COLLEGE OF SCIENCE OF TECHNOLOGY

DESIGN OF A CO-DIGESTION BIOGAS PLANT TO CURB DEFORESTATION- CASE STUDY OF PHALOMBE BOARDING SECONDARY SCHOOL IN MALAWI

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A dissertation submitted to the African Centre of Excellence in Energy for Sustainable Development

College of Science and Technology

University of Rwanda in partial fulfilment of the requirements for the degree of

MASTERS OF SCIENCE IN RENEWABLE ENERGY (REE)

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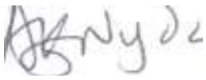
Month and Year of submission: **OCTOBER, 2020**

DECLARATION

I, Austin Kawelamzenje Nyirenda to the best of my knowledge, hereby declare that the work presented in this thesis titled **"The design of a co-digestion biogas plant to curb deforestation; with a case study of Phalombe Boarding Secondary School in Malawi,"** is my own work and has never been presented in any institution of higher learning for any academic reward or qualification.

Signature  Date : 10/12/20.

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ACKNOWLEDGEMENTS

I am very grateful to the Almighty God for having enabled me through my studies.

I extent my sincere appreciation to my Supervisor KAYIBANDA Venant PhD, for his generous heart and attitude he showed me throughout my research.

I am also very thankful to my respondents for having provided me with the data that I needed for this study. I really appreciate the work done by Mr. Chizombwe and Mr. Paul Naluso, head teacher and deputy head teacher respectively of Phalombe Boarding Secondary School in Malawi for administering my questionnaire on my behalf. I thank the village heads namely Mbodi, Bokosi and Seven surrounding Phalombe Boarding Secondary School for taking their time to respond to my questionnaire. I also thank my wife, Mirriam Banda, in identifying the right people to give me the information I needed in Malawi while I was stuck here in Rwanda due to travel restrictions arising from the global Covid-19 pandemic and for her direct involvement in data collection for this research work. I wish to thank my daughter Ruth Nyirenda and son Austin Junior Nyirenda for the encouragement they have been giving me to work hard throughout my masters study period.

Finally I also would like to thank the Malawi University of Science and Technology (MUST) for granting me a study leave in order to pursue the study of this Masters of Science Degree in Renewable Energy at the African Centre of Excellence in Energy for Sustainable Development (ACE-ESD) here at the University of Rwanda's College of Science and Technology (CST).

May the Almighty who never fails reward you all accordingly!

ABSTRACT

Biogas is one of the renewable sources that are used for cooking, lighting and heating our homes. The raw materials used to produce biogas are human waste, crop residues, food waste and many more other wastes which are biodegradable. Through anaerobic process, biodigesters are used to convert these wastes into biogas which is rich in methane. A co-digestion biogas plant that uses human, animal, agriculture and canteen food waste has been designed to produce biogas that can be used for heating, cooking and lighting at Phalombe Boarding Secondary School in Malawi. This thesis is about the design of a co-digestion biogas plant that will be constructed at the school which is at present solely dependent on firewood as a source of energy for cooking and heating. Various studies have shown that co-digestion of human waste with agricultural or canteen food wastes improves biogas production efficiency, C/N ratio and stability of the digestion process. Phalombe Boarding Secondary school has a population of 562 students and 195 members of staff including their dependants. It uses approximately 52 tons of firewood in a school term; 156 tons in one academic year of three terms. One ton costs **US$19.00**. Therefore, 156 tons cost the school approximately **US$3,000.00** in one academic year. The school also spends **US$344.00** per month on electricity for lighting, translating into **US$1,032.00** in one academic term of approximately 4 months. The amount of money spent on electricity in an academic year of three terms is approximately **US$3,096.00.** Thus in total, the school spends approximately **US$6,096.00** on firewood and electricity for cooking and lighting. A field survey at the school was carried out to appreciate the problem the school is facing so that a solution could be found. It was concluded that construction of a biogas plant at the school was the best option to save the money the school is currently spending on lighting and cooking and also to curb deforestation which is rampant since the school and surrounding communities get their firewood from the natural forests surrounding them. Biogas is a cheap, clean, green and environmental friendly source of energy to replace firewood. Common biodigesters in use worldwide have been discussed in this thesis. Based on factors such as energy demand at the school, availability of feedstock, size of the digester, biogas yield, life span of the biodigester and availability of construction materials, the type of biogas plant suitable for this purpose has been selected and designed. These design parameters were arrived at through a baseline survey and literature reviews. Through a questionnaire, a detailed energy demand analysis was carried out from whose results a fixed dome biogas plant of digester size **62 m^3**, gazometer of size **19 m^3** and digestate collection tank size of **61 m^3** has been designed. A cost estimate of the design has been carried out to appreciate the economic viability of the biogas technology and is estimated at **US$5,277.00** An OBA simulation of gas production is run using the calculated/estimated substrate and the results show that with this design, methane gas production in access of **60%** of the total biogas produced is achievable. The cost of constructing a biogas plant at the school being less than what the school is spending currently on firewood and electricity, a recommendation has been made to adopt the technology in order to reduce the financial burden the school is facing.

LIST OF ACRONYMS

V_T	Total Volume of digester
V_o	Operating Volume
VS	Volatile Solids
V_g	Volume of Gazometer
VFA	Volatile Fatty Acids
V_c	Volume of Collection/Digestate tank
US$	United States Dollar
TS	Total Solids
SCOD	Solluted Chemical Oxygen demand
Q	Quantity of substrate
PVC	Polyvinyl Chloride
pH	Power of Hydrogen (Measure of acidity/alkalinity)
ORM	Organic Raw material
OLR	Organic Loading Rate
OBA	Online Biogas App
MK	Malawi Kwacha
kWh	Kilo watt hour
HRT	Hydraulic Retention Time
GTZ	Germany Agency for Technical Cooperation
GHG	Greenhouse Gas
DM	Dry Matter
DFM	Daily Feeding Material
COVID	Corona Virus Disease
CO_2	Carbon dioxide
CH_4	Methane
CH_3OH	Methanol
CH_3COOH	Ethanoic acid
CH_3CH_2OH	Ethanol
$CH3CH_2COOH$	Propionate
$C_6H_{10}O_4$	Cellulose

C_6H1_2O6	Glucose
H_2O	Water
H_2	Hydrogen
CAD	Computer Aided Design
C/N	Carbon to Nitrogen ratio
VS	Volatile solids
L	Litre
m^3	Cubic metre
Kg	Kilogram
AD	Anaerobic Digestion

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CHAPTER ONE

1.1 Introduction

This study is about the design of a co-digestion biogas plant which is suitable for use by Phalombe Boarding Secondary School to replace firewood as a source of energy for cooking and lighting. In this chapter the sections covered include background to the study, statement of the problem, purpose of the study, study objectives, scope of the study, expected outcomes and significance of the study.

1.2 Background and Motivation

Most boarding secondary schools in Malawi depend on wood fuel for kitchen activities such as cooking food and heating water as main source of energy. This contributes to deforestation and also places a financial burden on these schools due to ever increasing prices of firewood.

Biogas offers a great alternative for fuel for cooking, heating, and lighting. It also addresses the issues of human waste disposal. It reduces the impacts on the environment which are mostly caused by deforestation and greenhouse gas emissions into the atmosphere. Biogas is a combustible mixture of gases that primarily consists of Methane(55 -65%)and Carbon dioxide (35 - 45%): Table 5 [11]. The other trace elements are nitrogen, hydrogen and hydrogen sulphide. These gases (mainly methane and carbon dioxide) are produced from the decomposition of organic wastes through anaerobic digestion. Methane gas is very combustible. It can be used for cooking, heating and lighting. The use of biogas technology has the advantages of reducing deforestation through reduced use of firewood where it is over-dependent, reducing greenhouse gases emission hence addressing the effects of climate change. Biogas technology improves the respiratory health of people using it due to its cleaner cooking environment. There are several designs of biogas plants across the world and the designs depend on geographical location, availability of substrate and climatic conditions. Some biogas plants are fixed underground while others are constructed above the ground. Out of the different biogas digesters, the fixed dome model developed by China and the floating drum model developed by India have continued to perform well until today [1].

The size of the digesters depends on the location, number of households, and the amount of substrate available every day. Biogas plant models can be modified in order to suit the conditions of Malawi and Phalombe Secondary School in particular. This research thesis is therefore aimed at seeking to make modification of the available performing biogas designs in Malawi that only use one type of substrate for digestion. The designed biogas plant will make use of human waste and canteen food wastes to co-digest them to produce biogas for cooking and lighting at the school to replace firewood.

Mzuzu University in Malawi under the faculty of Renewable Energy has been implementing fixed dome biogas projects in rural areas of Malawi using single digestion in an effort to preserve the carbon sink and switch to a cleaner and more efficient alternative to firewood. One of the beneficiaries of this project is Ruguwa Mhlanga Village, a rural village north east of Mzuzu [2]. Similarly, tubular polyethylene biogas digesters have been developed and tested in Zomba in Malawi by the Swedish University of Agricultural Sciences in conjunction with University of Malawi (Chancellor College) to reduce deforestation and support climate change mitigation and adaptation. Waste management and agricultural productivity can also be improved as a result of biogas technology. Further, the development and promotion of biogas within the energy sector can propel the establishment of new enterprises thereby creating a whole range of opportunities for jobs and small and medium enterprises both in urban and rural areas. [3]

With all the advantages above in mind, the construction of a biogas plant at Phalombe Boarding Secondary School will be very vital. The biogas plant will use human waste from school toilets and canteen food waste from students canteen as feedstock (substrate) for co-digestion. The biogas plants that are currently in use in Malawi use single digestion(only one type of feedstock). This research study aims at addressing this gap by introducing co-digestion. To supplement the feedstock it will also be using animal manure and crop residues such as rice straw/bran from the surrounding communities. Phalombe is one of the highest rice- producing districts in Malawi but does not make use of rice bran after rice milling. Millions of tons of rice bran are not used and are either burned into ashes or just thrown away. The district is also engaged in animal farming which includes goats, cows and pigs. From these farm animals farm manure can be collected and be used as a daily feeding material/feedstock for the biogas plant.

1.3 Problem Statement

Biogas has been used in most parts of the world for cooking, heating and lighting. In Africa, countries such as Kenya, Uganda, Ethiopia, Tanzania, Rwanda, Cameroon, Burkina Faso and Benin have benefited from this technology through National Biogas programs initiated by their governments **.** In Malawi, little has been done to promote this technology. Since access to electricity is still very low at present, Malawi's main source of energy for cooking is firewood. Over 90% of the population in Malawi is heavily reliant on firewood as their primary source of energy for cooking This results in deforestation, pollution of the environment and great monetary expenditure to buy firewood, more especially by boarding schools. Almost all government boarding schools use firewood as their primary source of energy for cooking. One amongst such schools is Phalombe Boarding Secondary School. Currently it uses approximately 52 metric tonnes of firewood per school term for cooking and which cost the school approximately US$1000 per term. It is against this background that this research wants to solve the problem of lack of energy and overdependence on firewood at this school. The problem will be solved by designing a co-digestion biogas plant that will use human and canteen food wastes. The school has enough substrate that can be used for biogas production from human waste provided by the school population which stands at 757 people and from food left overs in the students' canteen. To supplement this, it will also use cow manure and agricultural wastes such as rice bran from the surrounding villages. Once the plant is installed at the school, it will curb deforestation and reduce the amount of money the school spends on cooking and lighting.

1.4 Study Objectives

1.4.1 General Objective

The general objective of this study is to design an affordable co-digestion biogas plant for use at Phalombe Secondary School in Malawi.

1.4.2 Specific Objectives

The following were the specific objectives of this research study:

1. To design a co-digestion anaerobic biogas plant for biogas production using locally available resources.
2. To determine the feasibility of the design by carrying out a cost estimate and compare it with the current expenditure on firewood for cooking at the school.

1.5 Study Scope

This study focused on designing a co-digestion biogas plant using human and canteen food wastes as the primary feedstock. To supplement this feedstock, the study also proposed the use of agriculture waste such as rice straw and animal waste as daily feeding materials to produce enough methane gas for cooking and lighting at Phalombe Boarding Secondary School. Since the school had all along been using firewood as its source of energy for cooking and heating, the study also focused on the economic viability of a biogas energy technology as an alternative energy source to firewood that would be recommended for use in most of the institutions in Malawi that solely depend on firewood as the source of energy for cooking.

1.5.1 Geographical scope

The study was carried out in Phalombe District and at Phalombe Secondary School in particular. Phalombe is a district in the Southern Region of Malawi. The district covers an area of 1,633 km^2 and has a population of 114,265 people(**Appendix 10).** Phalombe Secondary School and all other rural communities in Phalombe district use firewood as the only source of energy for cooking. Since continuous use of fuel wood results into deforestation, the project therefore aimed at curbing this problem by designing a co-digestion biogas plant that will produce gas for cooking , heating and lighting. Phalombe District has been chosen for this study because there is high deforestation from mountains namely Michesi and Mulanje mountains (**Appendix 6**). The district has an area of 1,245 km^2 under cultivation and settlements and has 11,805.5 hectares of forestry cover. Being along the lake shore of Lake Malombe, Phalombe district grows a lot of rice for both consumption and commercial purposes. There are several rice schemes such as Nkhulambe and Chakalamba **(Appendix 6)** run by Small holders Farmers Association. Rice is a number one cash crop in Phalombe district. After processing rice, thousands of tons of rice bran/husks are just thrown away and cause environmental threat when they are decaying. This rice bran is a good daily feeding material (DFM) for a bio digester since it improves the N/C ratio. Phalombe district has a very favourable climate for livestock production such as cattle, goats, pigs and chicken from whose wastes Phalombe Secondary school can utilize as daily feeding material for the bio digester at the school. Phalombe district is located in a moderate to hot zone which has very good weather conditions for biogas production. Its monthly temperatures range from 25^{o}C to 28^{o}C but temperatures of more than 30 ^{o}C are obtained in the hot summer season **(Appendix 9)** . The major environmental issues of the District include: land degradation, deforestation, threat to fish resources, threat to biodiversity and water resources and sanitation. The main sources of energy in Phalombe district are firewood and charcoal. This is due to unaffordability to use electricity because its price is very high. About 98.3% of the population in Phalombe district uses firewood for cooking. The picture in **appendix 5** is a testimony that the women of Phalombe district use firewood for their kitchen activities.

1.6 Significance of the Study

The study aims at helping Phalombe Secondary School to adapt the use of an anaerobic biogas technology to replace firewood which is the only source of energy at the school for cooking. The use of firewood has not only proven to be expensive but has also depleted forest reserves in Phalombe District. There are a lot of food leftovers per meal taken by the students and vegetable peelings which are improperly disposed of, causing environmental threats and the school's community health risks. By co-digesting human waste and these canteen food wastes in an anaerobic biodigester for biogas production for cooking and lighting, Phalombe Boarding Secondary School will reduce overdependence on firewood, improve waste disposal and reduce the costs the school is currently incurring on firewood and lighting. If the technology is adapted the following additional benefits will be achieved:

Increased use of biogas energy: The community surrounding the school and even beyond that area will have an appreciation of the advantages gained in using biogas hence will also adopt the technology

Reduced deforestation: Areas surrounding the school and beyond will stop over-dependence on firewood and charcoal as their primary sources of energy for cooking and heating as the result of the introduction of this renewable energy source. This will save a lot of forests from being deforested as is the case now.

Reduced land degradation: When trees are cut down, the land becomes bare. This leads to soil erosion thereby degrading the land. The use of biogas in Phalombe will reduce this problem as people in the area because people will reduce cutting down of trees for firewood.

Improvement of people's health: This will be achieved through the following:

- Pollution free environment: Biogas does not pollute the environment. Therefore those people that will use this biogas technology will be ensured of clean air while doing their kitchen cores.

- Reduced burden by women: Women go out to far places in search of firewood. This activity risks their health as they become tired every time they come from this activity. The use of biogas technology will bring their energy requirements at their door step thereby reducing the burden they would endeavour by searching firewood.

Climate change mitigation: Deforestation contributes to atmospheric greenhouse gas emissions such as carbon dioxide. This happens when trees are burnt down during charcoal production. Thus, the reduction of use of wood energy for cooking and heating will help to reduce deforestation; thereby mitigating the effects of climate change.

1.7 Organization of the Study

This study is presented in six chapters as follows:

Chapter One: This chapter covers introduction, background and motivation, problem statement, study objectives, study scope and significance of the study.

Chapter Two: This chapter is about Literature review

Chapter Three: This chapter is about Research Methodology

Chapter Four: This chapter is about System analysis and Design

Chapter Five : This chapter is about Results and discussion

Chapter Six: This chapter is about Conclusion and Recommendations of the study

CHAPTER TWO

2.1 LITERATURE REVIEW

This chapter gives definitions of some key terms used in this study, a detailed literature review on energy situation in Malawi from work done by different scholars so far, Biogas system description and production processes, biogas plant parts and their functions, shapes of commonly used biogas plants worldwide, comparison of different types of biogas plants, the AD process and its biochemistry, biogas production from human waste, co-digestion of biodegradable wastes for biogas production and its benefits, productivity and stability of biodigester systems, factors influencing biogas production, advantages of the AD process, biogas usability and its equivalent values and advantages of co-digestion of biodegradable wastes. This literature had been extracted from articles, journals, books on biogas technologies and their designs and any other information obtained from the internet related to biogas plants' requirements and their working principles.

2.1.1 Definitions of some key terms

Biogas plant: It is a technology used to process organic matter to produce biogas.

Fixed Dome plant: It is a closed biodigester/reactor with immovable rigid gas chamber and a digestate collection tank

Biodegradable waste: It is a material which can be decomposed by bacteria or other natural organisms

Digestate: It is the material remaining after the anaerobic digestion of biodegradable feedstock

Substrate: It is a mixture of organic material(ORM) and water which is fed into a biodigester to produce biogas

Biodigester: It is a water and air tight tank/chamber used for anaerobic digestion of biodegradable material to produce biogas.

Co- digestion: It is the simultaneous digestion of a homogenous mixture of multiple substrates.

Hydraulic Retention Time (HRT):It is the average amount of time the substrate stays in a reactor for digestion.

Gas production rate: It is the rate at which gas is produced per day in cubic metres of the substrate.

Organic Loading Rate (OLR): It is the amount of substrate fed per unit volume of the digester capacity per day.

Anaerobic digestion (AD): It is a sequence of processes by which microorganisms break down biodegradable material in the absence of oxygen.

Methanogenic bacteria: It is the bacteria which is responsible for anaerobic digestion to produce methane gas

Agitation: It is the process of manually or mechanically stirring the substrate in the digester tank

Mesophilic temperature: It is a temperature which ranges from 20 ^oC to 40 ^oC where mesophilic bacteria operate

Thermophilic temperature: It is a temperature range of between 50 ^oC and 60 ^oC where thermophilic bacteria responsible for methane production operate

Simulation: It is the representation of the behaviour or characteristics of one system through the use of another system, especially a computer program designed for the purpose.

