UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

Rwanda University

College of Science and Technology

Title of the Project: **Feasibility Study of Production of Bio Methane from Biodegradable Waste in Rwanda**
(Case study: NDUBA Landfill site)

PROJECT ID: ACEESD/REE/21/11

A proposal submitted to the African Center of Excellence in Energy studies for sustainable development (ACE-ESD)

In Partial Fulfillment of the Requirement for the Degree of Masters of Science in Renewable Energy

By: Ghadi Niyomufasha (REG: 220000203)

Advisor: Prof. Zachary Siagi

November 2021
Kigali-Rwanda

CERTIFICATION

This is to certify that the master's dissertation entitled **"Feasibility Study of Production of Bio Methane from Biodegradable Waste in Rwanda. Case study: NDUBA Landfill site"** was carried out by Ghadi NIYOMUFASHA in partial fulfillment of the requirement for the Award of Master's Degree in Renewable Energy at the African Center of Excellence in Energy for Sustainable Development -University of Rwanda, College of Science and Technology.

This dissertation proposal has been submitted for examination with my approval as a university advisor.

Prof. Zachary Siagi ____16/11/2021____

Thesis Advisor Signature

DECLARATION

I, Ghadi NIYOMUFASHA, announce that this Dissertation entitled **“Feasibility Study of Production of Bio Methane from Biodegradable Waste in Rwanda. Case study: NDUBA Landfill site”** is my own work, and has not been presented for a degree in University of Rwanda or any other universities. This dissertation supervised by Prof. Zachary Siagi, is my property and work, and also all sources of materials that used for this dissertation work have been fully acknowledged.

Names: Ghadi NIYOMUFASHA

Signature:

Date of Submission: 11/11/2022

DEDICATION

This master’s thesis is highly dedicated to Almighty God.

To my Family, Parents, brothers, sisters and friends,

To my supervisor and classmates.

Thanks to you all for your ending encouragement and supports.

ACKNOWLEDGEMENTS

This is my highly wish to take this opportunity to express sincere thanks to individuals or groups who have contributed on my achievement of this project. Therefore, I would first like to thank Almighty God for his endless love and blessings that is always sufficient to me. I sincerely thank Prof. Zachary Siagi, my project supervisor, for his constant support through the course and for providing necessary facilities to carry out this thesis work, and also all lecturers for their guidance and comfort that was given to me while conducting Master's courses and thesis.

I thank the administration of University of Rwanda-College of Science and Technology, Especially the African Center of Excellence in Energy Studies for Sustainable Development (ACE-ESD) under World Bank for their support, for suggestions and constructive recommendations during my studies and thesis work.

Last not least, I deeply thanks to my family especially my wife Mushimiyimana Jeannette, I also give my sincere thanks to my relatives, friends and all my classmates for their beneficial interventions.

ABSTRACT

Wastes (Biodegradable and Non- Biodegradable) generation is increasing rapidly in these days as result of expansion of economic activities and rapid growth of population in Rwanda, particularly in city areas. The wastes generated mainly contain biodegradable materials which are good indicator for producing Biogas and this biogas can generate Biomethane once biogas is upgraded. This thesis is intended to evaluate the feasibility of biomethane production in Rwanda especially in Kigali city where there is large amount of wastes generation.

During this thesis a case study of Nduba Landfill site in Kigali City was studied, Data about Wastes (Biodegradable and Non- Biodegradable) generation were collected. During data collection, Observation and interviews were used for primary data. Data gathered from workers of Nduba dumpsites, Staff of different company, other sources.

The effect of substrate on biogas yield was studied by using Biodegradable waste in laboratory scale experiment using water displacement method to monitor the volume of biogas produced. The biogas produced by Biodegradable waste was monitored and recorded over a period from 8th October to 8th November 2021 which is equal to 30 days. The results show that 100 g of Biodegradable waste with 100 ml of water and 5g of cow dung as inoculum, from 30th day Biodegradable waste produce 20 ml of Biogas. So, 100 g of Biodegradable waste produce 20 ml of Biogas which means 1 kg produce 200 ml which is equal to 0.0002 m^3.

Conferring to the results of the study, it was found that as Organic waste generation increase and also Biogas production is increased which in turn increase Methane and Biomethane generated. This study show that Biogas, Methane and BioMethane production increase as the Years increase and on graph which combine Biogas, Methane and BioMethane, graph line of Biogas is higher than graph line of Methane and BioMethane because volume of Biogas is higher compared to volume of Methane and BioMethane.

The study concludes that once Bio Methane increase as organic Biodegradable Waste increase, as Biodegradable Waste increases also Biogas which in turn increases Bio Methane produced. Therefore, the Bio Methane Production from Biodegradable Waste in Rwanda is Feasible

TABLE OF CONTENT

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

ACE-ESD: African Center of Excellence in Energy studies for sustainable development
MW: Mega-Watt
CH_4: Methane
CO_2: Carbon dioxide
H_2: Hydrogen
O_2: Oxygen
NH_3: Ammonia
H_2S: Hydrogen sulphide
N_2: Nitrogen
HRT: Hydraulic Retention Time
PSA: Pressure swing adsorption
REMA: Rwanda Environment Management Authority
THT: Tetrahydrothiophene
SRB: Sulfate-reducing bacteria
Pb: Lead
Zn: Zinc
Cu: Copper
Fe: Iron
Hg: Mercury
Cd: Cadmium
Cr: Chromium
Ni: Nickel
Co: Cobalt

CHAPTER I: GENERAL INTRODUCTION

1.0 INTRODUCTION

Now days, energy is key to many things without energy or low of energy, the development of country is very difficult and also there is a large challenge of gathering the customers' growth of energy need without making any harmful on surrounding environment. The contamination of surrounding or environment is happening due to increasing of burning of fossil fuels. Renewable energy comes ahead to answer the problem of environment pollution by reducing dependence on fossil fuels. Renewable energy from Biodegradable Waste known as Biogas which is used directly to produce electricity and heat or as an energy source for cooking can be utilized to reduce need of using fossil fuels. Biomethane is a gas resulting from biogas, which is produced by removing CO2 gas and other contaminant from biogas which is process known as biogas upgrading, Biomethane can be utilized as other gas which are commonly used in transportation sector.

1.1Background

Biomethane is a gas resulting from biogas, which is produced by removing CO2 gas and other contaminant from biogas which is process known as biogas upgrading. Its back ground begins with back ground of biogas. In 10th century B.C. the biogas was used for heating bathwater in Assyria, in 1890s UK also has used biogas to fuel street lamps. In 1921, Chine constructed a $8m^3$ biogas tank fed with household waste and later that decade founded a company to popularise the technology. In 1920, the German was introduced the first sewage treatment plant to feed biogas into the public gas supply, and also in German, the biggest biogas plant which use agricultural waste began to operate in 1950[1]. In 1970s there was increase of technology which based on biogas production due to high prices of oil which motivate researcher to search on alternative energy sources.

During this period in the 1970s and the first half of the1980s, Chinese government encouraged the use of biogas in every rural family and facilitated the installation of more than seven million digesters. At end of year 1988, 4.7 million domestic biogas digesters were found in China. By the end of year 2007, Government of Indian provided funding for building around four million family-sized biogas plants [1]. Biomethane is obtained by upgrading Biogas by removing carbon dioxide and other trace components. In 1980s, the first biogas upgrading plants were introduced [2]

1.1.1 Country Profile

Rwanda is a blocked-in country, which known as ’The Land of a Thousand Hills’, whose capital city is Kigali city. Land Area of Rwanda is 26,338 square Kilometres; Rwanda is surrounded by four countries which are: Uganda at north, Burundi at south, Tanzania at east, and the DRC at west. Rwanda has four languages which are official like: Kinyarwanda, English, French and Kiswahili, Rwanda’s National anthem is “Rwanda Nziza” (Rwanda, Our Beautiful), Rwanda’s currency is Rwandan franc (RWF), to drive cars in Rwanda , the right hand side of the road is used, Rwanda’s demonym is Rwandan, Rwandese, Rainfall is 750-850 mm/year, Average Temperature is between 24.6 - 27.6^{o}c,Hottest months are August, September; Altitude is Ranging between 1000-4500m above sea level. In Rwanda, the highest point is Karisimbi which measure 4,519 m; Rwanda has Main National Parks which are Akagera National Park and was created in 1934 which has Area of 1080 square kilometers, Nyungwe Forest which became National Park in 2004 whose total area is 1019 square kilometers, National Park of Virunga which was created on 1st/10/1925, its total area is 160 square kilometers ,the last is Gishwati & Mukura Forest Reserve which became a national park in 2015 whose total area is 3,558 Ha. Rwanda has five volcanoes, 23 lakes and rivers [3], [4] the estimation of Rwanda population is approximately 11,809,300 people conferring to the 2017 census. The current growth rate of population in Rwanda was estimated to be 2.37 percent in 2013 and it is estimated to decrease to 1.89 in 2032. Density’s Population of Rwanda is considered as one which is high in Africa and it is assumed to be 467 people per square kilometer [5].

Kigali city which is a capital city of Rwanda has 730 km^2 and its population is around 1,223,000 people, its annual average temperature is about 20˚C and Kigali city has one landfill which is known as Nduba landfill, which is at North East of Kigali at Gasabo District, Nduba hill at Muremure cell at 10 Km from Kigali Center [6].

1.1.2 Energy Profile

Rwanda as developing country has the following sources of Energy: hydro, solar, geothermal, methane gas, biomass peat, and wind [7].

In July 2018, Ministry of Infrastructures shown that the installed capacity in Rwanda was 218 MW, with 212.5 MW generated 5.5 MW which was imported [8]. In 2019, Total Installed capacity was 221.1MW [9].

In 2021, Installed capacity per technology were: Hydropower is 104.628 MW, equivalent to 44%; Methane is 29.79 MW, equivalent to 12%; Solar is 12.05 MW, equivalent to 5%; Peat is 15 MW, equivalent to 6%; Thermal power 58.8 MW, equivalent to 25%, Geothermal is 0 MW, equivalent to 0%; Import is 18.1 MW, equivalent to 8%. Total Installed capacity was 338.368 MW [10] as shown in figure1

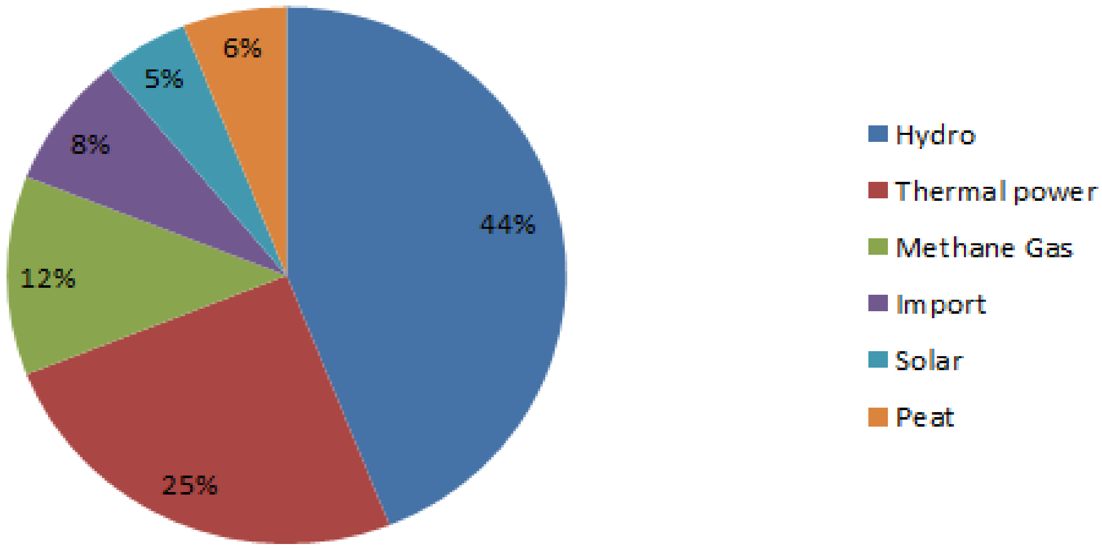


Figure 1: Shows the Installed capacity of Energy in 2021.

1.2 Statement of the Problem

As Rwanda is developing country, we need Energy in order to develop our country like developed country. Energy may come from Renewable Energy Sources or Fossil fuel but the Energy from Fossil fuel can cause problem to environment like emissions of gas and greenhouse effect. The use of Biomethane from biogas, which is produced by removing CO2 gas and other contaminant from biogas which is process known as biogas upgrading ,is a solution to environmental pollution because reduce dependence of fossil fuel; there will be reduction of gas emissions and greenhouse effect. Then due to inefficiency or not enough of energy, dependence on fossil fuel, need for making Rwanda cities clean, gas emissions and greenhouse effect, the use of Bio Methane from Biodegradable Waste in Rwanda will be a solution for many issues and challenges.

1.3 Objectives

1.3.1 Major Objectives

The main objective of this thesis is Biogas production and predicts the Bio Methane produced from Biodegradable Waste as commercial product.

1.3.2 The Specific Objective

- Determine the rate at which Biodegradable Waste is produced.
- Determine the quality & quantity of Biogas produced from biodegradable waste.
- To Predict the Bio Methane that can be produced.

1.4 Scope of the study

The scope of this thesis which is titled Feasibility Study of Production of Bio Methane from Biodegradable Waste is carried out in Rwanda country at Kigali city especially at NDUBA Landfill site and Bio Methane will be produced by upgrading biogas with some method of biogas upgrading to Bio Methane not by using gasification of solid biomass.

1.5 Expected Outcomes and Significance of the Study

1.5.1 Expected Outcome of the Study

- Reduce dependency of fossil fuels in country.
- Provide better solution for environmental pollution.
- Better solution for solid waste management.
- Reduce inefficiency or not enough of energy.
- Having cities clean due to Better solution for solid waste management.
- Reduce gas emissions and greenhouse effect.

