira , 2009).

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 (van Nes & Nhete, 2007). 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).

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

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

2.2 CONCEPT OF ANAEROBIC DIGESTION

Anaerobic digestion is the controlled degradation of organic waste in the absence of oxygen and in the presence of anaerobic micro-organisms (Ojolo et al, 2007). The digestion process is carried out using an airtight reactor and other equipment used for waste pre-treatment and gas retrieval. The process generates a product called "biogas" that is primarily composed of methane, carbon dioxide, and compost products suitable as soil conditioners on farmlands (Koberle, 1995).

Monnet (2003) noted that anaerobic digestion can be used either to treat biodegradable wastes or produce saleable products such as heat/electricity, soil amendment etc. the most valuable use of anaerobic digestion is to combine both waste management and the use of the bi-products. It is unlikely that anaerobic digestion will be a viable treatment without using the biogas and the digestate (Monnet, 2003). The qualities of the biogas and digestate will vary depending on the feedstock and its contamination. Furthermore, the use of biogas and digestate can also involve further treatments, such as composting of digestate.

Monnet (2003) further stated that the process of anaerobic digestion can be further divided into four stages: pre-treatment, digestion, gas upgrading and digestate treatment. He noted that the level of pre-treatment depends on the type of feedstock, for example, manures need to be mixed whereas municipal solid wastes (MSW) are sorted and shredded.

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

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

2.2.1 Biochemical Processes in Anaerobic Digestion

Anaerobic digestion is a naturally occurring process of decomposition and decay, by which organic matter is broken down into its simpler chemicals components under anaerobic conditions. Anaerobic microorganisms digest the organic materials, in the absence of oxygen to produce methane and carbon dioxide as end products under ideal conditions. The biogas produced in anaerobic digestion plant usually contains small amount of hydrogen sulphide (H_2S) and ammonia (NH_3), as well as trace amount of other gases (Monnet, 2003). The science underlying anaerobic digestion can be complex. Thus the process is best understood if split into four main stages.

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.

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

Hydrolysis/liquefaction: In the first stage of hydrolysis, or liquefaction, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble

molecules such as sugars, amino acids and fatty acids. The complex polymeric matter is hydrolyzed to monomer, e.g., cellulose to sugars or alcohols and proteins to peptides or amino acids, by hydrolytic enzymes, (lipases, proteases, cellulases, amylases, etc.) secreted by microbes. The microbial cell is impermeable to the cellulose molecule so the organism must excrete extracellular enzymes in order to make the carbon source available. The extra cellular catalysts act hydrolytically, converting the insoluble materials to soluble sugars that penetrate the cell membrane. The large molecular complex substances are solubilized into simpler ones (especially volatile acids, which are low molecular weight organic acids) with the help of extracellular enzyme excreted by the acid forming bacteria. The phase is also known as polymer breakdown stage. For example, the cellulose consisting of polymerized glucose units are first broken down to dimers (disaccharides), and then to monomers (monosaccharide) such as glucose by cellulolytic bacteria, which excrete enzyme called cellulose. The most common anaerobic cellulose fermenters in nature appear to be members of the genus Clostridium (Karki *et al.,* 2005).

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: Hydrolysis is immediately followed by the acid-forming phase of acidogenesis. In this process, acidogenic bacteria turn the products of hydrolysis into simple organic compounds, mostly short chain (volatile) acids (e.g., propionic, formic, lactic, butyric, or succinic acids), ketones (e.g., ethanol, methanol, glycerol, acetone) and alcohols. The specific concentrations of products formed in this stage vary with the type of bacteria as well as with culture conditions, such as temperature and pH (Ostream, 2004).

Typical reactions in the acid-forming stages 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: The next stage of acetogenesis is often considered with acidogenesis to be part of a single acid forming stage. Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are reduced through these pathways. Acetogenesis occurs through carbohydrate fermentation, in which acetate is the main product, and other metabolic processes (Themelis and Verma, 2004).

The result is a combination of acetate, CO_2, and H_2. The role of hydrogen as an intermediary is of critical importance to Anaerobic Digestion reactions. Long chain fatty acids, formed from the hydrolysis of lipids are oxidized to acetate or propionate and hydrogen gas is formed. Under standard conditions, the presence of hydrogen in the solution inhibits the oxidation. The reaction only proceeds if the hydrogen partial pressure is low enough to thermodynamically allow the conversion. 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. Mata-Alvarez et al. (2003) noted that the concentration of hydrogen, measured by partial pressure, is an indicator of the health of a digester.

For example, the free energy value of the reaction that converts propionate to acetate, shown in equation (2.4), is +76.1kJ, so that this reaction is thermodynamically impractical. When acetate and hydrogen are consumed by bacteria, however, the free energy becomes negative. In general, for reactions producing H_2, it is necessary for hydrogen to have a low partial pressure for the reaction to proceed.

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

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.

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

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

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

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: Finally, in the last stage methane is produced by bacteria called methane formers (also known as methanogens). The methanogenic anaerobic bacteria involved in this stage, known as methanogenesis or methane fermentation, are the same fastidious bacteria that occur naturally in deep sediments or in the rumen of herbivores (Igboro, 2011). They carry out methane formation either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digesters results in that the acetate reaction is the primary producer of methane (Monnet, 2003). The methanogenic bacteria include *methanobacterium, methanobacillus, methanococcus and methanosarcina*. Methanogens can also be divided into two groups: acetate and H_2/CO_2 consumers. *Methanosarcina spp*. and *methanothrix spp.* (also, methanosaeta) are considered to be important in anaerobic digestion both as acetate and H_2/CO_2 consumers. The methanogenesis reactions can be expressed as follows:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2.8)$$

(Acetic acid) (Methane) (Carbon dioxide)

$$2CH_3CH_aOH + CO_2 \rightarrow CH_4 + 2CH_3COOH \quad (2.9)$$

(Ethanol) (Carbon dioxide) (Methane) (Acetic acid)

$$CO_2 + 4H_2 \rightarrow CH4 + 2H_2O \quad (2.10)$$

(Carbon dioxide) (Hydrogen) (Methane) (Water)

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

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. Figure 2.1 shows the anaerobic digestion process.

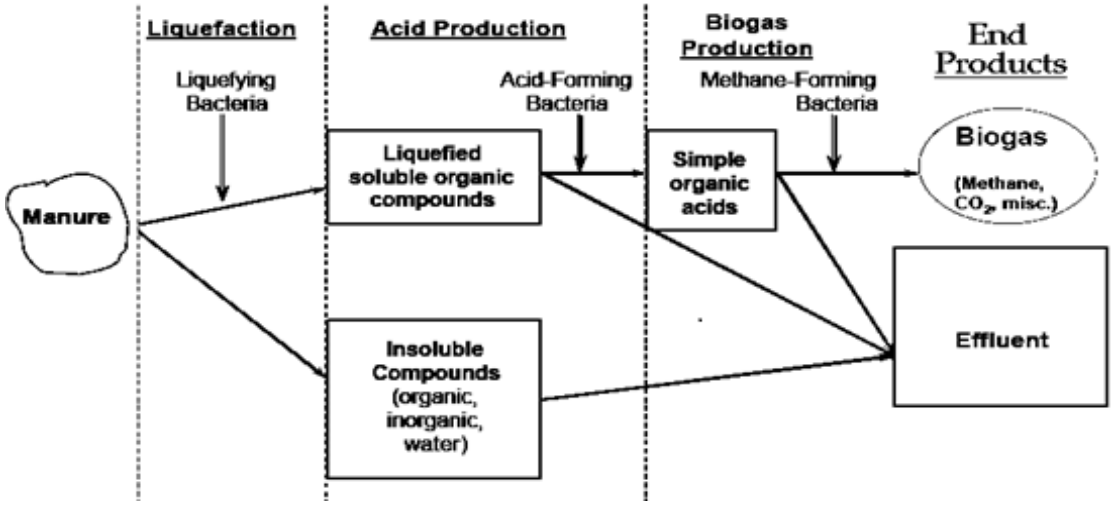


Figure 2.1: Anaerobic Digestion Process (Jones, 2006)

2.2.2 Important Operating Parameters in Anaerobic Digestion Process

There are several conditions and variables that must be applied in order to obtain a proper breakdown of the organic compounds. The rate at which the microorganisms grow is of paramount importance in the anaerobic digestion process. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system. Some of these parameters are discussed as follows (Verma, 2002, Monnet, 2003).

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.

Temperature of anaerobic digesters: There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic and thermophilic ranges. The mesophilic range is between 20°C-40°C and the optimum temperature is considered to be 30°C-35°C. The thermophilic temperature range is between 50°C-65°C (Verma, 2002). It has been observed that higher temperatures in the thermophilic range reduce the required retention time (Verma, 2002).

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

Monnet (2003) noted also that thermophilic digesters are more efficient in terms of retention time, loading rate and nominally gas production, but they need a higher heat input and have a greater sensitivity to operating and environmental variables, which makes the process more problematic than mesophilic digestion. He also noted that the sterilization of the waste is linked to the temperature; the higher it is the more effective it is in eliminating pathogens, viruses and seeds. On the other hand, when the ambient temperature goes down to 10°C, gas production virtually stops (Karki *et al*, 2005).

pH of Anaerobic Digesters: The pH values of the input mixture play very important role in methane formation. The acidic condition is not favourable for methanogenic process. The optimum biogas production is achieved when the pH value of input mixture in the digester is between 6 and 7. The pH in a biogas digester is also a function of the retention time. In the initial period of fermentation, as large amounts of organic acids are produced by acid forming bacteria, the pH inside the digester can decrease to below 5. This inhibits or even

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

Retention Time: Retention time (also detention time) is the average duration of time a sample remains in the digester. In a cow-dung plant, the detention time is calculated by dividing the total volume of the digester by the volume of slurry added daily. Usually, for a cow-dung plant a detention time of 40 to 60 days is required depending upon the temperature. Thus, the fermenting pit should have a volume of from 40 to 60 times the slurry added daily. But for a night-soil digester, a longer detention time (70 to 90 days) is needed in order to kill the pathogens present in human faeces.

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).

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).

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).

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).

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.

2.2.3 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.

Carbon-Nitrogen (C/N) Ratio of Feed Materials: This is the ratio of carbon to nitrogen present in the organic matter. Gas production is optimum when C/N ratio of the input is between 20 and 30. C/N ratio of cow/buffalo dung is about 25 and hence ideal for biogas production.

Maintaining Anaerobiosis in the Anaerobic Digesters: Methanogenic bacteria are anaerobic organisms. In aerobic condition, most of these bacteria are inactive in metabolism, thus digesters should be totally airtight to maintain strictly anaerobic condition. In many places, digesters are buried in the Earth to maintain anaerobiosis condition.

Addition of Succulent Plant or Algae: For the effective and high production of biogas from cow dung and animal dung many succulent plants or algae are added. Green algae, water hyacinth and lemon grass are added in the digester. The amount of biogas produced from the algae was twice (344 ml/g dry algae) of that obtained from cow dung (179/g dry cow dung) alone. Also, the duration of gas evolution increased with increasing the proportion of slurry. The calorific value of the gas was 4800 K cal/m^3 and the percentage of methane was 55.4 percent.

2.2.4 End Products of Anaerobic Digestion.

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

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

2.3 BIOGAS

2.3.1 Biogas Composition

Biogas is the mixture of gas produced by methanogenic bacteria while acting upon biodegradable materials in an anaerobic condition. This gas is primarily composed of 50 to 70% methane (CH_4) and 30 to 40% carbon dioxide (CO_2), with smaller amounts of

hydrohen sulphide (H_2S) and ammonia (NH_3). Trace amounts of hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), saturated or halogenated carbohydrates and oxygen (O_2) are occasionally present in the biogas. Usually the mixed gas is saturated with water vapour and may contain dust particles and siloxanes (Monnet, 2003). Methane is virtually odorless and colorless. It burns with a smokeless clear blue flame and is non toxic. The approximate composition of the biogas is presented in Table 2.2.

Table 2:2 Average Composition of Biogas

Composition	**Percentage (%)**
Methane (CH_4)	50-70
Carbon dioxide (CO_2)	30-40
Hydrogen (H_2)	5-10
Nitrogen(N_2)	1-2
Water vapour(H_2O)	0.3
Hydrogen Sulphide (H_2S)	Traces

Source: Shrestha (2010)

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

The first gas from a newly filled biogas plant contains too little methane. The gas formed in the first three to five days must therefore be discharged unused. The methane content depends on the digestion temperature. Low digestion temperatures give high methane content, but less gas is then produced (Sasse, 1988). The methane content also depends on the feed material. Some typical values of methane content for different feed materials are as shown in Table 2.3

Table 2.3: 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

Source: Sasse (1988)

Biogas is somewhat lighter than air and has an ignition temperature of approximately 700°C (diesel oil 350°C; petrol and propane about 500°C). The temperature of the flame is 870°C (Sasse, 1988).

However the main constituents of biogas are CH_4 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).

2.3.2 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 2.3 below.

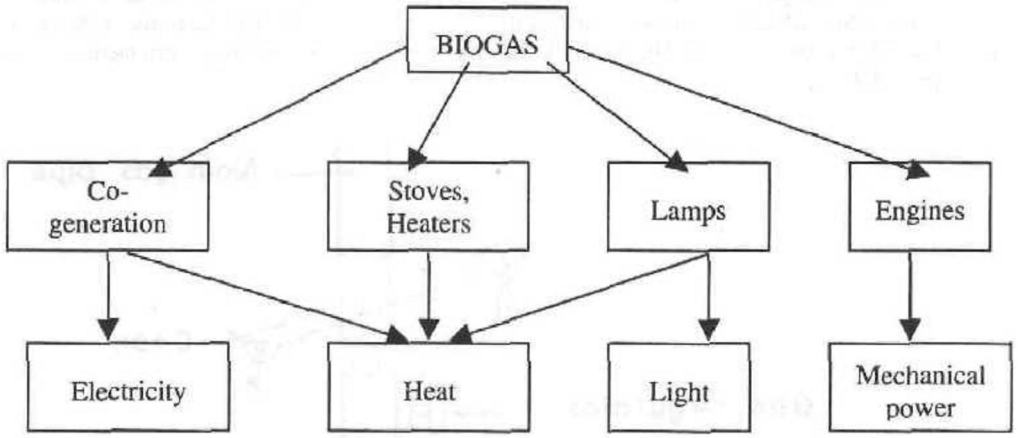


Figure 2.2: Possible Uses of Biogas (Karki *et al*, 2005).

i. Cooking

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

ii. Lighting

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

iii. Refrigeration

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

iv. Biogas-fueled Engines

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

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

v. Electricity Generation

Generating electricity is a much more efficient use of biogas than using it for gas light. From energy utilization point of view, it is more economical to use biogas to generate

electricity for lighting. In this process, the gas consumption is about 0.75 m^3 per kW hour with which 25 40-watt lamps can be lighted for one hour, whereas the same volume of biogas can serve only seven lamps for one hour (Karki *et al*, 2005).

Small internal combustion engines with generator can be used to produce electricity in the rural areas with clustered dwellings. Biodigesters can be used to treat municipal waste and generate electricity (Karki *et al*, 2005). One of the options to utilize biogas is to produce electricity using a gas engine or gas turbine.

Acccording to Igboro (2011), other benefits of biogas include

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

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

2.3.3 Effects of Biogas System

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

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

2.3.4 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.

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:

- Water scrubbing;
- Polyethylene glycol scrubbing;
- Carbon molecular sieves and
- Membrane separation

b. Hydrogen Sulphide Removal:

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

- Lime scrubbing;
- Air/oxygen dosing to digester biogas;
- Iron chloride dosing to digester slurry;
- Iron oxide;
- Activated carbon;
- Water scrubbing and
- NaOH scrubbing

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

2.4 DIGESTATE

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

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

untreated liquid manure (Monnet, 2003). More so, it reduces the odour nuisance by about 80%.

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).

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

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

advantages over raw manure applications, as the ammonia uptake by plants is higher than for organic nitrogen (Monnet, 2003).

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

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

2.5 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.

2.5.1 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 ArrowBio 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.

2.5.2 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.

Classification 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.

a. 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.

b. 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.

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.

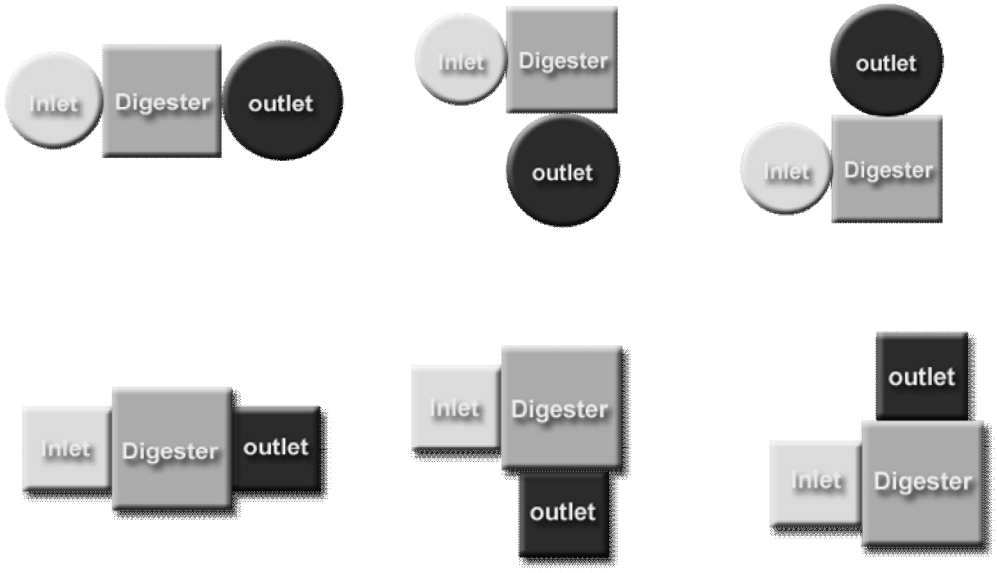


Figure 2.3: Design of Biogas Systems According to Orientations of Inlet and Outlet

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.