Total Solids (TS): They are dissolved solids plus suspended and settleable solids in a liquid. TS for most manures and sludge ranges between 10 and 16%

Volatile Solids (VS): It is the organic fraction of TS that can be digested and produce biogas. It is measured as a percentage of TS. It represents fraction of the material that can be transformed into biogas and ranges between 70 and 90% of the TS content for most manure and sludge from municipal waste.

2.1.2 Present energy situation in Malawi

At present, Malawi's utilization of energy resources is heavily dominated by firewood which is mainly sourced from indigenous forests. Firewood provides 93% of all household energy needs.

Very few people in Malawi have access to electricity. Cooking using electricity is also very expensive. With a population of 18.6 million people in 2018, Malawi's per capita consumption of electrical energy is still low and is estimated at 93 kWh per year compared with an average of 432 kWh for Sub - Saharan Africa[4]. Burning of charcoal and wood fuel provides approximately 94% of the energy in Malawi [5]. As per 2018 population and housing census, the national electrification rate in Malawi was 10%, with 37% of the urban population and only 2% of the rural population having access to electricity [6]. The World Bank report of 2019 shows that access to electricity in Malawi stands at 12.7% of the population. Current annual household consumption of firewood and charcoal stands at some 7.5 million tons, exceeding sustainable supply by about 3.7 million tons.

Given its relatively small land-mass, Malawi's current population stands at 18.6 million people, this large and ever-growing population is heavily dependent on fuel wood. Almost 99% of the energy that is used for cooking and heating comes from biomass. Since the population of the country keeps on growing, there is too much dependence on forest reserves as sources of firewood. This results in depletion of the forest resources that leads to deforestation and land degradation. About 87% of the population uses firewood and 8% charcoal in order to meet their energy needs for cooking and heating. Only 11% of the 18.6 million people are connected to the national grid [7]**.** Electricity and gas are only intermittently available and considered to be expensive for cooking. Therefore firewood and charcoal are the major cooking fuels, even in the urban areas. Firewood provides over 50% of the urban cooking fuel and nearly 100% in the rural areas. [6]

Mostly women and children collect firewood and this can take several hours per day, leaving this group with less time for education, employment and recreation. The use of firewood and other forms of biomass as a cooking fuel is also directly related to exposures of the hazardous particles from the smoke that these fuels produce when burnt.

According to a newspaper article "clean cooking for tidy markets", June 20, 2020 by James Chavula**,** the Department of Energy Affairs in Malawi estimates that currently one in a hundred(1:100) Malawians use gas for cooking. This is so because the value added tax on the commodity, its cylinders and stove is very high [7]. This makes the technology unaffordable to most people in Malawi.

The very few biogas plants that are in use in Malawi use single digestion whose substrate is either animal manure or human waste. There is no biogas plant that runs on co-digestion. Looking at the numerous advantages of co-digestion(discussed in this chapter), there is need to promote co-digestion. It is therefore this gap that needs to be addressed in the promotion of this technology in Malawi.

2.1.3 Biogas System description and production process

Biogas is a type of gas which is produced by anaerobic digestion of biodegradable substances such as human, animal, agricultural and kitchen waste by anaerobic bacteria. Anaerobic digestion excludes oxygen. This process takes place inside a biogas plant called the bio digester. The bio digester is air tight to allow anaerobic bacteria to grow and digest the wastes. During this process the microbes transform the wastes to a biogas consisting mainly of methane and carbon dioxide. Methane gas is produced in larger quantity (55 - 65%) than Carbon dioxide (35 - 45%) [11] and there are small traces of hydrogen and nitrogen gases. Methane is a clean and renewable gas. It can be used for cooking, heating and lighting depending on the need of the end user.

2.1.4 Main parts of a biogas plant and their functions

The main parts of a biogas plant include:

(i) Mixing tank: A mixing tank is used to mix biodegradable waste with water. All impurities are removed from the mixture and the compound formed is called the slurry. The slurry is then fed into the bio digester through a pipe which is inclined at an angle of 45^0 or more to aid gravitation flow of the slurry.

(ii) Bio digester: A bio digester is a chamber in which chemical and microbiological reactions take place. It is a chamber in which daily feeding material (DFM) is fed so that microbiological reactions take place. This chamber is called the bio-reactor or anaerobic reactor. It is built in such a way that it eliminates air by making it water and air tight in order to provide anaerobic conditions inside it. Biodigesters can be in the form of a circle or a rectangle. The circular shape has a fixed dome which provides for an air free chamber as there are no corners or voids inside it that can trap air. The rectangular shaped bio digester cannot be 100% air tight and is bound to keep air inside, mainly in the corners, hence not a suitable design for anaerobic digestion.

(iii) **Gas holder/Gazometer:** This is the part of a biogas plant which keeps the gas that has been produced. It can be a floating steel drum which rises according to the volume of gas produced or a fixed dome top part of the bio digester.

(iv) **Overflow tank/Digestate tank**: This tank is used to keep the slurry which has been digested. This slurry is rich in nitrogen and other elements and as such it is used as an organic fertilizer.

2.1.5 Bio digester Requirements

No matter which design is chosen, the digester must meet the following requirements:

(i) Water/gas tightness - water tightness in order to prevent seepage and the resultant threat to soil and groundwater quality; gas tightness in order to ensure proper containment of the entire biogas yield and to prevent air entering into the digester (which could result in the formation of an explosive mixture).

(ii) **Insulation** - if and to which extent depends on the required process temperature, the local climate and the financial means; heat loss should be minimized if outside temperatures are low, warming up of the digester should be facilitated when outside temperatures are low.

(iii) Minimum surface area - keeps cost of construction to a minimum and reduces heat losses through the vessel walls. A spherical structure has the best ratio of volume and surface area. For practical construction, a hemispherical construction with a conical floor is close to the optimum.

·(iv) **Structural stability** - sufficient to withstand all static and dynamic loads, durable and resistant to corrosion.

(v) Internal and external forces - Two relevant forces act on the digester. The external active earth pressure causes compressive forces within the masonry. The internal hydrostatic and gas pressures cause tensile stress in the masonry. Thus, the external pressure applied by the surrounding earth must be greater at all points than the internal forces. Round and spherical shapes are able to accept the highest forces and distribute them uniformly. Edges and corners lead to peak tensile stresses which can result in cracking [33].

2.1.6 Shapes of bio digesters

For structural strength for a vessel carrying fluids, an egg-shaped vessel has proven to be the best possible construction although it is more expensive as compared to other designs such as rectangular shapes. For this reason, it is usually employed in large scale sewage treatment plants. The Chinese fixed dome designs are of similar shape, but less expensive and are thus commonly used types of bio digesters**.** [8].

2.1.7 Types of biogas plants, comparison, their advantages and disadvantages

(i) **The Fixed dome bio digester**

A fixed-dome plant comprises of a closed, dome-shaped digester with an immovable, rigid gas-holder and a displacement pit, also named 'compensation tank' or digestate tank. The gas is stored in the upper part of the digester. When gas production commences, the slurry is displaced into the compensating tank. Gas pressure increases with the volume of gas stored, i.e. with the height difference between the two slurry levels. If there is little gas in the gas-holder, the gas pressure is low. Figure 1 shows fixed dome biodigester

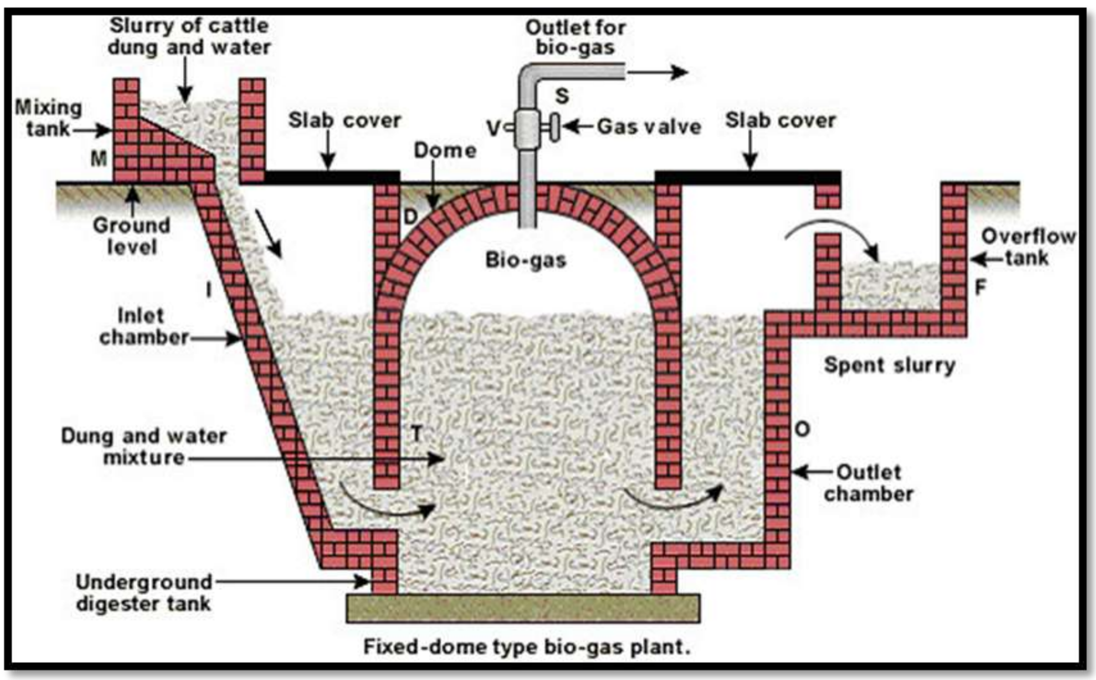

Figure 1. Fixed Dome Biogas Plant

Source : GTZ Biogas Digest volume II, Biogas application and Product Development, energypedia.info

(ii) **The floating drum bio digester**

Floating-drum plants consist of an underground digester and a moving gas-holder. The gas-holder floats either directly on the fermentation slurry or in a water jacket of its own. The gas is collected in the gas drum, which rises or moves down, according to the amount of gas stored. Figure 2 shows the floating drum biogas plant

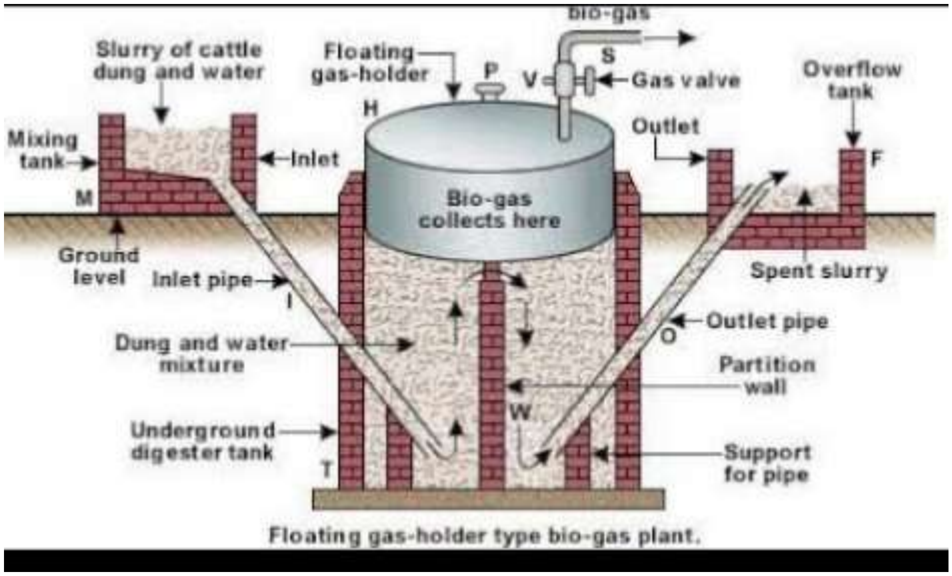

Figure 2. Floating Drum Biogas Plant

Source : GTZ Biogas Digest volume II, Biogas application and Product Development, energypedia.info

(iii) **The Polythene Tube Biogas Plant**

The Low-Cost Polyethylene Tube Digester model consists of tubular polyethylene film (two coats of 300 microns) bent at each end around a 6 inch PVC drainpipe and is wound with rubber strap of recycled tire-tubes. Figure 3 shows the polyethylene tube biogas plant

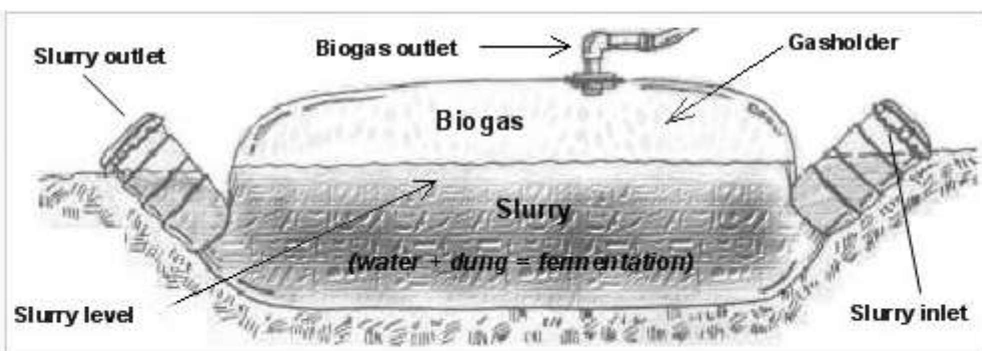

Figure 3. Polyethylene Tube biogas Plant

Source: GTZ Biogas Digest volume II, Biogas application and Product Development, energypedia.info

2.1.8 Comparison of the three types of bio digesters

Table 1. Comparison of the three types of biogas plants

Factors	Fixed dome	Floating Drum	Tubular design
Gas Storage	Internal gas storage up to $20m^3$	Internal storage drum size is small	Internal, eventually external plastic bags
Gas pressure	60 to 120 mbar	Up to 20 mbar	Around 2mbar
Skills of contractor	High skills require. Masonry and plumbing knowledge required	High skills require. Masonry and plumbing knowledge required	Medium skills required, plumbing knowledge require
Availability of materials	Yes	Yes	Yes
Durability of materials	Very high, 20 years	High but drum is the weakness	Is medium. Depends on the type of liner used
Agitation	Self agitated by biogas pressure	Manual steering	Not possible
Sizing	6 to 124 m^3 digester volume	Up to 20 m^3	Combination possible
Gas leakage through walls	No leakage. The dome is plastered inside. The whole plant is covered with earth. The plant is constructed underground, protecting it from physical damage and saving place.	Susceptible to leakage. Plant not protected from physical damage	Susceptible to leakage
Methane emission	High	Medium	Low

Source: Researchgate.net

2.1.9 Construction materials for Fixed dome, Floating drum and Tubular biogas plants

Table 2 shows the basic construction materials required by each type of the three biogas plants

Table 2. Basic construction materials of biogas plants

Fixed dome	Floating drum	Tubular plant
Cement, Sand, Gravel, Quarry stones, water, burnt bricks, PVC, galvanized steel pipes, Flexible hose pipe, pipe connectors, Lime, Black enamel paint, black plastic pipe	Cement, sand, Gravel, Quarry stones, water, burnt bricks, PVC, galvanized steel pipes, steel drum, flexible horse pipe, pipe connectors, oil paint/ bitumen paint	Biodigester unit (Fermenting reservoir), gas vent tubes, PVC connectors (reducers and Tees)

Source: energypedia.info and https://www.appropedia.org/Polyethylene_tube_digester

2.2.0 Advantages and disadvantages of Fixed dome, Floating drum and Tubular bio digesters

Further comparisons in terms of advantages and disadvantages were made amongst the three types of biodigesters.. Table 3 shows the advantages and disadvantages of Fixed dome, Floating drum and the tubular biogas plants

Table 3.Advantages and disadvantages of Fixed dome, Floating drum ad Tubular biogas plants

Type of Biogas plant	Advantages	Disadvantages
Fixed dome digester	• Low initial cost • Long useful life span • No moving or rusting parts involved • Compact basic design • Less land required if built underground • Low maintenance	• Requires high technical skills for gas tight construction • Requires heavy construction materials • Amount of gas produced is not immediately visible

Floating Drum Digester	• Simple and easy to understand operation • Visible stored gas volume • Constant gas pressure • Relatively easy construction	• High material cost • Short lifespan because of steel drum corrosion • High maintenance cost because of regular painting of the drum
Tubular design	• Low initial cost • Simple design • Simple and easy to operate • Relatively easy construction • Low maintenance costs • Less land required for construction	• Relatively short life span • High susceptibility to damage • Low gas pressure • High impact on environment(less environmental friendly)

Table 3 source: Researchgate.net

2.2.1 Comparison between floating drum, fixed dome and the tubular bio digester in terms of construction, corrosion reisistance, maintenance and thermal insulation

Another comparison between floating drum and fixed dome in terms of cost of construction, corrosion, maintenance and thermal insulation was made. Table 4 shows the three types of biodigesters in terms of construction, corrosion resistance and thermal insulation.

Table 4. Comparison of the three biogas plants in terms of cost, resistance to corrosion, maintenance and thermal insulation

Feature	**Floating Drum**	**Fixed Dome**	**Tubular design**
Cost	More(Due to steel drum)	Less	Less
Corrosion	Yes (likely in steel drum)	No	No
Maintenance	More • Drum requires painting • Flexible pipe requires replacement	Less • No steel parts used • Gas pipe is fixed type	Complicated. Difficult to repair damage to a plastic bag
Thermal insulation	Bad	Good (due to underground construction)	Depend on the type of lining used

Source: Biogas energy slideshare.com

2.2.2 Biogas production from biodegradable waste

Biodegradable waste is fed into the bio digester through the mixing tank where it is mixed with water in a required proportion. It is then fed into the bio digester through a plastic pipe or stainless steel pipe inclined at an angle of 45^0 to aid flow by gravity. Inside the bio digester grows anaerobic bacteria that feed on the wastes by digesting them to produce biogas. This bacteria is fed on daily basis, thus the feeding material is called daily feeding material (DFM). The anaerobic bacteria covert these organic wastes into methane gas through a process called anaerobic digestion.

This is a digestion process in which biodegradable waste is converted into compost in the absence of oxygen. This means that the environment in which the conversion takes place is oxygen free. This process produces compost(solid digestate) along with biogas. The compost is very rich in plant nutrients such nitrogen, phosphorus and potassium and can be used as organic manure/ fertilizer. This fertilizer is commonly known as **NPK**

2.2.3 Anaerobic digestion (AD) process for biogas production

In short, the anaerobic process occurs in three distinct stages. However the comprehensive AD occurs in four stages. The three stages are Hydrolysis, Acidogenesis and Methanogenesis and are described as follows:

(i) Decomposition of plant or animal matter by bacteria into molecules such as sugar. This process is called **Hydrolysis**

(ii) Conversion of decomposed matter into organic acids. This process is called **Acidogenesis.**

(iii) Organic acid conversion to methane. This process is called **Methanogenesis** [9]

Biogas yields range between 55% to 65% [11]. The gas yield depends on factors such as the type of daily feeding material and the design of the biogas plant.

2.2.4 Biogas composition

Table 5 shows the constituents and percentage composition of biogas.