1.5.2 Significant of the Study

This thesis titled Feasibility Study of Production of Bio Methane from Biodegradable Waste will be useful to the country, society, researchers; etc. the use of Bio Methane from Biodegradable Waste in Rwanda will be a solution for many issues and challenges such as: inefficiency or not enough of energy, dependence on fossil fuel, need for making Rwanda cities clean, gas emissions and greenhouse effect. Then Bio Methane produced by upgrading biogas will reduce dependency of fossil fuels in country, Provide better solution for environmental pollution, Reduce inefficiency or not enough of energy, Reduce gas emissions and greenhouse effect, etc. also Biomethane will be used as transport fuel and is suitable for use in the transport sector.

1.6 LIMITATION

During this study of “Feasibility Study of Production of Bio Methane from Biodegradable Waste in Rwanda. Case study: NDUBA Landfill site” I have accoutered with some limitation like lack of enough equipment for doing experiment and the most challenge is lack of Membrane separation technology or other technology to upgrade Biogas for producing Biomethane as result, I predict the Bio Methane produced from Biodegradable Waste.

CHAPTER II: LITERATURE REVIEW

2.1 BIOGAS

Biogas is gas generated from organic material of several feedstocks, such as agricultural residues, energy crops, the organic fraction of municipal solid waste, industrial organic waste, etc in a process called anaerobic digestion. The residue or the byproduct of Biogas is used as fertilizers in agricultural. Biogas is a mainly composed with methane, carbon dioxide and other components such as hydrogen sulphide, nitrogen, etc.

2.1.1 BIOGAS COMPOSITION

During anaerobic digestion, in which organic materials are broken down by a group of bacteria in absence of oxygen and biogas can be produced. The biogas is mainly composed by methane and Carbon dioxide with certain percentage of other gases such as: Hydrogen sulphide (H_2S), Nitrogen (N_2), Oxygen (O_2), Hydrogen (H_2), Ammonia (NH_3) as indicated in Table 1.

Table 1: BIOGAS COMPOSITION [11]

Gases	Symbol	% by volume
Methane	CH_4	55-65
Carbon dioxide	CO_2	35-45
Hydrogen	H_2	0-1
Oxygen	O_2	0-2
Ammonia	NH_3	0-1
Hydrogen sulphide	H_2S	0-1
Nitrogen	N_2	0-3

2.1.2 BIOGAS PRODUCTION

Biogas produced may come from different categories such as: Substrate from origins of farms, Industrial by-products, Waste from private households and municipalities, etc feed waste, harvest waste and energy crops are examples of Substrate from origins of farms, by-products of food processing or waste from fat separators are examples of Industrial by-products and examples of Waste from private households and municipalities are: organic fraction of the municipal solid waste , market waste from vegetable market, fish market etc., expired food or food waste.

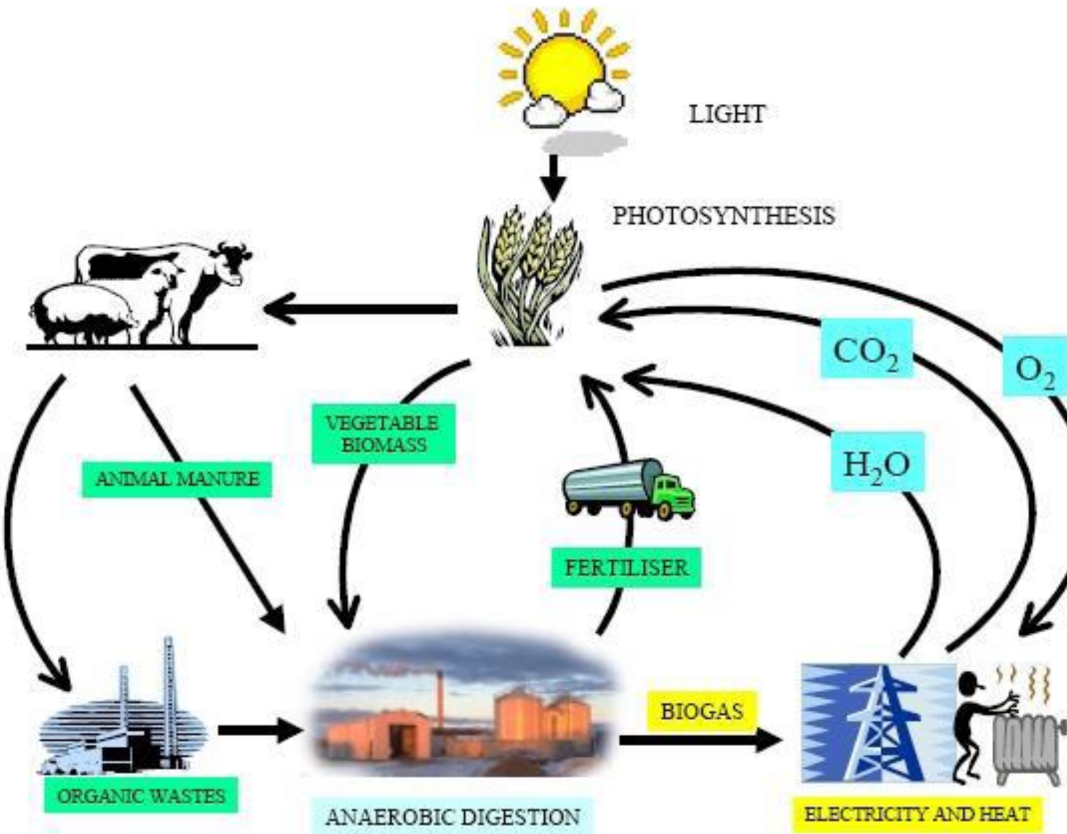


Figure 2: Biogas Production Cycle [12]

During the biogas production in Anaerobic Digestion, complex, large organic molecules are broken down into small organic molecules. Here are four stages involves in biogas production which are: Hydrolysis followed by Acidogenesis and followed by Acetogenesis, the last is Methanogenesis [13] [14].

At each stage specific bacteria known as: Hydrolytic, Acidogenic, Acetogenic and Methanogenic are involved to carry out the decomposition process.

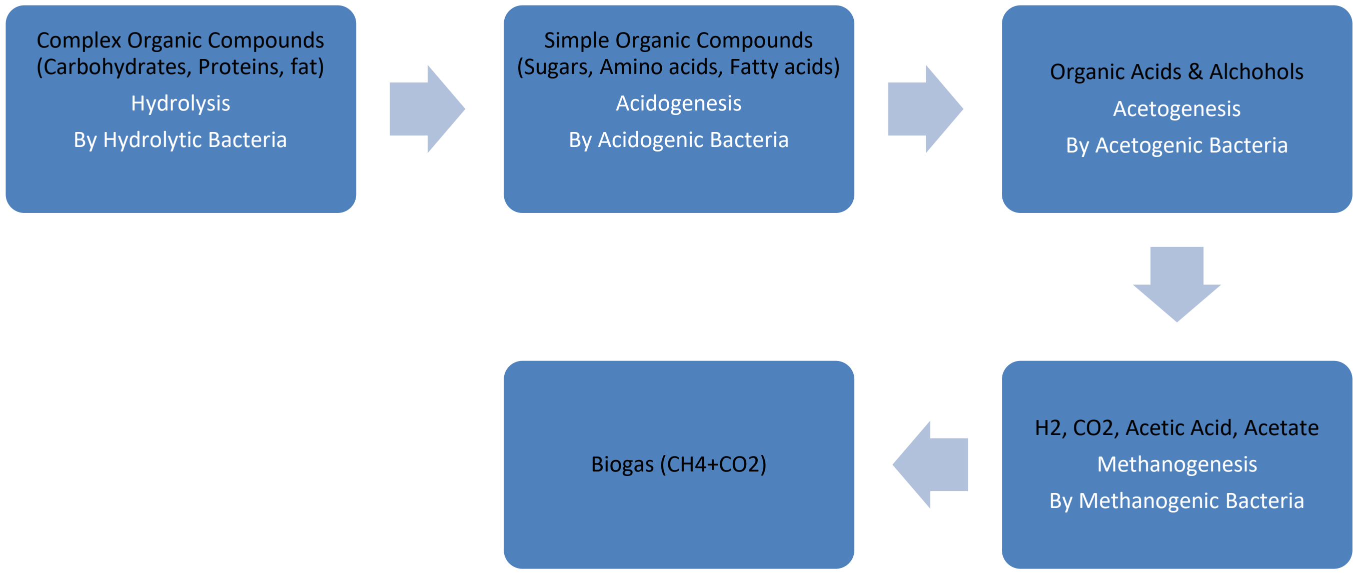


Figure 3: The Anaerobic Digestion Process with their specific bacteria for decomposition process. [14]

Hydrolysis Stage

Hydrolysis Stage is the first stage of Anaerobic Digestion Process which involves breakdown of Complex Organic Compounds such as: Carbohydrates, Proteins, fat, etc into Simple Organic Compounds like Sugars, Amino acids, Fatty acids, etc by using Hydrolytic Bacteria. During the hydrolysis process, some enzymes are used to break down Complex Organic Compounds into Simple Organic Compounds. As result complex and large organic Compounds are became broken into small parts. Enzymes that are used for the hydrolysis process is shown in Table 2.

Table 2: Enzymes used in the hydrolysis process. [14] [15]**.**

Enzymes	**Substrate**	**Breakdown Product**
Proteinase	Proteins	Amino acids
Cellulase	Cellulose	Glucose and Cellobiose
Hemicellulase	Hemicellulose	Sugars (glucose, xylose, mannose and arabinose)
Amylase	Starch	Glucose
Lipase	Fats	Fatty acids and glycerol
Pectinase	Pectin	Sugars (galactose, arabinose, polygalactic and uronic acid

Acidogenesis stage

Acidogenes is stage is the second stage of Anaerobic Digestion Process which is also known as fermentation ,at this stage the Simple or small Organic Compounds produced during the the first stage process are fermented. In acidogenesis stage, acidogenic bacteria involves by producing an acidic environment in the digestion tank and products from hydrolysis process are transformed into certain products such as organic acids (acetic, propionic acid, butyric acid, succinic acid, lactic acid etc.), alcohols, ammonia (from amino acids), carbon dioxide and hydrogen and hydrogen sulphide, the resulting organic compounds are still large and are not suitable for methane production [14].

Acetogenesis stage

Acetogenesis stage is the third stage of Anaerobic Digestion Process, during acetogenesis stage the acetogenic bacteria are used to broken down the products generated for the period of the acidogenesis stage into simple molecules. During this stage acetogenic bacteria produce acetic acid,hydrogen gas, carbon dioxide and energy (heat) but hydrogen gas is consumed which is lowering its concentration at low levels [14].

Methanogenesis stage

Methanogenesis stage is the last stage of the anaerobic digestion process, the Methanogenic bacteria are involves and methane are produced. Methanogenic bacteria break down acetate into two parts (Equation 1), methane is formed by using one carbon and the other carbon is used to form carbon dioxide

$$CH_3COOH \rightarrow CH_4 + CO_2 \qquad \text{(Equation 1)}$$

2.1.3FACTORS AFFECTING BIOGAS PRODUCTION

During the biogas production in Anaerobic Digestion some parameters influence production of biogas, the performance of biogas plants depends on those parameters and when those parameters are well controlled within operating range, the maximum biogas will be produced. The parameters which influence production of biogas are: [14] [16].

1. Temperature
2. pH value
3. C/N Ratio
4. Retention Time
5. Loading Rate

6. Mixing
7. Etc.

Temperature

Temperature is one of important parameter which influences production of biogas; the biogas production is largely affected by internal temperature of the digester. During anaerobic digestion process, There are three groups or range of temperature each group has its own characteristic and its own group of bacteria. The following are three groups or range of temperature. [14] [16] [17]

Psychrophilic (Less than 15^{o}C)

Mesophilic (15^{o}C – 45^{o}C)

Thermophilic (45^{o}C – 65^{o}C)

As long as temperature increase, the biogas production and methane also increase, microorganisms are most active in Mesophilic and Thermophilic range of temperature range. According to figure 4, it is obviously that as long as temperature increase, the biogas production and methane increase.

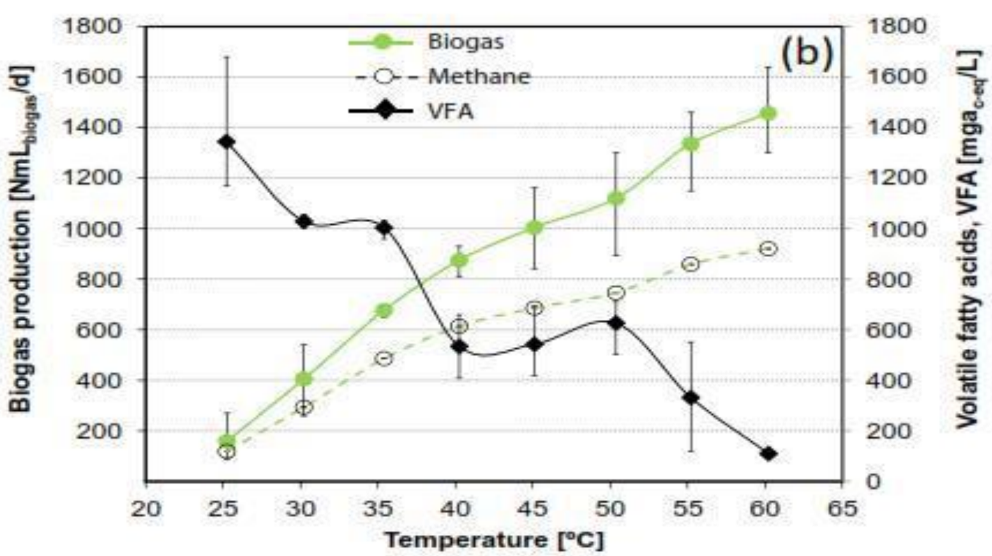


Figure 4 : Methane and Biogas production with temperature [16].

***pH* Value**

In anaerobic digestion process, *pH* is important parameter which influences production of biogas, depends on temperature which is inside the digester some microorganisms require different optimal pH value. The methane generation decrease due to drop of pH value; the range of pH value in which the biogas production will be maximum lie between 6.5 to 7.2. As long as temperature increase, the pH value also increase as shown in figure 5 .due to adjustment or control of pH value the biogas production improved by nearly 67% [16], Figure 6 shows the variation of biogas production with adjustment of pH and without adjustment of pH.