Classification Based on Buried Positions of Anaerobic Digesters: Biogas digesters can be erected in either of the following ways:

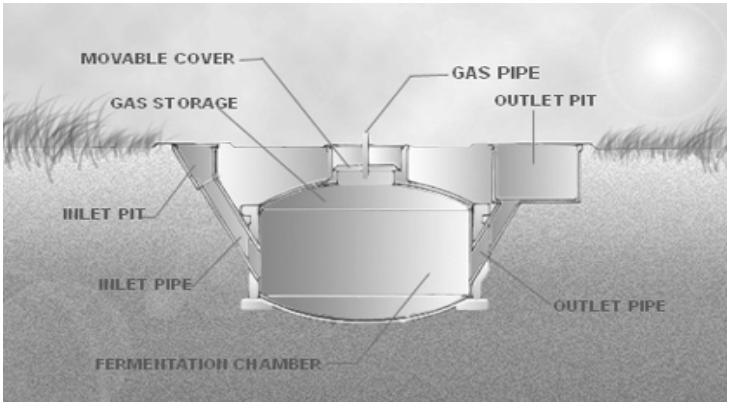


Figure 2.4(a): Underground digester

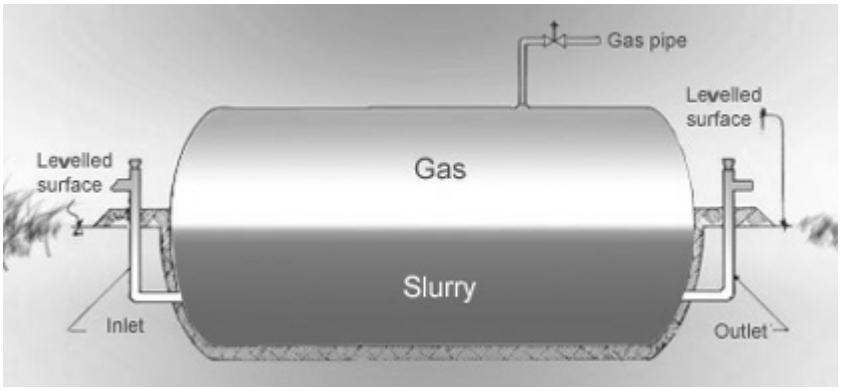


Figure 2.4(b): Semi-Buried digester

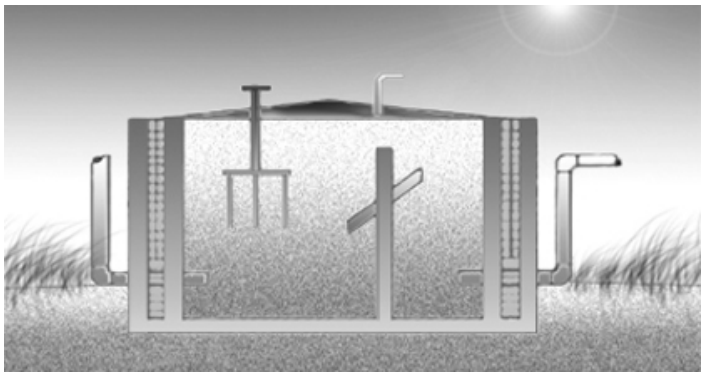


Figure 2.4(c): Ground digester

2.5.3 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.

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).

2.5.4 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, 1996,2001; Okagbue, 1988; Ubalua, 2008). Many other raw materials available in Nigeria have been critically assessed for their possible use in biogas production by (Odeyemi, 1983). 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 Akinluyi and Odeyemi (1986), Abubakar (1990), Lawal et al. (1995), Matthew (1982),

Ojolo et al. (2007) and Zuru et al. (1998). Atuanya and Aigbirior (2002) reported the feasibility of biogas production using a UASB reactor of 3.50 L capacity.

Ilori et al. (2007), 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. Alkan-Ozkaynak and Karthikayan (2011) has demonstrated a high yield of biogas from the anaerobic digestion of corn stillage. Seeding of co-digested pig waste and cassava with wood ash was reported to result into significant increase in biogas production compared with unseeded mixture of pig waste and cassava peels (Adeyanju, 2008). Fariku and Kidah (2008) reported good biogas production from anaerobic digestion of waste shells of *Lophira lanceolata* fruit. The potential use of local algal biomass for biogas production in Nigeria was recognised by Weerasinghe and Naqvi (1983). Odeyemi (1981) compared four other substrates, namely *Eupatorium odoratum*, water lettuce, water hyacinth and cow dung as potential substrates for biogas production. *Eupatorium odoratum* gave the highest yield of biogas and cow dung was the poorest substrate. He concluded that *E. odoratum* was a cheap source of biogas in Nigeria because of its luxuriant and ubiquitous growth. These laboratory studies demonstrated the potential of biogas production from agricultural waste, industrial and urban waste and animal waste in Nigeria.

More so, Ahmadu (2009) compared the biogas production from cow dung and chicken droppings while 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.

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.

2.6 SAFETY CONSIDERATION IN HANDLING BIOGAS PLANTS

There are a number of safety issues to be considered when working with a biogas system. Some of these as reported by Anonymous (2012) are as discussed below:

2.6.1 Fire/Explosion

Methane, which is makes up from 0% to 80% of biogas, forms explosive mixtures in air, the lower explosive limit being 5% methane and the upper limit 15% methane. Biogas mixtures containing more than 50 % methane are combustible, while lower percentages may support, or fuel, combustion. With this in mind no naked flames should be used in the

vicinity of a digester and electrical equipment must be of suitable quality, normally "explosion proof". Other sources of sparks are any iron or steel tools or other items, power tools (particularly comutators and brushes), normal electrical switches, mobile phones and static electricity.

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

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

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

2.6.2 Disease

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

2.6.3 Asphyxiation

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

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

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

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

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

2.7 SUITABLE WASTES FOR ANAEROBIC DIGESTION

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

a. Industrial waste and waste water:

b. Sewage sludge:

c. Farm waste

d. Municipal solid waste

e. Green waste

2.7.1 Anaerobic Co-digestion

The anaerobic co-digestion is the simultaneous treatment of more than one substrate in the same digester. According to Mata-Alvarez (2003), the mixing of several wastes types has positive effects on the anaerobic digestion process because it improves the methane yield, improves the process stability and achieves a better handling of the waste. In addition, such a system is economically more favourable as it combines different waste streams in one common treatment facility. To enhance biogas production and assist in municipal organic waste management, anaerobic digestion with the addition of co-substrates, i.e. co-digestion, has been considered an effective, low-cost, and commercially flexible approach to reduce process limitations and improve methane yields (Alatrise-Mondragon et al., 2006). Anaerobic co-digestion process with the addition of low-cost municipal organic wastes could also be given consideration and as such, municipally available organic wastes including fats, oils and grease (FOG) and kitchen waste (KW), could be employed as the potential co-substrates. Cotrell (2008) recorded a 50% increase in biogas generation at a full-scale digester using FOG as a co-substrate. Kabouris et al., (2008) also investigated FOG as a co-substrate and reported significantly higher methane generation. (Li et al., 2002; Gunaseelan, 2004; Carucci et al., 2005; Gómez et al., 2006; Labatut et al., 2010) evaluated food wastes as co-substrates and succeeded in enhancing methane yield production. However, the physical and chemical nature of organic wastes and inocula can vary considerably, and the organic waste loading rate to the anaerobic digesters is critical in pilot or full-scale applications (Gelegenis et al., 2007)

2.8 DEVELOPMENT OF ANAEROBIC DIGESTER

2.8.1 Basic Considerations for Digester Construction

Among other site specific factors, the criteria for the selection of an ideal design should be based on the following considerations:

- It should be simple in terms of construction and operation,
- It should be cost effective and durable so that the general population is able to embrace this technology,
- It should be efficient, i.e., the gas production should be optimum per unit volume of a biogas plant for given type and quantity of input,
- It should be constructed using local materials as much as possible; and
- Repair and maintenance requirement should be minimal.

The biogas plant is also commonly known as a bio-digester, bioreactor or anaerobic reactor (Karki *et al.*, 2005).

2.8.2 Design Theories of Anaerobic Digester Plants

Various models of anaerobic digester plants have been developed. There are three practical models of biogas plant in the context of developing countries (Karki *et al*, 2005). These are Floating Drum Plants, Fixed Dome Plant and Deenbandhu. These and other models developed and tested over the years are briefly discussed below.

***Floating Drum Digester*:** The floating drum biogas plant was designed by Jasu Bhai J. Patel in 1956 which is popularly known as Gobar Gas Plant. The design was later approved

and adopted by the Khadi Village Industries Commission (KVIC) of India In 1962. From thence, the design became the KVIC design. This KVIC design is presented in Figure 2.5.

In the KVIC design, the digester chamber is made of brick masonry in cement mortar. A mild steel drum is placed on top of the digester chamber to store the gas produced. Thus, there are two separate structures for gas production and collection. When methane gas is produced, the gas pressure pushes the mild steel drum upwards and as the gas is being used the drum gradually lowers down. Thus, by observing the level of drum, one can assess the gas volume available. Since the mild steel drum practically 'floats" above the digestion chamber, the KVIC design is also known as the floating drum biogas plant. Apart from the KVIC model where the gas holder floats directly in the fermenting slurry (figure 2.5), the gas holder floats in a separate water jacket in other designs.

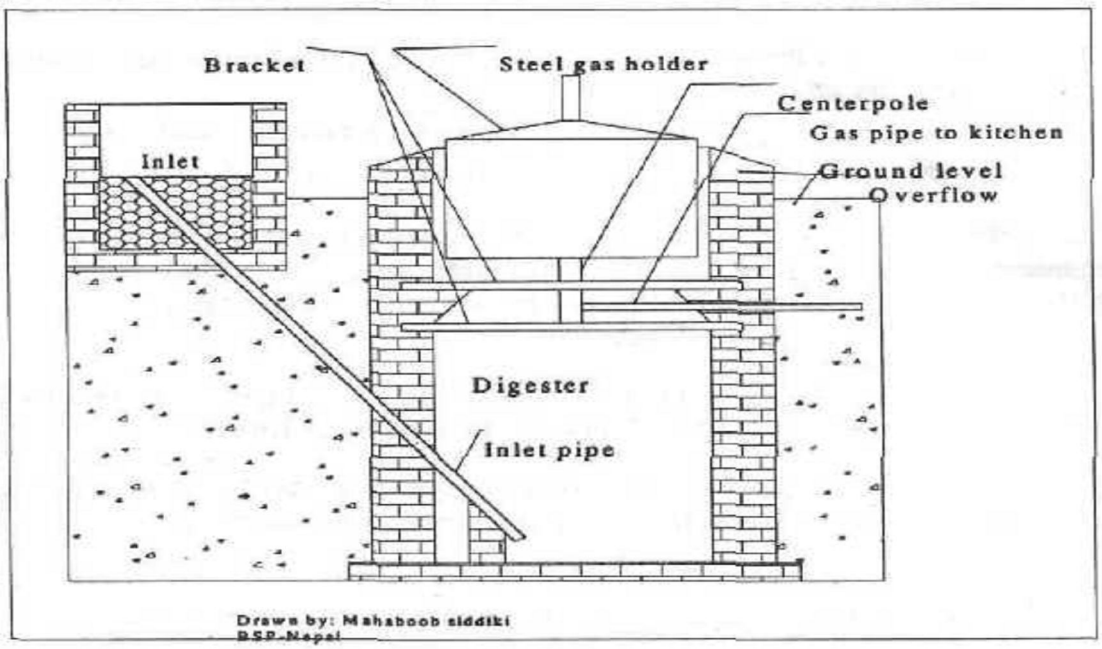


Figure 2.5: KVIC Floating Drum Gas Holder system (Karki *et al*, 2005).

***Fixed Dome Digester*:** Fixed dome Chinese model biogas plant (also called drumless digester) was experimented in China as early as the mid 1930's. This model consists of underground brick masonry (cement mortar) compartment for the digestion chamber with a concrete dome on the top for gas storage. Thus, in this design the digestion chamber and the gas storage dome are combined as one unit. Based on the principles of fixed dome Chinese model, various countries have put forth modified designs to suit their local conditions. For example, Gobar Gas and Agricultural Equipment Development Company (GGC) of Nepal has developed a design commonly known as the GGC model. Compared to the Chinese fixed dome model, the GGC model is easier to construct as this structure has less curved profiles (e.g., digester bottom is horizontal instead of concaved), A typical Chinese model fixed dome biogas plant is presented in Figure 2.6.

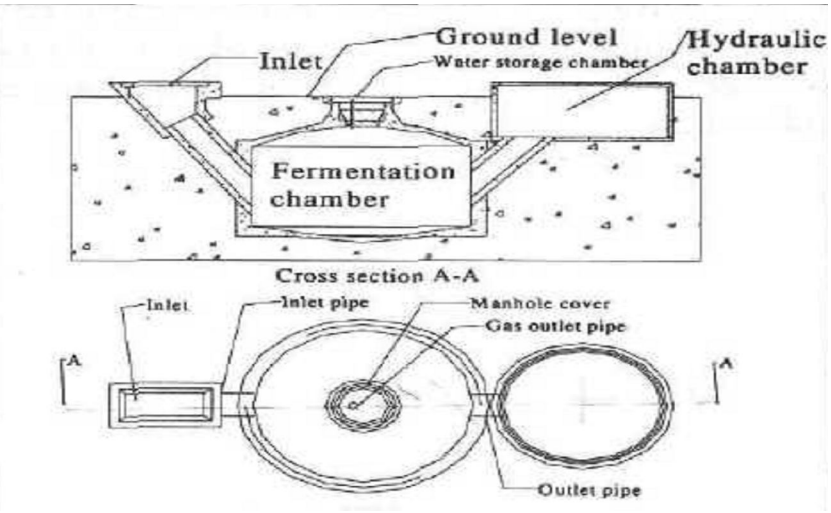


Figure 2.6: Chinese Model Fixed Dome Biogas Plant (Karki *et al*, 2005)

Deenbandhu Model: The Deenbandhu (Hindi translation, "friend of the poor") model was developed in 1984 by the Action for Food Production (AFPRO), New Delhi in an effort to lower the investment cost of the fixed dome plant. Although, the Deenbandhu plant is also

based on the fixed dome model, the dome structure is constructed of brick masonry instead of concrete. A typical design of the Deenbandhu model is presented in Figure 2.7.

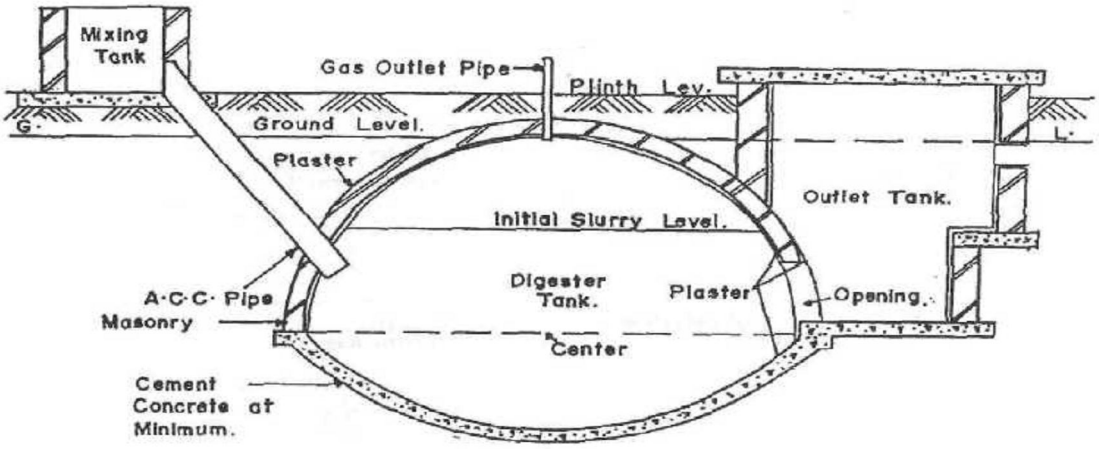


Figure 2.7: Deenbandhu Biogas Plant (3 m^3 Gas Production/Day) (Karki *et al*, 2005)

***PVC Bag Digester*:** This design was developed in Taiwan in 1960s. This type of digester was developed to replace bricks/stone masonry or mild steel (Karki *et al*, 2005). The system consists of a long digestion bag or fermentation bag and a gas reservoir bag. Both are made of two or three layers of polyethylene tubing, 21μc thick and 1m in diameter. The length of the main bag determines the total digestion chamber volume. The digestion bag is half buried in a trench and is connected at one end to a small mixing and collection tank and at the other end to a slurry holding pit. Figure 2.8(a) shows the Plastic bag digester and the connections to the inlets and outlets respectively. The gas reservoir has a capacity of 1.8 m^3 and is usually suspended either in the kitchen or the stable as shown in figure 2.8(b) (http://ease-vn.org.vn).