Table 5. Constituents of biogas and their percentage composition [11]

Constituents	**% Composition**
Methane, CH_4	55 - 65
Carbon dioxide, CO_2	35 -45
Hydrogen Sulphide, H_2S	0 -1
Nitrogen, N_2	0 - 1
Hydrogen, H_2	0 - 1
Carbon monoxide (CO)	0 - 3
Oxygen, O_2	0 -2

2.2.5 AD biogas production flow process involving three stages

Figure 4 shows the schematic diagram of biogas flow production process.

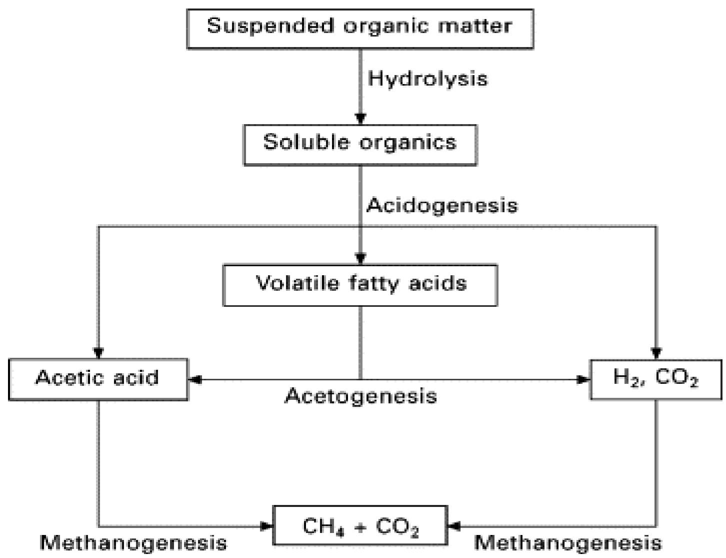

Figure 4. Schematic diagram of biogas production process

Source :Marc J. Rogoff PhD, Francois Screve Meng, MBA, in Waste-To-energy Third Edition; 2019.

2.2.6 The biochemistry of AD process involving four stages

The four stages of the AD process as shown in figures 4 and 5 below, are Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. They are described as follows:

(i) Hydrolysis

This is the first stage in which complex organic materials are broken down into their constituent monomers. The process is known as hydrolysis. This process produces soluble proteins. These proteins are converted into amino acids; fats to fatty acids, glycerol and triglycerides. Complex carbohydrates such as polysaccharides, cellulose, lignin, starch and fibre are converted into simple sugars, such as glucose.

Fermentative bacteria are responsible for the creation of monomers, which are then available to the next group of bacteria. Hydrolysis is catalyzed by enzymes excreted from the bacteria, such as cellulase, protease, and lipase. If the feedstock is complex such as raw cellulolytic waste, which contains lignin, the hydrolytic phase is relatively slow [12]. For this reason, woody waste is not an ideal feedstock for the anaerobic digestion. Carbohydrates, on the other hand, are known to be more rapidly converted via hydrolysis to simple sugars and subsequently fermented to volatile fatty acids (VFA). A hydrolysis reaction where organic waste is broken down into a simple sugar, in this case glucose, can be represented by the following chemical equation [12,13]

Cellulose + water ⟶ Glucose + Hydrogen

$$C_6H_{10}O_4 + 2H_2O \longrightarrow C_6H_{12}O_6 + 2H_2 \quad (1)$$

(ii) Acidogenesis

Hydrolysis is immediately followed by the acid-forming phase of acidogenesis. In this process, acidogenic bacteria turn the solubilised monomers produced by hydrolysis into simple organic compounds, mostly short chain volatile fatty acids (e.g., propionic, formic, lactic, butyric, or succinic acids), ketones (e.g., ethanol, methanol, glycerol, and acetone) and alcohols. The specific concentrations of products formed in this stage vary with the type of bacteria as well being influenced by the culture conditions, such as temperature and pH [12]. Typical reactions in these stages are shown below. The important acid in this stage is ethanoic acid CH_3COOH. This acid is used as a substrate in the formation of CH4. Production of VFAs in this stage is increased when the pH is greater than 5, whereas the production of ethanol (C_2H_5OH) is characterized by a pH of less than 5, with the reaction coming to a halt at a pH of less than 4. The acidogenesis can be summarized by the following equations:[16]

$$C_6H_{12}O_6 \longleftrightarrow 2\,CH_3CH_2OH + 2CO_2 \quad (2)$$

$$C_6H_{12}O_6 + 2H_2 \longleftrightarrow 2CH_3CH_2COOH + 2\,H_2O \quad (3)$$

$$C_6H_{12}O_6 \longrightarrow 3CH_3\,COOH \quad (4)$$

Both acidogenic and acetogenic processes produce $\mathbf{H_2}$ and $\mathbf{CH_3COO^-}$ which are substrates for methanogenic bacteria.

(iii) Acetogenesis

The next stage of acetogenesis is often considered with acidogenesis to be part of a single acid forming stage. The long chains volatile fatty acids (VFA) formed during Acidogenesis are oxidized to acetate or propionate and hydrogen gas by the acetogenic bacteria. The waste product for this process is Hydrogen. For this reason this stage is also known as dehydrogenation. Acetogenic bacteria require a low H_2 partial pressure in order to conserve energy for growth. The role of hydrogen as an intermediary is of critical importance to anaerobic digestion reactions to support the growth of methanogenic bacteria for the conversion of CH_4. The free energy value of the reaction that converts propionate to acetate is shown in equation 5, where 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 **[**14**,** 15]

$$CH_3CH_2COO- + 3H_2O \longleftrightarrow CH_3COO^- + H+ + HCO_3 + 3H_2 \quad (5)$$

$$C_6H_{12}O_6 + 2H_2O \longleftrightarrow CH_3COOH + 2CO2 + 4\,H2 \quad (6)$$

$$CH_3CH_2OH + 2H_2O \longleftrightarrow CH_3COO- + 3H_2 + H^+ \quad (7)$$

The reactions above are two way, releasing H_2. Methanogenic bacteria are responsible for decomposition of the acid phase products into acetate (**CH_3COO^-) .** The acetogenic and methanogenic bacteria use H_2 released in the acetogenic process. In this stage , approximately 70% of CH_4 is formed through the reduction of **CH_3COO^-.** Approximately 25% of CH_3COO^- and about 11% of H_2 are formed in this stage of AD. The VFAs produced in the acidogenic stage are further broken down in this stage by hydrogen - producing acetogenic microorganisms for the production of CH_3COOH, CO_2 and H_2. This is because some amount of H_2O from the previous stages is still available and acts as an electron source to facilitate the conversion of the VFAs.

(iv) Methanogenesis

This the fourth and final stage of the AD process. The methanogenic anaerobic bacteria involved in this final stage, known as methanogenesis or methane fermentation can produce methane in two ways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methanogenic bacteria convert CH_3COOH and H_2 into CH_4. These bacteria are strictly anaerobic such that they are very vulnerable to small amounts of Oxygen (47). They grow slowly and are very sensitive to changes in the environment. They can absorb and digest the smallest of the substrates. The reactions that occur during this stage are as follows. [15,16]

Acetate conversion:

$$2CH_3CH_2OH + CO_2 \longrightarrow 2CH_3COOH + CH_4 \quad (8)$$

Followed by: $$CH_3COOH \longrightarrow CH_4 + CO_2 \quad (9)$$

Methanol conversion:

$$CH_3OH + H_2 \longrightarrow CH_4 + H_2O \quad (10)$$

Carbon dioxide reduction by hydrogen

$$CO_2 + 4H_2 \longrightarrow CH_4 + H_2O \quad (11)$$

The major substrates in this stage are acetic acid, methanoic acid, carbon dioxide and methanol and dimethyl sulfate

According to Sharma KR in his book "Kinetics and Modeling in Anaerobic Processes, in Anaerobic Technology for Bioenergy Production: Principles and Applications, Biogas production process can also be described in a flow diagram has show in figure 2.[17]

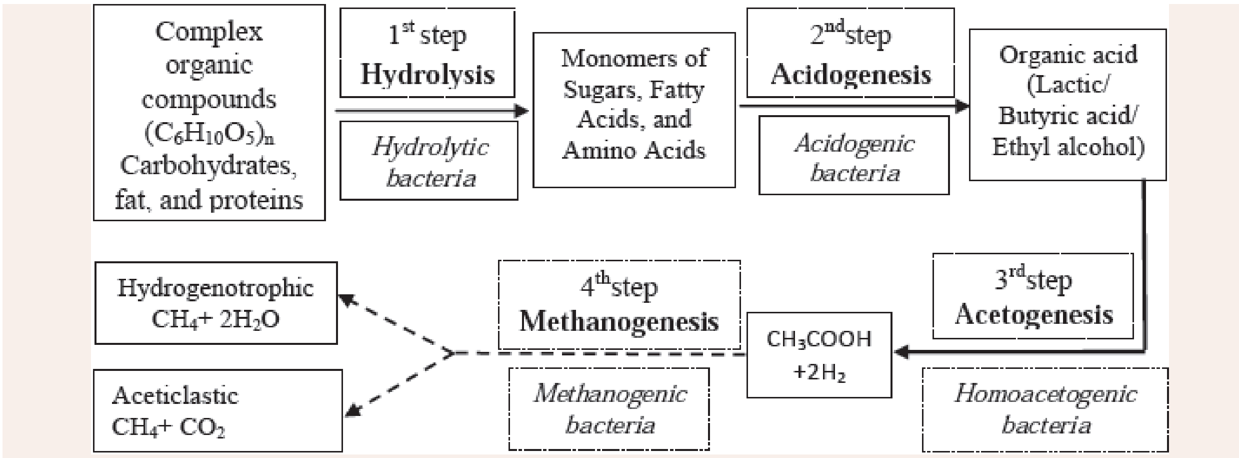

Figure 5. Flow diagram of biogas production by anaerobic digestion

Source: https://www.researchgate.net/publication/320196911

As seen in figure 5 above, anaerobic digestion is only a completed one through all the four stages namely hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. Each stage has its unique microbes(bacteria) that are responsible for digestion in that stage and with dissimilar environmental conditions such as temperature. Figure 6 further illustrates the biochemistry of the biogas production process [13]

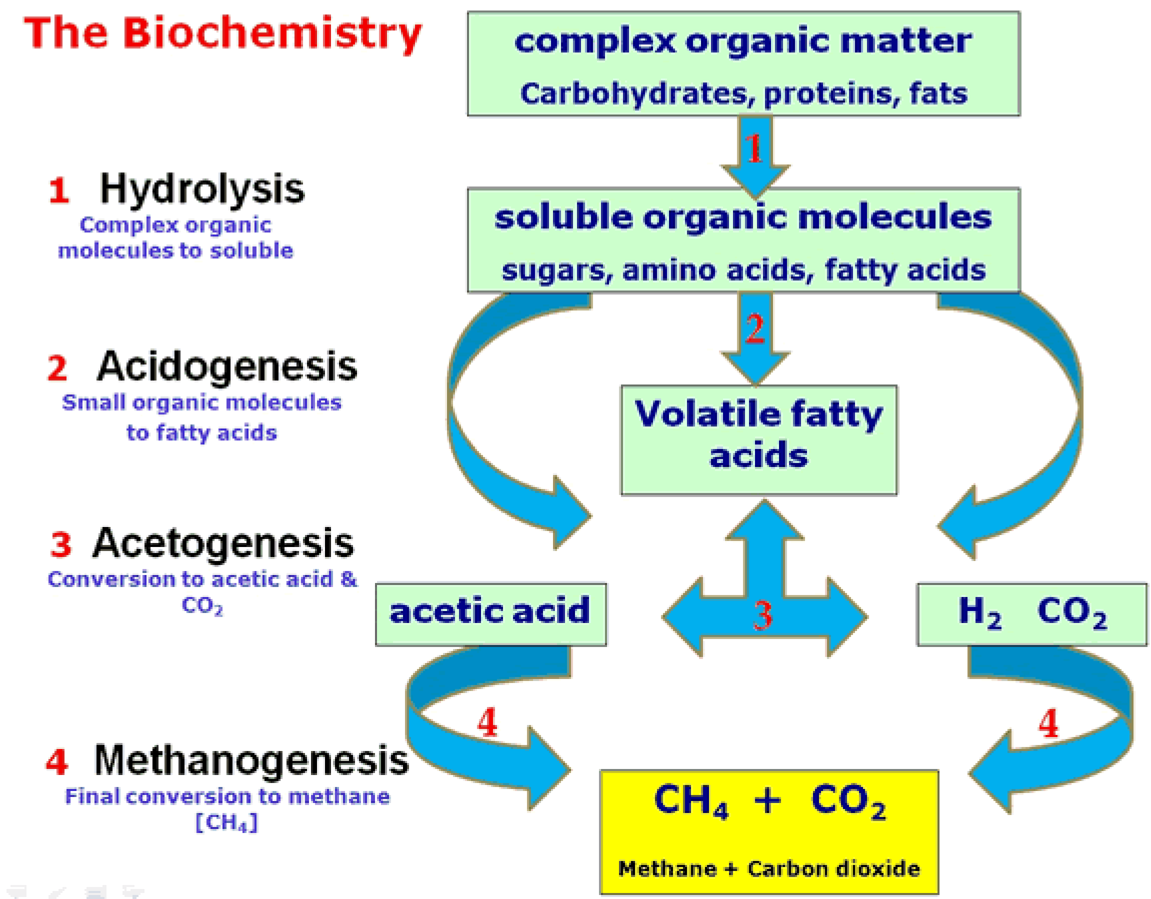

Figure 6. Biochemistry of biogas production

Source: [“http//www.readigesters.com/digesterbasics.php(accessed August, 2010),” 2010.]

The digested waste, called the effluent, exits the bio digester through the digestate/overflow tank and can be used as organic fertilizer for crop production. The gas produced is stored in a chamber called the gas holder. This gas holder can be in the form of a floating drum or a fixed top chamber that forms part of the bio digester. The time taken for the bio digester to produce gas is called the hydraulic retention time (HRT). The hydraulic retention time depends on the type of daily feeding material and biodegradable nature of waste water. A short HRT yields in higher hydrogen production. It restricts Methanogenic activity. On the other hand, a longer HRT induces a shift from acidogenic process to the required Methanogenic process which produces more methane gas than hydrogen gas. In other words, a longer HRT is unfavourable for hydrogen production.[9]

This study is aimed at producing more methane gas than other gases hence a longer HRT is desirable.

2.2.7 Biogas production from human organic waste

According to Marco Bortolin, et al., 2018 in their research paper titled 'Biogas Micro - production from human organic waste', the key results from the lab test of their prototype of the biogas digester showed that a specific biogas production of about $0.15m^3/kg$ in normal conditions with an organic load rate of about $0.417\ kg/m^3/day$ was achievable. The mass fraction of methane in the biogas mix was 74%. Such results were from a full lab test and they recommended that they should be refined and further validated. The areas of refinement included longer digestion time (hydraulic retention Time, HRT), slurry composition variations for co-digestion, environmental condition changes and different tank designs[18]

Their prototype was a small scale domestic anaerobic digester to produce biogas for local micro-consumption. The system included a waterless toilet connected to a simple bio digester for biogas micro-production under anaerobic conditions. They simulated the one-day living conditions of a 5 person family. They followed the mixing composition which had been already carried out by another researcher in this field and was as follows: 3 kg of human faeces, 1.9 kg of urine and 0.9 kg of raw water. The mixing ratio of human waste to water that included urine was almost 1: 1. The organic load rate was adapted to normal conditions and was $0.417\ kg/m^3/day$.[18]**.** The study also explored the three major types of domestic biogas digesters used in developing countries, their means of construction, their advantages and disadvantages. The tree common designs are the plug flow digester, the fixed dome digester and the floating drum digester

2.2.8 Influence of temperature on biogas production efficiency

Literature review was done to find out about the influence of temperature on biogas production efficiency with an aim of relating the temperatures of Phalombe Boarding Secondary School where a biogas plant will be constructed. Literature revealed that temperature remains one of the crucial factors which are responsible for the reaction rate, stability and microbial activities during anaerobic digestion of biodegradable waste in the reactor/bio digester.

According to Shiwei Wang, Fang Ma, et al in their article entitled "Influence of Temperature on Biogas Production Efficiency and Microbial Community in a Two-Phase Anaerobic Digestion System", the results of the influence of temperature on biogas efficiency and the microbial community structure showed that the contents of solluted chemical oxygen demand (SCOD) and Volatile Fatty acid(VFA) in the acidogenic and methanogenic phases maintained temperature levels ranging from 25 -35 ^oC. It was also found out that methane content of biogas could be maintained higher than 50% if temperatures were above 25 ^oC. In their analysis of microbial community structure, it was found out that the dominant functional bacteria were acinetobacter, acetitomaculum and bacillus in the acidogenic phase and cernachaeum in the methanogenic phase at the above range of temperature. These are the bacteria responsible for anaerobic digestion of biodegradable waste.

It was also reported in this article that the performance of the acidogenic and methanogenic phases could decrease at a lower temperature of 20^{o}C. Thus for high biogas production efficiency, moderate temperatures of above 25 ^{o}C were desired [19]. Phalombe district has average monthly temperature of 27.5 ^{o}C which is favourable for biogas production. The temperatures in Phalombe District go above 38 ^{o}C in February, May, September and October. **(Appendix 9).**

Zilin Song, Jiajia Qin et.al in their study to find out the effect of human excreta mixture on biogas production, they carried out a laboratory scale- simulated experiment using self designed constant temperature anaerobic fermentation equipment. The results showed that increasing the temperature during biogas production improved biogas generation efficiency of human excreta. It was also concluded that the other way of improving biogas generation efficiency of human excreta is by co-digesting it with agriculture wastes such as wheat or corn straw which have high carbon content. This high carbon content is required to improve the carbon /nitrogen (C/N) ratio during anaerobic digestion [20].

According to Ramaraj and Yuwalee Unpaprom in their research article titled "Effect of temperature on the performance of biogas production from duckweed", the effect of fermenter temperature on biogas and methane production efficiency were investigated. The results showed that as temperature was increased there was an increase in the biogas and methane production. The highest amount of methane production was when the bio digester was operated at 35 ^{o}C. At this temperature biogas production was 10377 ml and methane yield was 64.47% [21].

In the study of Production of Biogas from Banana and plantain peels, Llori OM, Adebusoye AS et.al reported that temperature is one of the crucial factors in biogas generation during anaerobic digestion. This is so because methane producing bacteria operate most efficiently at temperatures ranges of 30 - 40 ^{o}C(mesophilic temperature) or 50 -60^{o}C (thermophilic temperature) [22].

2.2.9 Co - digestion of biodegradable wastes

Various studies have been carried out on co-digestion of biodegradable waste and its advantages. Shanti Kala Adhikari, et al. in their research paper titled 'Improving Biogas production efficiency through co-digestion of cattle dung with crop residues : a case study in Nepal' found out that co-digestion of crop residues with cow dung could improve domestic biogas production up to 150% compared to the single digestion. Their findings suggested that co-digestion improved biogas production efficiency by supplementing the daily feedstock deficit and better nutrient value [23].