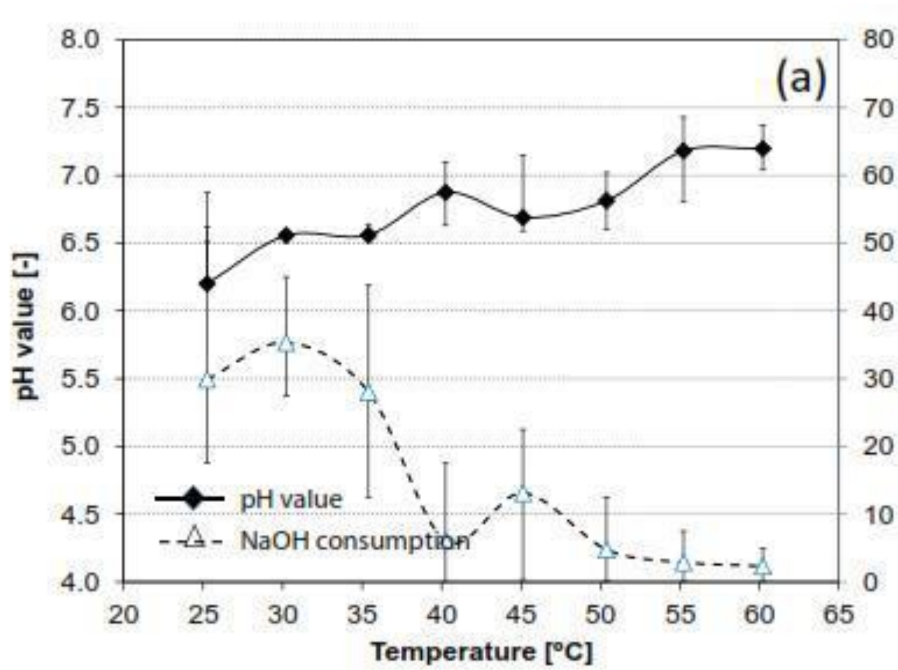


Figure 5: pH Variation with Variation of temperature [16].

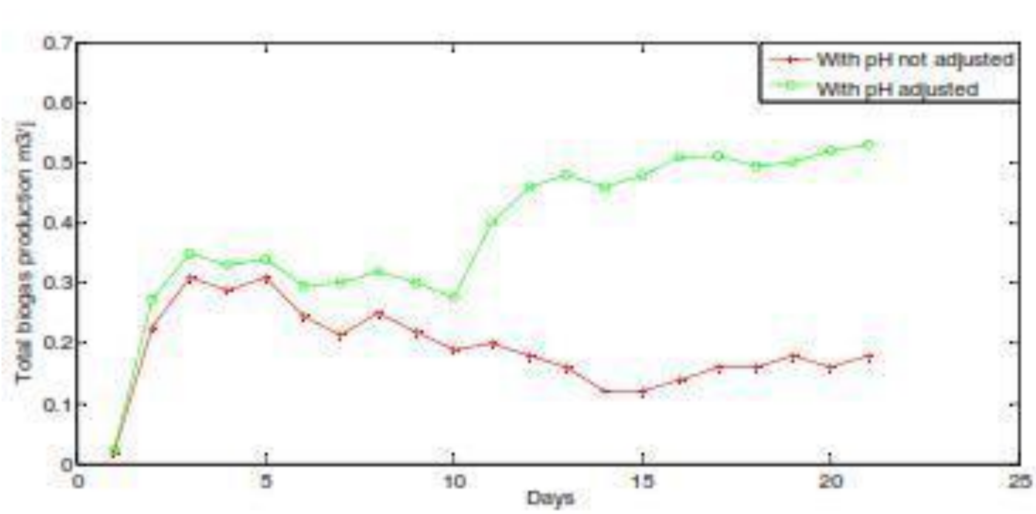


Figure 6: Biogas production with and without adjusting of pH [16].

C/N Ratio

C/N ratio, this ratio represents the Relationship between carbon and nitrogen that are present in organic materials. Nitrogen is very essential because is used for synthesis of amino acids and proteins and also can be converted to ammonia which has purpose of maintaining pH at favorable conditions for microorganisms. Too much C/N ratio increase nitrogen which in turn leads to ammonia formation, as result there is decrease in biogas production. The optimum C: N ratio for microbes is 20-30:1 [14] [16].

When C/N ratio is below or above optimum value of C: N ratio can affect the stability of system and reduce the biogas production; figure 7 shows the variation of methane production with variation of C/N ratio.

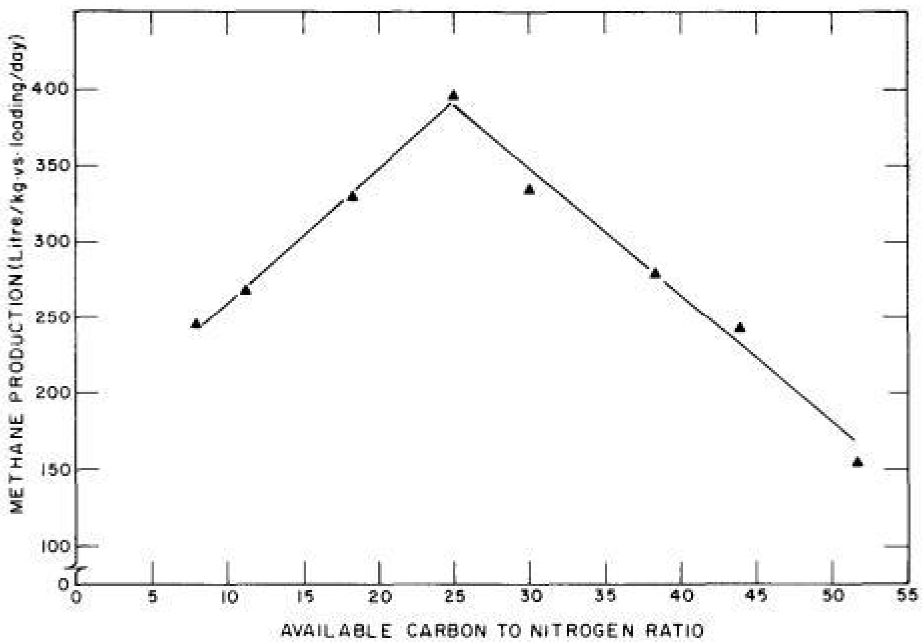


Figure 7: Methane production for different C/N ratios [16]**.**

Hydraulic Retention Time (HRT)

Hydraulic Retention Time is a period of time in which organic material that are in the digester is digested completely. The retention time depends on many factors such as: composition of substrate, interior temperature of the digester, etc; at higher interior temperature of digester reduces or lower the time required for Retention Time. Hydraulic Retention Time is between 10 and 25 days but also climate can affect Retention Time, Hydraulic Retention Time is around 100 days in cold climate conditions while in warmer climates is between 30-50 days [14].

Variation of biogas produced with Variation of retention time is indicated in figure 8

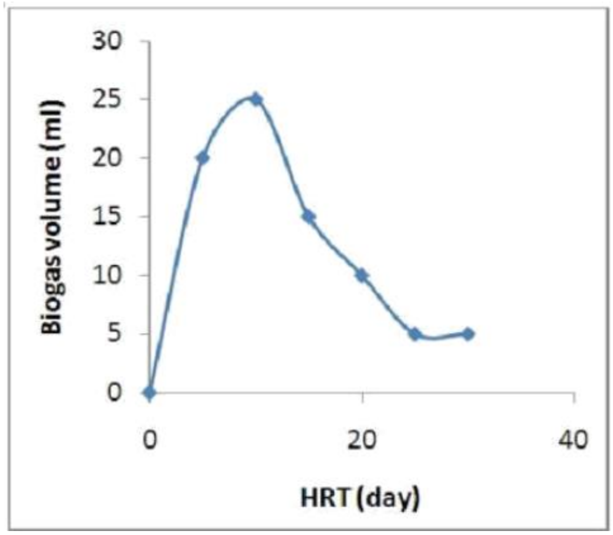


Figure 8: Variation of biogas production with Variation of hydraulic retention time [16].

Organic Loading Rate

Organic Loading Rate is very important in influencing Biogas production, Organic Loading Rate is known as amount of raw materials or Organic waste that needed to be fed in digester per day or daily. Overloading the digester reduces methane production because there will be more substrate than bacteria which needed to decompose Organic waste and also more acids may accumulate and inhibit methane production due to acidic situation in which is difficult to be survived by micro-bacteria. Under loading digester also reduces methane production because of alkaline solution which is also not good for bacteria that are used during anaerobic digestion. [18]

Mixing/ Agitation

Mixing is one of the factors which affect biogas production, during mixing there will be direct contact between substrate, nutrients and microorganisms which allow uniform temperature distribution this lead to good mixture in digester. Mixing has some advantages which are: Prevent organisms which produce methane to be washed out by the liquid, reduce sedimentation therefore reduces the possibility of foaming. Figure9 shows the variation of biogas production with and without Mixing/ Agitation.

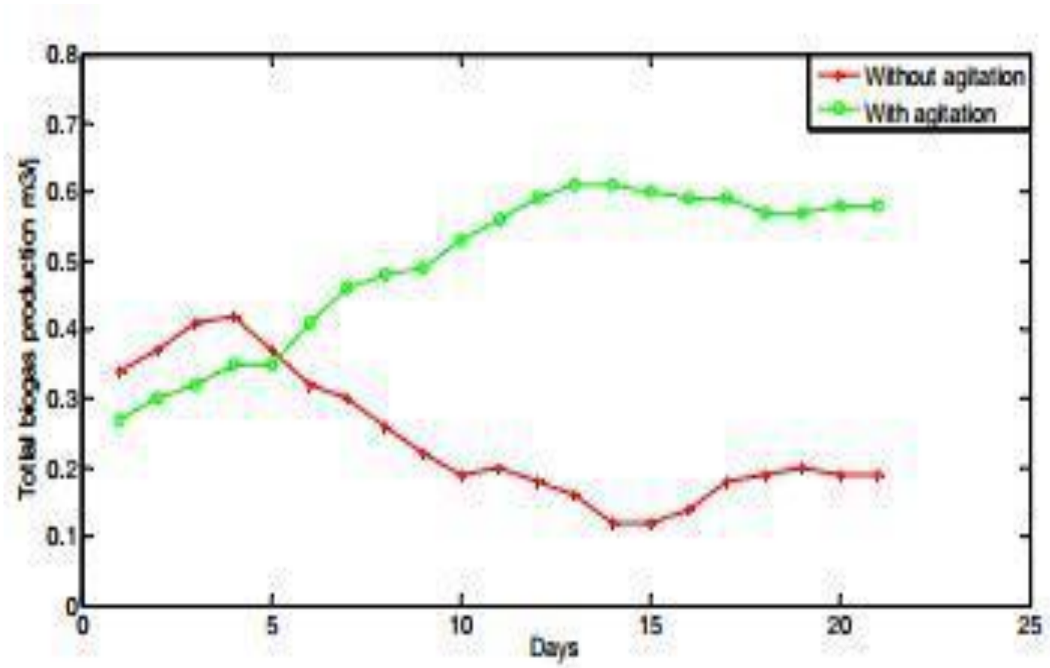


Figure 9: variation of biogas production with and without Mixing/ Agitation [16].

2.1.4 INHIBITORS OF METHANE FERMENTATION

Inhibitory Substances are Substances which can inhibit or retard the process of anaerobic digestion and cause failure of biogas production when are present in very high concentrations. The presence of an inhibitory material causes biogas production to decrease. Some of Inhibitors which can inhibit anaerobic processes known as toxicants are: ammonia, sulfides, ions of light metals, heavy metals, antibiotics, etc

2.1.4.1 Ammonia

Although ammonia is an essential nutrient for the growth of bacteria, but if its presence in Bio-digestion is at high level of concentrations, it can inhibit methanogenesis throughout anaerobic digestion process. In biogas production, Ammonia may be considered as potential inhibitor particularly in composite substrates, like manure or the organic fraction of municipal waste [19]. Ammonia can be produced from biological degradation of nitrogenous matter, typically in proteins, and urea.

In aqueous solution, there are two main forms of inorganic ammonia which are Ammonia ions ($NH_4^{+)}$ and free ammonia (NH_3). Due to its freely permeability through cell membranes, free ammonia is considered as the main cause of the inhibition of methanogensis. Concentration

Ammonia ions (NH_4^{+}) and free ammonia (NH_3)depends on the pH and temperature, as values of pH and temperature increase, there will be the formation of toxic molecular ammonia. [20]

Table 3: Effect of Sulfide and Ammonia Concentrations on Anaerobic Treatment [21].

Effect on Anaerobic Treatment	NH_4+NH_3-N mg/l	S^- mg/l
Beneficial	50-200	<50
No Adverse Effect	200-1000	50-100
Inhibitory at greater pH values	1500-3000	100-200
Toxic	>3000	>200

2.1.4.2 Sulfides

Sulfate can be founded in several types of industrial wastewater; sulfate is decomposed to sulfides in anaerobic reactors with help of sulfate-reducing bacteria (SRB). At higher concentrations, Sulfides become toxic to methanogens. Hydrogen sulfide (H_2S) is the most toxic form of sulfide Due to its permeability through cell membranes, the presence of Hydrogen sulfide (H_2S) in biogas decreases its potential of use and economic value because Hydrogen sulfide (H_2S) is an acidic and toxic gas. Then Hydrogen sulfide can be removed in biogas before using due to its corrosion on combustors, pipes, etc. By diluting, adding iron salt solutions to wastewater, the toxicity of sulfides is reduced [20].

2.1.4.3 Ions of light metals

Very high concentrations of salts tend to make bacterial cells dehydrate due to the change in osmotic pressure. So salt is considered as Toxicity, its toxicity is mostly determined by ions with a positive charge. Sodium, potassium, calcium, and magnesium are examples of Ions of light metals which are in fermentation tanks. Too much amounts of Ions of light metals can decelerate the growth of microbes which in turn inhibit the activity of microbes during anaerobic digestion, as result there will be the destabilization of cell membranes and also there will be the decrease in biogas production. Ions of light metals may come from decomposition of organic materials in the substrate and also in Wastewater.