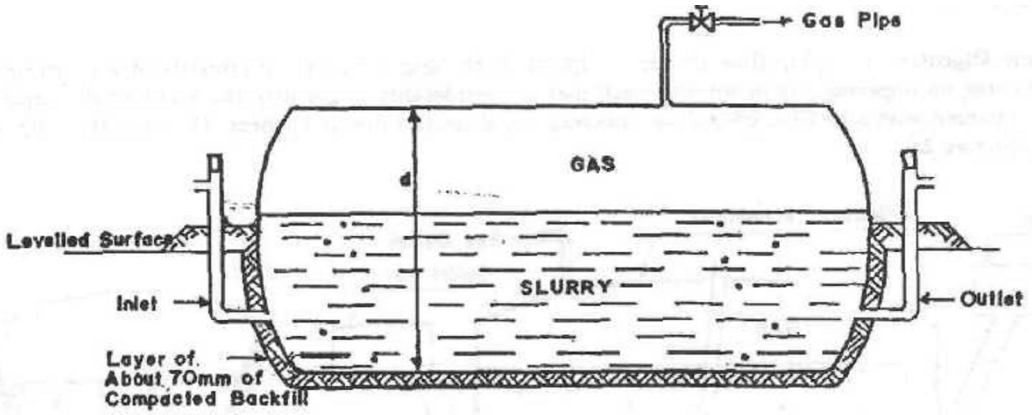


Figure 2.8(a): Taiwanese PVC Bag Digester (Karki *et al*, 2005) (Karki *et al*, 2005)



Figure 2.8(b): Bag Gas Reservoir in Kitchen (http://ease-vn.org.vn)

***Plug Flow Digester*:** The plug flow design is similar to the bag digester. It consists of a concrete lined (or lined using an impermeable member) trench that is considerably larger than the width or the depth. The reactor is covered with a flexible gasholder, concrete or galvanized iron (GI) sheet. Figure 2.9 shows a typical Plug flow digester.

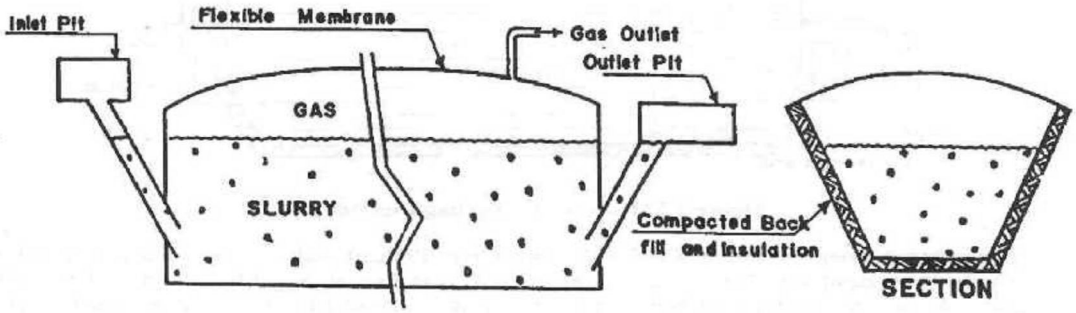


Figure 2.9: Plug Flow Digester (Karki *et al*, 2005)

***Anaerobic Filter*:** The anaerobic filter was developed in 1950's to use relatively dilute and soluble wastewater with low level of suspended solids. It is often used in the treatment process of sewer waste system that is combined with storm drainage in the developed countries. This is one of the earliest and simplest types of design developed to reduce reactor volume. Different types of non-biodegradable materials have been used as the packing media for anaerobic filter reactors such as stones, plastic, coral etc. The methane forming bacteria form a film on the large surface of the media and are not carried out of the digester with the effluent. For this reason these reactors are also known as "fixed film" or "retained film" digesters (Figure 2.10).

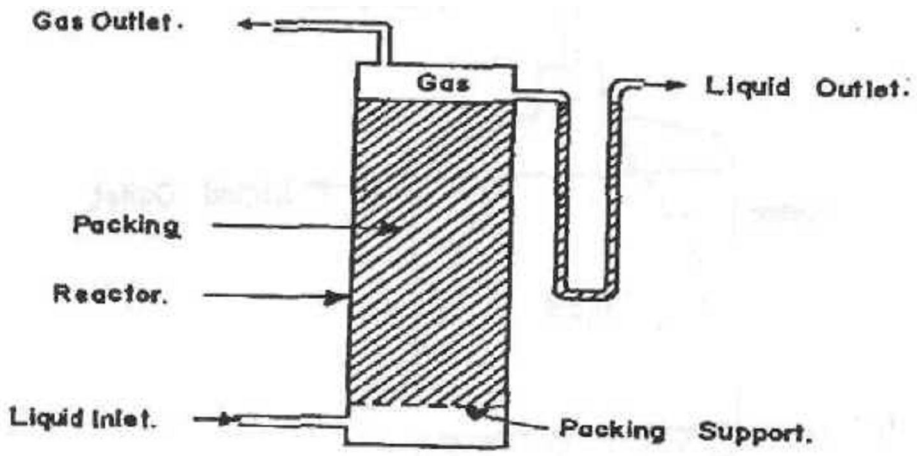


Figure 2.10: Anaerobic Filter (Karki *et al*, 2005)

***Tunnel Type Plant*:** The tunnel design of biogas plant was inspired by the work on plug flow trench reactors done at Cornell University. Its difference is that this plant is totally underground and includes gas storage using displacement principle which means there is movement and mixing of the slurry in and out the reservoir and thus, the plant is not strictly a plug flow reactor (UMN, 1985).

The design of Tunnel Plant is schematically presented in Figure 2.11.

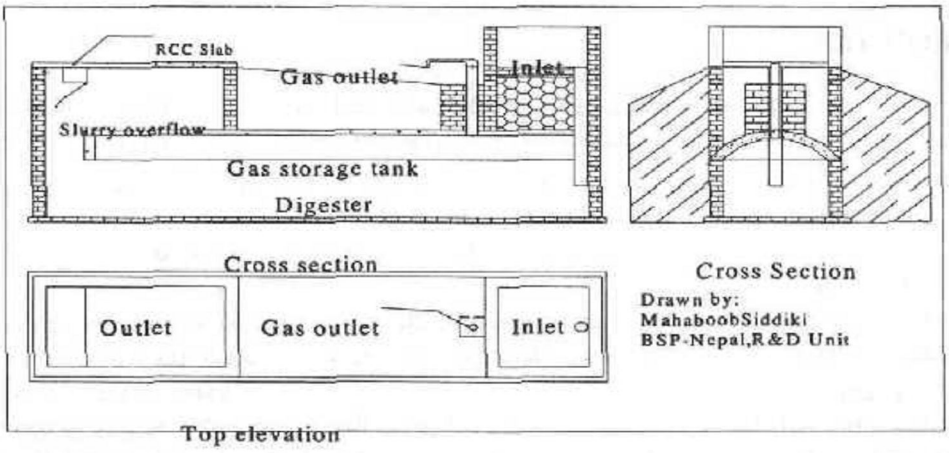


Figure 2.11: Tunnel Type Biogas Plant (Karki *et al*, 2005)

Upflow Anaerobic Sludge Blanket (USAB): The USAB design was developed in the 1980s in The Netherlands. It is similar to the anaerobic filler in that it involves a high concentration of immobilized bacteria in the reactor. However, the USAB reactors contain no packing medium; instead, the methane forming bacteria are concentrated in the dense granules of sludge blanket which covers the-lower part of the reactor. The inflow is fed from the bottom of the reactor and biogas is produced while the liquid flows up through the sludge blanket. These types of reactors are often used in Europe to treat sewer and industrial waste that are dilute. A sketch of the USAB design is presented in Figure 2.12.

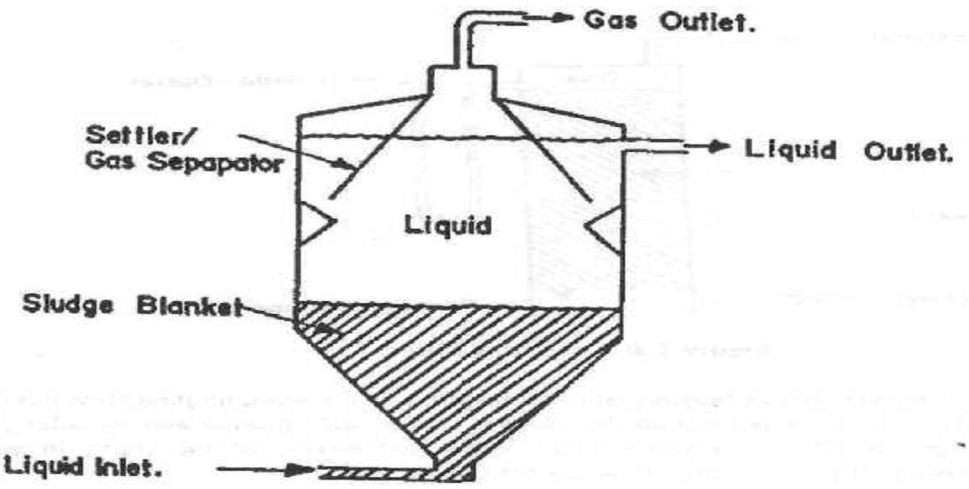


Figure 2.12: Upflow Anaerobic Sludge Blanket (USAB) (Karki *et al*, 2005)

***Kitchen waste Biogas Model*:** A 200-liter experimental model biogas plant based on fixed dome principles but fabricated from mild steel shell has been designed by Ajoy Karki for use at his residence in Lalitpur, Nepal. This plant has successfully demonstrated that biogas can also be generated at household level using kitchen wastes as feed materials. Gas storage space is provided at the upper dome, which is fixed and the input is fed from the inlet as shown in Figure 2.13.

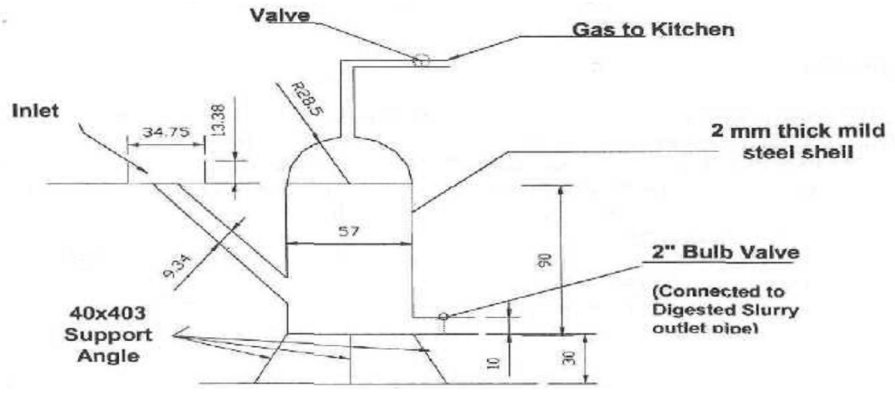


Figure 2.13: Karki's Kitchen Waste Biogas Model (Karki *et al*, 2005)

The VACVINA biogas model: The first VACVINA biogas units were built in May 1998 in Vietnam as a combination of principles of Fixed Dome and Plastic Bag digesters as well as the application of septic tank technology. It consists of a flat-top rectangular underground digestion chamber with external plastic gas reservoirs. An ingenious system of inlet siphon allows the new material to be dropped unto the surface of the fermenting liquid thus breaking any accumulated scum. Figure 2.14 shows a schema of the VACVINA biogas model (http://ease-vn.org.vn).

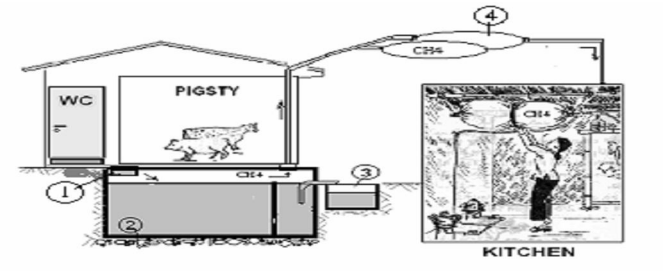


Figure 2.14: VACVINA Biogas Model (http://ease-vn.org.vn).

2.8.3 Site Selection

In order to ensure the sustainability of a biogas installation, a careful selection of the best site for the plant must be made. The factors that should be considered in making the decision are:

- Distance between the proposed site and the location where gas will be consumed (i.e. Kitchen) should be as close as possible since gas pipes are expensive;
- Distance between the site and the supply of input materials (i.e., cow shed) should also be as close as possible to save input carrying efforts;

- Distance between the site and the location where the effluent can be stored (e.g., compost pits) should be as close as possible. Close distance helps to ensure that the effluent can flow into the storage pit without much handling;

- Distance between the site and sources of water such as wells should be far enough to prevent contamination (say 10 to 15 m). However, it should be noted that if the water source is too far, it will take more time and effort to prepare the slurry since for given volume of dung an equal volume of water should be added;

- Distance between the sites and trees/bamboos should be far enough to prevent damage to the structures from the roots of the plants;

- Ground water depth should be investigated. Construction will be relatively easy at locations where the ground water table is low.

- The ultimate bearing pressure of the foundation should be adequate to support the load of the biogas plant and the slurry inside.

- The direction of the prevailing wind should be considered so that the smell from the biogas plant will not be a nuisance to residential areas.

At any particular site it may not be possible to fulfill all of the above criteria. However, efforts should be made to meet as many of the above listed criteria as possible such that the cost is lowered and the plant operation becomes less cumbersome (Karki *et al*, 2005).

CHAPTER THREE

MATERIALS AND METHODS

3.1 MATERIALS

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

i. pH meter model pHS-2S, (SHANGHAI JINYKE REX, CHINA) was used to measure the pH of slurry every week day throughout the retention period.

ii. Gallenhamph Weight balance, Mettler P160N was used for measuring the weight of evaporating dish and sample for Total Solid analysis.

iii. Gallenhamph Water bath was used to evaporate the sample for total solid analysis to dryness.

iv. Thermometers: (2/1 ^{0}C made in England) : was used to obtain daily temperature of the digester as well as the ambient temperatures for Samaru, Zaria.

v. A 25-liter Plastic bucket: Was used for measuring equal volume of waste to water to form slurry.

vi. Shovels: was used to ensure proper mixing and packing of dung from site and at the plant.

vii. Waterproof sacks: was used to convey dung to site

viii. Funnel: was used to feed the slurry into the reactor so as to minimize spillage of slurry.

ix. A portion of land was acquired within the ground of the Department of Water Resources and Environmental Engineering ($N11^0$ 09.043', $E007^0$ 38.904') on which the set up was installed (Plate I). The direction of the prevailing wind was taken into consideration in the choice of the site.

3.2 DESIGN OF PILOT SCALE ANAEROBIC DIGESTERS

The design theory adopted for this study combines the 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.

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.

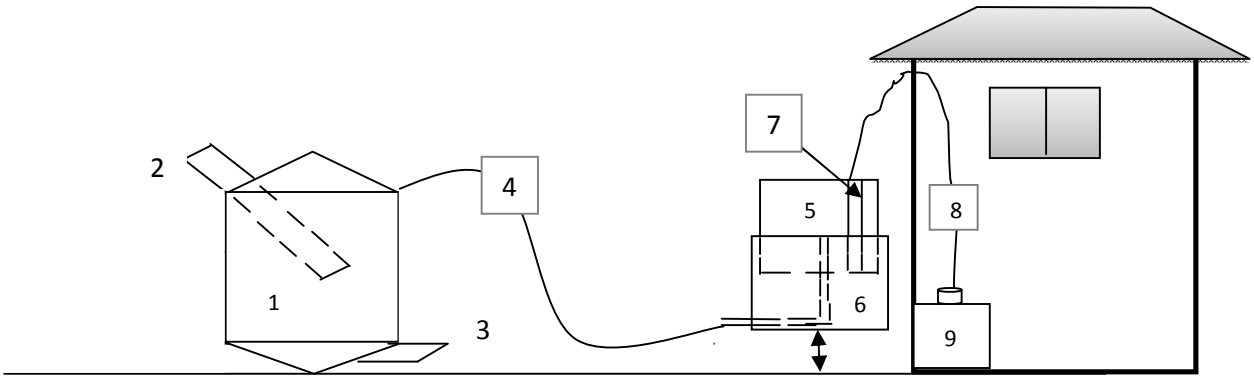


Figure 3.1: Schematic View of the Plant set up

1. Digester Body 2. Feedstock Inlet pipe 3. Effluent Outlet pipe
4. Hose from digester to gas holder 5. Gas holder 6. Water Jacket 7. Rule
8. Hose to Cooking Stove 9. Cooking Stove in the kitchen

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 makes the best use possible of the restricted compound space.

iv. As low cost as possible without sacrificing life expectancy

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, http://ease-vn.org.vn)

3.2.1 Design Considerations

Digester Design:

i. Operating Volume:

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

The operating volume of the digester (V_o) is determined on the basis of the chosen retention time (RT) and the daily substrate input quantity (S_d), and is given as (Ahmadu, 2009):

$$V_o = S_d \times RT \ [m^3 = m^3/day \times number\ of\ days] \quad (3.1)$$

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

Substrate input (S_d) = Biomass (B) + Water (W) (m^3/day) (3.2)

In most agricultural plants, mixing ratio of dung to water varies from between 1:1 to 2:1.

ii. Total Volume:

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

$$V_T = V_o / 0.8 \quad (3.3)$$

iii. Digester dimensions:

Having determined the total volume of the digester, a ratio for the dimensions can be adopted, depending on the chosen geometric shape of the digester. For a cylindrical digester, the chosen geometry for this work,

$$V_T = \pi r^2_d h_d \quad (3.4)$$

where V_T = Total volume of digester

r_d = radius of digester

h_d = height of digester

iv. Digester Temperature:

The digester is designed to operate within the mesophilic temperature range (20-40^{o}C). This can be achieved by natural heating from the sun. An absorptive surface is required for the digester; this is to absorb solar radiation during the day time. An insulating material is required for the digester at night, this is to retain the heat within the digester and keep temperature fluctuations within manageable limits.