Cheerawit Rattanapan, Lalita Sinchai et.al carried out a study on co-digestion of canteen food waste and domestic water waste under organic loading rate and temperature optimization. The food waste used in the study was collected at a university in Thailand. The results they got showed that the Carbon/Nitrogen (C/N) ratio was **5.29** $\pm 2.40 : 1$**.** This was so because the domestic waste water used had a low concentration of carbon source [24]. According to Lin et al the optimum C/N ratio for anaerobic digestion is **20 - 30:1**[25]**.** Therefore there is need for co-digestion with domestic waste water with wastes which have high carbon content. These wastes include agriculture wastes such as rice husks/bran. It was reported that co-digestion with these agriculture wastes would improve anaerobic digestion potential. Also co-digestion of canteen food wastes with municipal waste water improves the C/N ratio. It also improves the stability of the co-digestion process [27].

Many recent studies have shown that co-digestion of food wastes is an economical and a viable solution to reduce energy demand by the every growing global population. It is economically a good solution to avoid waste. Hence the suggestion by Kochi, K.; Plabist, M. et al to co-digest food wastes and other wastes [26]**.**

Food wastes provide several advantages if used as daily feeding materials for bio digesters. These advantages include low total solid(TS) content, high soluble organic content, ease of degradability and high energy content per amount of dry mass [27]**.**

However, this depends on the source of the food wastes. According to De Clercq et.al**,** Restaurant and canteen food waste account for 50% of the total amount of food waste.[28]**.** Kitchen wastes contain high nitrogen components and thus generation of high concentration of ammonia is inevitable [29]**.** Addition of nitrogen rich- substrates such as animal manure could balance the combustion of carbon rich biomass such as rice straw and further increase the biogas yield and volumetric production rate [30]. According to S.O Dahunsi et al, the results of their study of co-digestion of food waste and human excreta for biogas production showed that co-digestion of food waste and human excreta were good substrates for biogas production hence the need to effectively use them to solve problems resulting in environmental pollution from use of fossil and wood fuels, deforestation and land degradation resulting from the use of firewood as sources of energy for cooking, heating and lighting [31]. Mukumba, P. et al carried out a study in co-digestion of cow manure and donkey manure. The results showed that the highest biogas yield was obtained by mixing 50% cow manure and 50% of donkey manure by mass. In their study they also found out that cow manure produced lower gas yield than donkey manure. The reason was that donkey manure have a higher caloric value than cow manure and hence produce more biogas with a higher methane content than cow manure. Their study concluded that co-digestion was one and simple way to optimize biogas production rate [32].

2.3.0 Productivity and stability of bio digester systems

According to Linus Naik, Bedru Balana et al, productivity of a bio-digester system is defined as the amount and quality of the biogas evolved per unit of feedstock fed into the system while Stability of the bio-digester system is defined as the consistency in the amount of gas produced and the regularity of the production**.** In their article, they reported that research had been done to determine the main factors that affect productivity and stability of anaerobic digestion. These include microbial population in the bio-digester, Acidity (pH) of the substrate in the bio-digester, the carbon to nitrogen (C/N) ratio in the substrate, temperature in the bio digester, particle size of the substrate, the organic loading rate (OLR), the hydraulic retention time (HRT) total solid content (TS value), inhibition and toxicity of the substrate. [33]

For the four stages in a anaerobic digestion namely hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis to be carried out successfully, microbial population is of paramount importance because each stage is carried out by different sub sets of microorganisms, operating in their own niche environment [34]**.** This population is naturally occurring. However inoculation is important during the early stages of the digestion process and is done by introducing microbial material such as cow dung before the intended substrate is added. This will reduce the start up phase to reach maximum production very soon [35]**.**

During anaerobic digestion, different digestion stages require different levels of pH. For example, a pH of 5.5 to 6.5 is required for Acidogenic bacteria. A pH of 7.8 - 8.2 is preferred for methanogenic bacteria [36]**.** The pH affects the functionality of the microorganisms [34].

If the pH gets too low, the Methanogenesis cannot convert the organic acids produced from the hydrolysis phase. Organic acids lower the pH and hence the system fails. The organic acids produced in the hydrolysis phase posses inhibitory substances such as volatile fatty acids (VFA), ammonium and sulphides. So the best way to control this problem is by making sure that the substrate is either alkaline or not easily hydrolyzed so as to cause a drop in the pH [33].

2.3.1 Factors that influence biogas production

(i) **The carbon - nitrogen mass ratio (C/N).**

The biodegradable material should not have too much nitrogen to avoid evolvement of ammonium gas which inhibits the digestion process. At the same time, the substrate should not have too much carbon which causes the hydrolysis process to be completed too quickly and the pH to drop. The optimum C/N ratio is **20 - 30: 1** [37]. If the C/N ratio is too high (the substrate having excess carbon in it) the anaerobic digestion will slow down. Table 6 shows the C/N ratio for some commonly used biodegradable wastes

Table 6. C/N ratio for some biodegradable raw materials [38]

Raw material	C/N Ratio
Duck dung	8
Human excreta	8
Chicken dung	10
Goat dung	12
Pig dung	18
Sheep dung	19
Cow dung	24
Water hyacinth	25
Municipal solid waste	40
Elephant dung	43
Maize straw	60
Rice straw	70
Wheat straw	90

(ii) Temperature: In general, the higher the temperature, the higher the rate of anaerobic decomposition. However at higher temperatures above 65^{o}C, the rate of biogas production decreases because the microbial population starts to die. So large scale anaerobic digestion systems are designed to operate at either mesophilic temperatures(30 - 40 ^{o}C) or thermophilic temperatures(50 - 60^{o}C) with constant temperature achieved by isolation and thermal heating [27]**.**

(iii) Particle size: The smaller the particles in the substrate the higher the productivity of the bio-digester system due to the increased surface area for increased biological activity [27]**.**

(iv) Organic loading Rate (OLR): For maximum biogas production the organic loading rate needs to be optimized. If the OLR is higher than normal, the digestion process becomes unbalanced. This is due to the excessive production of Volatile Fatty Acids (VFA). These acids are inhibitory to the anaerobic digestion process. If the loading rate is maintained, based on frequent or continuous additions of substrate to the bio digester, a good result of biogas production will be obtained.

Ejiroghene Kelly Orhorhoro, Patrick Okechukwu Ebunilo, et al in their study to find the effect of organic loading rate on biogas yield reported that in order to have a stable bio digester, a loading rate of 1.4 kg $VS/m^3.d$ was recommended and can yield the highest production of methane at 64% and a rate of 0.25 m^3 CH4/kg VS input [39].

(v) Hydraulic Retention Time(HRT) : For maximum efficiency of the digester, the HRT should be optimized. If the HRT is too high, the microbial population leaves the system before it can reproduce and degrade the waste.

(vi) Inhabitation and toxicity: The microbes responsible for anaerobic digestion can be inhibited by substances present in the effluent waste. These are ammonium, halogenated compounds, heavy metals, cyanide and the metabolic by-products of micro organisms such as ammonium, volatile fatty acids and sulphide [40**,** 41].

2.3.2 Advantages of anaerobic digestion process

Anaerobic digestion of biodegradable waste has several advantages. The following are some of the advantages**:**

(i) Anaerobic digestion reduces the emission of the greenhouse gases by maximizing the production of methane gas. Methane is an environmental friendly gas.

(ii) The digestate, which remains after anaerobic digestion is rich in plant nutrients such as Nitrogen, Phosphorous and Potassium. Hence it is used as organic fertilizer.

(iii) The odour associated with decaying matter is reduced if animal wastes are digested anaerobically.

(iv) The biogas produced and the organic fertilizer from the digestate can be sold, thereby generating income from wastes.

(v) Anaerobic digestion is capable of destroying a variety of pathogenic and faecal micro-organisms that can be detrimental to human health

2.3.3 Biogas usability and its equivalent values

Table 7 shows biogas usability and equivalent values when applied for lighting, cooking, fuel replacement, shaft power and electricity generation. Table 8 confirms that co-digestion of animal waste, human waste and agriculture waste can yield more biogas than single digestion.

Table 7. Biogas usability and equivalent

Application	**1 m^3 biogas equivalent**
Lighting	Equal to 60 - 100 Watt bulb for lighting for 6 hours
Cooking	Can cook 3 meals per day for a family of 5 to 6 people
Fuel replacement	0.7 kg of petroleum
Shaft Power	Can run a one horse power motor for 2 hours
Electricity generation	Can generate 1.25 kWh of electricity

Source: Journal of Energy in Southern Africa, cape Town, 2018

Table 8 shows the ultimate biogas yields for some biodegradable materials

Table 8. Ultimate gas yields for some different materials

Materials	**Yield(m^3/kg daily solids)**
Cow manure	0.34
Poultry manure	0.48
Human manure	0.40
Straw/rice bran/rice husks	0.17
Grass	0.43

Leaves	0.30
Water hyacinth	0.40

Table 8: Source: Omer, 2009c [57]

2.3.4 Advantages of co-digestion of biodegradable wastes

The existing literature shows that there is potential in co-digestion of biodegradable wastes to produce biogas. However, co-digestion is not practised in Malawi. Of the few biogas plants that have been installed, there no plant that runs on co-digestion. From the existing literature it is clearly shown that co-digestion has many advantages over single digestion. Some of these advantages are:

(i) Co-digestion improves biogas production efficiency by supplementing the daily feedstock deficit and better nutrient value.

(ii) Co-digestion of canteen food wastes with other wastes such as rice straw, human waste and municipal waste water improves the C/N ratio. It also improves the stability of the co-digestion process.

(ii) Many recent studies have shown that co-digestion of food wastes is an economical and a viable solution to reduce energy demand by the every growing global population. It is economically a good solution to avoid waste which can cause GHG emissions whose effects are global warming and climate change. It is for these advantages that the design of a co-digestion biogas plant is desired for use at Phalombe Boarding Secondary School

CHAPTER THREE

3.1 RESEARCH METHODOLOGY AND DESIGN

This chapter describes the methods used by the researcher to come up with the proper design of the biogas plant at Phalombe Boarding Secondary School. The areas covered in this chapter are: Research procedure which include study area and its population, study focus group, data collection methods which include personal/face to face interviews, observation methods and questionnaire method. A detailed analysis of the research methodology is done which includes baseline survey and energy demand assessment at the school. The factors to consider when designing a biogas plant. Selection of the type of biogas plant to be designed for use at Phalombe boarding Secondary School is made through several steps that include comparisons based on construction materials, life span, ease of operation, thermal insulation, digester volume/capacity, gas storage, gas pressures, methane emission, maintenance costs, agitation and corrosion resistance. Using these factors, ranking method for selecting the best type of biogas plant for this study has been applied. The Fixed Dome Biogas has been selected and designed.

3.2 Research procedure

3.2.1 Place of Study

This study was carried out at Phalombe Secondary school. The school is 1 km away from the central district of Phalombe and is situated 0.5 km away from Michesi Hill Forest which is the other source of firewood for the school's kitchen activities**(Appendix 6).** The firewood is supplied to the school by people who sign contracts with the school(**Appendix 1**). But this is through illegal cutting down of forest trees by these suppliers since individual woodlots cannot meet the demand for firewood at the school and surrounding areas

3.2.2 Study focus group

The researcher engaged the school head and its members of staff to come up with the total energy demand at the school. The researcher also engaged village heads to establish the availability of livestock that would provide daily feeding material(substrate) for the bio digester at the school to supplement the already available daily feeding material at the school. The village heads engaged were Mbodi, Bokosi and Seven. Also interviewed were owners of rice mills around Phalombe Secondary School who could provide rice husks/bran for free to be used for co-digestion.

3.2.3 Data collection methods

The researcher used various methods of data collection for this study which included literature reviews concerning biogas plant designs and biogas production using different bio degradable wastes either as single substrate or co-digested with other wastes, questionnaire, interviews and observation. Primary data was collected through baseline survey that included a questionnaire **(Appendix 1)** and personal observations at and around Phalombe secondary school where the study was carried out. Telephone interviews were also used to collect more data. Secondary data was collected through literature reviews, that included books, journals/articles and websites. Data gathered from literature review was used to determine the type of biogas to be used at Phalombe secondary School. Data for daily feeding material (DFM) was collected from both surrounding households and the administrator of the school . Also collected was data on the number of times of cooking per day at the school, number of staff and students at the school, disposal of kitchen waste, and annual temperatures of Phalombe district. All this data was required to come up with an appropriate design of a biogas plant that could supply Phalombe Secondary School with the right amount of gas for cooking and lighting. Other design considerations were based on the hydraulic retention time and total solid content in the manures. From literature review, the TS value desired is 8% and HRT is greater than 20 days. From this information, a TS value of 8% and HRT of 40 days was used in the design calculations for the biogas plant to be constructed at Phalombe Secondary School.

3.2.3.1 Interviewing and observation methods

Due to travel restrictions between countries due to covid-19 pandemic, the researcher engaged the head teacher of Phalombe Secondary school to administer a questionnaire that was designed by the researcher to get as much information as possible from the community surrounding the school**.(Appendix 1).** But before this, in August 2019 the researcher personally visited the study area to appreciate the energy crisis Phalombe Secondary School was facing in carrying out its kitchen activities such as cooking. It was observed that the only affordable source of energy for cooking and heating was firewood. There were piles upon piles of wood fuel at the school's kitchen.(**Appendix 4).** The researcher was also privileged to have face-face interviews with both the head teacher of the school and its head cook to appreciate the need for an alternative source of energy to be used at the school..

3.2.3.2 Questionnaire method

The researcher designed a simple and very clear questionnaire to make sure every respondent understood and answered the questions easily. It had close ended as well as open ended questions but the questions which were dominant were close ended questions. The respondents were the administrator of the school, the head cook, the three village heads surrounding the school and owners of rice mills around the school.

(**Appendix 1**)

3.2.4 Detailed analysis of the research methodology

3.2.4.1 Baseline survey

This is the first activity which a researcher undertakes in order that he establishes what the situation is at a place of his research study before the project is implemented. This is the primary research where data is gathered first hand from source by asking individuals questions either in person, on paper, by phone or online. For this study, the tools used in the survey were face to face interviews, online and questionnaire methods. This survey was conducted at Phalombe Secondary School and its surrounding areas. The survey at the school was conducted by the researcher to collect as much information as possible on the status of energy use/demand at the school for both cooking and lighting while the baseline survey in the surrounding areas of the school was conducted to assess the availability of substrate to supplement human and canteen food waste once the biogas plant had been constructed and started operating. Face to face interviews were conducted involving members of staff at the school, cattle farmers and rice millers in the surrounding areas of the school. The first baseline survey involving face to face interviews was conducted by the researcher in 2019 at the school and in the villages surrounding the project site. This year,2020, due to travel restrictions from one country to another as a result of the COVID-19 pandemic, the researcher prepared and sent a questionnaire to the relevant authorities of Phalombe Boarding Secondary School in Malawi to administer the questionnaire on his behalf. The respondents of this questionnaire were the administrator of the School, Mr. Paul Naluso, the head cook at the school, the village heads and rice millers surrounding the school. The questionnaire is attached in **appendix 1.**

3.2.4.2 Energy demand assessment

Through a questionnaire, data for energy demand for cooking and lighting was collected **(Appendix1).** This helped the researcher to know how much electrical energy per day was being used by the school for lighting in the school class rooms, staff houses, kitchen, laboratories and hostels. Also collected was data on the amount of firewood the school was using per school term. The electrical energy demand and the energy demand for firewood were then summed up and converted into biogas equivalence. It was from this sum of energy demand that the calculations for the size of the biogas plant were based. The respondents of the questionnaire on electrical energy demand at the school for lighting were the head teacher of the school and other members of staff on duty during evening study times at the school. On the demand for firewood, the respondent of the questionnaire was the head cook. The respondents for energy demand for lighting at staff houses of the school were the head teacher and his fellow members of staff who are housed in the school compound. The electrical energy demand requirement was based on electrical energy used by the staff members for lighting in their houses, electrical energy used in the class rooms and offices for lighting during study times, electrical energy used in the laboratories, student hostels, student kitchen, dining hall/canteen and store room where kitchen facilities are kept . The electrical energy demand in kWhr was summed up and converted to energy demand in Joules/day. This was then be converted to biogas flow rate per day(m^3/day) as biogas equivalent from electricity demand. Wood energy demand was calculated based on the amount of firewood the school is using in an academic term or year. This was then converted to the amount of fire wood the school uses per day. Using the firewood to biogas- equivalent conversion, the researcher came up with the amount of biogas in m^3 required per day(m^3/day) for cooking at the kitchen as an alternative source of energy.

The total amount of biogas required per day at the school for cooking and lighting was calculated by summing up the biogas equivalence for electrical lighting and firewood to biogas equivalent in m^3/day. Using the sum of biogas equivalence per day required at the school for cooking and lighting, the amount of human waste required per day to be fed into the digester was determined. Based on the total amount of substrate to be fed into the bio digester (human and kitchen waste) and an estimated HRT of 40 days, the sizing of the Biodigester, Gazometer and the Digestate Collecting Tank was carried out.

3.2.4.3 Factors to consider in designing a biogas plant

In the design of a biogas plant suitable to co-digest biodegradable organic waste, with high production of biogas, several factors have to be considered. Factors such as the type of waste, rate of chemical degradation, type of biogas reactor and local environmental conditions have a major influence on the performance of such plants.

In order to produce methane gas, there are important conditions to be fulfilled and these include the following: a substrate which is well mixed, a working temperature of around 35^{o}C in the bio digester, a substrate which has a good C/N ratio. The recommended C/N ratio ranges from 20 to 30:1. The recommended total solid(TS) content in the substrate. This is 8%. And the rate at which the biodegradable organic materials are fed into the bio digester. This is called the Organic feeding rate. If the bio digester is overfed, volatile fatty acids will accumulate in the bio digester. These fatty acids will inhibit microbes which are responsible for anaerobic digestion [1, 42]**.**

The biogas plant at Phalombe Secondary School will use human waste from students and staff toilets, kitchen wastes, animal waste and rice husks/bran. Because human waste has a C/N ratio of 8,Table 6 [38], there is need to improve this ratio by using rice straw. This will improve the rate of chemical degradation in the biodigester, thereby increasing biogas production.