Table 4: Stimulatory and Inhibitory Concentrations of Base Cations [22].

Cation	Stimulatory (mg/l)	Moderately Inhibitory (mg/l)	Strongly Inhibitory (mg/l)
Sodium, Na^+	100-200	3500-5500	8000
Potassium, K^+	200-400	2500-4500	12,000
Calcium, Ca^+	100-200	2500-4500	8000
Magnesium, Mg^+	75-150	1000-1500	3000

2.1.4.4 Heavy metals

Heavy metals also are another important group of compounds which can inhibit the production of biogas. Some examples of heavy metals are: lead (Pb), zinc (Zn), copper (Cu), iron (Fe),mercury (Hg), cadmium (Cd), chromium (Cr), nickel (Ni), cobalt (Co), and molybdenum. Heavy metals are not biodegradable and for this reason can be accumulated in cells membranes. The heavy metal, their toxicity is one of disturbances and low efficiency during methane fermentation processes and will reduce biogas production. The heavy metals at higher concentrations can be obtained in industrial and municipal wastewater in addition to sewage sludge.

2.2. BIOMETHANEPRODUCTION, STORING, DISTRIBUTION & END USAGE

Biomethane comes from biogas, biogas is produced from waste products and is mainly made by methane (CH_4) and carbon dioxide (CO_2), once Biogas is cleaned up by removing everything such as: Carbon dioxide (CO_2), Hydrogen sulphide (H_2S), Nitrogen (N_2), Hydrogen (H_2), Oxygen (O_2), Ammonia (NH_3),.. Except the methane the result is known as Biomethane. Biomethane has the same quality as natural gas, then can be used in place of natural gas in such condition that biogas should pass in three stages which are: Clean-up, Upgrading and Odorisation. Biogas cleaning and biogas upgrading are two production processes in which Biomethane can be obtained. Biogas cleaning phase consists of removing several impurities like: hydrogen sulphide, water vapour and minor impurities while biogas upgrading phase consists of removing carbon dioxide and enhancing quality of the methane content.

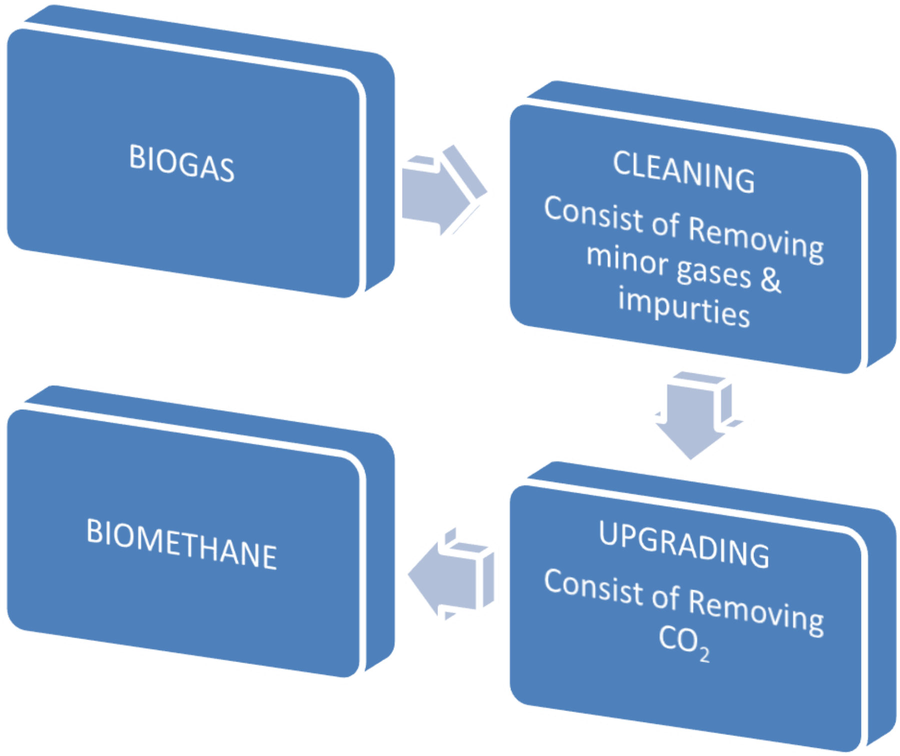


Figure 10: Process of Biogas conversion to Biomethane.

2.2.2 Biogas Upgrading to Biomethane

Biogas Upgrading means separation of methane (CH_4) to carbon dioxide (CO_2), and then the concentration of methane in treated biogas is increasing.

Methods for Upgrading Biogas to Biomethane

During upgrading biogas to Biomethane which is considered as higher fuel standard, the methane (CH_4) is separated to carbon dioxide (CO_2) and then specific caloric value of methane is increased. There are some techniques used for biogas upgrading which are: water scrubbing, Pressure swing adsorption, adsorption (physical and chemical), cryogenic separation, membrane technology, biological upgrading, etc. [23] [24] [25]

Pressure swing adsorption (PSA)

During this method of Pressure swing adsorption, adsorptive medium is used to separate gases. The mixture of gases penetrate through a surface of solids (adsorbents) such as: activated carbon, Zeolites, activated charcoal, silica gel, synthetic resins, etc and then unwanted contaminants are trapped by the size of molecular sieve. Adsorption rate is improved by using pressure at (4 to 7 bar) and temperature range (5- 35 ^{o}C) [25].The process occurs in vertical columns in which absorbents are included under four steps which are: adsorption, depressurization, desorption and pressurization. During pressurization step which done in pressurized column methane-rich gas passed through but $CO_2$is adsorbed. CO2, N2, O2and H2S are separated from gas streams by selectively adsorption of CO2 over CH4 onto the porous adsorbents with a high specific area, because CH4 molecule is larger than the other gas molecules. It is necessary to dry the gas and remove H2S previous to CO2 adsorption sinceH2S will adsorb irreversibly to the molecular sieves. Numerous columns are linked together in order to form continuous operation and also energy need for gas compression will be reduced. The off-gas should be treated for avoiding releasing methane to the atmosphere, for this method of Pressure swing adsorption96–98% of methane and 2–4% methane losses will be obtained. [24]

Table 5: Advantages and Disadvantages of Pressure swing adsorption [23].

Advantages	Disadvantages
High gas quality Low methane losses Dry process Low energy demand No chemical use	Complex process Pre-treatment needed

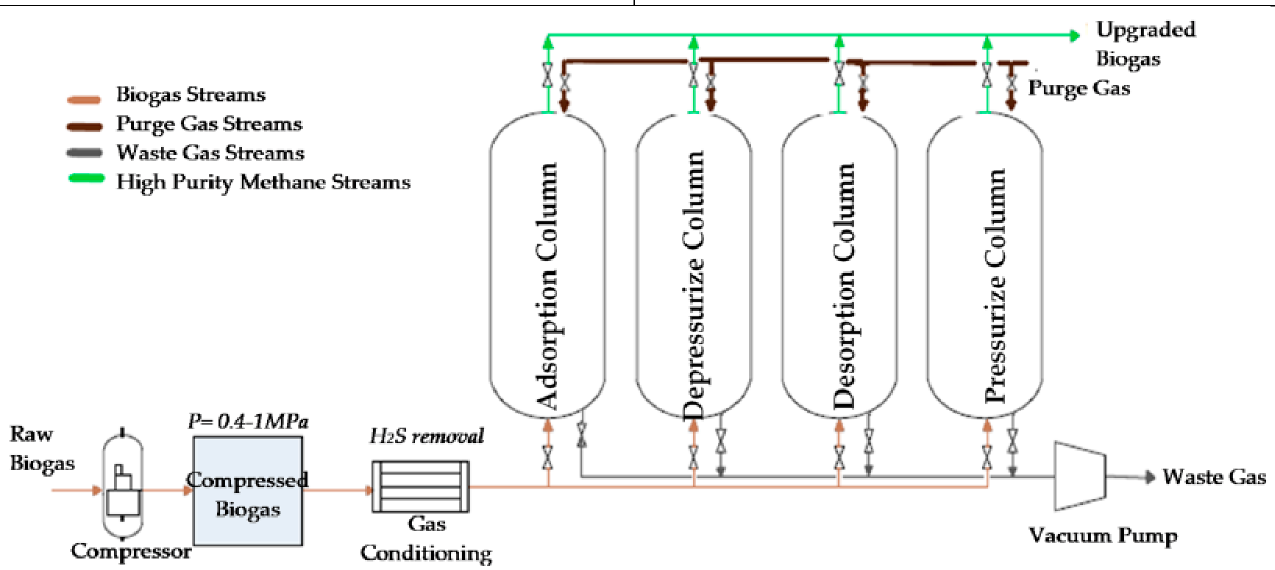


Figure 11: Biogas upgrading by Pressure swing adsorption technology [23] [24].

Membrane Separation

During biogas upgrading by Membrane Separation**,** membranes are made from materials which are permeable to water, carbon dioxide and ammonia while Hydrogen sulphide and oxygen permeate via membrane at certain amount, nitrogen and methane pass in small amount. Membranes are made by hollow fibres which are packed together. Filter is used to retain water, aerosols and oil droplets before biogas enters to the hollow fibres.

Membrane Separation is based on property of permeability of the membranes which may be gas to gas separation or gas to liquid separation. In gas to gas separation both side of the membranes are in gas phase while gas to liquid separation liquid absorbs Hydrogen sulphide (H_2S) and carbon dioxide (CO_2) molecules are diffusing via the membranes. Recirculation of off-gases can be used for reducing the loss of methane during process. Biogas temperature and pressure difference between the two sides of the membrane are two factor which drive Membrane Separation [24].

Feed known as raw biogas, the permeate (CO_2 and other gases) and the retentate (mainly CH4) are three flow which are identified during Membrane Separation technology. Drying and desulphurizing of raw biogas before entering to membranes is very essential for extending life span of membranes and also separation will be optimized [25].

Table 6: Advantages and Disadvantages of Membrane Separation technology [23].

Advantages	Disadvantages
Environmental friendly Low energy consumption Low cost Simple process	Low membrane selectivity Pre-treatment necessary Low CH4 purity.

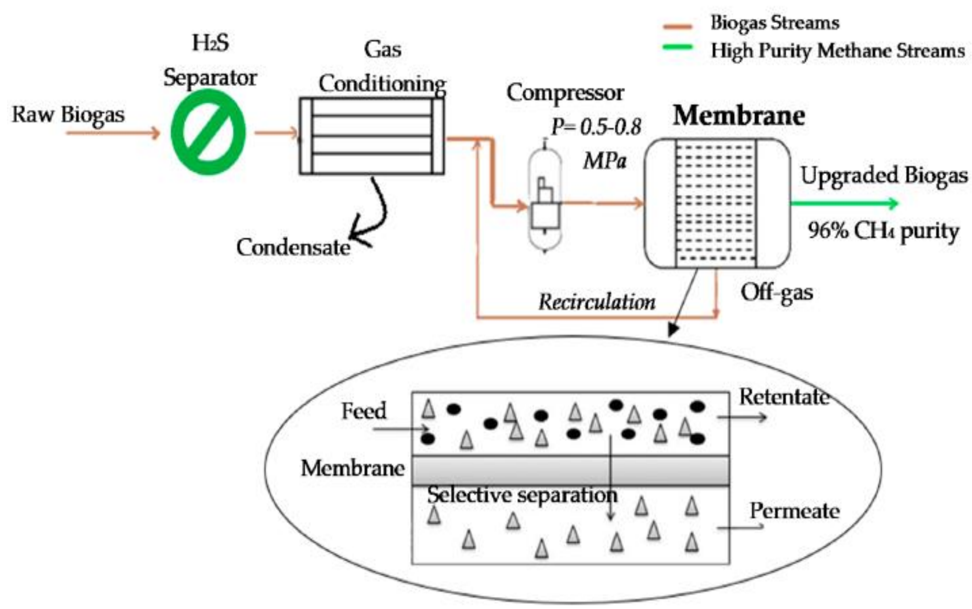


Figure 12: Schematic process of Biogas upgrading by Membrane Separation Technology [23].

Water scrubber technology

Water scrubber technology is technology used to upgrade biogas to biomethane. The solubility of Carbon dioxide in water is more than the solubility of methane; therefore Carbon dioxide is dissolved at higher rate than methane especially at lower temperatures as shown in figure 13.

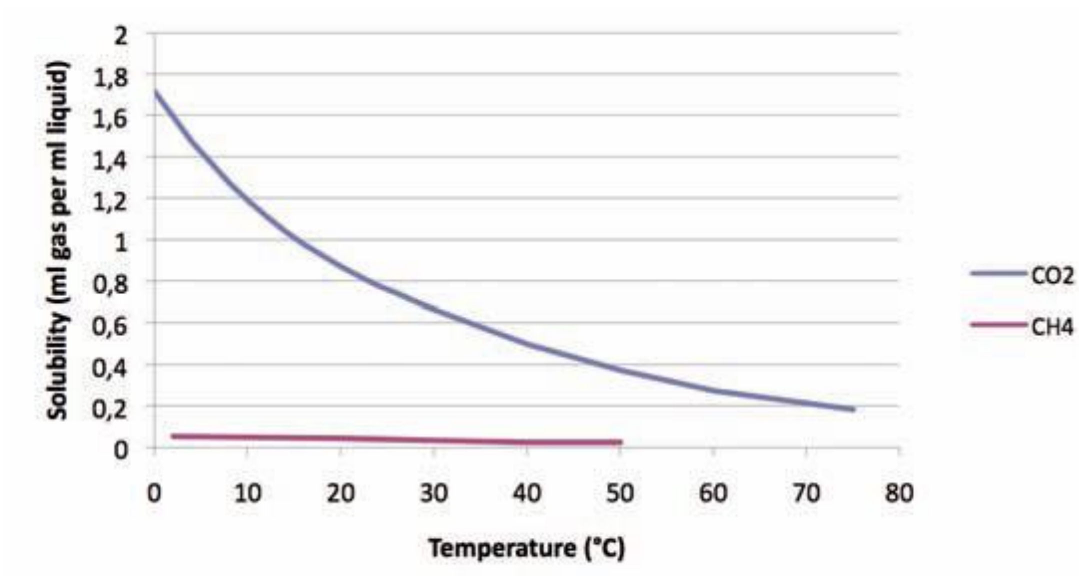


Figure 13: Rate of Solubility in water of methane and carbon dioxide [26].