Gas Holder System Design:

i. Gas holder volume (V_g):

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

- Cover the peak consumption rate (gc_{max}) for the period of maximum consumption (tc_{max}), $V_g = V_{g1}$ (3.5)

- Hold the gas produced during the longest Zero consumption period

(tz), $V_g = V_{g2}$ (3.6)

From equation (3.5)

$$Vg_1 = gc_{max} \text{ X } tc_{max} \quad (3.7)$$

From equation (3.6)

$$V_{g2} = G_h \text{ x } tz_{max} \quad (3.8)$$

Where,

gc_{max} = maximum hourly gas consumption (m^3/hr)

tc_{max} = time of maximum consumption (hr)

G_h = hourly gas production (m^3/hr) = G ÷ 24hrs/day

G = daily gas production (m^3/day)

t_Z = maximum zero consumption time (hrs)

The larger value, (V_{g1} or V_{g2}) determines the size of the gas holder. A safety margin of 10-20% is then added (Ahmadu, 2009).

ii. Gas holder dimensions:

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

$$V_g = \pi r^2_g h_g \quad (3.9)$$

Where,

V_g = volume of gas holder `

r_g = radius of gas holder

h_g = height of gas holder (Ahmadu, 2009)

iii. Water jacket design:

The water jacket holds the water in which the gas holder floats. It should be of the same geometrical shape as the gas holder. The radius should be a little larger than that of the gas holder to give clearance for sliding of the gas holder (Ahmadu, 2009).

$$R_j = r_g + c \tag{3.10}$$

Where, r_j = radius of water jacket

r_g = radius of gas holder

c = clearance

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

$$h_j = h_g \tag{3.11}$$

Where,

h_j = height of water jacket

h_g = height of gas holder

Volume of water jacket (V_j) is given by (Ahmadu, 2009):

$$V_j = \pi\ r_j^2\ h_j \tag{3.12}$$

r_j = radius of water jacket

h_j = height of water jacket

Guide Frame Design:

The guide frame is to guide the gas holder in its upward displacement and prevent it from tilting. It's also to provide a maximum displacement position for the gas holder. It consists of two rods mounted on opposite sides of the gas holder, sliding through corresponding slides ways on the water jacket.

Length of the rods should be a little less than height of gas holder to give allowance for welding onto the gas holder. Any convenient length can be taken for this allowance, let this be denoted c, thus

Length of guide frame (L_f)

$$L_f = h_g - c \tag{3.13}$$

Where h_g = height of gas holder.

C =allowance

On the guide frame is a maximum displacement point at a distance

$$L_f - d_{max} \tag{3.34}$$

Where d_{max} is a distance taken from the bottom tip of the frame, with a hole drilled at this point and a pin inserted. With this, at maximum displacement of the gas holder, a portion of it is still submerged in the water seal, thereby providing rigidity and safety.

The guide frame merely guides the gas holder in its upward displacement, thus it's not under the action of any load or force. Therefore, any convenient safe diameter can be adopted (Ahmadu, 2009).

Force on Gas Holder (Fg):

The force on the gas holder is given as:

$$F_g = P_g \times A_g \quad - \quad - \quad - \quad - \quad - \quad - \quad (3.15)$$

P_g = Pressure in gas holder

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

Gas Pipe Diameter:

The gas pipe diameter is selected based on the flow rate of biogas through the pipe and the distance between the digester and gas holder. (i.e. length of pipe required). The values can be checked from standard tables to determine the required pipe diameter (Ahmadu, 2009).

3.2.2 Construction of Biogas Digestion plant.

Biogas plants were constructed to digest the five substrates for the study which were similar in design and would be operated simultaneously to ensure fair basis for comparison of results.

3.2.3 Material Selection

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

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.

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:

- Relatively cheap.
- Provides reflective surface thereby minimizing heat build up inside the gas holder and within the water seal.
- Good tensile strength and easy to roll by machine to required design geometry.
- Provides gas tightness to store biogas

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.

3.2.4 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. Details of the materials, equipment and fabrication processes for the construction of anaerobic digester and gas collection system are shown in appendix I (e).

3.3 PROCESS DESCRIPTION FOR ANAEROBIC DIGESTION OF COW DUNG, CHICKEN DROPPINGS AND *CYMBOPOGON CITRATUS*

3.3.1 Method of Biomass Collection, Slurry Preparation and Digester Loading

The design volume of the identical anaerobic digesters was sized according to the amount of volatile solids that must be treated daily and the period of time the material will remain in each of the digesters (Retention time). The primary structure consists of a Mild steel digestion tank which is strong enough to withstand the weight and pressures of the contained slurry, and painted to prevent corrosion. The tank is air tight and is clearly placed above the ground level and outside the shed where it is exposed to the sunlight for partial heating. A gas holder tank made from thin sheet metal was also designed and fabricated (See appendices VI) and used to temporarily store the biogas until it was used to produce heat or used to replace or supplement the supply of cooking gas.

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

i. Cow dung from Zango Abattoir;

ii. Chicken droppings from NAPRI

iii. *Cymbopogon citratus* (Lemon grass) from gardens within Area BZ staff Quarters, Ahmadu Bello University main campus, Zaria;

iv. Cow dung with *Cymbopogon citratus* (Lemon grass) and

v. Chicken droppings with *Cymbopogon citratus* (Lemon grass)

Cow dung, chicken droppings and *Cymbopogon citratus* (Lemon grass) were the biomass resources used as feed materials for this work. Cow dung was obtained (fresh and free from impurities) from Zango abattoir while the chicken droppings were gotten (fresh and free from impurities such as wood filings) from the poultry department (Deep Litter section) of the National Animal Production Research Institute, Shika-Zaria. They were both transported to the research site. The lemon grass (*Cymbopogon citratus*) on the other hand was gotten from gardens around some houses within Area BZ staff quarters, Ahmadu Bello University Zaria using kitchen knife stuffed into sack and transported to the mechanical workshop of Agricultural Engineering Department for crushing with the Hammer mill before they were transported to the research field for further pre-treatment.

Partly decomposed slaughter house waste was used as seed material all the substrates digested in this study. The cow dung and chicken droppings were each pre-fermented for a

period of 15 days in a plastic drum while the lemon grass (*Cymbopogon citratus*) was pre-fermented for 40 days before being fed into the digester (Karki *et al.*, 2005).

6kg of the respective pre-fermented wastes mixed with water to form slurry in the ratio 1:1 by volume were separately introduced into each tank through an inlet pipe of 50mm at the top of the digester tank. In the case of the synergies of the cow dung and chicken droppings respectively with lemon grass, each co-substrate contributed 50% (3kg) each to make the 6kg of biomass which was then mixed with water to form slurry in the ratio 1:1. The slurry is 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 were 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 10mm 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.

3.4 EVALUATION OF THE TECHNICAL PERFORMANCE OF THE ANAEROBIC DIGESTION OF THE SUBSTRATES.

The evaluation of the technical performance of the anaerobic digestion process was carried out with respect to the gas production and the treatment efficiency of each of the digester systems. The reactors were monitored for the 30- day retention time in the following areas.

i. Measurement of gas production,

ii. Analysis of feedstock and effluent to evaluate the treatment efficiency of each digestion process.

3.4.1 Measurement of Gas Production for the Five Substrates Digested

The gas holder was calibrated with the aid of a rule (Figure 3.1) to enable the reading of the daily gas production of the five substrates in the anaerobic digesters.

Produced biogas measurement was done each day shortly before sunset. The biogas produced was taken as the total gas content of the gas holder.

The produced biogas was measured by computing the volume of the gas holder floating over water level in the water jacket on a daily basis. The gas holder is an inverted cylinder with a base diameter of 0.25m.

The base area, $A = \prod d^2/4 = \prod \times 0.25^2 \div 4 = 0.0491 m^2$

The height of cylinder above water level was read off on the rule attached to the gas holder for calibration.

Let this height (h) $= x$, which varies.

Volume of biogas at atmospheric pressure is obtained as the volume of cylinder above water level, given by

Volume, $V = \prod d^2 h/4 = Ah$ where $h = x$

Substituting for A from above,

$\therefore V = 0.0491\, x\, m^3$

where V=volume of biogas

x = height of cylinder above water level.

In the evening, when the cooking test were concluded (about 7pm), the gas holders were completely emptied. The values given by the rules were written down in order to obtain the daily production by subtracting this value by the one of the day before.

3.4.2 Measurement of Physico-Chemical and Bacteriological Parameters of Feedstock and Residue

In order to evaluate the treatment efficiency of the anaerobic digestion process on the respective substrates, the following parameters were measured.

i. Total Solids: this was measured in order to estimate all the organic and inorganic solid matter thereby characterizing the feedstock and the effluent and describe the waste reduction. The measurement of the total solids was carried out according to the standard method for the examination of water and wastewater previously described in APHA (1995) and Estoppy (2010).

ii. Bacteriological Analysis: The concentration of the pathogens in the feedstock and effluent was measured to determine if the pathogens removal is sufficient to use the effluent for irrigation. Total coliform count was carried out on the samples taken

from both the feedstock and residues from the four reactors containing animal waste using the plate count method. The samples were also analyzed for presence of Salmonella, Escherichia coli, Shigella and Klebsiella. All the analysis was carried out according to previously described standard methods (Bopp *et al.,* 2005; Gomis *et al.,* 2001; Mindy *et al.,* 2003; www.umanitoba.ca).

The pH and temperature of the feedstock and effluent were also taking and recorded.

3.5 DAILY MONITORING OF OPERATIONAL PARAMETERS

In order to study and determine the most feasible local environmental conditions to optimally operate the developed biogas facilities, various physical and chemical parameters were monitored to check the status of the digester. Monitoring of the plant was carried out every day between 0800 and 1800 hours. Readings were taken to record digester and ambient temperatures and pH. Discussed below are the physic-chemical parameters monitored, reasons why and the instruments used for the monitoring.

3.5.1 Temperature

This gives the kinetic energy of atoms or molecules. It was measured to determine the feedstock influence on the temperature and consequently, the metabolism of the bacteria. 2/1 ^{0}C Thermometers (made in England) were used to measure the temperature of the digester and that of Samaru. The digester temperatures were taken three times daily, i. e.

0900hrs, 1300hrs and 1800hrs respectively while the ambient Samaru temperature was recorded at 1300hrs daily.

3.5.2 pH

This gives the intensity of acidic or basic character at a given temperature. It was measured to determine the feedstock influence on the acidity/alkalinity and consequently, the metabolism of the bacteria. Samples were analysed at ambient temperature with a pH meter model pHS-2S, (SHANGHAI JINYKE REX, CHINA). The meter was calibrated every day. Analysis was carried out immediately after sampling to avoid loss of carbon dioxide from the sample. The pH analysis was carried out on every working day throughout the period of study.

3.6 UPGRADING OF BIOGAS PRODUCED

The biogases produced were in turn passed through water and slaked lime to remove hydrogen sulphide and carbon dioxide respectively. The volume of gas produced in each case was noted for each of the substrates digested. A comparison of these volumes was also used to estimate the methane content of each of the gases produced

3.7 Domestic Cooking with Produced Gas

The performance evaluation of the gases produced from the five substrates digested was carried out by boiling water and rice. A biogas stove burner designed in the Department of Water Resources and Environmental Engineering (Igboro *et al*., 2011) was used to boil water and rice in turn before and after scrubbing the gas for removal of carbon dioxide. The time taken for the various tasks was determined from a stop watch. Boiled water was determined by observing bubbling and steam rising from the boiling water while the rice was cooked and ready to be eaten. 0.1 litre of water and 0.18kg (1 cup) of rice were respectively used in the evaluation.

The cooking rate (Cr) and the biogas consumption rate (Q) were determined. These tests were confirmatory to the first evaluation of the stove burner on fabrication.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

Pilot scale anaerobic digesters were designed and fabricated for the digestion of the five substrates in this study. The details of the design and fabrication are presented in tables in this chapter. More so, the experimental results obtained during the monitoring period in the study were analyzed using statistical methods. They are presented in tables, graphs, pie charts, and histogram and discussed as follows.

4.2 DESIGN OF PILOT SCALE ANAEROBIC DIGESTER

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, $d_d = 0.25m = 25cm$ (See appendix Ia)	Total gas holder volume, $V_g = 1.21 \times 10^{-3} m^3$ Gas holder height, $h_g = 0.25m = 25cm$ Digester diameter, $d_g = 0.25m = 25cm$ (See appendix Ib)	Length of pip = 1m Diameter of pipe = 0.0127m (1/2 inch) (See appendix Ic)	Water jacket height, $hj = 0.25m = 25cm$ Water jacket diameter, $dj = 0.27m = 27cm$ (See appendix Id)

4.3 TECHNICAL PERFORMANCE AND QUALITY OF RESIDUE

4.3.1 Measurement of gas production for the Five Substrates Digested

Fig 4.1 and 4.2 respective show the daily and cumulative gas production from the five substrates digested in this study.

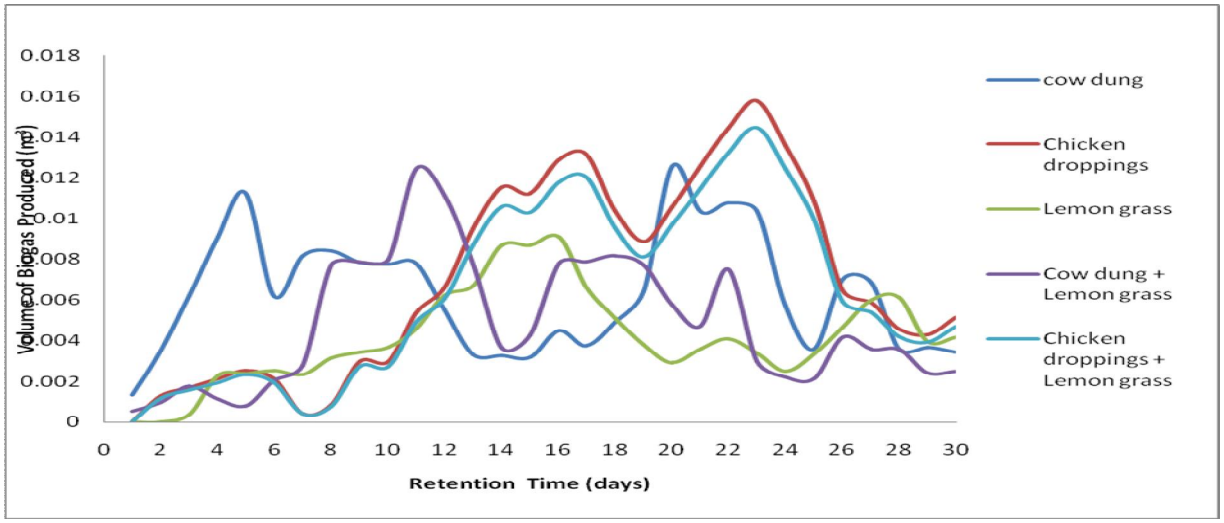


Fig 4.1: Daily gas production for the five substrates Digested.