3.2.4.4 Selection of the type of biogas plant

The tool used for this method was literature reviews on the common types of biogas plants in use globally for biogas production namely the Floating drum, Fixed dome and the Polythene tube biodigester. The researcher gathered information of these types of biogas plants in terms of construction methods, availability of materials used in construction, durability of materials, gas pressure holding ability, gas leakage trough walls, gas pressure capacity, their life span, gas holding capacity, maintenance costs, their versatility in terms of construction(in high or low weather conditions), methane emission from each type and other factors that should be considered when designing a biogas plant were sourced through this literature search. Each type of the three biogas plants mentioned above was thoroughly evaluated and the best design suitable for use at Phalombe Secondary school was selected. Ranking method was used for the selection process **(Table 9)**

3.2.4.5 Ranking method for selecting the best type of biogas plant for the design

For decision making, criteria - based tables and scales were drawn from which the best type of biogas plant to be designed for use at Phalombe Boarding Secondary school was selected. The ranking method that had a scale of 0 to 3 scores was used for the selection process with 3 as the highest score and 0 the lowest score under each design objective/criterion. Table 9 shows the results of the ranking method

Table 9. Ranking method of design selection

Design objective/Criteria	**Evaluation scale**	**Floating Drum Biogas plant**	**Fixed Dome Biogas plant**	**The Polyethylene Tube Biogas Plant**
Thermal insulation	Table 4	1	3	1
Digester volume/Sizing	Table 1	2	3	1
Methane emission	Table 1	2	3	1
Maintenance cost	Table 3 & 4	1	2	3
Life span	Table 3	2	3	1
Gas storage	Table 1	2	3	1

Gas pressure	Table 1	2	3	1
Gas leakage through walls	Table 1	2	3	1
Ease of construction	Table 3	2	1	3
Durability of materials	Table 1	1	3	2
Cost of construction	Table 4	2	1	3
Availability of construction materials	Table 1 & 2	3	3	3
Agitation	Table 1	2	3	0
Corrosion resistance	Table 4	1	3	3
TOTAL SCORE		**25**	**37**	**24**

Based on detailed information above about each of the three types of biogas plants, the fixed dome was selected. Although high skilled labour is required in the construction of a fixed dome bio digester, it has several advantages over the other types of bio digesters in anaerobic digestion as shown in the table of comparison, advantages and disadvantages (**Tables 1 & 3**). Therefore it was the preferred choice in the design selection. It consists of a digester with a fixed, non movable gas holder which sits on top of the digester .When gas production starts, the slurry is displaced into the overflow tank. Gas pressure increases with the volume of the gas stored and the height of difference between the slurry level in the digester and the slurry level in the compensation tank. There are no rusting steel parts in its construction hence long life (20 years or more). The plant is constructed underground, protecting it from physical damage and saving space. The underground digester is protected from low temperatures at night and cold seasons.

CHAPTER FOUR

4. 1 SYSTEM ANALYSIS AND DESIGN

4.1.1 Design of the biogas plant

Calculations for the sizing of the Biodigester tank, Gazometer, Digestate collection tank and Mixing tank were performed based on energy demand and available substrate at the school. These calculations were based on the fixed dome biogas plant which was selected as the best design suitable for use at Phalombe Secondary School. The information used in the design was taken from the following articles/books [44, 45].

4.1.2 Parameters to consider when designing a biogas plant

The size of a biogas plant depends on the following factors: Quantity of available biomass, Quality of available biomass. Kind of biomass, The digesting temperature [1,8].

According to Ogur, E.O. et al, designing of the bio-digester should also take into consideration the following parameters: The size of the digester to be constructed, The purpose for which it has been designed
The sizing of the digester is also based on parameters such as:

(i) **Health criteria.** If the purpose of constructing the bio digester is to reduce possible transmission of disease, parameters such temperature and the hydraulic retention time (HRT) are of paramount importance to allow complete digestion

(ii) **Production of organic fertilizer or soil conditioner.** In this case, parameters of paramount importance are stabilization of the bio digester and the means by which the digestate will be stored.

(iii) **Production of energy source**: in this case, to get optimum gas production, the following parameters must be taken into consideration: the type of biodegradable materials to be fed in the bio digester, the concentration of the substrate, the kinetic constants. Here temperature plays a great role. The changes in temperature will affect kinetic constants.

(iv) **End user requirements**: The design of a bio digester based on end user requirements will take into consideration important parameters such as the availability of water in that area, the availability of daily feeding materials, financial input and climatic conditions of that particular area, including its geographical location. The output parameters include the energy required by the end user for cooking, heating or lighting. So this can be energy requirement in kWh or methane requirement in cubic meters per day [45]. This design has taken the 'end user requirement' approach.

4.1.3 Designing the size of a biogas plant

All biogas plants have two useful parts that help to design the size of biogas plants. These parts are the digester which is the tank body and the gazometer which is commonly known as the dome. So for design calculations these two main parts are considered. Other parts which have to be calculated are the sizing of the mixing tank and the digestate tank.

The volume /size/capacity of a biogas plant depends on the hydraulic retention time(HRT) and the daily feeding material (DFM). The daily feeding material consists of organic biodegradable materials and water to be mixed with it. In this research DFM include human waste, cow dung, canteen food waste and waste water. Rice bran/straw will be used for improving the C/N ratio of human waste.

Phalombe secondary school has an enrolment of 562 students and 195 members of the staff including their dependants **(Appendix 1).** According to literature research, one adult human produces an average of 0.5 kg of human waste [48]. Therefore with a population of 757 people at the school, 378.5 kgs of human waste are expected per day. For a simple biogas digester, the hydraulic retention time is at least 40 days. But practical experience has shown that hydraulic retention time can reach as far as 60 to 100 days if there is shortage of daily feeding material. However, long hydraulic retention times can increase the amount of gas produced by the bio digester by 40% of the initial production **[37].** Since this study's main objective was to come up with a big plant required to produce large quantity of biogas to satisfy the needs of the school, a hydraulic retention time (HRT) was to be estimated at 40 days(minimum).

4.1.4 Design calculations

4.1.4.1 Energy demand calculations

The main objective of this study was to design a biogas plant that would curb deforestation in Phalombe district by use of a renewable, clean and affordable energy source for cooking at Phalombe Secondary School. To come up with the correct size of the biogas plant that can serve the two purposes of cooking and lighting at the school, detailed calculations were carried out to determine the energy demand at the school as shown in table 10 (a, b, c, d, e and f).

Table 10(a, b, c, d, e, f): Energy demand calculations

Description	Energy demanded
8 Study class rooms, 2 x 22 W fluorescent bulbs per class and lighting time of 4 hours(18:00 - 21:00 Hrs)	$8 * 2 * 4 * \frac{22}{1000} = \mathbf{1.4\ kWh}$

b. Laboratories

Description	Energy demanded
Biology, Chemistry and Physics labs, 2 x 22 W fluorescent tubes each, lighting time of 4 hours	$3 * 2 * \frac{22W}{1000} =$ **0.4 kWh**

c. Student hostels

Description	Energy demanded
12 hostels, 10 rooms per hostel, each room uses 1 x 22 W fluorescent tube, 5 hours lighting time **(18:00 - 22:00 Hrs)**	$12 * 10 * 5 * \frac{22W}{1000} = \mathbf{13.2\ kWh}$
2 x 22 W security lights per hostel for 10 hours(18:00 - 04:00 Hrs)	$2 * 12 * 10 * \frac{22W}{1000} = \mathbf{5.3\ kWh}$

d. Staff houses

Description	**Energy demanded**
40 houses, 3 bulbs per house, 10 W with an average lighting period of 6 hours (18:00 - 00.00 Hrs)	$40 * 3 * 6 * \frac{10W}{1000} = 7.2\ kWh$
One security light of 22W per house with a lighting period of 10 hours	$1 * 40 * 10 * \frac{22W}{1000} = 0.8\ kWh$

e. Students Kitchen

Description	**Energy demanded**
3 x 22 W fluorescent tubes for 6 hours lighting	$3 * 6 * \frac{22W}{1000} = \mathbf{0.4\ kWh}$
2 x 22 W fluorescent tubes security lights for 10 hours	$2 * 10 * \frac{22W}{1000} = \mathbf{0.4\ kWhr}$

f. Dining Hall and Store room

Description	**Energy demanded**
Dining hall: 8 x 22 W fluorescent tubes for 2 hours	$8 * 2 * \frac{22W}{1000} = \mathbf{0.4\ kWh}$
Store room: 1 x 22 W fluorescent tube for 6 hours	$1 * 6 * \frac{22W}{1000} = \mathbf{0.1\ kWh}$

Total energy demand = (1. 4 + 0.4 + 13.2 + 5.3 + 7.2 + 0.8 + 0.4 + 0.4 + 0.4 + 0.1) kWh = 29.6$\approx$ $\mathbf{30\ kWh}$

4.1.4.2 Energy conversion

$1\ kWh = 3.6 * 10^6\ Joules$

Therefore 30 kWh = $3.6 * 10^6\ joules * 30 \frac{kWh}{1kWh} =$ **$108\ MJ$/day**

Assuming that this is possible with a HRT of 40days as per researcher's design and using the calorific value of biogas as 20MJ/m^3, then daily biogas flow rate can be calculated as follows:

Daily Biogas flow rate = daily energy requirement ÷ calorific value of fuel = $\frac{108\ MJ}{20\ MJ}$ = **5.40 m^3/** day.

4.1.4.3 Firewood to biogas equivalent

Phalombe Secondary School uses 52 tons of firewood in a school calendar. The school runs on three terms of 12 weeks each on average. 12 weeks is equal to 84 days

Therefore the number of tons of firewood required per day = $52 * \frac{1}{3*84}$ = **0.206 ton/**day

But 1 ton = 1000 kg

Therefore 0.206 ton /day = $1000 * 0.206 \frac{kg}{day} = \mathbf{206\ kg}\ /day$

According to Biogas Digest Volume III, Biogas applications and product development, biogas costs and benefits, ISAT , GTZ,

1m^3 biogas = 5.5 kg of firewood [47]

So if 5.5 kg = 1m^3 of biogas,

Therefore 206 kg of firewood = $1 * \frac{206}{5.5}\ m^3\ of\ biogas$ = 37.45.27 **m^3/day**

Therefore total amount of biogas required at Phalombe Secondary School for lighting and cooking is equal to (5.40 m^3 + 37.45 m^3**)/day = 42.85 m^3/day**

Quantity of human waste required = (Amount of gas produced per day)÷ Gas production per kg from human waste = $\frac{42.85}{0.15}\ kg = \mathbf{286\ kg}$**/day. [38]** With the number of people at Phalombe secondary being 757 and on average a human being produces 0.5 kg of human waste, we expect the amount of human waste produced in a day to be 0.5 * 757 kg **= 378.5 kg/day.** This amount of human waste exceeds the requirement per day. Therefore Phalombe secondary School has enough human waste to supply the digester to be constructed at the school.

From this organic material (ORM) will be added kitchen waste of 60 kg/day

Therefore total ORM = (286 + 60) kg/day = **346 kg**/day

Add 1:1 ratio of ORM to Water = 346kg/day *2 **= 692** kg/day substrate

And according to Momoh et al (2013),[44]

Total solids (TS) = 16% of mass of substrate = 16% * 692 kg/day = 110.72kg/day

Quantity (Q) of substrate is given as Q = TS/8%

Therefore the required Q $=\frac{110.72}{0.08}\ kg = \mathbf{1384}\ kg$/day

4.1.5 Sizing of the Digester, Gazometer, Digestate Collection Tank and Mixing Tank

4.1.5.1 Sizing of the Digester

Given Q = **1384 kg/day, HRT = 40 days** and **density of slurry = 1000kg/ m^3**

The operating volume of the digester, $V_o = Q * \frac{HRT}{1000}\ m^3 = 1384 * \frac{40}{1000}\ m^3 = \mathbf{55.36\ m^3}$

But $\mathbf{V_o = 90\%\ V_T}$ where V_T is total volume of the digester [38]

Therefore $\mathbf{V_T = V_o/90\%} = \frac{55.36}{0.9}\ \mathbf{m^3 = 61.51\ m^3}$

According to Momoh et al 2013, the height of a digester is **4 times** its radius

i.e**. h = 4r**

But $V_T = \pi r^2 h = \pi r^2 * 4r = 4\pi r^3$

$V_T \div 4\pi = r^3$

$r = \sqrt[3]{(61.51/4\pi)}$

$= 1.698\ m = \mathbf{1.7\ m}$ [44]

Diameter of the digester = $2r = 2 * 1.7m = 3.4\ m$

Height of the digester = $4r = 4 * 1.7\ m = 6.8\ m$

4.1.5.2 Sizing the Gazometer

According to M.I. Alfa et al 2017, the volume of biogas from cow dung per kg = 0.000616 m^3[44]**.** According to Omar 2009 (table 2), biogas yields (m^3 / kg daily solids) for cow manure and human wastes are 0.3 and 0.4 respectively. The difference between the two yields is very small. The yield from human waste will be improved by the addition of canteen food wastes as per the researcher's design of the biogas plant. For this reason a value of 0.000616 m^3 is used to calculate the volume V_g of the gazometer as follows:

V_g = Volume of biogas/day * DFM * HRT

Where Volume of biogas per day = 0.000616 m^3, DFM = 692 kg/day and HRT = 40 days

$V_g = 0.000616\ m^3/kg *$ 692 kg/day * 40 days = **17.05 m^3**

An allowance of 10% is given.

Therefore $V_g = V_g + (0.1 * V_g) = 17.05 + (0.1 * 17.05)m^3 = \mathbf{18.76\ m^3}$

In practice, the ratio **$V_g : V_o$** where V_o is the operating volume of the digester, which is commonly used is between **1:3** and **1:5** [43, 44, 47]. According to this design the ratio is 18.76 : 55.36 = **1:3** so the design is feasible.

Taking the height the gazometer to be 4 times its radius, the diameter and height of the gazometer can be calculated as follows:

$V_g = \pi r^2 h$ where h = 4r

$V_g = \pi r^2 * 4r = 4\pi r^3$

$r = \sqrt[3]{(Vg/4\pi)} = \sqrt[3]{(18.75/4\pi)} = \mathbf{1.14\ m}$

D = 1.14 m *2 = $\mathbf{2.28\ m}$, H = 1.14 m *4 = $\mathbf{4.56\ m}$

4.1.5.3. Sizing the Digestate collection Tank (Overflow tank)

The Digestate tank can take the shape of a rectangle, square or circle. For the digestate collection tank a 10% allowance is given for mixing

(i) Circular tank sizing

Volume of collection tank, V_c = Vo + (0.1xVo)

V_c = 55.36 + (0.1 x 55.36)

V_c = 60.89 m^3

The height of the tank is 1.5 times its radius

But $V_c = \pi r^2 h$

Therefore $V_c = \pi r^2 x\ 1.5 r$

$V_c = \pi r^3 x\ 1.5$

60.89 = 1.5 πr^3

$r^3 = 40.597\ m$

r **= 3.44 m**

D **= 6.88 m**

h = 1.5r = 1.5 x3. 44 m **= 5.16 m** $\approx \mathbf{5.0\ m}$ [44]

(ii) For a square base tank, the volume will remain the same i.e 60.89 m^3 and height of 5.0 m

Volume, $V = L^2 * H$

Therefore 60.89 m^3 = 5.0 L^2

$\boldsymbol{L^2 = 60.89/5.}$ = 12.178 m^2

$\boldsymbol{L = \sqrt{12.178\, m^2} = 3.5\, m}$

4.1.5.4. Sizing mixing tank for kitchen wastes/agriculture waste/ cow dung

Since the tank will be accommodating 60 kg of kitchen wastes per time, the following dimensions have been suggested to be reasonable:

Depth of mixing tank = 1.0 m

Diameter of mixing tank = 0.9 m

Volume of mixing tank = $\boldsymbol{\pi r^2 h}$ $= \pi \times (0.3\ m)^2 \times 1.0\ m$= **0.28 m^3**

Table 11 shows a summary of the sizing of the designed Fixed Dome Biogas plant.

Table 11. Summary of the sizing of the Fixed dome biogas plant

Parameter	**Volume(m^3)**	**Height(m)**	**Radius(m)**	**Diameter (m)**	**Thickness (m)**	**Length (m)**	**Width (m)**
Bio-digester	61.51	6.80	1.70	3.40	0.32	-	-
Gazometer	18.76	4.56	1.14	2.28	0.32	-	-
Mixing tank for Kitchen waste	0.57	0.90	0.45	0.90	0.15	-	-
Digestate Tank	60.89	5.00	3.44	6.88	0.0.32	3.50	3.50

4.1.6 Development of a detailed biogas plant drawing

Detailed drawings were produced to be used by the masonry builders when constructing the biogas plant. A computer aided Design (Auto CAD) software was used for the drawing in figure 8 while figure 7 was sourced from Rwandan Standards Board. This is the standard Fixed dome biogas plant that is used worldwide. The major dimensions in table 12 are from the calculations in the sizing of the Digester tank, Gazometer, Digestate tank and the Mixing tank.

The detail drawing in figure 7 will be used by the masonry builders to construct a biogas plant at Phalombe Secondary School. The Mixing and Biodigester (Reactor) tanks are cylindrical while the Digestate tank is square

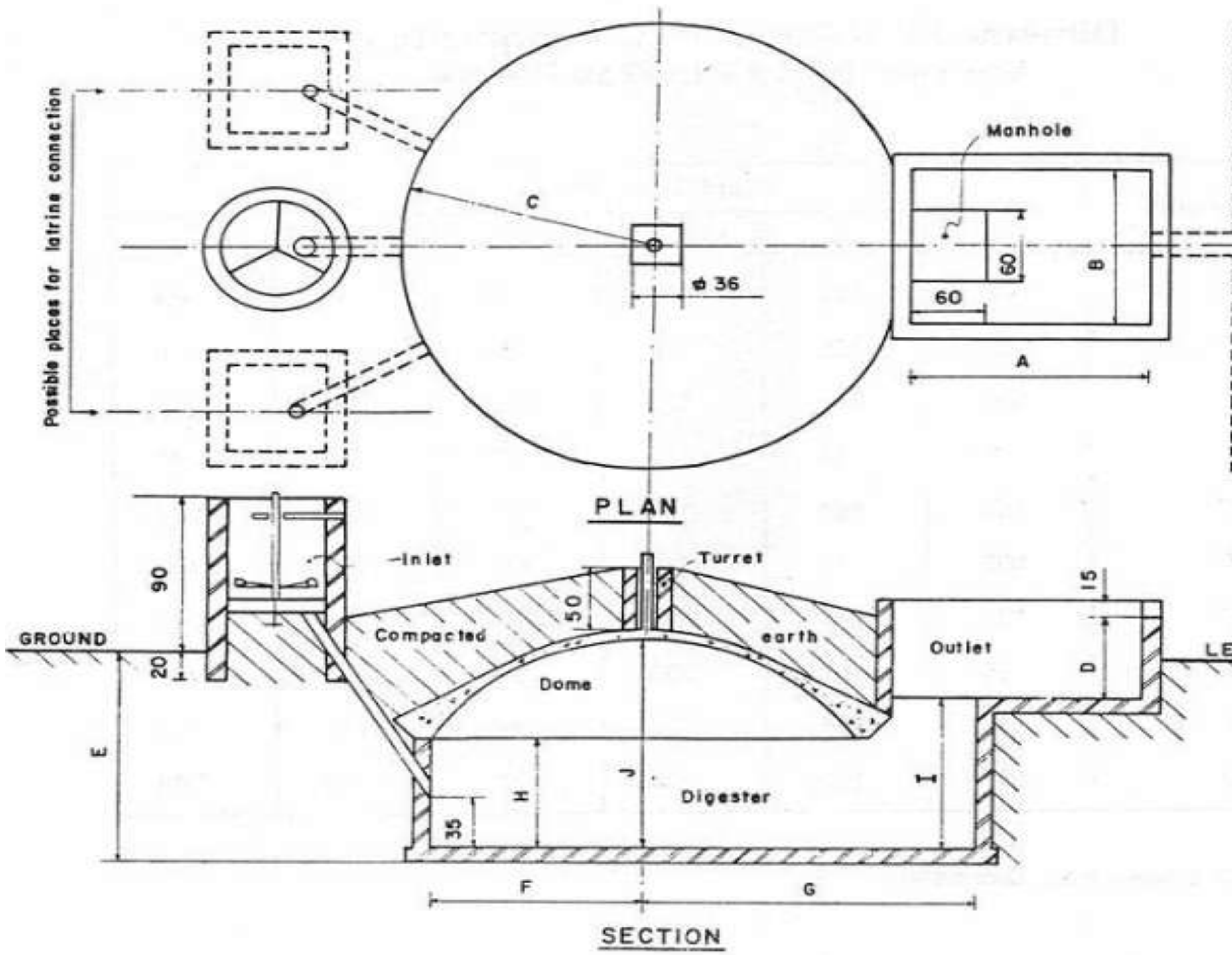

Figure 7. Detail drawing of Fixed Dome Biogas Plant

Source: Rwandan Standards Board DRS 306

Table 12. Major dimensions of the fixed dome biogas plant.