The compressed raw biogas is added to an absorption column which is filled with water that is pumped by high pressure pump in this case the compounds of Carbon dioxide and sulphurous are dissolved in the water.

The water is used as solvent in which carbon dioxide is dissolved in scrubber column while concentration of methane in gas phase will be increased, and then the higher concentration of methane is obtained in gas leaving the scrubber column. In absorption column, there is water and this water leaves absorption column in order to be moved in which flash tank where carbon dioxide, methane are dissolved but carbon dioxide is at large amount while methane is in small amount.

Desorption column which is filled with plastic packing, is used when water needed to be recycled. In this desorption column water meet with flow of air in which carbon dioxide is released in it. Then the recycled water is moved back to absorption column but water is cooled down before for purpose of achieving the huge difference in solubility among carbon dioxide and methane.

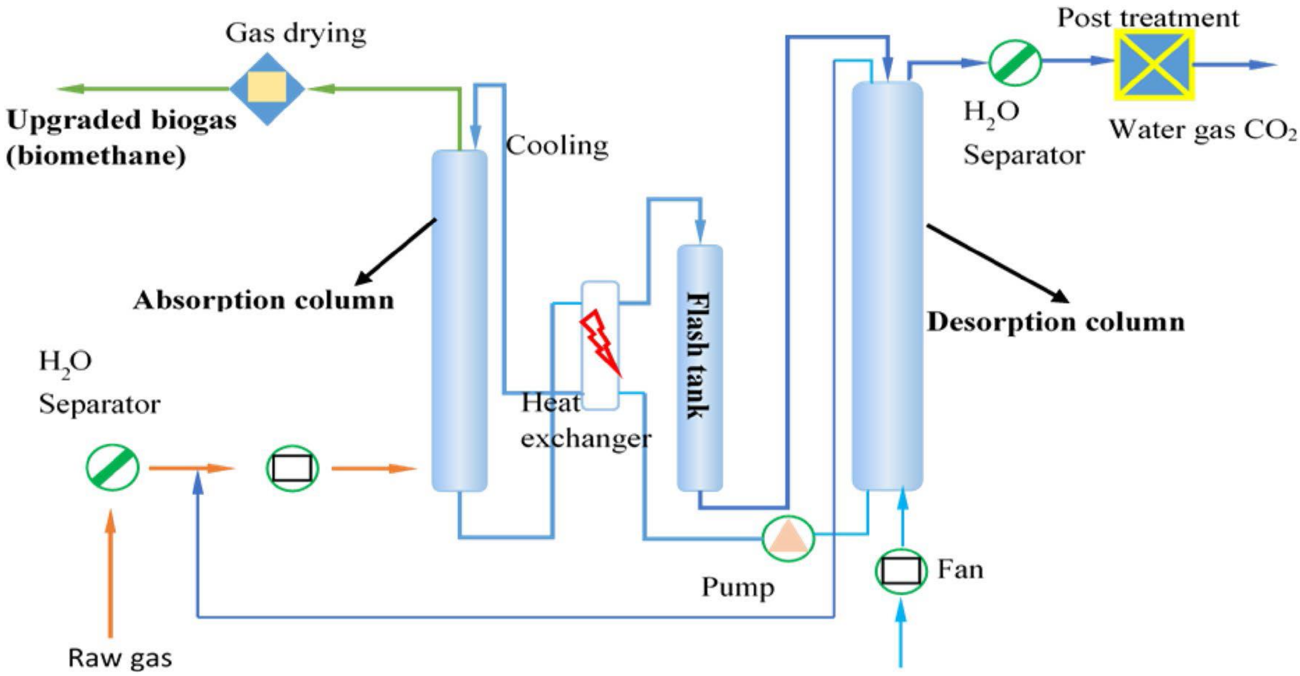


Figure 14: Schematic process of Biogas upgrading by water scrubbing [24].

2.2.3 Biomethane Storing

Biomethane like other renewable energy which comes from renewable sources such as: solar, wind, etc need storage in order to meet the demand of customer. Due to unpredictability of Biomethane production which can increase or decrease depends on Biodegradable waste produced. In order to meet or maintain an appropriate mechanism for continuous supply of energy from Biomethane,

Biomethane storage is required. Biomethane storage technologies are: Gas grid storage, Below-ground reservoir storage, Compressed tank storage, Liquefied storage, Bottling Storage, etc.

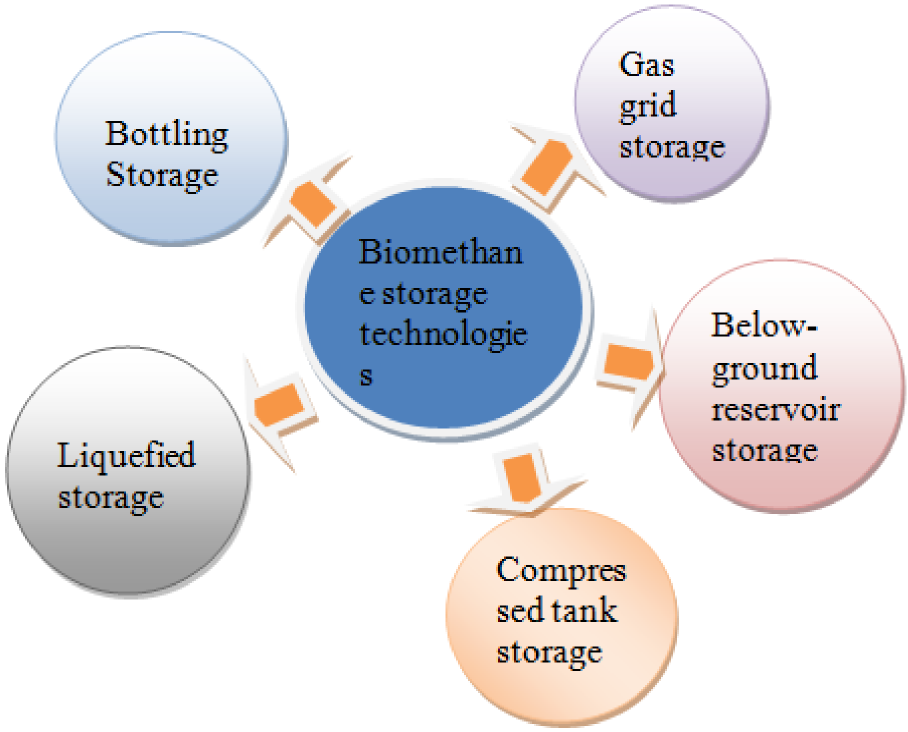


Figure 15:Biomethane storage technologies [27]

Gas grid storage

Storing of biomethane with Gas grid storage is more convenient in the country where it has natural gas grids before. Initial investment cost for Gas grid storage is lower and also has high energy efficiency with significant environmental benefits such as encouragement of using vehicles powered by biomethane. The gas grids are managed with public or private company which makes challenge/limitation to supplier who want to inject biomethane into gas grids, for this challenge supplier should negotiate for grid access to public or private company and also biomethane should meet quality of gas grid standards in order to be injected to gas grids. [27]

Below-ground reservoir storage

There are some technologies used to store Biomethane Below-ground such as: depleted gas and oil reservoirs, aquifers and salt caverns. This storage method can store Biomethane in large quantity which is above 300 billion m^3 all over the world. [27]

This technology of salt caverns has high injection and removal/withdrawal ratio with high turnover ratio compared to depleted gas and oil reservoirs and aquifers. Due to high tightness of the geological structure, low investment cost, infrastructure for injection / removal of gas which already exist, Depleted gas and oil reservoirs become good technology for storing biomethane but some limitation of this method is low turnover rates for removal of the gas due to requirement of minimum biomethane which is saved as cushion gas.

Aquifer is used to store Biomethane and is popular but in this day is not recommended due to its unfavorable characteristics. In the place where other storage option are available, Aquifer is not good choice due to its limited tightness, low rates of turnover, etc. below-ground storages should locate near/ close to the consumption or customer for purpose of minimizing transmission costs from point at which biomethane is stored.

Compressed tank storage

This method of storing biomethane, Supplier or producers of biomethane fills biomethane in large pressurized gas containers and those containers are transported to gas filling stations which are centralized at one point. Compressed tank storage may be in different shape such as cylindrical, pipe tanks, spherical, etc. For Compressed tank storage with spherical shape operates at pressure up to 10 bars while pipe tanks operate at pressure up to 100 bars. [27]

For Compressed tank storage to use on-site applications, Low-pressure biomethane storage tank are used but when stored biomethane require to be transported at certain distance (over long distance) high-pressure tanks are recommended. In Compressed tank storage, care should be taken into consideration such as fixing pressure relief valves and rupture disks for safety.

Liquefied storage

Liquefied biomethane is produced by cooling biomethane in gaseous form to pressures which is close to atmospheric pressure approximately to 111 K. Liquefied biomethane (LBM) is around to 1/600th the amount of biomethane which is in the gaseous state which means that Liquefied biomethane has higher energy content than biomethane which is in the gaseous state. [27]

Liquefied biomethane has good characteristic to their end user due to not being explosive and toxic. Liquefied storage has advantage of having low emissions level in its life cycle of emissions due to its lower leakage/ reduced leakages. Storage tank of liquefied biomethane should be erected to a foundation which is made in concrete and due to unnecessary heat transfer comes from environment good insulation is required. There are different liquefied biomethane Storage tank which are above-ground such as single containment tank, double containment tank and full containment tank. Where single containment tank has no external protective cover but is made in steel, double containment tank has external protective cover and full containment tank which has three layer inner(nickel steel tank), outer(external protective cover which is concrete) and space between inner and outer layer which is known as insulation layer for minimizing heat transfer. To transport Liquefied biomethane, suitable insulated tanker trucks are used.

Bottling Storage

Bottling is other method used for storing Biomethane, this method is somehow similar to compressed tank storage but for Bottling method , there is small volumes of bottles which makes Bottling method having operating characteristics differ from compressed tank storage. Bottling method is suitable for using to small scale or smaller end users like households, small commercial users, etc. Bottled biomethane can be used in remote area where there is limited access to electricity, traditional biomass which is used for cooking and stored biomethane in bottle can be used as cooking fuel for commercial cooking or domestic cooking. Bottled biomethane can be stored from different way such as station for refueling gas, storage tank and gas grid.

2.2.4 Biomethane end usage

Biomethane is produced from upgraded biogas and may have different usage once is obtained. Biomethane has two main types of end usage which are: providing biomethane to end use consumers (transportation fuel, industrial applications like process heating, cooking fuel and electricity provision) and providing ancillary services for grids which are related to heat, gas grids and power.

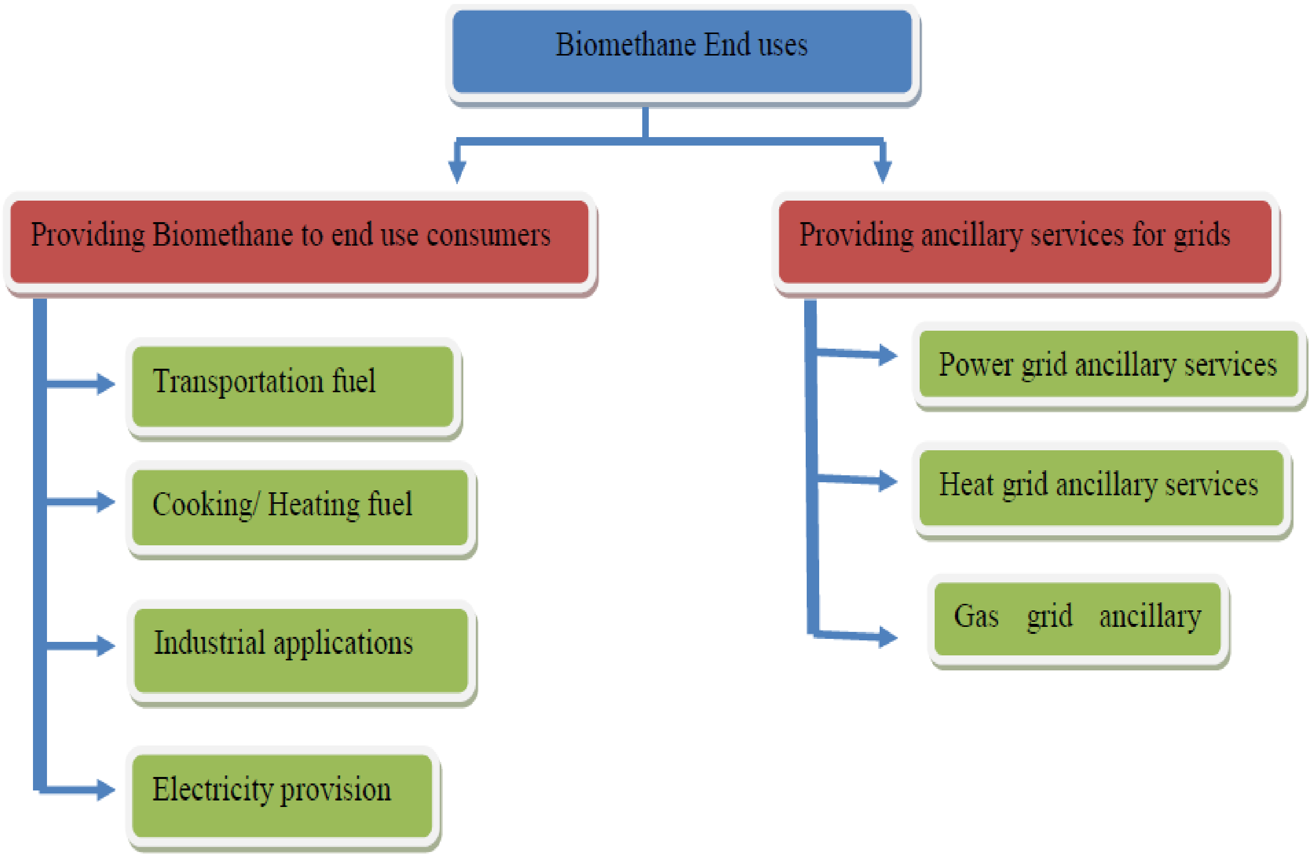


Figure 16:Biomethane end usage

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Introduction

Research methodology describes the methods and techniques that will be used during conducting this research project titled "Feasibility Study of Production of Bio Methane from Biodegradable Waste in Rwanda (Case study: NDUBA Landfill site)".those methods and techniques used to gather the information needed either from the field (primary data) or from other sources (secondary data), data collection, data gathering procedures, interview and analysis of those data collected from different sites and people will be discussed.