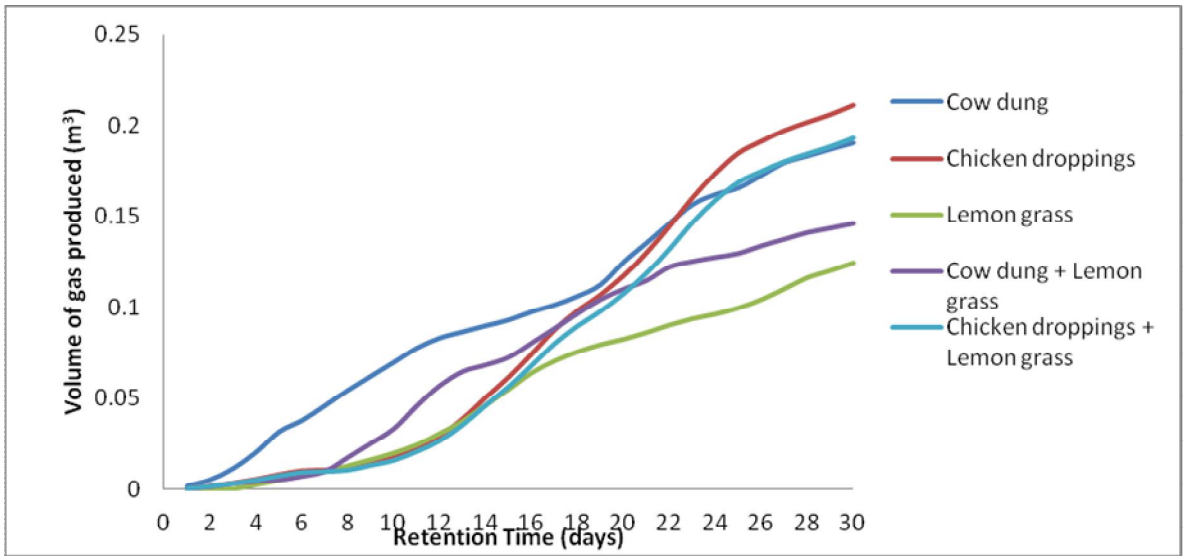


Fig 4.2: Cumulative gas production for the five substrates Digested.

The peaks in Figure 4.1 signify the fluctuation in the quantity of gas produced from each substrate possibly due to variation in environmental conditions. Figure 4.1 shows that gas production in cow dung, and its co-digestion with lemon grass started on the first day, those of the chicken droppings and its co-digestion with lemon grass began on the second day while that of lemon grass was recorded on the third day of set up. These fast rates of production relative to previous studies (Ojolo *et al,* 2007, Ahmadu, 2009) could be attributed to the extended pre-fermentation periods. Chicken droppings had the highest average daily gas production of 0.00703m^3/day (0.00434m^3/day after scrubbing), cow dung and lemon grass respectively produced 0.00635m^3 (0.00417m^3 after scrubbing) and 0.00416m^3 (0.00299m^3 after scrubbing) of biogas daily. The respective co-digestion of cow dung and chicken droppings recorded average daily gas production of 0.00487m^3 (0.00334m^3 after scrubbing) and 0.00644m^3 (0.00425m^3 after scrubbing) respectively. Figure 4.2 shows that the Chicken droppings only produced more biogas than the cow dung, lemon grass and their respective co digestions. A total of 0.211m^3 (0.035m^3/kg,

0.375 m^3/m^3 of slurry day) of biogas was produced from the chicken droppings, while cow dung and lemon grass produced 0.191m^3 (0.032 m^3/kg, 0.340 m^3/m^3 of slurry day), 0.125 m^3 (0.021 m^3/kg, 0.222 m^3/m^3 of slurry day) respectively. The co digestion of Lemon grass with cow dung and chicken droppings respectively produced 0.146m^3 (0.024 m^3/kg, 0.260 m^3/m^3 of slurry day) and 0.193m^3 (0.032 m^3/kg, 0.343 m^3/m^3 of slurry day) of biogas before the gases were scrubbed.

This could be attributed to the nature of organics present in the substrates which also, is a function of the feeds the animals were exposed to (in the case of the animal wastes) and the slow rate of decomposition of the lemon grass. The poultry feeds used in NAPRI are very rich in organics and are carefully administered to them to prevent any possible contamination. The cow dung from abattoir on the other hand contains food from the large and small intestine of the cow mixed with blood, small bit of meat and other organics; hence it contains more organic wastes which accounts for the higher methane content relative to the chicken droppings. After scrubbing for removal of carbon dioxide, the volume of gas from cow dung, chicken droppings and lemon grass were 0.125m^3 (0.021m^3/kg, 0.222m^3/m^3 of slurry day), 0.130m^3 (0.022 m^3/kg, 0.231m^3/m^3 of slurry day), 0.090 m^3 (0.015 m^3/kg, 0.160m^3/m^3 of slurry day) respectively while the co digestion of Lemon grass with cow dung and chicken droppings respectively produced 0.100m^3 (0.017m^3/kg, 0.178m^3/m^3 of slurry day) and 0.127m^3 (0.0.021m^3/kg, 0.226m^3/m^3 of slurry day) of biogas. Figure 4.1 also reveals that the maximum daily production of 0.016m^3 was recorded for chicken droppings on the 23rd day of set up while the peak values for cow dung, lemon grass, cow dung + lemon grass and chicken droppings + lemon grass were 0.013m^3 (day20), 0.009 m^3 (day 16), 0.012 m^3 (day 11) and 0.014m^3 (day 23) respectively.

These could be attributed to the nature of the feed materials as the prevailing condition of the environment.

The higher and faster biogas generation in reactor A (Cow Dung only) and B (Chicken droppings only) could be attributed to the faster rate of decomposition of animal intestinal wastes which have already undergone a form of digestion in the digestive system of the cows and the chickens respectively. Therefore, the action of bacteria on this category of waste is fast relative to the lemon grass that was undergoing the first form of decomposition since it has not undergone one prior to digestion. The relative biogas yield from the substrates could be attributed also to the organic matter content of the wastes which confirms the submissions of earlier studies carried out on cow dung and poultry droppings (Ojolo et al., 2007 and Ahmadu et al., 2009, Igboro, 2011). However, it must be borne in mind that the digestive system of the animal will influence the amount of organic matter in its faeces (Ahmadu et al., 2009). The higher biogas production from poultry droppings could also be attributed to the available nutrient in the droppings. This is substantiated by Ojolo et al. (2007) that substrates should contain adequate amount of carbon, oxygen, hydrogen, nitrogen, sulfur, phosphorous, potassium, calcium, magnesium and a number of trace elements.

The drops in levels of gas production and subsequent peak could be associated to microbial succession in the reactors.

4.3.2 Measurement of Physico-Chemical and Bacteriological Parameters of Feedstock and Residue

a. Total Solid Content of Feedstock and Residue:

The total solid content of the feedstock and residue were determined following the standard method for the examination of water and wastewater previously described in APHA (1995) and Estoppy (2010).

Figure 4.3 shows a comparison of the total solids for both the feedstock and effluent for the five substrates digested in this study.

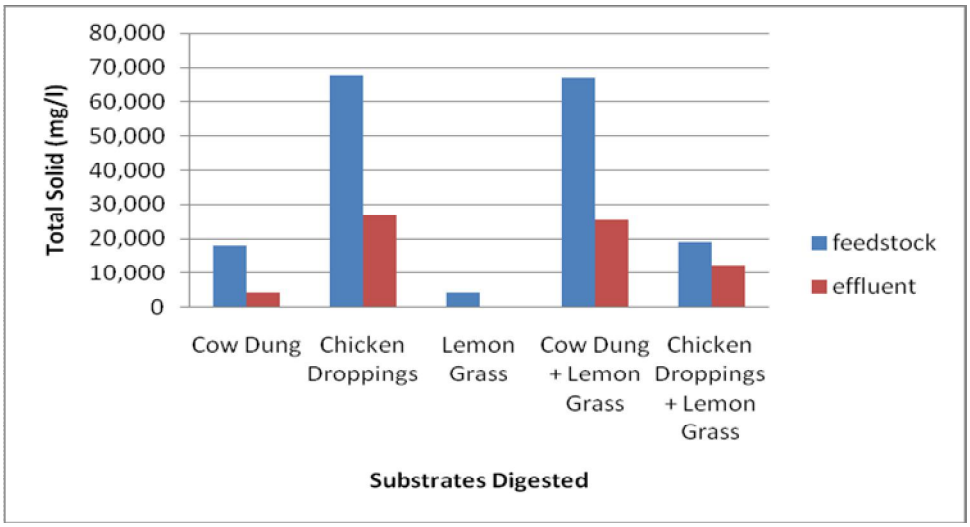


Figure 4.3: Comparison of Total Solids of Feedstock and Residue of Five Substrates

The calculation of the total solids contents of the feedstock and the effluent confirms the conversion performance of the digester (treatment efficiency). There was a reduction in total solid content of 75.3 %, 60.1%, 98.2%, 61.9% and 35% for cow dung, chicken droppings, lemon grass, cow dung + lemon grass and chicken droppings + lemon grass respectively. The long period of pre-fermentation of the lemon grass (40 days) possibly explains the high percentage reduction of the total solid content of the lemon grass.

a. Pathogen Content of Feedstock and Residue:

Table 4.2 gives the total Coliforms counted in the feedstock and the residue of the five substrates digested.

Table 4.2: Total Coliforms counted in Feedstock and Residue

Sample	Total Coliforms (CFU/100ml)				
	Cow Dung	**Chicken Droppings**	**Cow Dung + Lemon Grass**	**Chicken Droppings + Lemon Grass**	**Standard WHO (2004)**
Feedstock	4.0×10^8	2.00×10^8	2.00×10^8	7.00×10^8	10^5 or 10^6 when exposure is limited
Residue	2.00×10^7	6.00×10^7	1.00×10^7	1.00×10^7	
% Reduction	95	70	95	99	

Furthermore, Table 4.2 shows that the reduction in total coliforms for Cow Dung and its co-digestion with Lemon grass were 95% each while chicken droppings and its co-digestion with lemon grass respective had 70% and 99% reduction in total coliforms. Notwithstanding these high percentage reductions, the total coliform contents of 2.00×10^7 CFU/100ml, 6.00×10^7 CFU/100ml, 1.00×10^7 CFU/100ml and 1.00×10^7 CFU/100ml for cow dung, chicken droppings, cow dung + *Cymbopogon citratus,* and chicken droppings + *Cymbopogon citratus* residues were still above the tolerable limits for irrigation for unrestricted crops (crops that are consumed raw). Thus, care should be taken when handling animal dung substrates either in the digestion process or in the application as fertilizer to avoid the risk of infection.

Table 4.3 shows the results of the biochemical tests carried out on the isolates from both the feedstock and the residue.

Table 4.3: Results of Biochemical Characterization of Isolates from Feedstock and Residue

Source	Substrate	BIOCHEMICAL TEST						Organism
		Indole	MR	VP	Citrate	H_2S	Motility	
Feedstock	Cow dung	+	+	-	-	-	-	*E. coli*
		-	+	-	-	-	-	*Shigella spp*
		-	+	-	+	+	+	*Salmonella spp*
		-	-	+	+	-	-	*Klebsiella spp*
	Chicken droppings	+	+	-	-	-	-	*E. coli*
		-	+	-	-	-	-	*Shigella spp*
		-	+	-	+	+	+	*Salmonella spp*
		-	-	+	+	-	-	*Klebsiella spp*
	Cow dung + Lemon grass	+	+	-	-	-	-	*E. coli*
		-	+	-	-	-	-	*Shigella spp*
		-	+	-	+	+	+	*Salmonella spp*
		-	-	+	+	-	-	*Klebsiella spp*
	Chicken droppings + Lemon grass	+	+	-	-	-	-	*E. coli*
		-	+	-	-	-	-	*Shigella spp*
		-	+	-	+	+	+	*Salmonella spp*
		-	-	+	+	-	-	*Klebsiella spp*
Residue	Cow dung	-	+	-	+	+	+	*Salmonella spp*
		-	-	+	+	-	-	*Klebsiella spp*
	Chicken droppings	-	+	-	+	+	+	*Salmonella spp*
		-	-	+	+	-	-	*Klebsiella spp*
	Cow dung + Lemon grass	-	+	-	+	+	+	*Salmonella spp*
		-	-	+	+	-	-	*Klebsiella spp*
	Chicken droppings + Lemon grass	-	+	-	+	+	+	*Salmonella spp*
		-	-	+	+	-	-	*Klebsiella spp*

Key: MR= Methyl Red; VP=Voges Prospkeur; H_2S= Hydrogen Sulfide.

The results reveal that *Salmonella spp*, *Klebsiella sp*., *E. coli* and *Shigella spp*. were present in the feedstock but only *Salmonella spp* and *Klebsiella spp* were found in the residue. Although the numerical estimate of these organisms were not done, their presence in the residue in addition to the values of the total coliforms suggest that the digestate may not be safe for direct application as fertilizer for crops that are eaten raw thus further treatment is advised. This is not to discourage the use of digestate for improvement of soil fertility but that care should be taken to avoid disease transmission. Nevertheless, the reduction in total coliforms and the removal of *E.coli* and *Shigella,* suggest that the anaerobic digestion process could remove pathogens of feacal origin if properly designed and utilized although this study could not establish if an increase in retention time could further reduce the pathogens to tolerable limit.

4.4 DAILY MONITORING OF OPERATIONAL PARAMETERS

In order to determine the most feasible local environmental conditions to optimally operate the developed biogas facilities the pH and the temperatures were adequately monitored as operational parameters. The following results were obtained.

4.4.1 Digester and Samaru Temperature during Biogas Production

Table 4.4 shows the average digester temperatures for the five substrates observed at a point of observation within the digesters, and the ambient temperatures for Samaru during the period of these experiments.

Table 4.4: Average Daily Digester and Ambient Temperatures for Five Substrates

Average Temperature	**Reactor A Cow Dung**	**Reactor B Chicken Droppings**	**Reactor C Lemon Grass**	**Reactor D Cow Dung + Lemon Grass**	**Reactor E Chicken Droppings + Lemon Grass**
Digester(^{o}C)	32.4	32.7	32.9	32.9	32.2
Ambient (^{o}C)	37				

The average ambient temperature observed during the study was 37^{0}C while the average digester temperatures for each of the five substrates digested were respectively 32.4^{0}C, 32.7^{0}C. 32.9^{0}C, 32.9^{0}C and 32.2^{0}C. These values show that there is negligible difference in the average digester temperatures for the five reactors which provides a common base for comparison of results. In addition, Figure 4.4 shows the fluctuations of temperature within the respective digesters throughout the retention period of 30 days.

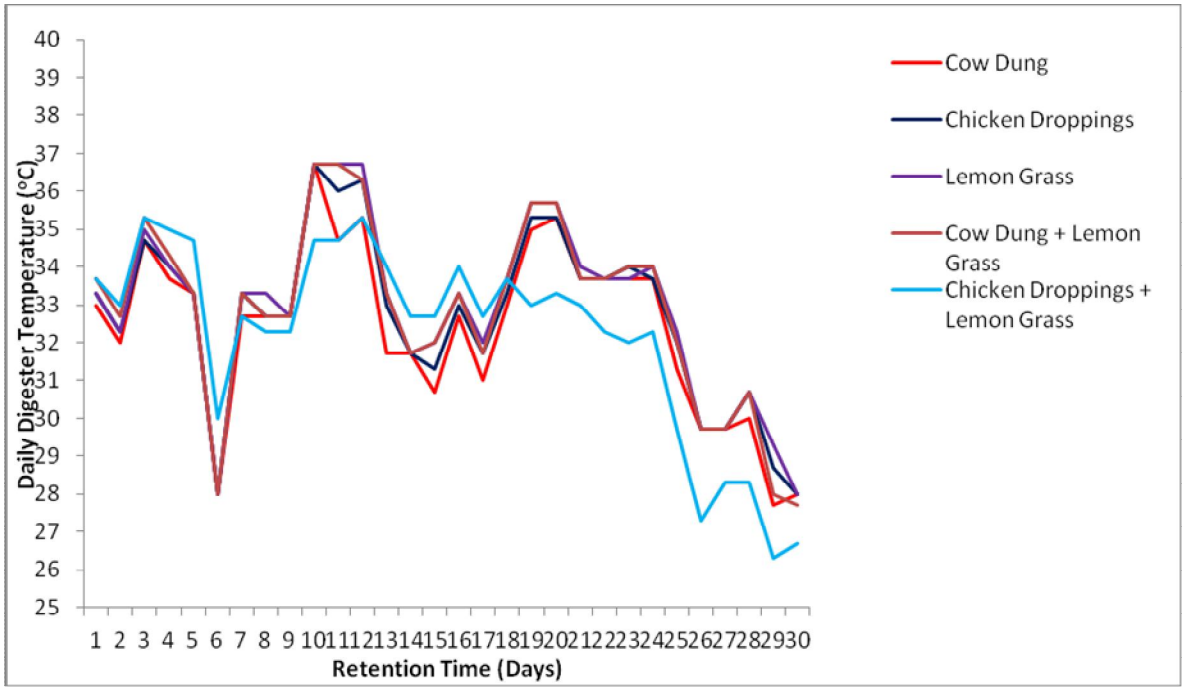


Fig 4.4: Daily Digester Temperatures for the Five Reactors.

Figure 4.4 reveals that the temperatures within the five digesters fluctuated optimally between 26°C and 37°C which conforms to the mesophilic range. The foregoing show that the digesters operated within the mesophilic temperature range; and that it is possible to install digesters that will operate within this range in Samaru. This agrees with the findings of previous studies (Ahmadu, 2009, Igboro, 2011).

4.4.2 Feedstock's pH during Digestion

Figure 4.5 shows the pH of the digester contents monitored daily (Except Saturdays and Sundays) during the digestion period.