Component	Dimension (m)	Component	Dimension	Component	Dimension
A	3.50	E	6.80	J	6.80
B	3.50	F	1.70		
C	1.70	G	2.62		
D	5.00	H	5.66		
E		I	5.86		

4.1.6.1 Biogas Plant design layout

Figure 8 shows biogas plant layout out Phalombe Boarding Secondary School

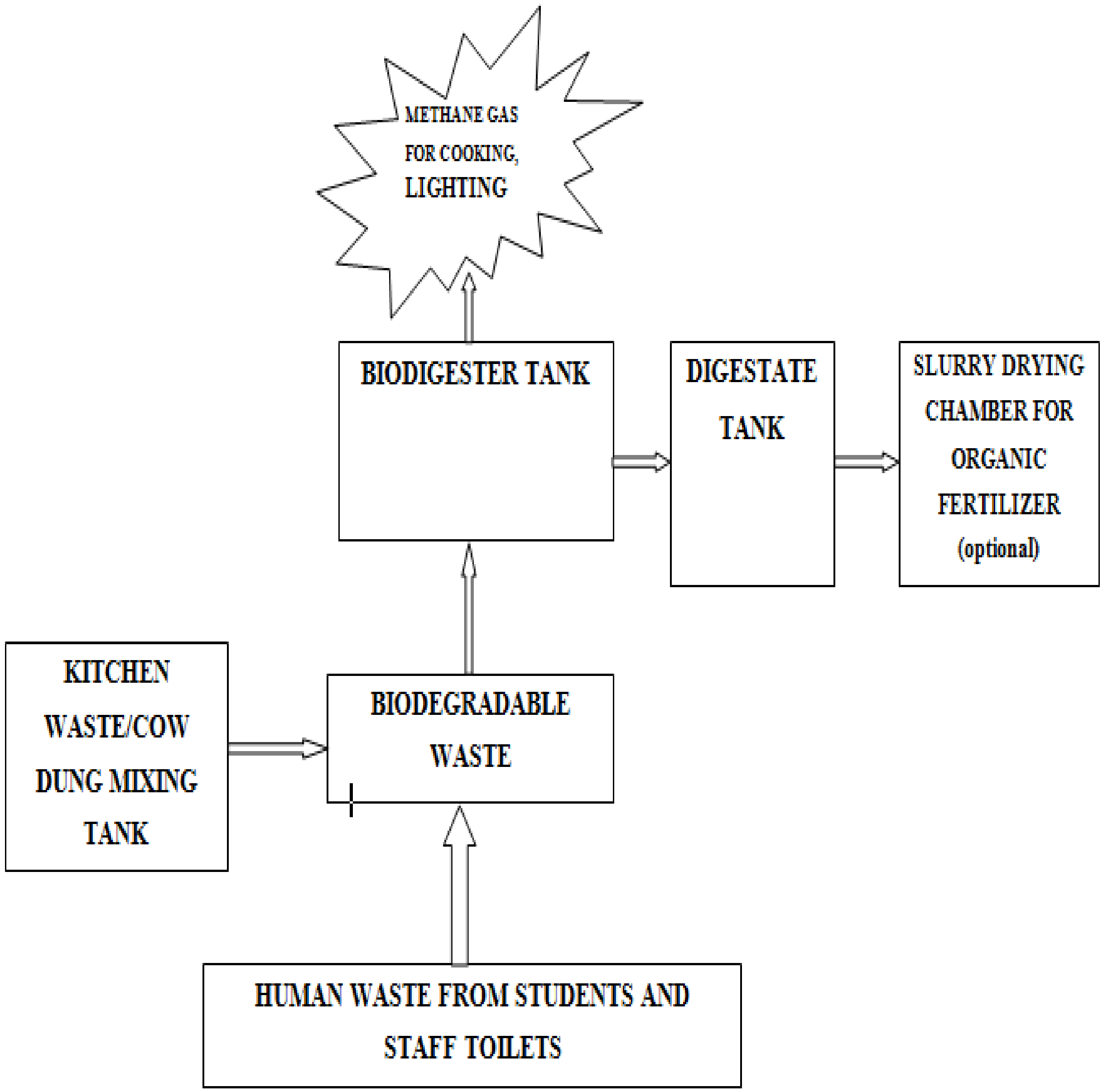

Figure 8. Biogas plant layout

4.1.7 Design cost estimates

The size of the designed biogas plant was used to estimate the cost of building this biogas plant at the school. The costs of using firewood for cooking and electricity for lighting at the school were compared with that of building the designed biogas plant. Bills of quantities for the sized biogas plant were used to come up with the cost of constructing the biogas plant at the school. The cost estimate is as follows:

4.1.7.1. Costing of the biogas plant

Table 14 shows a bill of quantities for the 62 m^3 biogas digester

Exchange rate: MK800 = US$1

Table 13. Bill of quantities for a 62 m^3 biodigester

ITEM	DISCRIPTION	QTY	UNIT	UNIT PRICE ($)	AMOUNT ($)
1	**ACCESSORIES**				
	Black enamel paint	15	Litres	20.0	300.00
	110 mm PVC Pipe	20	length	8.75	175.00
	Watering can	3	No	5.0	15.00
	Flexible hose	600	meter	0.38	228.00
	Wheelbarrow heavy duty	2	No	50.00	100.00
	Thread tapes	12	No	0.044	0.53
	Shovels (excavation work)	4	No	10.00	40.00
	Hoes/ handles (excavation work)	6	No	4.38	26.28
	Pails	3	No	6.25	18.75
	Black plastic sheet	2	No	4.38	8.76
	Butterfly valves or Gate valve	6	No	6.88	41.28
	G.I. Union 0.5 inch	10	No	0.63	6.30
	G.I. Elbow 0.5 inch	10	No	0.63	6.30
	G.I. Tee joint 0.5 inch	10	No	0.63	6.30
	G.I. Socket 0.5 inch	12	No	0.63	7.56
	G.I. Nipple 0.5 inch	12	No	0.63	7.56
	G.I. Pipes 0.5 inch	14	length	8.75	122.5

	G.I. R. Bush 0.5 inch	20	No	0.63	12.60
	Lime	10	kg	0.75	7.50
	Paint brush	4	No	4.38	17.52
	Wire brush	2	No	4.38	8.76
	SUBTOTAL				**1156.50**
2	**BUILDING MATERIALS**				
	Bricks	20,000	No	0.025	500.00
	Transport			50.00	50.00
	Cement (50kg)	60	Bags	10.00	600.00
	Transport			50.00	50.00
	Quarry stones	12	Tons	10.63	127.56
	Transport			10.00	10.00
	Fine Sand	4	Tons	2.50	10.00
	Transport			18.75	18.75
	Course sand	10	Tons	6.25	62.50
	Transport			10.00	10.00
	SUBTOTAL				**1,388.81**
3	**OTHER COSTS**				
	Shuttering materials	60 pieces of timber	No	1.25	75.00
	Transport				37.50
	Outlet covers (student and staff kitchens)	2	No	4.38	8.76
	Training of biogas users	2	days		125.00
	SUB TOTAL				**246.26**
4	**LABOUR**				
	Mason (skilled)	2	No	5.00/day for	300.00

				30 days	
	Casual labour (water/ construction)	6	No	37.5	225.00
	Plumber	2	No	5.00/day for 10 days	100.00
	SUBTOTAL				**625.00**
5	**ADMINISTRATION**				
	Board & Lodgings	1	No	25.00/day for 30 days	750.00
	Communication	1	No	1.45/day for 30 days	43.50
	Consultation, reporting, supervision fee	1	No	21.00/day for 30 days	630.00
	Transport / fuel	1	No	12.50/day for 30 days	375.00
	Survey	1	No	31.25/day for 2 days	62.50
	SUBTOTAL				**1,861.00**
	GRAND TOTAL				**5,277.57**

4.1.8 Simulation of biogas production using quantities of substrate in the design

A Biogas software called Online Biogas App (OBA) was used to simulate biogas production from the amount of substrate that was calculated/estimated in the design. Three biogas production simulations were run **(Figures7 - 9)** using

(i) Human waste only as a substrate

(ii) Canteen food waste only as a substrate and

(iii) Mixture of Human and Canteen food waste (Co-digestion)

The results for each simulation were then analysed

4.1.8.1 Design Simulation

This design simulation was based on the type of biomass, amount of biomass, molecular composition of the biomass, PH in the biodigester and the temperature required for methane gas production. This Biogas Simulation software was written and developed by Sasha D., Hafner and Charlotte Rennuit with assistance from Jon Katz. The name of the Software is Online Biogas App (OBA).

4.1.8.2 Inputs and outputs for OBA simulation Software

The inputs for this simulation process are as follows:

(i) Substrate composition (%)

(ii) Mass of the substrate (kg) or L/kg

(iii) Substrate biodegradability (%) DM

(iv Substrate partitioning to cell synthesis (%)

(v) Reactor pH and

(vi) Reactor temperature (^{o}C)

The outputs are as follows:

(i) Methane production

(ii) Carbon dioxide production

(iii) Nitrogen production and other impurities

(iv) Total Biogas production

In order to generate more biogas, the temperature in the biodigester must be increased [21]**.** Methane producing bacteria will operate most efficiently if temperatures in the biodigester are in the range of 30 - 40 ^{o}C for the mesophilic bacterial activity and 50 - 60 ^{o}C for the thermophilic bacterial activity [22]. The thermophilic temperature is responsible for methane production and is reached after a longer HRT (40 - 60 days). A longer HRT is favourable for the production of more methane gas than a shorter HRT which produces more hydrogen gas than methane [34]. A pH of 7.8 to 8.2 is preferred for methanogenic bacteria to digest the waste for production of methane gas [25]. It is against this background that simulation used a temperature of 55 ^{o}C and pH of 7.8 (neutral) to calculate biogas production.

This biogas plant uses human waste as well as kitchen food waste as biomass material for feeding the biodigester. The parameters for each type of biomass are tabulated in table 14

Table 14. Parameters for simulation of biogas production

Biomass	**Quantity in kg**	**Macro molecular composition**	**Temperature in the reactor with HRT of 40 days**	**pH in the reactor**
Canteen food waste	60	Carbohydrate 45%, Proteins 15%, Lipids 40%	55 ^{o}C	7.5
Human Waste	286	Carbohydrates 7-15% (average 11%) Water 65% Ash 15% Fats/lipids 15% Nitrogen 3% Protein 3%	55 ^{o}C	7.5
Canteen Food waste plus Human waste (Co-digestion)	346	Carbohydrate 56%, Protein 18%, Ash 15%, Lipids 30%		

4.1.9 Results of simulation

4.1.9.1 Simulation of biogas production from human waste

The amount of human waste whose mass was 286 kg as amount of organic material in the design was used as input into the digester. The macromolecular composition of the human waste was 11% carbohydrate(DM), 3% protein (DM), 15% lipids (DM) and 15% ash (DM).Since human wastes are highly biodegradable, the substrate degradability was estimated at 90%. The reactor pH was 7.5 with a mesophilic temperature of 55 ^{o}C. Figure 9 shows the results of theoretical gas production using human waste

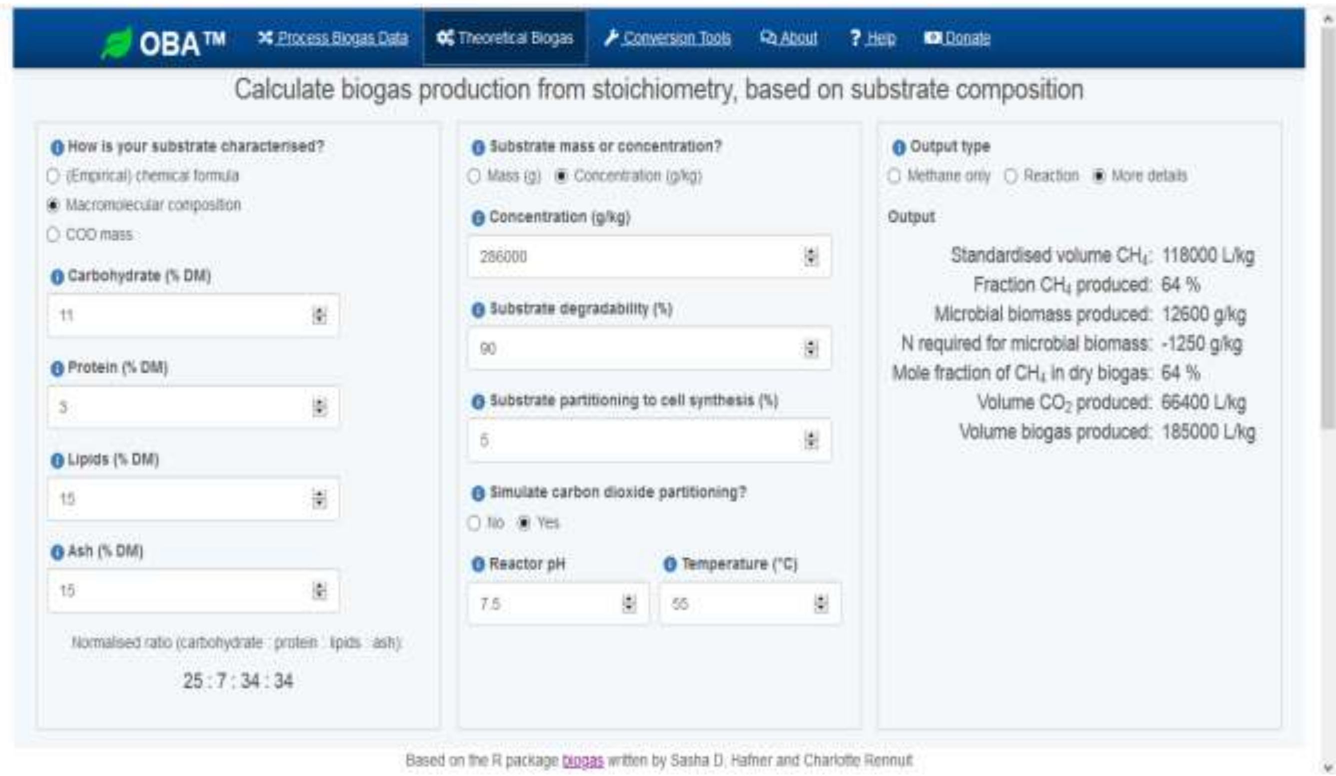

Figure 9. Theoretical biogas production from human waste

4.1.9.2 Simulation of biogas production from canteen food waste

The amount of canteen food waste whose mass was 60 kg as amount of organic material in the design was used as input into the digester. The macromolecular composition of the canteen food waste was 45% carbohydrate(DM), 15% protein (DM), 40% lipids (DM) and 0% ash (DM).Since canteen food wastes are highly biodegradable, the substrate degradability was estimated at 90%. The reactor pH was 7.5 with a mesophilic temperature of 55 ^{o}C. Figure 10 shows the results of theoretical gas production using canteen food waste

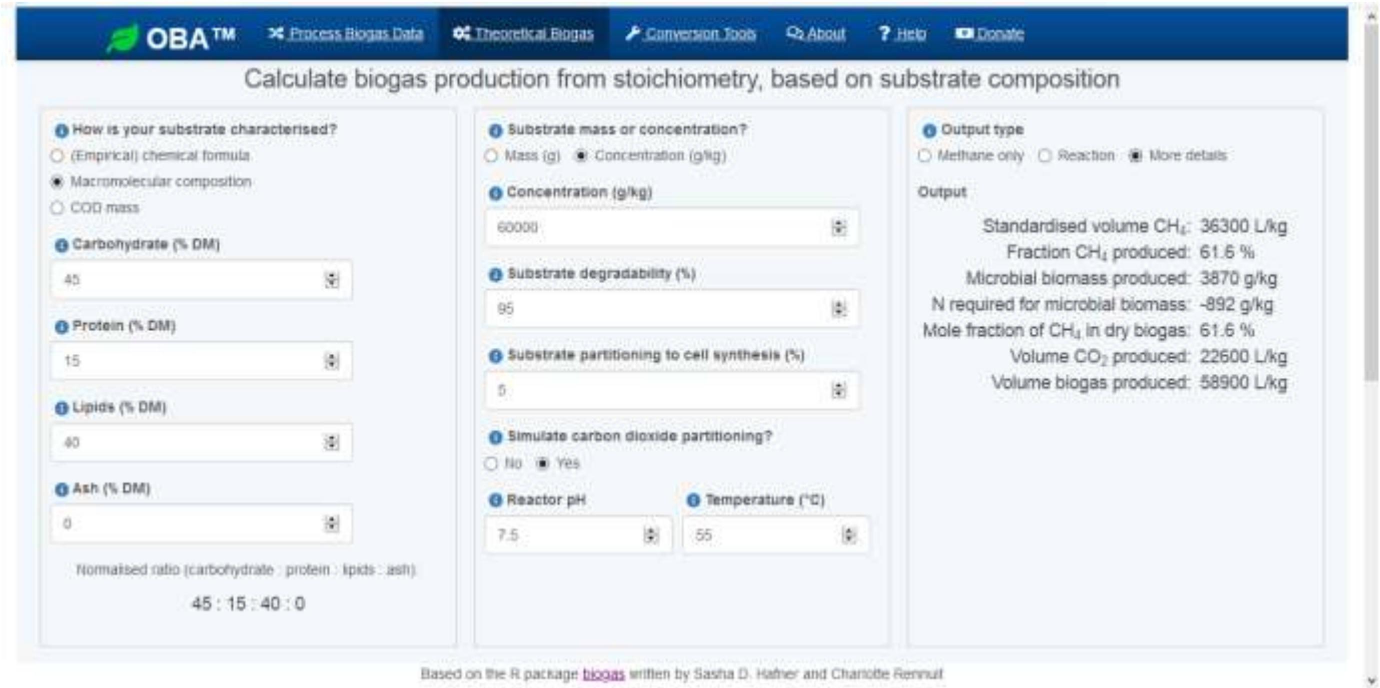

Figure 10. Theoretical biogas production from canteen food waste

4.1.9.3 Simulation of biogas production using co-digestion of human and kitchen food waste

The amount of canteen food waste whose mass was 60 kg was mixed with 286 kg of human waste making a total co-digestion substrate of 346 kg as amount of organic material in the design was used as input into the digester. The macromolecular composition of the mixture was 56% carbohydrate(DM), 18% protein (DM), 30% lipids (DM) and 15% ash (DM).Since both human and canteen food wastes are highly biodegradable, the substrate degradability was estimated at 90%. The reactor pH was 7.5 with a mesophilic temperature of 55 ^{o}C. Figure 11 shows the results of theoretical gas production using co-digestion of human and canteen food wastes