Methodology used

In order to carry out my project a literature review is carried on, and I refer to the data collected from workers of Nduba dumpsites, Staff of different company and also data collected from Kigali City, Ministry of Environment, Rwanda Environment Management Authority (REMA),…

In this project of Feasibility Study of Production of Bio Methane from Biodegradable Waste in Rwanda (Case study: NDUBA Landfill site), there are eight steps through which Bio Methane is obtained.

- Receiving Feedstock from different area
- Sorting.
- Storage of Biodegradable Waste
- Input to Anaerobic Digestor
- Anaerobic Digestion
- Biogas Production/ Storage
- Biogas Cleaning
- Biogas Upgrading
- Bio Methane

During this study, laboratory experiment is used to find biogas production from Biodegrable waste and there are some Equipment/Apparatus that are used which are: Water Bath, Erlenmeyer Flasks used as Digester, Outlet hose pipe for Biogas, Weighing Balance, Rubber Tube, and Bucket with water for displacement method, Graduated Measuring Cylinder for Gas Collector, Stand With clamp.

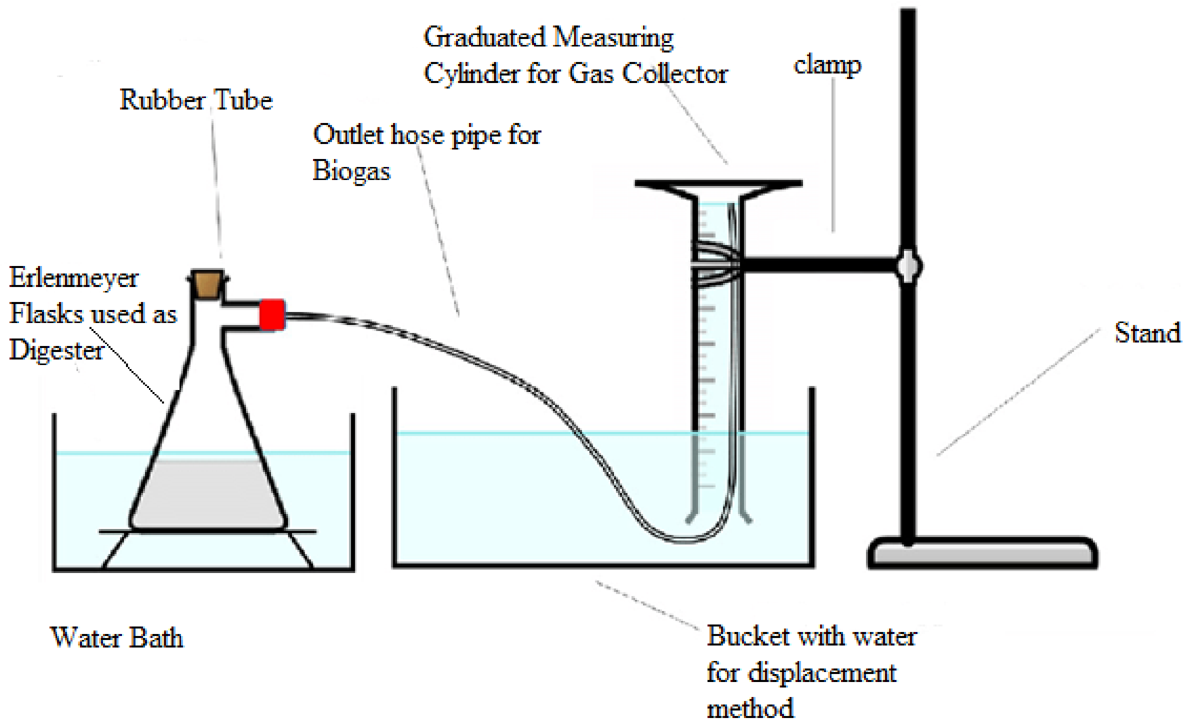


Figure 17: Experiment set-up for biogas production from Biodegradable waste

Experimental Details

Water displacement method will be used; the set-up for this method is shown in Figure 17. The feed to the digester will be prepared by mixing 100 g of Biodegradable waste with 100 ml of water and 5g of cow dung as inoculum. The mixture will be fed into the Biodigester bottle which is taken as Erlenmeyer flasks and connected to the Outlet hose pipe. The biogas will be collected by graduated measuring cylinder. The biogas produced was determined by noting the quantity of water displaced from the graduated measuring cylinder to Bucket with water for displacement method.

Figure 18: Shows Experiment set-up for biogas production from Biodegradable waste.

Figure 19: Shows the sample of Biodegradable waste in Erlenmeyer Flask used as Digester.

For Biomethane production, Membrane separation technology will be used. Figure 20 shows different stage for achieving Biomethane from Biogas.

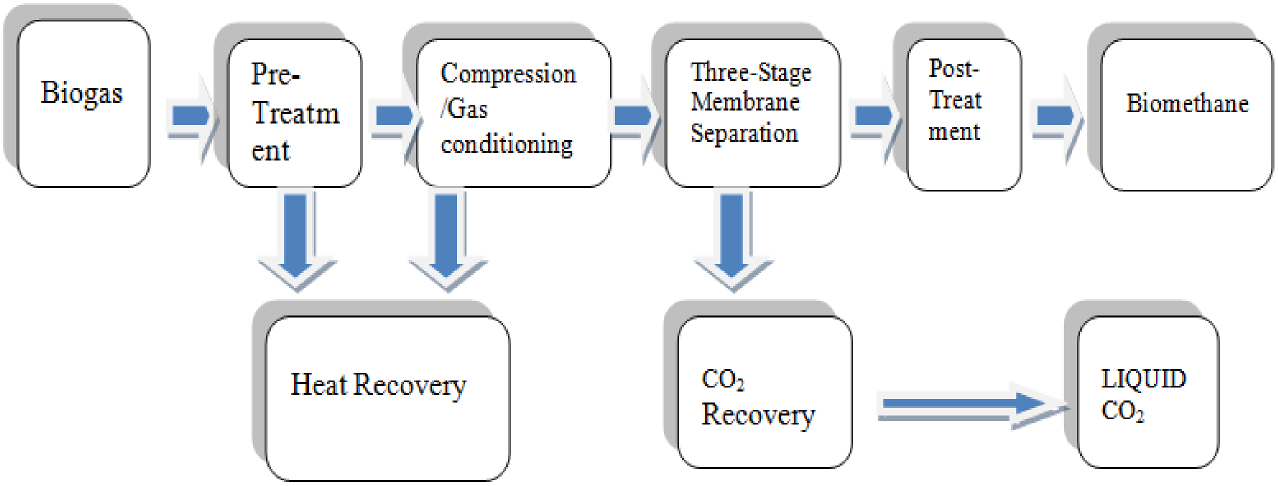
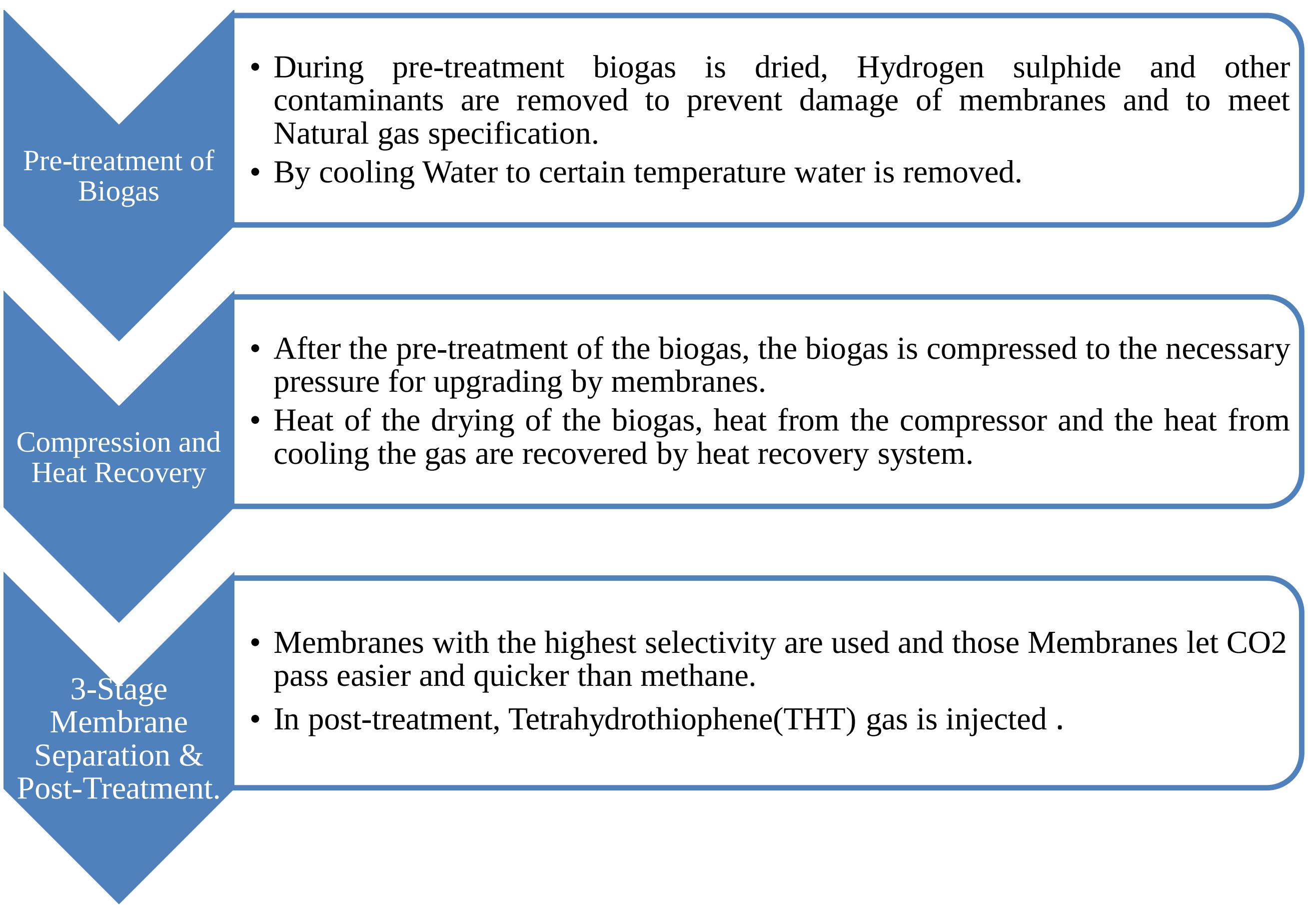


Figure 20: Methodology used to achieve Biomethane from Biogas.



CHAP IV: DATA ANALYSIS AND RESULT DISCUSION

4.1. DATA ANALYSIS

During this study which was conducted with the aim of determining Bio Methane Produced from Biodegradable Waste collected and disposed at Nduba dump site. Population of Kigali City from 2014 to 2030 is shown in Table 7. This shows that as Population increase also solid waste generated should be increased.

Table 7: Population of Kigali City from 2014 to 2030 [28]

Year	Population	Growth Rate
2030	**1,568,247**	**3.45%**
2029	**1,515,880**	**3.39%**
2028	**1,466,131**	**3.34%**
2027	**1,418,776**	**3.30%**
2026	**1,373,438**	**3.28%**
2025	**1,329,829**	**3.25%**
2024	**1,287,952**	**3.24%**
2023	**1,247,551**	**3.25%**
2022	**1,208,296**	**3.28%**
2021	**1,169,889**	**3.34%**
2020	**1,132,101**	**3.41%**

2019	**1,094,796**	**3.49%**
2018	**1,057,836**	**3.60%**
2017	**1,021,081**	**3.60%**
2016	**985,604**	**3.60%**
2015	**951,359**	**3.60%**
2014	**918,304**	**3.60%**

Solid waste material generated at Nduba dump site with their percentage and organic waste generation is 74.5 % of total Solid waste material generated as shown in Table 8 [29].

Table 8: Solid waste material generated at Nduba dump site with their percentage.

Components	%
Organics	**74.5**
Paper and Cardboard	**5.4**
Glass	**1.1**
Metal (ferrous & aluminum)	**0.4**
Plastic	**3.2**
Textiles	**2.8**
Construction waste	**0.4**
Special care wastes	**0.2**
Wood	**0.8**
Ash	**0.3**
Dirt	**8.3**
Other wastes	**2.5**

From research and data collection from workers of Nduba dumpsites, Staff of different company and also data collected from Kigali City shows that waste collected per day varies. From [29]waste collected per day was estimated to be 618 tonnes and per capita waste generation is 0.55 kg/day. From [30] waste collected per day was estimated to be 638 tonnes and per capita waste generation is 0.57 kg/day. From [31]waste collected per day was estimated to be 450 tonnes and per capita waste generation is 0.6 kg/day. The average of per capita waste generation is 0.573 kg/day.

Table 9: Unsorted & Organic Solid waste generated From Year 2014 to 2030.