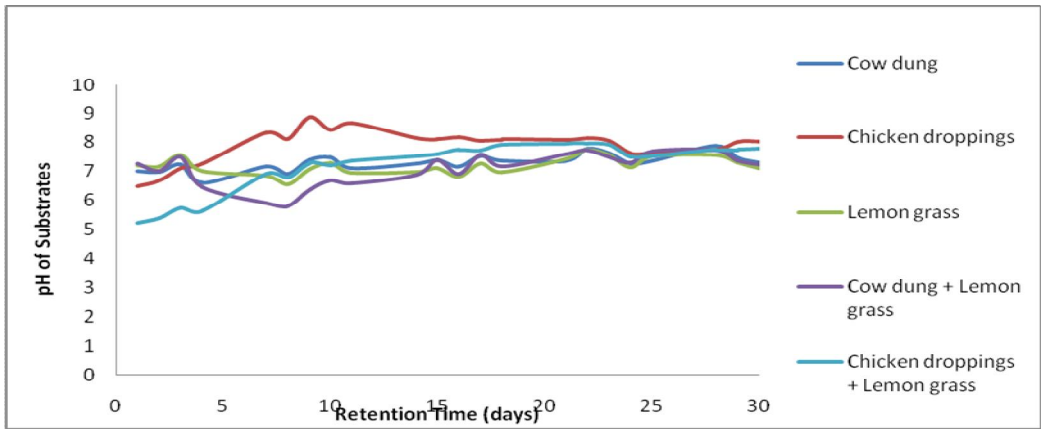


Figure 4.5: Daily pH of the Digester contents during the Study

It was observed that in the beginning, the pH values of the media in all the substrates digested were slightly neutral except in the chicken droppings and its co-digestion with lemon grass that were acidic. They gradually increased until they remained buffered around 7.5 to 8.0 when gas production was stabilized in all the reactors. In other words, 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), 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).

Figures 4.6 – 4.10 show the rates of change pH for all the substrates analysed throughout the period of study. The corresponding equations relating the rate of change with the retention time x is also shown in the figures.

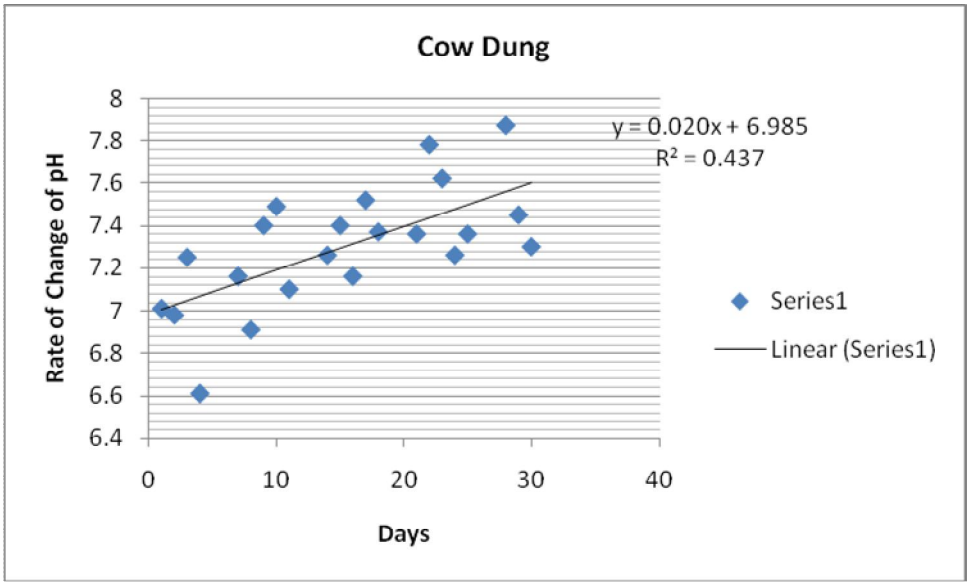


Fig 4.6: Rate of change in pH of the Cow Dung at various times intervals

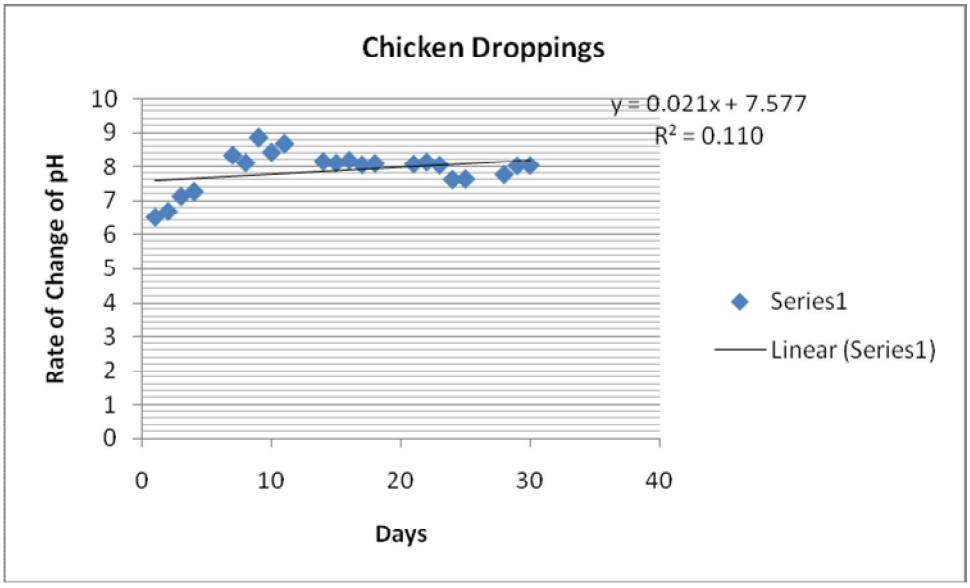


Fig 4.7: Rate of change in pH of the Chicken Droppings at various times intervals

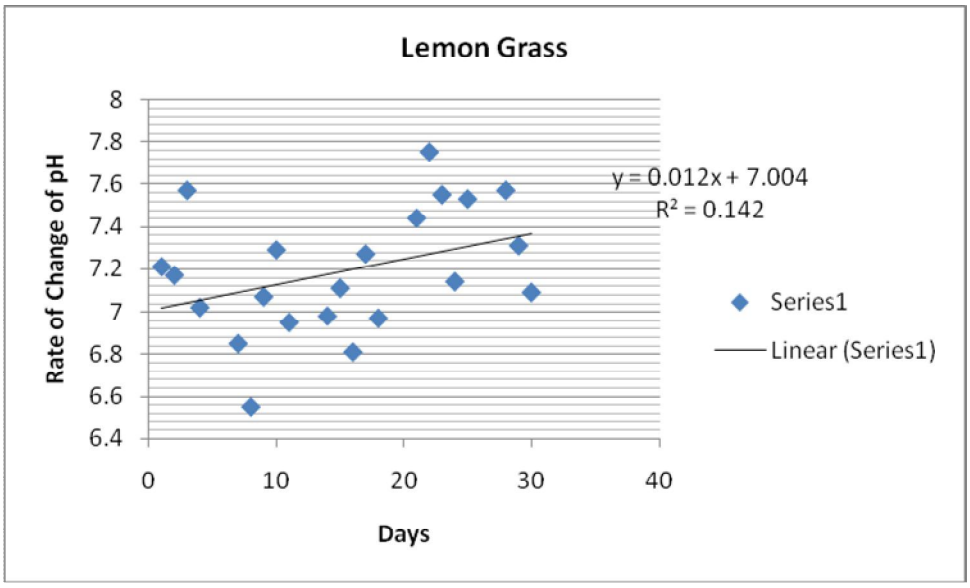


Fig 4.8: Rate of change in pH of the Lemon Grass at various times intervals

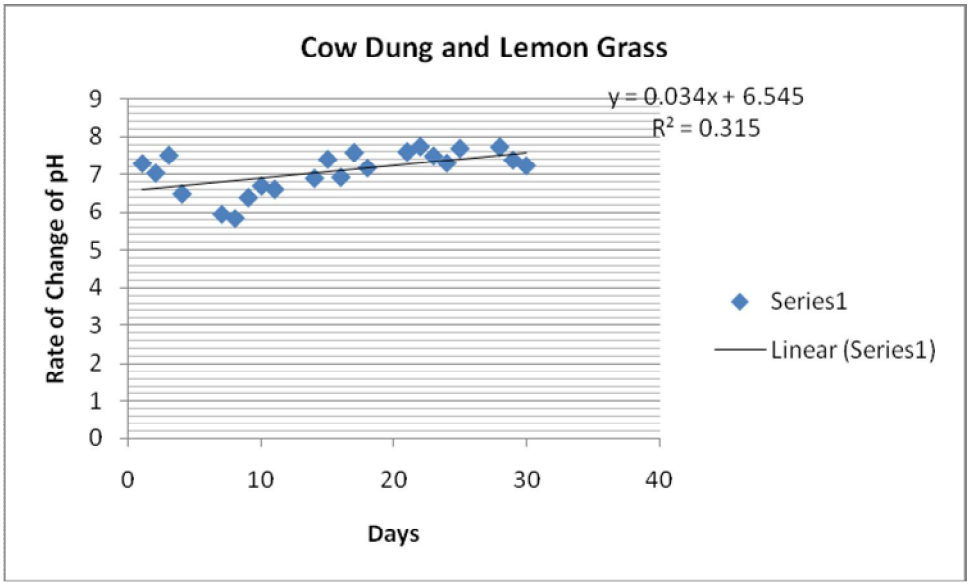


Fig 4.9: Rate of change in pH of the Cow Dung and Lemon Grass at various times intervals

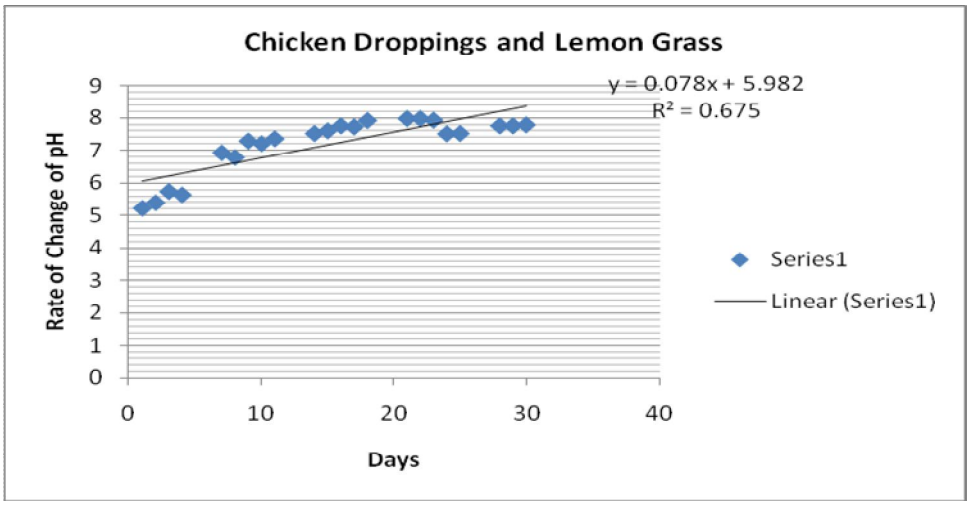


Fig 4.10: Rate of change in pH of the Chicken Droppings and Lemon Grass at various times intervals

4.5 UPGRADING OF BIOGAS PRODUCED

Fig 4.11 shows that there was a significant reduction in the volume of the gas produced after scrubbing by passing the gases through water and slaked lime respectively.

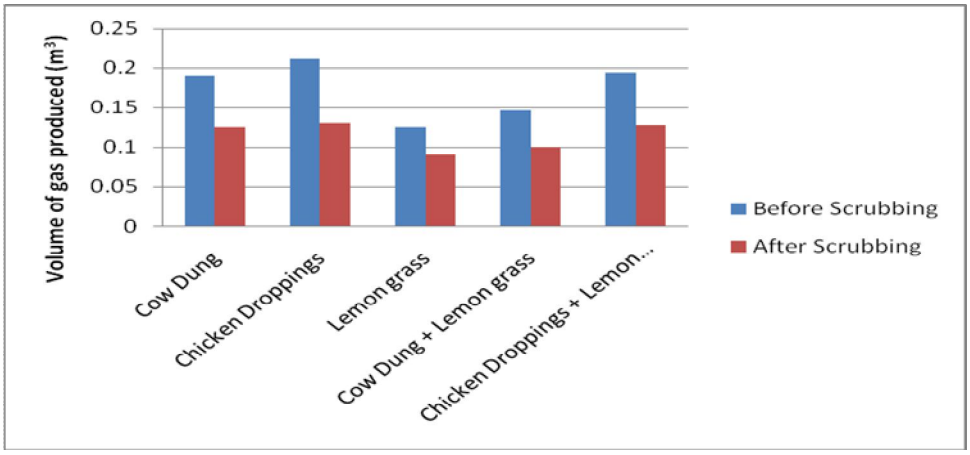


Figure 4.11: Comparison of Gas Volume before and after Scrubbing

The percentage reduction in volume could account for the removal of impurities such as carbon dioxide, hydrogen sulphide. This percentage reduction in volume was used to estimate the possible methane contents of the gases produced as shown on figure 4.12

Fig 4.12 shows the estimated methane content for all the substrates.

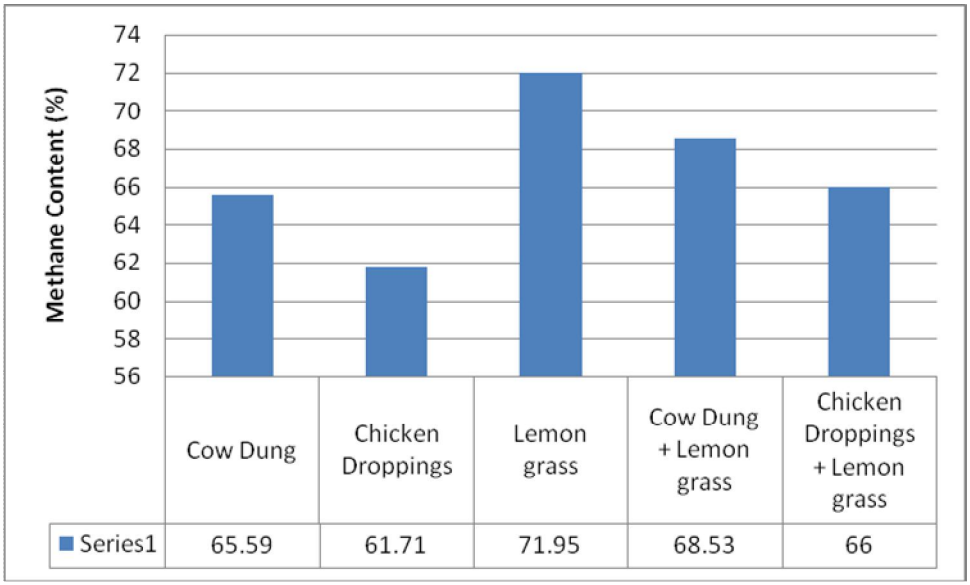


Fig 4.12: Estimate of Methane Content of Biogas from various substrates

It reveals that Lemon grass digested singly had the highest methane content (71.95%). The biogas produced from the co-digestion of cow dung and chicken droppings respectively with lemon grass had higher methane contents (68.53% and 66% respectively) than when they were digested singly (65.59% and 61.71% respectively) although not as much as the lemon grass digested alone. In the case of the synergies, the co substrates each contributed 50% (i.e. 3kg biomass) of what they produced when singly digested (i.e. 6kg biomass). This explains when the methane content of the synergy is not double what was obtained. Unlike the cow dung and chicken droppings, the lemon grass did not undergo any form of digestion prior to this anaerobic digestion thus not all the organics are available for the

degradation. This accounts for the lower volume of biogas from lemon grass digested alone (relative to cow dung and chicken droppings) as well as the drop in the methane content when co digested with the animal dung. This agrees with the findings in previous studies by Ojolo *et al.,* (2007).

4.6 DOMESTIC COOKING WITH PRODUCED GAS

Tables 4.5 shows the summary of the results for the cooking tests carried out on the gases produced before and after scrubbing. The times taken to boil 0.1L of water and parboil 0.18kg of rice were used to estimate the cooking rates in each case.

Table 4.5: Summary of Cooking Test Results

	Cooking Rates								**Biogas Consumption Rate (m^3/min)**
	Water				**Rice**				
	Before Scrubbing		After Scrubbing		Before Scrubbing		After Scrubbing		
	Time (min)	Rate **(L/min)**	Time (min)	Rate **(L/min)**	Time (min)	Rate **(kg/min)**	Time (min)	Rate **(kg/min)**	
Cow Dung	1.58	0.064	1.17	0.085	58.59	0.0031	43.39	0.0041	0.0058
Chicken Droppings	1.66	0.060	1.27	0.079	59.90	0.0030	45.83	0.0039	0.0061
Lemon Grass	1.27	0.079	0.88	0.12	47.10	0.0038	32.63	0.0055	0.0053
Cow Dung + Lemon Grass	1.42	0.070	1.01	0.10	52.66	0.0034	37.45	0.0048	0.0049
Chicken Droppings + Lemon Grass	1.50	0.067	1.10	0.091	54.13	0.0033	37.70	0.0045	0.0052

The biogas stove designed in the Department of Water Resources and Environmental Engineering (Igboro et al., 2011) was utilized to carry out this test. The time taken to cook, cooking rate and biogas consumption rates for water and food stuff are shown on the tables for all the samples. The results show that *Cymbopogon citratus* had the highest cooking rates before and after scrubbing the gas with slaked lime. For the scrubbed gas, the *Cymbopogon citratus* had cooking rates of 0.12 l/min and 0.0055kg/min for water and rice respectively, co-digestion of cow dung and *Cymbopogon citratus* had 0.10L/min and 0.0048kg/min respectively as cooking rates for water and rice while co digestion of chicken droppings and *Cymbopogon citratus* had 0.091L/min an 0.0045kg/min as cooking rates for water and rice respectively. The respective cooking rates for water and rice with the scrubbed cow dung gas were 0.085L/min and 0.0042kg/min while those for gas produced from chicken droppings only were 0.079L/min and 0.0039kg/min respectively. For the produced biogas before scrubbing, the cooking rates for water and rice respectively 0.079L/min and 0.0038kg/min for *Cymbopogon citratus,* 0.070L/min and 0.0034kg/min for co digestion of cow dung with *Cymbopogon citratus,* 0.067L/min and 0.0033kg/min for co-digestion of chicken droppings with *Cymbopogon citratus,* 0.064L/min 0.0031kg/min for cow dung only and 0.060 and 0.0030kg/min for chicken droppings only. These results agree with previous studies for cow dung and chicken droppings by Ahmadu (2009)where the cooking rates for water and rice were respectively 0.10L/min and 0.0048L/min for cow dung gas and 0.089L/min and 0.0042L/min for chicken droppings gas. The slight differences could be attributed to difference in atmospheric conditions at the times the experiments were carried out.