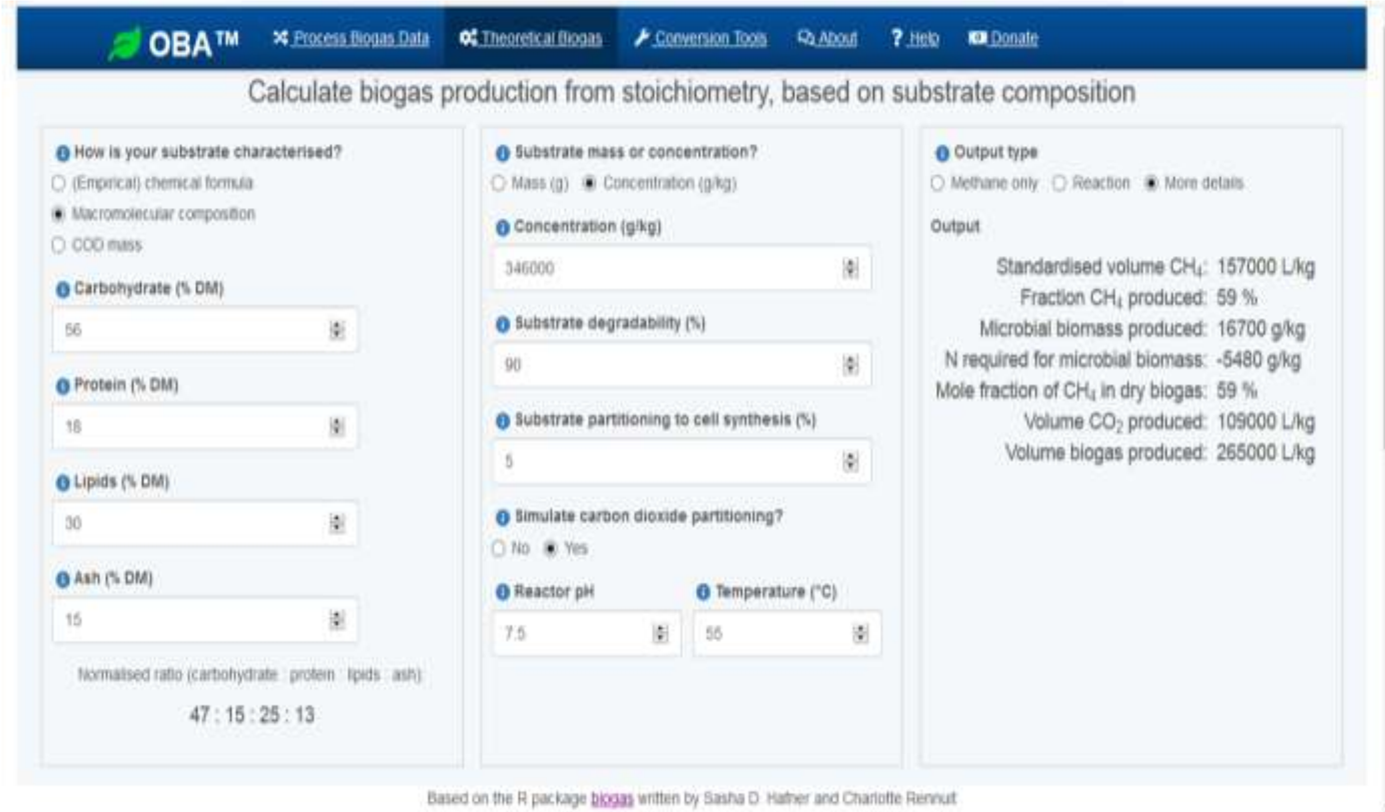

Figure 11. Theoretical biogas production from co-digestion of human and canteen food wastes

CHAPTER FIVE

5.1 RESULTS AND DISCUSSIONS

This chapter presents the results of the design including simulation of biogas production, comparison of the results with existing literature, discussion of the feasibility of the design, cost comparison between the design and the continued use of firewood as the source of energy for cooking at Phalombe Secondary School.

Introduction : This study design was based on the use of human and canteen food waste as substrate for the biodigester to produce methane gas that could be used for cooking and lighting at Phalombe Secondary School to replace firewood. With a school population of 757 people, design calculations/estimations were performed to find out the amount of human waste required per day. the design came up with an amount of human waste as 286 kg/day. An estimated 60 kg of canteen food waste per day was used, making a total ORM of 346 kg/day. These wastes were co-digested for biogas production. Based on the energy demand at the school, a $61m^3$ biogas plant that could co-digest these wastes was designed using theories from different researchers/articles.

5.1.1 Simulation of the design

Using human waste and canteen food waste separately as substrates and then using the mixture as substrate simulations were run (**figures 9 - 11**). The results were as follows:

5.1.1.1 Simulation 1: Theoretical biogas production from human waste

Table 15 shows the theoretic biogas production from human waste.

Table 15. Results of Simulation 1 from human waste

Input (Biomass)	**Qty (kg)**	**Macromolecular composition**	**Substrate degradability (%)**	**Temperature in the digester with HRT of 40 days**	**pH in the digester**	**Output**
Human Waste	286	Carbohydrates 11% Ash 15% Lipids 15% Protein 3%	90	55°C	7.5	Standardized volume of CH_4 118000L/kg **118m^3/kg,** Fraction of CH_4 produced **64%,** Mole fraction of CH_4 in dry biogas **64%,** Volume of CO_2 **66400L/kg** (**66.4m^3/kg)** Volume of biogas produced **185000L**/kg **(185m^3/kg)**

5.1.1.2 Simulation 2: Theoretical biogas production from canteen food waste

Table 16 shows the theoretic biogas production from canteen food waste

Table 16. Results of Simulation 2 from canteen food waste

Input (Biomass)	**Qty (kg)**	**Macromolecular composition**	**Substrate degradability (%)**	**Temperature in the digester with HRT of 40 days**	**pH in the digester**	**Output**
Canteen food waste	60	Carbohydrates 45% Ash 0% Lipids 40% Protein 15%	90	55°C	7.5	Standardized volume of CH_4 **36300L/kg (36.3m^3/kg),** Fraction of CH_4 produced **61.6%,** Mole fraction of CH_4 in dry biogas **61.6%,** Volume of CO_2 **22600L/kg (22.6m^3/kg)** Volume of biogas produced **58900L/kg (58.9m^3/kg)**

5.1.1.3. Simulation 3: Theoretical biogas production from co-digestion of human and canteen food wastes

Table 17 shows the theoretical biogas production from co-digestion of human and canteen food wastes

Table 17. Results of Simulation 3 from co-digestion of human and canteen food wastes

Input (Biomass)	**Quantity (kg)**	**Macromolecular composition**	**Substrate degradability (%)**	**Temperature in the reactor with HRT of 40 days**	**pH in the reactor**	**Output**
Human Waste +Canteen food waste	346	Carbohydrates 56% (DM) Ash 15% (DM) Lipids 30% (DM) Protein18% (DM)	90	55°C	7.5	Standardized volume of CH_4 **157000L/kg ($157m^3/kg$)** Fraction of CH_4 produced 59**%,** Mole fraction of CH_4 in dry biogas 59**%,** Volume of CO_2 **$109000m^3/kg$ ($109m^3/kg$)** Volume of biogas produced **265000L/kg ($265m^3/kg$)**

5.1.2 Analysis of the results and discussion

5.1.2.1 Simulation 1 analysis

Simulation 1 used 286 kg of human waste as feedstock, having macro molecular composition of 11% Carbohydrate, 15% Ash, 15% Lipids and 3% Protein. Having knowledge that the most common food at the school comprises maize flour, beans and vegetables, its degradability was assumed to be very high hence 90% was chosen. HRT was 40 days. With the reactor running at a pH of 7.5 and temperature of 55^oC, the total volume of biogas produced was 185000 L/kg (185m^3/kg) from which . the amount of CH_4 produced was 118000L/kg (118 m^3/kg) representing 64% methane gas from the total biogas produced. The amount of CO_2 produced was 66400L/kg(66.4 m^3/kg) representing 35.9% of the total gas produced.

5.1.2.2 Simulation 2 analysis

Simulation 2 used 60 kg of canteen food waste as feedstock, having macro molecular composition of 45% Carbohydrate, 0% Ash, 40% Lipids and 15% Protein. The degradability of canteen food was assumed to be very high hence 90% was chosen. HRT was 40 days. With the reactor running at a pH of 7.5 and temperature of 55^oC, the total volume of biogas produced was 58900 L/kg (58.9m^3/kg) from which . the amount of CH_4 produced was 36300L/kg (36.3 m^3/kg) representing **61.6%** methane gas production from the total gas produced. Amount of CO_2 produced was 22600L/kg(22.6 m^3/kg) representing **38.4%** of the total biogas produced.

5.1.2.3 Simulation 3 analysis

In simulation 3, 286 kg of human waste was co-digested with 60 kg of canteen food waste. The macro molecular composition of the mixture was 56% Carbohydrate (DM), 15% Ash(DM), 30% Lipids (DM) and 18% Protein(DM). The degradability of the mixture was assumed to be very high hence 90% was chosen. HRT was 40 days. With the reactor running at a pH of 7.5 and temperature of 55^oC, the total volume of biogas produced was 265000 L/kg (265m^3/kg) from which the amount of CH_4 produced was 157000L/kg (157 m^3/kg) representing **59%** Methane gas production from the total gas produced. The amount of CO_2 produced was 109000L/kg(109 m^3/kg) representing **41%** of the total biogas produced.

5.1.3 Graphical presentation and analysis of the results

Figures 12 and 13 show pie chart and bar charts for the mole fraction of methane in dry biogas produced from co-digestion of human and canteen food wastes

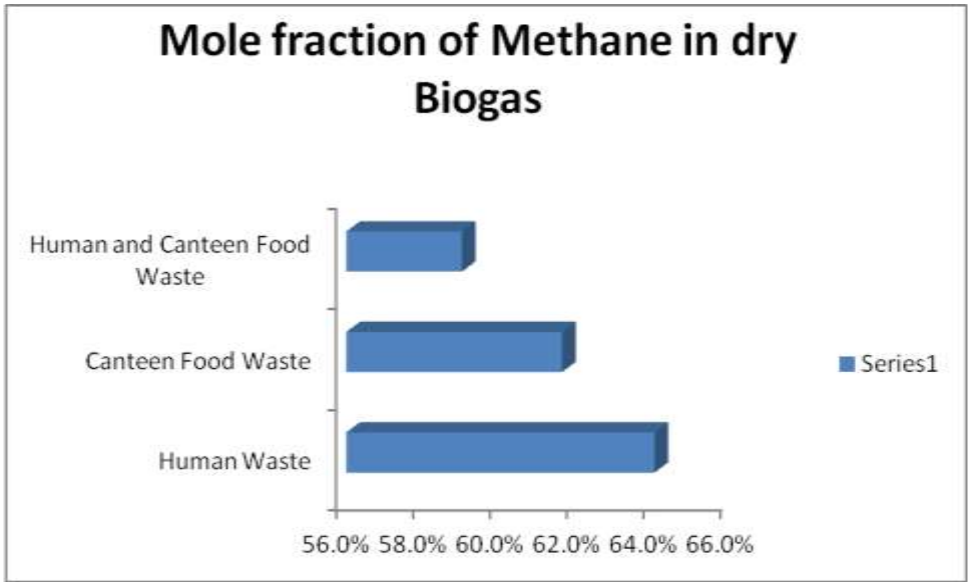

Figure 12. Bar chart showing Mole fraction of Methane in dry biogas

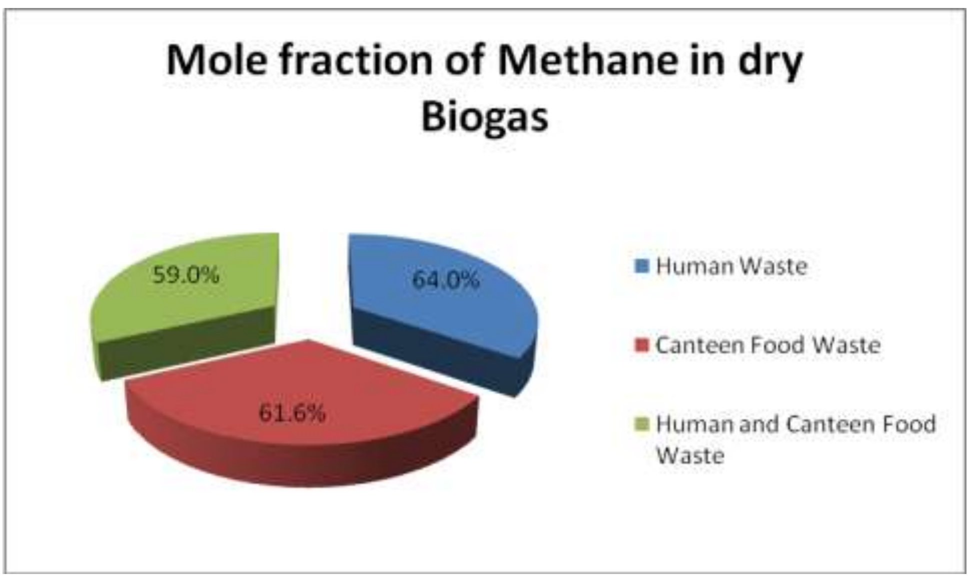

Figure 13. Pie chart showing Mole fraction of Methane in dry biogas

From the two graphs in figures 12 and 13 above it shows that single digestion of human waste and canteen food wastes gives results of 64% and 61.6% respectively. When the two types of wastes are co-digested, they also give a fairly good result of 59%; a figure which is within the bracket of 55 % - 65% methane composition in Table 5 **[11**]

From the simulation results 1 and 2 it can clearly be seen that both substrates(human and Canteen food waste) have the potential of producing enough biogas, with gas constituent compositions well comparable with table 5 **[11].**

Similarly if the two substrates are co-digested, it can also be seen that enough methane that is well comparable to the constituent compositions that we have in table 5 [11]. Study [45] reported that the quantity and quality of biogas produced from biodegradable wastes largely depends on the nature and composition of the digester feedstock, temperature, organic loading rate, HRT and C/N ratio. Proper management of the production process is also of great importance. This simulation exercise did not show the C/N ratio. In general, anaerobic microbes utilize carbon 25 - 30 times faster than nitrogen. So for efficient biogas production, the C/N ratio in the feedstock should be maintained at 20 - 30:1 [33, 34**].** This is the optimal value that can give out enough methane gas. However, the designer of this study will use rice straw/bran to improve the C/N ratio during the anaerobic co- digestion of these wastes. Plants such as rice straw have high percentage of carbon. For example rice straw has a C/N ratio of **70:1** Table 6 [38] such that it can be mixed with materials of low C/N ratio such as human waste to maintain this optimum C/N ratio thereby increasing the methane yield.

5.1.4 Comparison of simulated results with published results

5.1.4.1 Study of co-digestion of food waste and human excreta for biogas production

In the study of co-digestion of food waste and human excreta for biogas production [31], the value of biogas generated from a 40 litre laboratory- scale anaerobic digester was 84750 cm^3($0.08475m^3$) comprising 58% CH_4 and 24% CO_2 with a mesophilic temperature range of 22^oC - 30.5 ^oC throughout the study. The pH of the reactor ranged from 4.52 - 6.1. The simulated results of this design study obtained a CH_4 value 0f 59% which is slightly higher than what was found in this laboratory experiment. However it was argued that if a higher temperature, in this case 50 - 60 ^oC was reached during the anaerobic digestion process a higher percentage value of CH_4 yield would have been maintained because methane methanogenic bacteria which is responsible for methane production works efficiently at mesophilic temperature of 30 - 40 ^oC and thermophilic temperature of 50 - 60 ^oC . the study suggested the temperature of below 30 ^oC slowed the development of methanogenic bacteria responsible for CH_4 production, hence low yield.

In study [49] which was done to find out the yield of methane gas when fruit vegetable waste and food wastes were digested separately in anaerobic conditions, methane yields for fruit vegetable waste and food waste in m^3/kg vs were 35% and 60% respectively**.** This shows that there is potential in food wastes for methane gas production. The results are also very comparable with the value obtained through simulation of biogas production in canteen food waste **(61.6%)**

Ejiroghene Kelly Orhorhoro, Patrick Okechukwu Ebunilo in study [39] reported that with a proper organic loading rate into the biodigester , the highest methane production yield was 64%. The simulation results of this design agree with those of this study

5.1.4.2 Study of the design, Development and Evaluation of slaughterhouse Anaerobic plant Model

In the study of the Design, Development and Evaluation of slaughterhouse Anaerobic plant Model [44], a biodigester of volume 2.5m^3, gazometer volume of 0.7m^3 and digestate volume of 2.5m^3 was designed. With a HRT of 30 days, the total gas produced was 0.6108 m^3, with a maximum gas production of 0.037m^3/day while the maximum biogas potential was 0.771 m^3

This study has designed a biogas of volume 62 m^3. Mathematically it can be proved that:

If a 2.5m^3 biodigester produces 0.037 m^3/day of biogas,, then a 61m^3 biodigester will produce

$$\mathbf{0.037\frac{m^3}{2.5} * 62/day = 0.9176\ m^3/day}$$ of biogas.

We can assume that with a HRT of 40 days as per this design, the volume of biogas produced in the digester will be more than 0.9176 m^3/day. Taking this value of 0.9176 m^3/day of biogas production, it means that to satisfy the demand of biogas at Phalombe secondary school which is currently at 42.85 m^3/day as per the researcher's calculations, then this demand will be met within 47 days. But this is when the HRT is 30 days. Therefore, with a HRT of 40days as per this design and addition of rice straw to the substrate to improve the C/N ratio, then the demand can be met in less than 47 days. Therefore this is a viable design. It must also be mentioned here that proper management of the whole biogas production process is very vital to achieve good results.

5.1.4.3 Standard sizes /models of fixed dome biogas plants used in Bangladesh

Table 18 shows standard sizes of fixed dome biogas plants used in Bangladesh, India

Table 18. Standard sizes of fixed dome biogas plants used in Bangladesh, India

biogas plants used in Bangladesh

Rated daily gas production (m^3/day)	Effective digester volume (m^3)	
	Cow	Poultry
1.2	3.0	2.3
1.6	3.8	3.0
2.0	4.8	3.9
2.4	5.8	4.5
3.2	7.8	6.0
4.8	11.8	9.3

Source: derived from NDBMP (2013).

According to the table 21 above from IRENA article, 2013 we can compare the effective digester volumes and their respective rated biogas production with the new design. It can be seen that:

If a digester of volume 11.8 m^3 produces 4.8 m^3 of biogas per day, then from the new design of 62 m^3 digester we can get $4.8\frac{m^3}{day} * 62\frac{m^3}{11.8\ m^3} = \mathbf{25.2\ m^3/day\ of\ biogas}$. The energy demand at Phalombe Boarding School is found to be 42. 85 m^3/day. So at the rate of $25.2\ m^3/day\ of\ biogas$ this demand can be meet within a very short period of time.