N0	Year	Population	Unsorted Solid waste generated per day(kg)	Unsorted Solid waste generated per day(tonnes)	Unsorted Solid waste generated per year(tonnes)	Organic waste generated per day(tonnes)	Organic waste generated per year(tonnes)
1	2014	**918,304**	526188.192	526.188192	189427.7491	392.010203	141123.6731
2	2015	**951,359**	545128.707	545.128707	196246.3345	406.1208867	146203.5192
3	2016	**985,604**	564751.092	564.751092	203310.3931	420.7395635	151466.2429
4	2017	**1,021,081**	585079.413	585.079413	210628.5887	435.8841627	156918.2986
5	2018	**1,057,836**	606140.028	606.140028	218210.4101	451.5743209	162566.7555
6	2019	**1,094,796**	627318.108	627.318108	225834.5189	467.3519905	168246.7166
7	2020	**1,132,101**	648693.873	648.693873	233529.7943	483.2769354	173979.6967
8	2021	**1,169,889**	670346.397	670.346397	241324.7029	499.4080658	179786.9037
9	2022	**1,208,296**	692353.608	692.353608	249247.2989	515.803438	185689.2377
10	2023	**1,247,551**	714846.723	714.846723	257344.8203	532.5608086	191721.8911
11	2024	**1,287,952**	737996.496	737.996496	265678.7386	549.8073895	197930.6602
12	2025	**1,329,829**	761992.017	761.992017	274317.1261	567.6840527	204366.259
13	2026	**1,373,438**	786979.974	786.979974	283312.7906	586.3000806	211068.029
14	2027	**1,418,776**	812958.648	812.958648	292665.1133	605.6541928	218035.5094
15	2028	**1,466,131**	840093.063	840.093063	302433.5027	625.8693319	225312.9595
16	2029	**1,515,880**	868599.24	868.59924	312695.7264	647.1064338	232958.3162
17	2030	**1,568,247**	898605.531	898.605531	323497.9912	669.4611206	241006.0034

Biogas produced from pile of 10000 Mg of biodegradable waste varies between 2.8 to 3.8 million $m^3$and Methane content account 65% of biogas generated, Methane produced is upgraded up to 90% or more to obtain pure Biomethane [32].

From Experiment, data shows that 100 g of Biodegradable waste with 100 ml of water and 5g of cow dung as inoculum. From this period 8th October to 8th November 2021, experiment shows that

Biodegradable waste produce 20 ml of Biogas. So, 100 g of Biodegradable waste produce 20 ml of Biogas which means 1 kg produce 200 ml which is equal to 0.0002 m^3.One tonne of Biodegradable waste produce 0.2 m^3.

Table 10: Biogas, Methane & BioMethane produced From Organic waste generated in Year 2014 to 2030.

N0	Year	Organic waste generated per year(tonnes)	Biogas produced per year(m^3)	Methane produced per year(m^3)	BioMethane produced per year(m^3)
1	2014	141123.6731	28224.73462	18346.0775	16511.46975
2	2015	146203.5192	29240.70384	19006.4575	17105.81175
3	2016	151466.2429	30293.24858	19690.61158	17721.55042
4	2017	156918.2986	31383.65972	20399.37882	18359.44094
5	2018	162566.7555	32513.3511	21133.67822	19020.31039
6	2019	168246.7166	33649.34332	21872.07316	19684.86584
7	2020	173979.6967	34795.93934	22617.36057	20355.62451
8	2021	179786.9037	35957.38074	23372.29748	21035.06773
9	2022	185689.2377	37137.84754	24139.6009	21725.64081
10	2023	191721.8911	38344.37822	24923.84584	22431.46126
11	2024	197930.6602	39586.13204	39586.13204	23157.88724
12	2025	204366.259	40873.2518	26567.61367	23910.8523
13	2026	211068.029	42213.6058	27438.84377	24694.95939
14	2027	218035.5094	43607.10188	28344.61622	25510.1546
15	2028	225312.9595	45062.5919	29290.68474	26361.61626
16	2029	232958.3162	46591.66324	30284.58111	27256.123
17	2030	241006.0034	48201.20068	31330.78044	28197.7024

4.2. RESULT DISCUSION

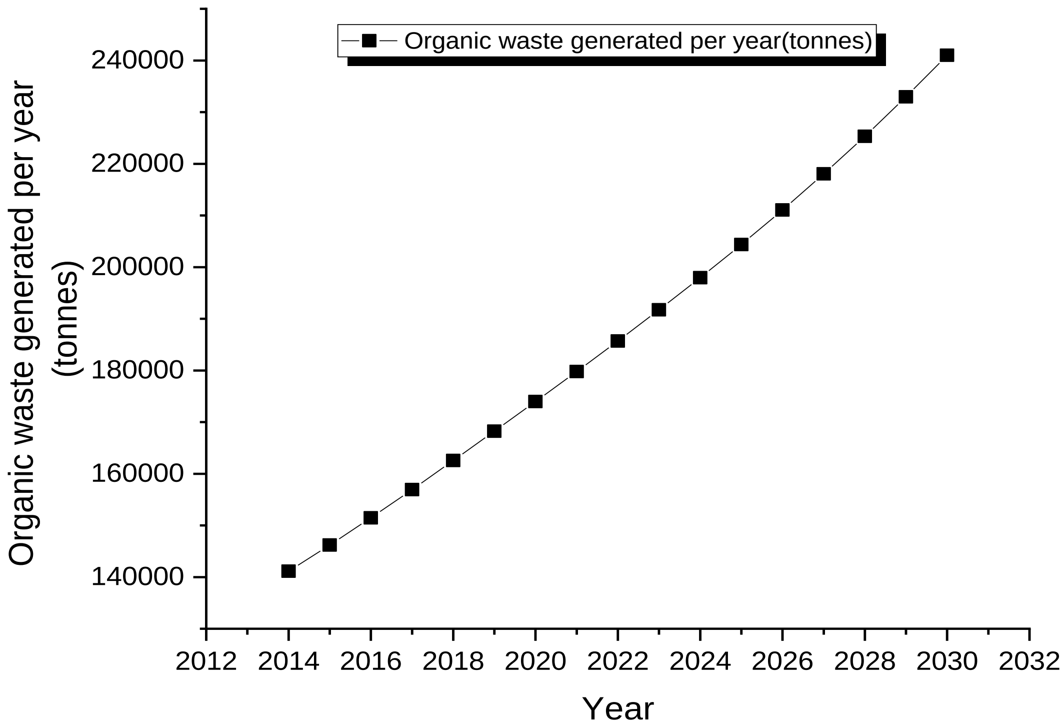


Figure 21: Organic waste generated From Year 2014 to 2030.

Due to rapid increase in urbanization and rapid growth of population in Kigali city, there increase in solid waste generated. Figure 21, shows Organic waste generated From Year 2014 to 2030. This shows that as the year increase also the Organic waste is increased.

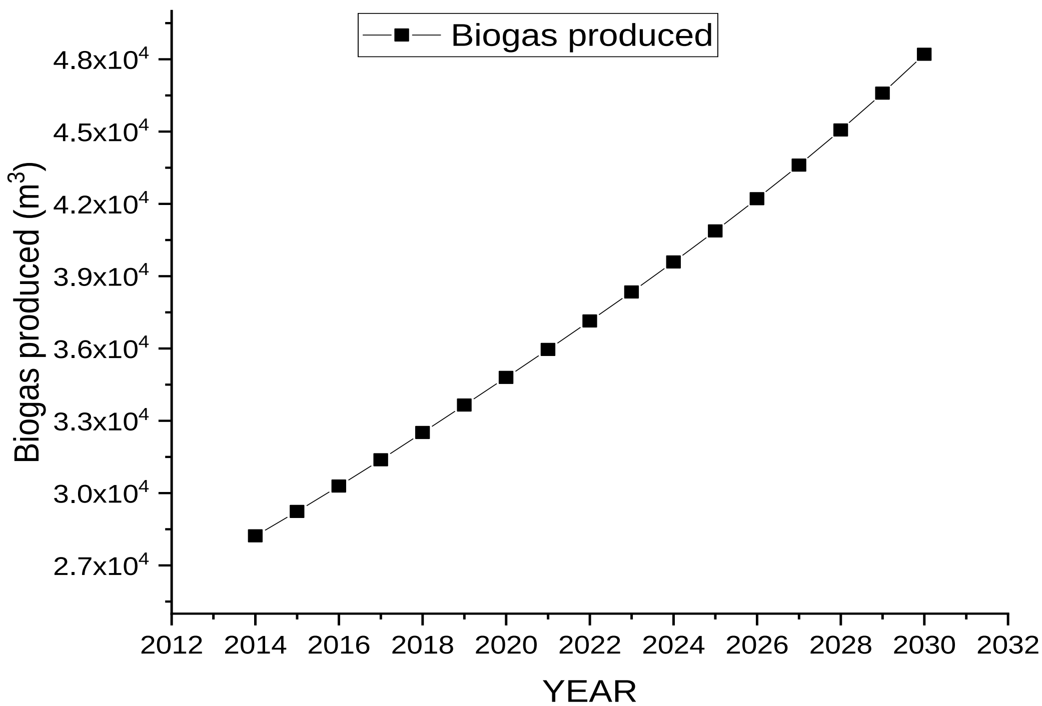


Figure 22: Biogas produced From Year 2014 to 2030.

Figure 22, shows Biogas produced From Year 2014 to 2030. This shows that as the year increase also the Biogas is increased.

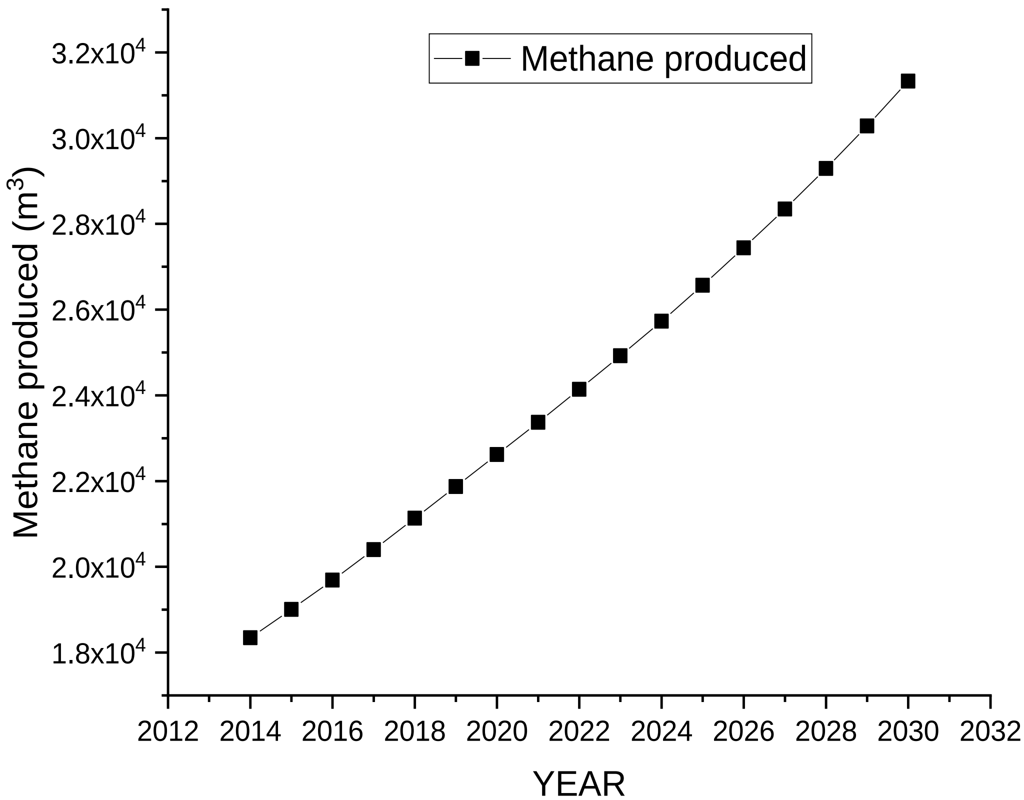


Figure 23: Methane produced From Year 2014 to 2030.

Figure 23, shows Methane produced From Year 2014 to 203. This shows that as the year increase also the Methane production will increase.

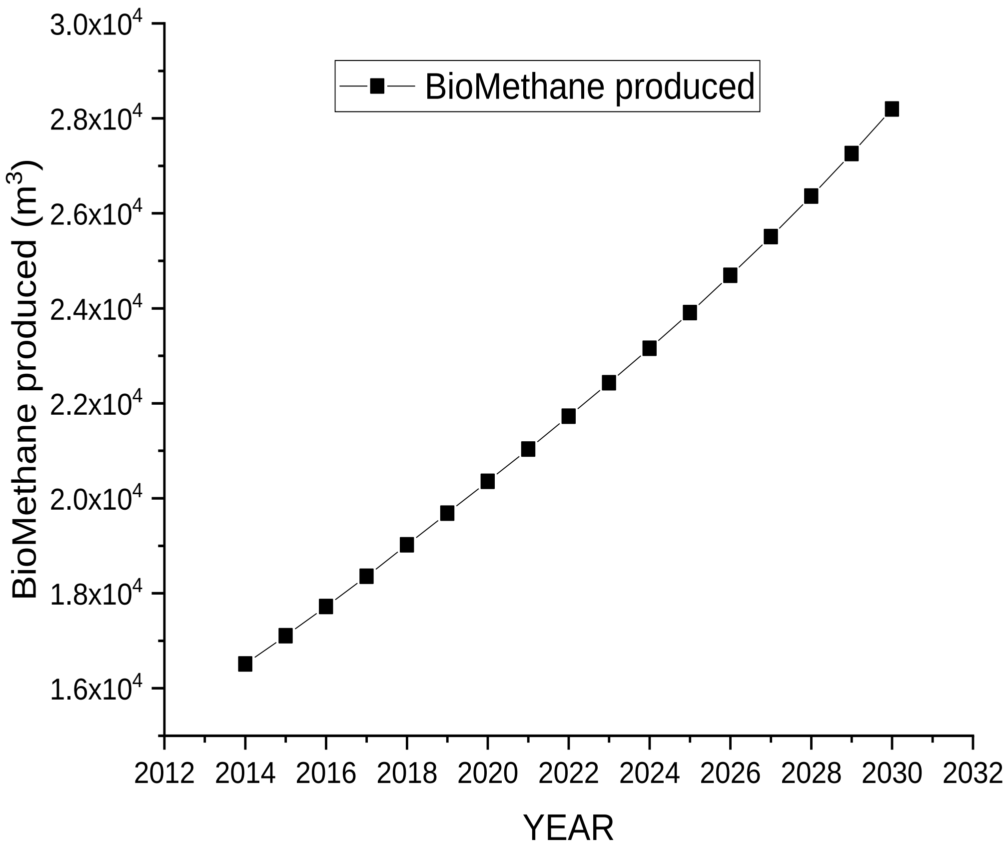


Figure 24: BioMethane produced From Year 2014 to 2030.