From the above results, the application of slaked lime to absorb carbon dioxide improved the heating efficiency of the biogas significantly. Thus, the application of small quantity of lime into the digester with utmost care will significantly improve the inflammability and the heating efficiency of the biogas (http://ease-vn.org.vn).

4.7 DEVELOPMENT OF STRATEGY FOR HARNESSING BIOMASS FOR LARGE SCALE BIOGAS PRODUCTION

The feed materials used for the production of biogas in this study are cow dung, chicken droppings and Lemon grass (*Cymbopogon citratus*). There is a need to ensure that they are sufficiently available to sustain the production level of biogas to meet the anticipated development. Thus, the following strategies for ensuring continuous availability of feed materials are proposed.

4.7.1 Estimation of Volume of Biogas for Daily Cooking and Digester Size for a Family of Six

The estimation of volume of biogas for daily cooking of a family of six was done based on the results obtained from the cooking tests for biogas from cow dung, chicken droppings and lemon grass as well as their respective co-digestion with *Cymbopogon citratus* after scrubbing with slaked lime. More so, the estimation of the digester size as well as the biomass requirements was done on the basis of the estimated gas volumes (see Appendix II). The results are summarized on Table 4.6.

Table 4.6: Daily Biogas Requirement, Digester Size and Biomass Requirements for a Family of Six

Substrates	Daily Biogas Requirement (m^3)	Digester size	Biomass Requirement (kg)
Cow Dung	3.84	23.	5,525
Chicken Droppings	4.32	25	5,923
Lemon Grass	2.64	16	3.799
Cow Dung + Lemon Grass	2.88	22	2,587 (of each substrate)
Chicken Droppings + Lemon Grass	3.18	19	2,245 (of each substrate)

NBS (2009) reported that there were about 28, 900,492 households in Nigeria as at 2006. More so, Ahmadu (2009) estimated the total amount of cow dung in Nigeria to be 632,250 tons per day. More so, Mathew (1982) in his survey reported that an estimated 8,500 tons of waste can be obtained from poultry daily in Nigeria. There is no record of the amount of lemon grass produced in Nigeria but it is assumed that 40% of the households in Nigeria plants at least 5 clusters of lemon grass. Lemongrass is commonly cultivated as a ratoon crop. It is first harvested at 4 to 6 months after planting followed by subsequent harvests at 2 to 3 month interval (Joy et al., 2006). Harvesting is done by cutting at 20 cm above the ground level (Sugumaran et al., 2005).It was observed from this study that 5 clusters of lemon grass weighed 6kg. Thus the available amount of lemon grass is estimated as:

$$5 \times 6 \times 28{,}900{,}492 \times 0.4 = 346{,}805{,}904kg$$

Thus 346,806 tons of lemon grass is available for biogas production in approximately 4 months. (i.e. 11,560 tons monthly).

Table 4.7 shows the biomass requirements for the total number of households as well as the available biomass for biogas production.

Table 4.7: Monthly Biomass Requirement and Availability for Total Number of Households in Nigeria.

Substrate	Quantity Required (tons)	Quantity Available (tons)	Additional Requirement (tons)
Cow Dung	159,675,000	18,967,500	140,707,500
Chicken Droppings	171,178,000	255,000	170,953,000
Lemon Grass	109,793	11,560	98,233

From table 4.7, additional 140,707,500 tons, 170,953,000 tons and 98,233 tons of cow dung, chicken droppings and lemon grass respectively are required to meet the biomass need for biogas production for all the households in Nigeria.

4.7.2 Strategy for Increasing the Availability of Cow Dung, Chicken Droppings and Lemon Grass

i. Provisions in form of large tanks could be made at the various abattoirs where the dung from the intestines of the slaughtered cows would be emptied. Thus, the accumulation of the cow dung would be fast. The dung would then be sold to people who desire to produce biogas at their respective households.

ii. The nature of chicken droppings and the way in which they roost makes collecting of the waste not very easy. However, the waste obtainable is still quite significant. Personnel could be delegated to coordinate the collection of cow dung and chicken droppings in farms and Agricultural institutes where these animals are raised in commercial quantities. Thus, the accumulation of the dung and droppings would be

fast and easy to sell to the populace. The existing channels of sales of these wastes in places like NAPRI could be used to sell the dung and droppings to those who need them.

iii. Lemon grass is a plant that grows on almost all kinds of soil. The cultivation does not require too much farm practices as they usually grow themselves. Sequel to this discovery of its values as an energy plant in addition to its medicinal value, institutions like the Ahmadu Bello University, the National Animal Production Research Institute, the National Research Institute for Chemical Technology and other similar institutions across the nation could use their unutilized vast lands to do a massive production of lemon grass which could be made available for the populace at affordable price for biogas production.

iv. Moreover, the possibility of planting lemon grass as a control for desert encroachment should also be exploited since it can grow on marginal soil. The Federal Ministry of Environment alongside the respective Ministry of Environment of the respective states in the savannah zone of the nation where desert encroachment is really a challenge could do this in partnership with the private sector. The Government could provide the land, the lemon grass and probably an incentive to private individuals who would plant the lemon grass and ensure the controlled harvesting and collection to a central place where they can be sold to the populace for biogas production while the Government agencies regulate the programme.

v. Households especially in the savannah vegetation zone of Nigeria should be encouraged to grow lemon grass around their houses to augment other means of supply.

vi. Should it be established that the leaves of lemon grass remaining after the extraction of the citral content for medicinal application is able to produce biogas, households could use these remains for biogas production after the medicinal application thereby solving waste management and energy problems at the same time.

Cow dung and chicken droppings are already widely in use by farmers for soil fertility improvement. In a recent study (Igboro, 2011), the residue of anaerobic digestion could be cured and used as organic fertilizer. Thus, the farmers who have hitherto used the cow dung and chicken droppings directly on their farms could produce biogas from the same cow dung and droppings and use the residues on their farms afterwards. This ensures the maximum reuse of these wastes.

4.8 COST ESTIMATES (BILL OF ENGINEERING MEASUREMENT AND EVALUATION)

Table 4.8 gives the detailed cost estimate of materials used in the fabrication of the pilot scale anaerobic digester plant.

Table 4.8: Cost Analysis for Construction a Pilot Scale Anaerobic Digester

S/No	Component	Material	Unit	Quantity	Unit Rate (₦)	Amount (₦)
1	Digester Body	1 mm Mild steal sheet	m^2	0.643	3,350	2154.05
2	Slurry Inlet Pipe	ϕ60mm Mild Steel pipe	m.	0.3	900	270
3	Slurry Outlet Pipe	ϕ60mm Mild Steel pipe	m.	0.06	900	54
4	Gas Holder	Thin sheet metal	m^2	0.259	1300	336.7
5	Water Jacket	1mm Mild steel	m^2	0.28	3350	938
6	Gas Pipe	ϕ10mm galvanized steel pipe	m.	0.5	300	150
7	5/6 inch Hose	Plastic	Yard	1	200	200
8	1/2 valve	Plastic	Nr	2	200	400
9	1/2x3/4 inches Butching	Aluminum	Nr	1	120	120
10	3/4 Nipple	Aluminum	Nr	1	80	80
11	5/6 Clip	stainless steel	Nr	3	20	60
12	ABRO Silicon Sealant		Nr	1	700	700
13	ABRO Epoxy 4 min kwik set sealant		Nr	1	400	400
14	Spraying					500
15	Workmanship					1700
16	Transportation					500
17	miscellaneous					500
	Add 10% Contingency					9062.75 906.28
	Total					**9,969.50**

The overall cost for producing one of the pilot scale Anaerobic Digester Plants used for this study is Nine Thousand Nine Hundred and Seventy Naira (**₦9,970.00**).

Table 4.9 shows the unit cost of gas production for each of the substrates

Table 4.9: Unit cost of Gas production for each Substrate digested

Unit Cost of Biogas (₦/Litre of gas)				
Cow dung	**Chicken droppings**	**Lemon grass**	**Cow dung + Lemon grass**	**Chicken droppings + Lemon grass**
52.20	47.25	79.76	68.28	51.66

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

From the results of the study conducted, the following conclusions can be made:

1. 25-litre biogas digester plants were designed modifying the Ajoy Karki's Biogas model (Karki, 2002), fabricated using locally available materials and tested under the existing weather condition in Zaria.
2. The biogas digester plants constructed in this study were used for the anaerobic digestion of cow dung, chicken droppings and lemon grass as well as co-digestion of cow dung and chicken droppings respectively with lemon grass. The study has shown that biogas can be produced from cow dung and chicken droppings (as observed in previous studies) as well as *Cymbopogon citratus* (lemon grass).
3. The methane contents for all the substrates digested were within the range given in literature. The co-digestion of the cow dung and chicken droppings respectively wit*h Cymbopogon citratus* improved the quality and quantity of methane produced and hence, the heating efficiency.
4. The monitoring of the plants established that all the plants worked satisfactorily with respect to their technical performance. The significant total solid reductions recorded (75.3 %, 60.1%, 98.2%, 61.9% and 35% for cow dung, chicken droppings, lemon grass, cow dung + lemon grass and chicken droppings + lemon grass respectively) indicate satisfactory treatment efficiency for all the plants. The four digesters containing cow dung and chicken droppings digested singly or co-digested

with *Cymbopogon citratus* show very high reduction in pathogen content, but still, the concentration of total Coliforms only allows for restricted irrigation according to the WHO-guidelines for "safe use of waste water, excreta and greywater".

5. 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 32±1°C which is within the mesophilic range.

6. The scrubbing of the produced gases to remove hydrogen sulphide and carbon dioxide will improve the heating efficiency of the gas. Although the energy outputs of the gases were not determined, the gases were able to boil potable water and rice in a period of time comparable with those of kerosene, electrical and butane stoves. The cooking rates for water were 0.079L/min, 0.070L/min, 0.067L/min, 0.064L/min and 0.060L/min for unscrubbed lemon grass, cow dung+ lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings respectively while those for scrubbed lemon grass, cow dung+ lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings were 0.12L/min, 0.10L/min, 0.091L/min, 0.085L/min and 0.079L/min respectively. The rice cooking rates were 0.0038kg/min, 0.0034kg/min, 0.0033kg/min, 0.0031kg/min, and 0.0030kg/min for unscrubbed lemon grass, cow dung+ lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings respectively while those for scrubbed lemon grass, cow dung+ lemongrass, chicken droppings + lemon grass, cow dung and chicken droppings were 0.0055kg/min, 0.0048kg/min, 0.0045kg/min, 0.0041kg/min and 0.0039kg/min respectively. The biogas stove burner developed in the Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria

was used to boil potable water as a confirmatory test of its performance. It had a performance consistent with the results obtained when it was first tested, that is average cooking rate of 0.095L/min and average biogas consumption rate of 0.0055m^3/min

5.2 RECOMMENDATIONS

1. The work done herein can be used to produce good quality biogas for use locally and internationally.
2. Although, the gas produced from Lemon grass had the highest cooking rate and methane content, its medicinal value will make it unavailable for use on a large scale, its synergy with cow dung will produce biogas of very high quality (68.53%) and high cooking rate (0.1L/min for water and 0.0048kg/min for rice) and should be preferred.
3. A comparative study of the use of spent digester slurry from different substrates digested singly and synergistically should be carried out so as to establish the optimum use of compost produced from the slurry.
4. Great caution has to be taken while using the residue as a fertilizer. It should only be used on crops (like vegetables) that are not eaten raw. The residue has to be applied directly on the roots and should not be spread on top of the vegetables. In addition, contact with mouth or wounds have to be avoided and hands must be washed thoroughly after use.
5. The implication of Salmonellae in the residue is a major health concern. It is therefore recommended that a further study to check if an extended retention period would further remove this pathogen be carried.

6. A purpose-built clay pot with adequate control to prevent gas leakage could be used as a digester especially in the rural areas where the substrates are available.

7. Lemon grass is a well-recognized medicinal plant as a result of its citral content. When the citral content is extracted for medicinal application, the possibility of using the leaves which are still rich in organics for biogas production should be exploited. The boiling for medicinal purpose would therefore be a form of pre-fermentation for optimum gas production. Thus, the leaves which could have been disposed as waste (after medicinal use) is adapted for energy production. Moreover, a comparative study of biogas from boiled lemon grass and fresh lemon grass should be carried out to test for the effectiveness of the former for biogas production.

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APPENDIX I

DESIGN OF PILOT SCALE ANAEROBIC DIGESTER

I (a) Digester sizing

The Anaerobic reactor adopted for this study is the batch type. 6kg of waste was used for all substrates digested during the study. This waste was mixed with water to form slurry in a ratio of one part of waste to one part of water by volume to arrive at the substrate input of $0.02m^3$/reactor.

From equation (3.2), S_d, = Biomass (B) + Water (W) m^3/ batch

$$= 0.01 + 0.01 = 0.02m^3/\text{ batch}$$

Where; S_d = Substrate input (for batch type digester)

A retention time of 30 days is chosen for this study.

For a batch type digester, the daily substrate input (batch input) equals the operating volume of the digester (V_0) (Kossmann et al., 2001) therefore from eqn (3.1)

$V_0 = S_d \times RT = 0.02m^3$

Where, V_0 = Operating volume of the digester

S_d = Daily substrate input, which is the net slurry input in the case of batch digester.

Table 1 shows the design calculations for the digester body.

Table 1: Digester Body Calculations

Input	Calculations	Output
$V_o = 0.020m^3$	From equation (3.3) $(VT) = {V_o}/{0.8}$ Total volume of digester (V_T) = ${0.020}/{0.8} = 0.025m^3$	$V_T = 2.5 \times 10^{-3}m^3$
$V_T = 0.025m^3$	From eqn (3.4) $V_T = \pi r^2_d h_d$ $\therefore r^2_d h_d = \frac{0.025}{\pi} = 0.00796m^3$ Where, r_d = Digester radius h_d = Digester height To obtain a cylindrical digester, larger in magnitude in height than in diameter, so as to ensure ease of construction, a ratio h_d:r_d of 4:1 was adopted.	$R^2_d h_d = 7.96 \times 10^{-3}m^3$
$r^2_d h_d = 0.00796m^3$ h_d: r_d = 4:1	${h_d}/{r_d} = {4}/{1} \Rightarrow h_d = 4r_d$ also $r^2_d h_d = 0.00796m^3$ $\therefore 4r^3_d = 0.00796m^3$ $r_d^3 = \frac{0.00796}{4} = 0.00199m^3$ $r_d = \sqrt[3]{0.00199} = 0.126m^3$ $\therefore h_d = 4 \times 0.126 = 0.504m$ Digester diameter = $2r_d$ $= 2 \times 0.126$ $= 0.252m$	Use Digester height = 50cm Digester Diameter= 25cm (See Drawing Annex1)

I (b) Gas holder sizing

- About 45kg dung produces close to 0.03m^3 gas/day (Mathew, 1982). Thus, 8kg of dung would produce about $\frac{0.03x8}{45} = 0.00533m^3$gas/day . This implies about $0.00533/24$ m^3/hr = 2.22 x $10^{-4}$$m^3$ gas/hr

Let this be the hourly gas production (G_h) = 2.22 x $10^{-4}$$m^3$ gas/hr

- A biogas stove requires 0.2 – 0.4m^3gas/hr (Ahmadu, 2009)

For this work, let this values be the maximum hourly gas consumption. Thus, gc_{max} = 0.2m^3/hr.

For the purpose of this work, we take the time of maximum consumption (tc_{max}) = 0.055hrs.

Also, the time of maximum zero consumption (tz_{max}) is taken as the interval between the last use of the day (night) to the first use next day (morning).For this work thus, tz_{max} = 10 hrs.

Table 2 shows the design calculations for the gas holder.