5.1.4.4 Use of conversion factors for biogas

If we use conversion factors in figure 14 we can calculate methane production from the biogas energy demand in this design.

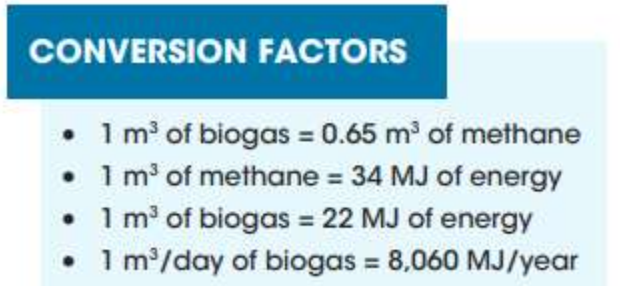

Figure 14. Conversion factors for Biogas

Source: [50]

From the table in figure 14,

1 m^3 of biogas $= 0.65\ m^3\ of\ methane$. There for the $25.2\frac{m^3}{day}\ of\ biogas,$ the methane gas produced will be $0.65\ m^3 * 25.2\frac{m^3}{day} = \mathbf{16.38\ m^3/day}$. from this value it can be assumed that meeting a demand of $42.85\ m^3/day$ can be can be achieved in 3 days after the HRT which in this design is 40 days. Study [51] proved that the best HRT is below 44 days because after this day biogas production becomes stable for some time and then drops. Also studies [37, 38] showed the same effect of HRT. So a HRT of 40 days for this design is a good time for digestion since by the time this day is reached production of biogas will be at its peak and the yield will be stable from the 44th day.

Using the value of $\mathbf{25.2\frac{m^3}{day}\ of dry\ \ biogas}$, the Mole fraction of CH_4 in dry biogas can be calculated as follows:

Amount of dry biogas production per day = $25.2\ m^3$

Amount of Methane production per day = $16.38\ m^3$

Therefore the Mole fraction of CH_4 in dry biogas $= \frac{16.38}{25.2} * 100\% = \mathbf{65\%}$. this value of mole fraction of CH_4 is approximately the same as the values found in the simulation results. Therefore the volume of this biogas plant designed in this study will be able to meet energy demand at Phalombe Boarding Secondary school.

5.1.5 Economic viability of the design

Initial investment costs for a fixed dome biogas digester may seem to be high. However it has more advantages than the other types of biogas plants namely: long life span(it can be there for 20 years or more), has no moving parts, no rusting parts, no leakage. The dome is plastered inside. The whole plant is covered with earth. It is constructed underground. This protects the plant from physical damage. Space is also saved which can be used for other purposes. If well managed, it has the highest methane production as compared to the other types. It is self agitated by biogas pressure and can be constructed in areas with low temperatures. It requires less maintenance, has good thermal insulation.

The amount of firewood used by Phalombe Secondary school per term is 52 tons **(Appendix 1).** In three terms it uses 156 tons of firewood. One ton costs **US$19.00**. Therefore 156 tons cost approximately **US$3000.00** The school spends **US$344.00** (Appendix 1) on electricity per month. A school term is approximately 4 months. This means that the school spends a total of **US$1032.00** per term. The school has three academic terms, so the total amount of money spent on electricity in one academic year is approximately **US$3,096.00** If these two expenditures are summed up (firewood plus electricity), the total expenditure in one academic year is approximately **US$6096.00** The cost of installing a biogas plant at the school is approximately **US$5,277.57.** This amount is less than the amount of money the school spends on firewood only in one academic year and it can be used to construct the biogas plant at the school. Therefore the use of a biogas plant will not only curb deforestation in the district but also make a great savings on the money the school is currently spending on firewood and electricity. This money can be used for other school requirements.

5.1.6 Estimated forest saving from use of biogas plant at Phalombe Boarding Secondary School

According to the Indian Agriculture Research Institute (ICAR), a single biogas plant with capacity 2.8 m^3 can save woodland of area 0.12 ha per year. Therefore with this designed biogas plant whose capacity is 62 m^3, it can save a forest area of 2.66 ha of woodland per year in Phalombe district.

CHAPTER SIX
6.1 CONCLUSION

This thesis has reviewed the common types of biogas plants that are used worldwide. There are several factors to be looked into when designing the type of biodigester to be used in a particular area. The choice of the right biodigester to be used in a particular area is of crucial importance when designing biogas plants. The design stage should take into consideration some very important parameters such as the type of substrate to be used, the continued availability of the substrate, availability of low cost construction materials, the shape of the biodigester, weather conditions of the area where the biogas plant is going to be installed, the life span of the biogas plant which is dependent on the quality of the materials used in the construction and masonry skills of the labour force.

6.2 RECOMMENDATIONS

Human and canteen food waste are the most common wastes in our homes and boarding schools and yet we do not utilize them by converting them to other forms such as methane gas production. Human wastes are disposed of in septic tanks after which time they are pumped out and thrown somewhere causing health risks to people around that area. Similarly canteen food waste are just thrown in dust bins making the place filthy. In Malawi there are no recycling technologies that can convert these wastes to something that does not pose health risks to humans once the wastes are disposed of. The use of clean technologies such as biogas for cooking and heating has been undermined by most developing countries. The results of this study have shown that human and canteen food wastes are good substrates to be co-digested in a biodigester order to produce biogas. Based on this design, a co-digestion biogas plant is the best option for Phalombe Boarding Secondary School to save money which is currently spent on firewood and electricity. Biogas provides energy which can be used for heating, cooking and lighting. Organic fertilizer produced from the slurry can be used for agricultural production. To overcome overdependence on wood fuel, the school should move towards the use of biogas energy. Investing in biogas technology will curb deforestation in the area which is rampant at present.

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LIST OF APPENDICES

Appendix 1: Questionnaire and answers used for the design of a biogas plant at Phalombe Secondary school

A QUESTIONNAIRE TO BE USED IN DESIGNING A BIOGAS PLANT AT PHALOMBE SECONDARY SCHOOL.

Introduction:

My name is **Austin K. Nyirenda**, a student at the University of Rwanda, pursuing a **Master of Science Degree in Renewable Energy**.(refer to my address below).

I am undertaking a research project that has to do with the **Design of a co-digestion biogas plant** that will use animal waste, human waste, agriculture and kitchen waste as daily feeding materials for the bio digester to produce biogas(methane gas) for cooking, heating and lighting. My case study is Phalombe secondary school where they use firewood as a source of energy for cooking and heating. Biogas will provide an alternative source to firewood to curb deforestation in the area.

Due to the corona virus pandemic, all the borders and airports in Rwanda have been closed hence I have been unable to come to Malawi and administer this questionnaire myself. This is why I am seeking your assistance, Sir.

This questionnaire has three sections.

SECTION A: To be answered by the School head, staff members and head cook where it is applicable

The following questions will be answered by the school administrator

1 How many students are enrolled at this school in each academic year? **562 students**

2. How many staff members are at this school inclusive of their families?

   39 staff members (approximately 195 people when family members are included)

3 Do you use flush toilets? Yes (teaching staff only)

4. How do you dispose of kitchen waste/garbage?

   Bins & some villagers come to collect kitchen left overs to feed livestock

5. Where do you get water supply for this school? **Tap & borehole**

6. Is the source of water perennial? **Yes**

7. Looking at piles of wood that is there at the kitchen it shows that the main source of energy for cooking and heating at this school is firewood. Where do you source this firewood?

We have suppliers who sign yearly contracts (they source from tree farmers' woodlots) and natural trees from nearby forests

8. Do you have an alternative source of energy for cooking and heating? **No**

9. How much firewood do you use per school term? (in tons; approximate figure required)

About 52 tones

10. How much does one ton of firewood cost? It costs **approximately U$19.00**

11. How many school terms do you have in an academic year? **3 terms**

12. Have you heard about biogas technology? **Yes**

13. If the answer is yes to question 12 above, what are its advantages?

Eco-friendly and **cheaper**

14. If a biogas plant is constructed at your school, how are you going to manage it for sustainability?

We will do according to instructions from the constructor apart from assigning an officer to be responsible for it.

SECTION B: To be answered by households surrounding the school (village heads, cattle farmers, rice farmers and rice millers)

15. How many villages are surrounding Phalombe Secondary School?(Names of village headmen required) **3 village heads namely Mbodi, Bokosi & Seven**

16. Do you have many tamed animals such as cattle, goats, chicken and pigs ? pictures of farm animals to be taken **Yes**

17. How do you dispose of animal manure? **Crop fields and pits**

18. We want to construct a biogas plant at Phalombe secondary school. This biogas plant will use animal, agriculture and kitchen wastes as daily feeding material. Are you willing to supply these materials to the school? Y**es**

19. Pictures of kitchen where there are piles of firewood (yes pictures taken)

20. How many staff members houses do you have at your school? **24 houses**

21. How many student hostels do you have? **12 hostels**

22. How many rooms does each hostel have? **There are 10 rooms per hostel**

23. How many class rooms for each class (form) do you have? **2 class rooms for each class.**

24. How much do you pay for electricity for the school per month?

MK250,000 to MK300,000 per month = US$344

SECTION C: to be answered by rice farmers and owners of rice mills

25. Phalombe is one of rice growing districts in Malawi and you process a lot of it in a growing season. How many growing seasons do you have? **One growing season**

26 How do you dispose of the rice husks/bran? **Hoarded behind our mills**

27. Phalombe secondary School wants to construct a biogas plant that will use agriculture wastes such as rice husks/bran as its daily feeding material for the bio- digester. Are you willing to give them free of charge? **Not exactly, we would need a little payment**

End of Questionnaire

Thank you for spending your precious time to answer this questionnaire. Be assured that all the information given in this questionnaire will remain confidential. May God bless you.

Warm regards,

Austin K. Nyirenda,

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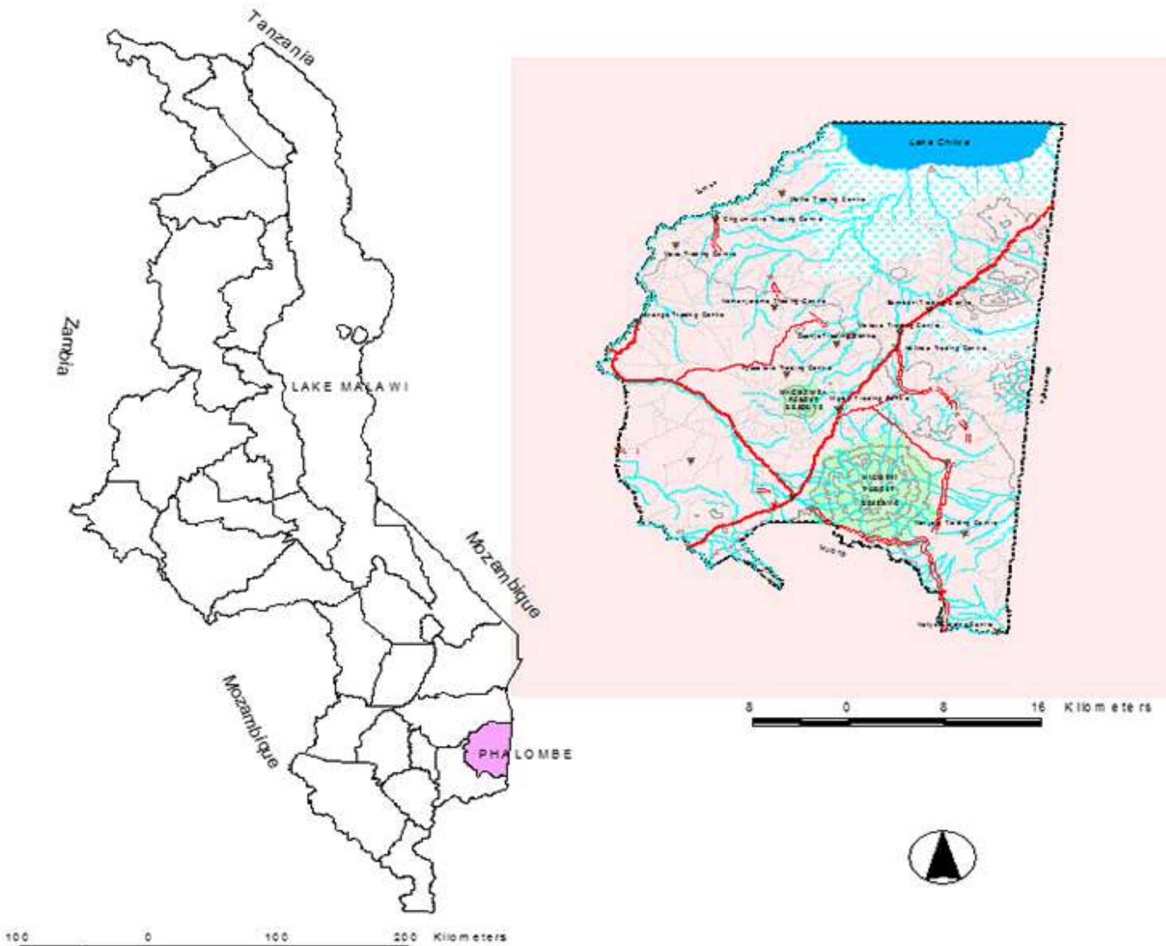
APPENDIX 2: Terrain of Phalombe Boarding Secondary School

Source : Photo by Austin K. Nyirenda, 2019

APPENDIX 3: Map of Malawi showing Phalombe District



Source: Atlas of Malawi

APPENDIX 4: Piles of firewood at Phalombe Boarding Secondary School kitchen.

Source: Photo by Austin K. Nyirenda, 2019

APPENDIX 5: Picture of Phalombe women who had harvested firewood from Michesi Forest

Source: Mulanje conservation Trust

APPENDIX 6: Map of Phalombe district showing Michesi forest area, perennial rivers and Chakalamba rice Irrigation scheme

Source: Phalombe Rice Irrigation Schemes Project

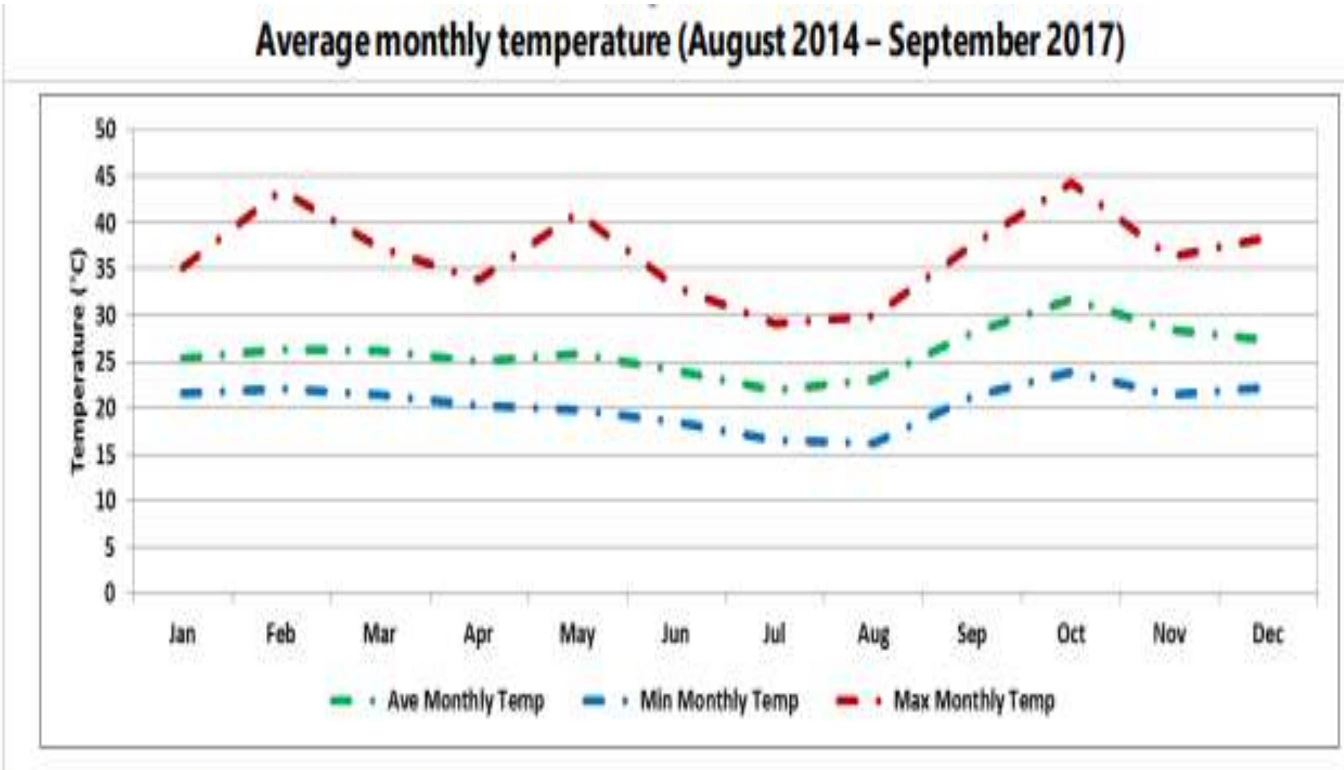
APPENDIX 7: Herds of Cattle around Phalombe Secondary School whose manure can be used to supplement the daily feeding material.

Source: Malawi drought report 2015 - 2016 by World Bank group

APPENDIX7: Rice growing areas along the river banks of Lake Malombe in Phalombe district whose husks/bran can be used to increase the C/N ratio in the biodigester

Source: Malawi drought report 2015 - 2016 by World Bank group

APPENDIX 9: Average monthly temperatures in Phalombe District



Source: *Songwe Hill Meteorological Station*

APPENDIX 10: Table showing population of southern region of Malawi including Phalombe district, 2019

				2018	2010	
Southern	**2.7**	**2.7**	**2.8**	**1,897,874**	**891,403**	**1,006,471**
Mangochi	3.6	3.5	3.7	352,575	163,270	189,305
Machinga	3.9	3.8	4.0	240,603	112,287	128,316
Zomba	2.5	2.5	2.5	167,958	79,650	88,308
Chiradzulu	2.1	2.2	2.1	69,271	33,704	35,567
Blantyre	2.8	2.8	2.8	111,814	53,719	58,095
Mwanza	3.4	3.5	3.4	38,712	18,933	19,779
Thyolo	2.0	1.9	2.0	130,984	58,945	72,039
Mulanje	2.6	2.7	2.6	160,158	77,545	82,613
Phalombe	3.0	3.1	2.9	114,265	56,561	57,704
Chikwawa	2.5	2.3	2.6	126,792	58,376	68,416
Nsanje	2.1	1.9	2.3	58,061	24,819	33,242
Balaka	3.2	3.1	3.2	121,805	56,939	64,866
Neno	2.4	2.4	2.4	29,952	14,606	15,346
Zomba City	2.5	2.3	2.7	23,512	10,777	12,735
Blantyre City	2.0	1.9	2.2	151,412	71,272	80,140

Source: Malawi National Statistical Office