Table 2: Gas holder calculations

Input	Calculations	Output
$gc_{max} = 0.2m^3/hr$ $tc_{max} = 0.055hr$	From eqn (3.7) $V_{g1} = gc_{max} \times tc_{max}$ $\therefore V_{g1} = 0.2m^3/hr \times 0.055hr = 0.011m^3$	$V_{g1}=$ $1.1 \times 10^{-2}m^3$
$G_h = 0.000222m^3/hr$ $tz_{max} = 10hrs$	From eqn (3.8) $V_{g2} = G_h \times tz_{max}$ $= 0.000222m^3/hr \times 10hrs = 0.00222m^3$	$V_{g2}=$ $2.22 \times 10^{-3}m^3$
$V_{g1} = 0.011m^3$ $V_{g2} = 0.00195m^3$	Volume of gas holder (V_g) is the greater value between V_{g1} and V_{g2}. V_{g1} is greater, $\therefore V_g = V_{g1}$, $V_g = 0.011m^3$ Allowing a safety margin of 10% $V_g = 0.011 \times 1.1 = 0.0121m^3$	$V_g =$ $1.21 \times 10^{-2}m^3$
$V_g = 0.0121m^3$	From eqn (3.9) $V_g = \pi r^2_g h_g = 0.0121m^3$ $\therefore r_g^2 \, h_g = \frac{V_g}{\pi} = \frac{0.0121}{\pi} = 0.00385m^3$ Where, r_g = radius of gas holder h_g = height of gas holder for ease of construction, a ratio $h_g:r_g$ of 2:1 was adopted	
$r_g^2 h_g = 0.00385m^3$ $h_g:r_g = 2:1$	$\frac{h_g}{r_g} = 2/1 \Rightarrow h_g = 2r_g$ also $r^2_g \, h_g = 0.00385m^3$ $\therefore 2 \, r^3_g = 0.00385m^3$ $r_g^3 = 0.00385/2 = 0.001925m^3$ $r_g = 3\sqrt{0.001925} = 0.124m$ $\therefore \; h_g = 2 \times 0.124 = 0.248m$ Gas holder Diameter = $2r_g$ $= 2 \times 0.124 = 0.248m$	Use Gas holder height =25cm Use Gas holder diameter = 25cm (See Drawing Annex 2)

I (c) Gas Pipe Calculations

About 45kg dung produces close to $0.03m^3$ gas/day (Mathew, 1982). Thus, 8kg would produce about $\frac{0.03x8}{45} = 0.00533m^3$ gas/day . This implies about $0.00533/24$ m^3/hr

$= 2.22 \times 10^{-4} m^3$ gas/hr

If this gas flows from the digester as it is produced, then we can take the flow rate as 2.22×10^{-4}m3 gas/hr.

The pipe length is taken as the distance from the top of the digester to the bottom of the water jacket and up the water surface. Allowing for flexibility, this is about 1m length. Using this flow-rate and length to check through standard tables, a pipe diameter of half inch (i.e. 0.0127m) would serve.

I (d) Design of Water Jacket

Table 3 shows the design calculations for the Water Jacket.

Table 3: Water Jacket calculations

Input	Calculations	Output
$r_g = 0.125m$ taking c = 0.01m	From eqn. (3.10) $r_j = r_g + c$, where r_j = radius of water jacket r_g = radius of gas holder c = clearance $r_j = 0.125 + 0.01 = 0.135m$ Diameter of water jacket = $2r_j$ 2 x 0.135 = 0.27m	Diameter of water jacket = 27cm (See drawing No. 3)
$h_g = 0.25m$	From eqn (3.11) $h_j = h_g$ Where h_j = height of water jacket h_g = height of gas holder $\therefore h_j = 0.25m$	height of water jacket = 25cm (See drawing No. 3)

I (e) Design of Water Jacket

Table 4 shows the parts, materials used, fabrication process and equipment used for the construction of the Anaerobic Digester and gas collection system.

Table 4: Details of Biogas System Fabrication

Component	Material	Process Description	Equipments Used
Digester body	1mm Mild steel sheet	- Cut out 786mm X 500mm and role into a cylinder of height, 500mm and diameter, 250mm. - Weld free ends together. - Cut out two circles of ϕ 250mm and weld to the top and bottom of the cylinder to form a closed cylinder. - Cut out two ϕ 60mm at indicated positions for slurry inlet pipe and slurry outlet pipe. - Cut out ϕ 10mm for gas outlet pipe at indicated position. (Positions are as indicated in drawing No. 1)	-Guillotine -Manual Rolling Machine -Arc welding set
Slurry inlet pipe	Mild steel pipe	- From mild steel pipe of ϕ 60mm cut out length 300mm	-Hack saw
Slurry outlet pipe	Mild steel pipe	- From mild steel pipe of ϕ 60mm cut out length 60mm	Hack saw
Gas holder	Thin sheet metal	- From thin sheet, cut 786mm X 250mm, roll out to a cylinder of ϕ 250mm - Rivet free ends together - From thin sheet metal, cut out circle of ϕ 250mm. - Join circle onto top face of cylinder (Positions as indicated in drawing no. 2)	- Tin snip - Manual Rolling machine Manual riveting tools
Water Jacket	1 mm Mild Steel sheet	- From 1 mm mild steel sheet, cut 849mm X 250mm, roll out to a cylinder of ϕ 270mm	-Guillotine -Manual Rolling

		- weld free ends together - From 1 mm mild steel sheet, cut out circle of ϕ 270mm. - Join circle onto bottom face of cylinder. - cut out hole of ϕ10mm from bottom side of the cylinder at indicated position (Positions as indicated in drawing no. 3)	Machine -Arc welding set
Gas inlet pipe	Galvanized steel pipe (ϕ 10mm, 2.5mm thick)	- Cut out length 150mm from pipe - Cut out another length 250mm from pipe - Weld pipes together at right angle as indicated in drawing - Fit the welded pipes into the water jacket and weld onto position as indicated in drawing	- Hack saw - Arc welding set
Gas Outlet Pipe	Galvanized steel pipe (ϕ 10mm, 2.5mm thick)	- Cut out 2 no pipe of length 100mm each from pipe - Fit each pipe onto the top of gas holder and digester then weld onto position as indicated in drawing 1 and 2 respectively.	- Hack saw - Arc welding set

APPENDIX II

ESTIMATION OF VOLUME OF BIOGAS FOR DAILY COOKING AND DIGESTER SIZE FOR A FAMILY OF SIX

II (a) Cow Dung as Substrates

In the case of cow dung gas, the biogas consumption rate was $0.0058m^3$/min. since it took 43.39 minutes to cook rice; it implied that $0.252m^3$ was used in cooking a meal (food stuff) for one person. Also, $0.136m^3$ would be required to boil 2 litres of water, sufficient for domestic use.

Assuming such meals is prepared twice a day and this quantity of domestic water is boiled once a day for breakfast for one person, then we have a total of:

$$(0.252 \times 2) + 0.136 = 0.640m^3$$

Thus, $0.64m^3$ of gas would be required for one person per day.

For a family of 6 persons, $(0.64 \times 6) = 3.84m^3$ of gas would be required daily.

From fig 4.2, it was shown that 6kg cow dung produced an average of $0.00417m^3$ of gas daily over a 30 days period for the scrubbed gas. The operating volume of the digester (V_o) used, as obtained from table 4.1 is $0.02m^3$.

Thus, $0.00417m^3$ gas/day requires $0.02m^3$ volume digester

$$\therefore 3.84m^3 \text{ gas/day requires } \frac{0.02}{0.00417} \text{ X } 3.84 = 18.4m^3$$

The total volume of the digester (V_T) as obtained from table 4.1 is given as

$$V_T = \frac{V_o}{0.8}$$

$$\therefore \quad V_T = \frac{18.4}{0.8} = 23m^3$$

Also, 0.00417m^3/day of gas requires 6kg dung over a 30 days period

$\therefore$ 3.84m^3/day will require $\frac{6}{0.00417}$ x 3.84 =5,525kg dung over a 30 days period.

One cow produces an average of 12kg dung daily (Karki *et al.,* 2005).

$\therefore$ 5,525kg of dung over a 30 days period will require $\frac{5525}{12 \text{ x } 30} = 15$ *cattle*

Thus a family of 6 will require a batch type digester of 23m^3 volume using 5,525kg of cow dung to meet domestic cooking needs for a period of 30 days.

II (b) Chicken Droppings as Substrates

In the case of chicken droppings gas, the biogas consumption rate was 0.0061m^3/min. It took 45.83 minutes to cook the food stuff. Thus, 0.280m^3 was used in cooking a meal (food stuff) for one person. Also, 0.155m^3 would be required to boil 2 litres of water, sufficient for domestic use.

Assuming such meals is prepared twice a day and this quantity of domestic water is boiled once a day for breakfast for one person, then we have a total of:

(0.280 x 2) + 0.155 = 0.715m^3

Thus, 0.72m^3 of gas would be required for one person per day.

For a family of 6 persons, (0.72 x 6) = 4.32m^3 of gas would be required daily.

From fig 4.2, it was shown that 6kg chicken droppings produced an average of 0.00434m^3 of gas daily over a 30 days period for the scrubbed gas. The operating volume of the digester (V_o) used, as obtained from table 4.1 is 0.02m^3, thus,

0.00434m^3 of gas daily requires 0.02m^3 digester

$\therefore$ 4.32m^3 of gas daily requires $\frac{0.02}{0.00434}$ x $4.32 = 19.9m^3$

The total volume of the digester (V_T) as obtained from chapter 3 is given by $V_T = {}^{V_o}\!/_{0.8}$

$\therefore V_T = {}^{19.9}\!/_{0.8} = 24.9m^3$

Also, 0.00434m^3/day of gas requires 6kg droppings over a 30 days period. Therefore, 4.32m^3/day will require ${}^{6}\!/_{0.00434}$ x 4.32 = 5973kg of dropping.

Therefore, a family of six will require a batch type digester of 25m^3 volume using 5,973kg of chicken droppings to meet domestic cooking needs for a period of 30 days.

II (c) *Cymbopogon citratus* as Substrates

In the case of biogas from *Cymbopogon citratus*, the biogas consumption rate was 0.0053m^3/min. since it took 32.62 minutes to cook the food stuff; it implied that 0.173m^3

was used in cooking a meal (food stuff) for one person. Also, $0.093m^3$ would be required to boil 2 litres of water, sufficient for domestic use.

Assuming such meals is prepared twice a day and this quantity of domestic water is boiled once a day for breakfast for one person, then we have a total of:

$$(0.173 \times 2) + 0.093 = 0.439m^3$$

Thus, $0.44m^3$ of gas would be required for one person per day.

For a family of 6 persons, $(0.44 \times 6) = 2.64m^3$ of gas would be required daily.

From fig 4.2, it was shown that 6kg *Cymbopogon citratus* produced an average of $0.00417m^3$ of gas daily over a 30 days period for the scrubbed gas. The operating volume of the digester (V_o) used, as obtained from Table 4.1 is $0.02m^3$, thus,

$0.00417m^3$ of gas daily requires $0.02m^3$ digester

$$\therefore 2.64m^3 \text{ of gas daily requires } \frac{0.02}{0.00417} \times 2.64 = 12.66m^3$$

The total volume of the digester (V_T) as obtained from chapter 3 is given by $V_T = {}^{V_o}\!/_{0.8}$

$$\therefore V_T = {}^{12.66}\!/_{0.8} = 15.83m^3$$

Also, $0.00417m^3$/day of gas requires 6kg substrates over a 30 days period. Therefore, $2.64m^3$/day will require ${}^{6}\!/_{0.00417} \times 2.64 = 3{,}799$kg *Cymbopogon citratus*.

Therefore, a family of six will require a batch type digester of 12.66m^3 volume using 3,799kg *Cymbopogon citratus* to meet domestic cooking needs for a period of 30 days.

II (d) Cow Dung and *Cymbopogon citratus* as Substrates

In the case of gas from co-digestion of cow dung gas with *Cymbopogon citratus*, the biogas consumption rate was 0.005m^3/min. since it took 37.45 minutes to cook the food stuff; it implied that 0.188m^3 was used in cooking a meal (food stuff) for one person. Also, 0.101m^3 would be required to boil 2 litres of water, sufficient for domestic use.

Assuming such meals is prepared twice a day and this quantity of domestic water is boiled once a day for breakfast for one person, then we have a total of:

$$(0.188 \times 2) + 0.101 = 0.477m^3$$

Thus, 0.48m^3 of gas would be required for one person per day.

For a family of 6 persons, $(0.48 \times 6) = 2.88m^3$ of gas would be required daily.

From fig 4.2, it was shown that 6kg cow dung and *Cymbopogon citratus* produced an average of 0.00334m^3 of gas daily over a 30 days period for the scrubbed gas. The operating volume of the digester (V_o) used, as obtained from table 4.1 is 0.02m^3.

Thus, 0.00334m^3 gas/day requires 0.02m^3 volume digester

$$\therefore 2.88m^3 \text{ gas/day requires } \frac{0.02}{0.00334} \text{ X } 2.88 = 17.2m^3$$

The total volume of the digester (V_T) as obtained from table 4.1 is given as

$$V_T = \frac{V_o}{0.8}$$

$$\therefore \quad V_T = \frac{17.2}{0.8} = 21.5m^3$$

Also, 0.00334m^3/day of gas requires 6kg substrates over a 30 days period

$\therefore$ 2.88m^3/day will require $\frac{6}{0.00334}$ x 2.88 =5,174kg dung and *Cymbopogon citratus* over a 30 days period.

Thus a family of 6 will require a batch type digester of 21.5m^3 volume using 2,587kg each of cow dung and *Cymbopogon citratus* to meet domestic cooking needs for a period of 30 days.

II (e) Chicken Droppings and *Cymbopogon citratus* as Substrates

In the case of gas from co-digestion of cow dung gas with *Cymbopogon citratus*, the biogas consumption rate was 0.0052m^3/min. since it took 39.70 minutes to cook the food stuff; it implied that 0.206m^3 was used in cooking a meal (food stuff) for one person. Also, 0.114m^3 would be required to boil 2 litres of water, sufficient for domestic use.

Assuming such meals is prepared twice a day and this quantity of domestic water is boiled once a day for breakfast for one person, then we have a total of:

$$(0.206 \times 2) + 0.114 = 0.526m^3$$

Thus, 0.53m^3 of gas would be required for one person per day.

For a family of 6 persons, (0.53 x 6) = 3.18m^3 of gas would be required daily.

From fig 4.2, it was shown that 6kg chicken droppings and *Cymbopogon citratus* produced an average of 0.00425m^3 of gas daily over a 30 days period for the scrubbed gas. The operating volume of the digester (V_o) used, as obtained from table 4.1 is 0.02m^3, thus,

0.00425m^3 of gas daily requires 0.02m^3 digester

$\therefore 3.18m^3$ of gas daily requires $\frac{0.02}{0.00425}$ x $3.18 = 15m^3$

The total volume of the digester (V_T) as obtained from chapter 3 is given by $V_T = {}^{V_o}\!/_{0.8}$

$\therefore V_T = {}^{15}\!/_{0.8} = 18.8m^3$

Also, 0.00425m^3/day of gas requires 6kg substrates over a 30 days period. Therefore, 3.18m^3/day will require ${}^{6}\!/_{0.00425}\ x\ 3.18$ = 4,490kg of droppings and *Cymbopogon citratus*.

Therefore, a family of six will require a batch type digester of 18.8m^3 volume using 2,245kg each of chicken droppings and *Cymbopogon citratus* to meet domestic cooking needs for a period of 30 days.

APPENDIX III

APPENDIX IV

APPENDIX V

APPENDIX VI

APPENDIX VII

APPENDIX VIII

PLATES



PLATE I: Experimental Set up on the First Day of Set up



PLATE II: Experimental Set up showing Early Days of Gas Production



PLATE III: Researcher Taking Gas production Measurements with Gas Holder at Full Capacity



PLATE IV: Researcher Taking pH Measurements



PLATE V(a): Citrate Test (+Ve and –Ve)



PLATE V(b): Methyl Red Test



PLATE V(c): Samples and Reagent bottles



PLATE V(d): Motility Test

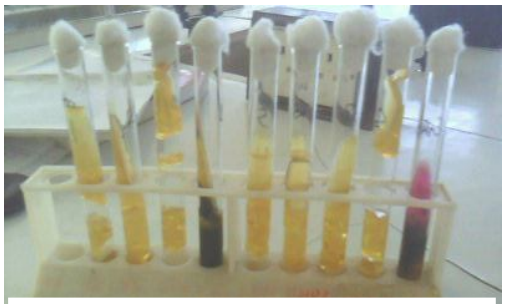


PLATE V(e): Indole on TSI



PLATE V(f): Indole Test (+Ve and –Ve)

PLATE V: Samples and Reagents for Various Biochemical Tests



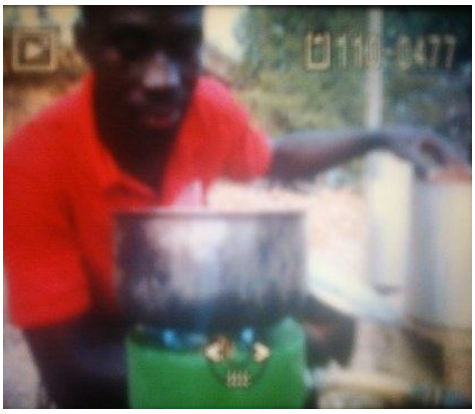


PLATE VI: Researcher Conducting the Gas Flammability and Cooking Tests for water and Food stuff