Figure 24, shows BioMethane produced From Year 2014 to 2030. This shows that as the year increase and BioMethane generated also increase.

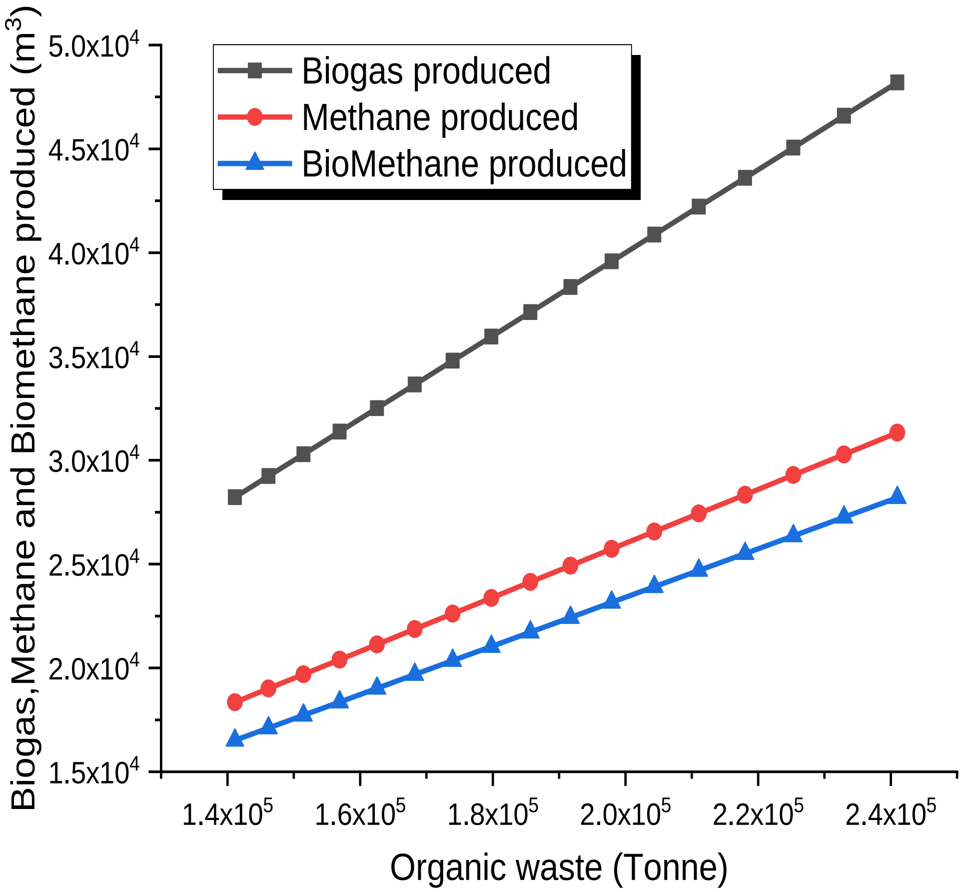


Figure 25: Shows that Biogas, Methane and BioMethane increase as Organic Waste increase.

Figure 25, shows a combination graph of Biogas, Methane and BioMethane produced. As Organic Waste increase and also Biogas, Methane and BioMethane production will increase. But graph line of Biogas is higher than graph line of Methane and BioMethane because volume of Biogas is higher compared to volume of Methane and BioMethane.

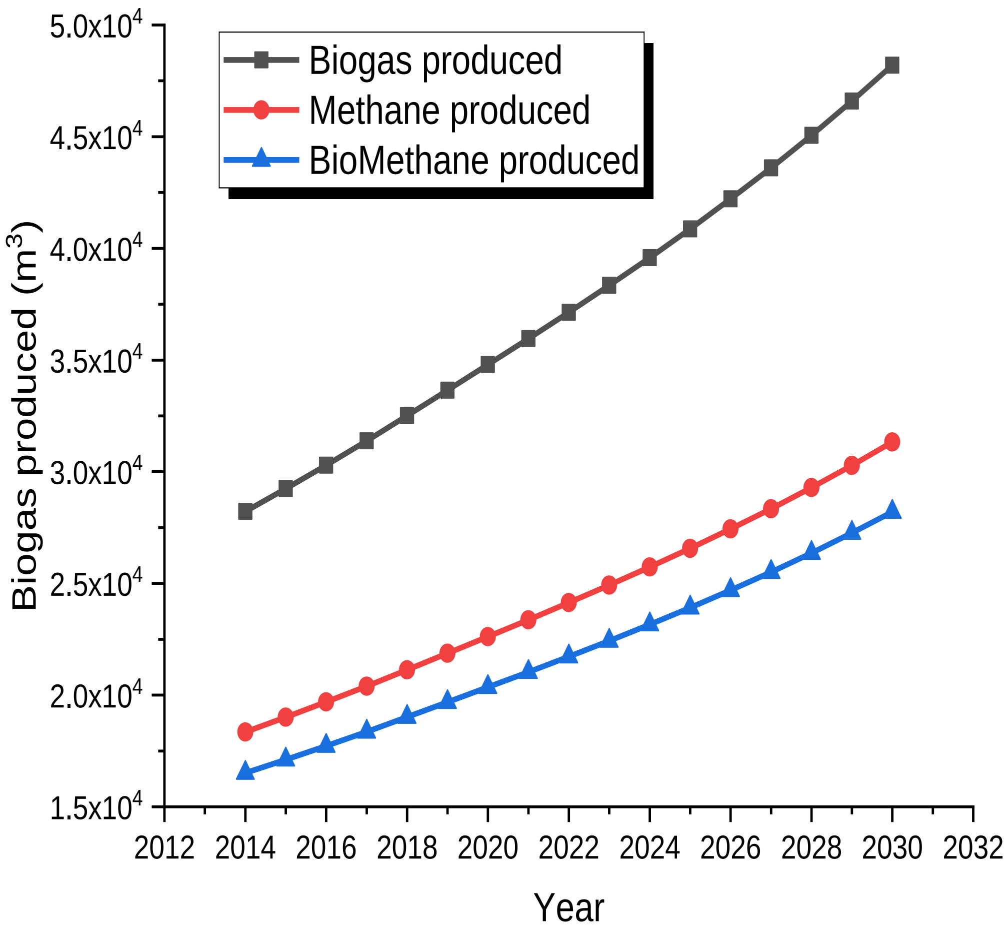


Figure 26: Biogas, Methane and BioMethane produced From Year 2014 to 2030.

Figure 26, shows a combination graph of Biogas, Methane and BioMethane produced From Year 2014 to 2030. This shows that as the year increase and Biogas, Methane and BioMethane generated also increase. But graph line of Biogas is higher than graph line of Methane and BioMethane because volume of Biogas is higher compared to volume of Methane and BioMethane.

CHAPTER V: CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

Due to pollution of environment caused by increasing of burning of fossil fuels, Renewable energy from Biodegradable Waste known as Biogas which is used directly to produce electricity and heat can be utilized to reduce dependence on fossil fuels and also Biomethane produced from upgrading biogas is good fuel which is used to reduce dependence on fossil fuels. During, Feasibility Study of Production of Bio Methane from Biodegradable Waste in Rwanda, Analysis shows that Bio Methane increase as organic Biodegradable Waste increase, as Biodegradable Waste increase also Biogas which in turn increases Bio Methane produced. Therefore, the Bio Methane Production from Biodegradable Waste in Rwanda is Feasible.

5.2. RECOMMENDATION

- Feasibility of Bio Methane Production from Biodegradable Waste depends on sorting efficiency, in Rwanda sorting of materials is difficult due to that Rwandan are not familiar with sorting, So government of Rwanda should establish regular mobilization via Radio program, Television program, social media and government of Rwanda should establish course known as sorting of material from primary to university.
- Due to lack of experience and technical knowledge of biomethane production technology, government should establish a program for Benchmarking from outside country.
- Due to lack of Laboratory for testing Biogas and Biomethane produced in our centre, Centre should provide such laboratory.

References

[1] T. Bond, M.R. Templeton, " History and future of domestic biogas plants in the developing world," *Article in Energy for Sustainable Development* , vol. 15 , no. DOI: 10.1016/j.esd.2011.09.003)., p. 347–354, 2011.

[2] Junginger, M., & Baxter, D. (Eds.), "Biomethane – Status and Factors Affecting Market Development and Trade Of a Joint Study on Behalf of IEA Bioenergy Task 40 and Task 37," 2014.

[3] "The National Institute of Statistics of Rwanda (NISR)," EICV4-2015.

[4] UNESCO-sida Program., "Country profile – Rwanda.," October 11, 2017.

[5] N. I. o. S. o. Rwanda, "Fourth Population and housing Census, Rwanda," 2014.

[6] Josephine Isugi,Dongjie Niu, "Research on Landfill and Composting Guidelines in Kigali City, Rwanda Based on China's Experience," *International Proceedings of Chemical, Biological and Environmental Engineering,* vol. 94 of IPCBEE , no. DOI: 10.7763/IPCBEE. 2016. V94. 10), 2016.

[7] Jean de Dieu Uwisengeyimana, Ahmet Teke, Turgay Ibrikci., "Current Overview of Renewable Energy Resources in Rwanda.," *Journal of Energy and Natural Resources.* , vol. 5, no. doi: 10.11648/j.jenr.20160506.13)., pp. 92-97, 2016.

[8] Minenfra, "Energy Sector Strategic Plan(2018/19 to 2023/24)," September 2018..

[9] Emmanuel Mudaheranwa,Ye-Obong Udoakah and Liana Cipcigan, " Rwanda's Energy Profile and Potential Renewable Energy Resources Mapping toward Sustainable Development Goals," *IEEE PES/IAS PowerAfrica,* 2019.

[10] "ANNUAL REPORT For Rwanda Energy Group," 2020-2021.

[11] Balat, M., and H. Balat, " Biogas as a Renewable Energy Source—A Review." Energy Sources, Part A: Recovery, Utilization, and Environmental Effects," no. doi:10.1080/15567030802089565., pp. 280- 1293, 2009.

[12] "The Sietch Blog. 2009. GE Makes Bio-Gas More Efficient. Accessed May 20, 2016. http://blog.thesietch.org/tag/biogas.)".

[13] Opeoluwa Dada and Charles Mbohwa, " Biogas Upgrade to Biomethane from Landfill Wastes: A Review, Kruger National Park. Procedia Manufacturing," in *International Conference on Sustainable Materials Processing and Manufacturing,SMPM,*, 23-25 January 2017.

[14] Muzenda, Edison, " Bio-methane Generation from Organic Waste: A Review." The World Congress on Engineering and Computer Science. San Francisco, USA: WCECS," 2014.

[15] Schnürer, A., and Å. Jarvis, " Microbiological Handbook for Biogas Plants: Swedish Waste Management U2009:03, Swedish Gas Centre Report 207 . Swedish Waste Management," 2010.

[16] Sithara Mary Sunny, Kiran Joseph, " Review On Factors Affecting Biogas Production," *International Journal For Technological Research In Engineering* , vol. 5, no. 9, 2018.

[17] Okonkwo P.C, Aderemi B.O ,Okoli C.S , "Factors Affecting Biogas Production during Anaerobic Decomposition of Brewery effluent- wastewater in a Fluidized Bed Digester," *Journal of Environment and Earth Science,* vol. 3, 2013.

[18] P. Mahanta, U.K. Saha, A. Dewan, P. Kalita and B. Buragohain, "Biogas Digester: A Discussion on Factors Affecting Biogas Production and Field Investigation of a Novel Duplex Digester," *Journal of the Solar Energy Society of India,* 2005.

[19] Yenigun O, Demirel B, " Ammonia inhibition in anaerobic digestion: a review. Process Biochem.," pp. 901-911, 2013.

[20] Małgorzata Czatzkowska, Monika Harnisz, Ewa Korzeniewska and Izabela Koniuszewska, "Inhibitors of the methane fermentation process with particular emphasis on the microbiological aspect: A review DOI: 10.1002/ese3.609," 2019.

[21] "https://lpelc.org/processing-biomass-into-biogas/".

[22] "https://lpelc.org/processing-biomass-into-biogas/".

[23] Amir Izzuddin Adnan, Mei Yin Ong , Saifuddin Nomanbhay , Kit Wayne Chew and Pau Loke Show, "Technologies for Biogas Upgrading to Biomethane: A Review," 2 October 2019.

[24] Olumide Wesley Awe, Yaqian Zhao, Ange Nzihou, Doan Pham Minh, Nathalie Lyczko, " A Review of Biogas

Utilisation, Purification and Upgrading Technologies: Review. Waste and Biomass Valorization,Springer," pp. 267-283, 2017.

[25] Beil, Michael, and Wiebke Beyrich, " Biogas upgrading to bimethane." In The Biogas Handbook, by Arthur Wellinger, Jerry Murphy and David Baxter, Woodhead Publishing Limited. doi:10.1533/9780857097415.3.342.," pp. 342-377, 2013.

[26] Anneli Petersson, Arthur Wellinger , "Biogas Upgrading Technologies – Developments and Innovations, IEA Bioenergy, available on www.iea-biogas.net," August 2014.

[27] Budzianowski WM, Brodacka M. , "Biomethane storage: Evaluation of technologies, end uses, business models, and sustainability.," *Energy Convers Manage ,http://dx.doi.org/10.1016/j.enconman.2016.08.071),* 2016.

[28] "World Urbanization Prospects- United Nations population estimates and projections of major Urban Agglomerations https://worldpopulationreview.com/world-cities/kigali-population)".

[29] P. Sylvie Mucyo, "Solid Waste Characterisation in Kigali City, Report Submitted For the Characterisation of Waste Disposed At Nduba Dumping Site," June 2019 .

[30] Kabera, T., Wilson, D., Nishimwe, H., " Benchmarking performance of solid waste management and recycling systems in East Africa: Comparing Kigali Rwanda with other major cities. Waste Management and Research.37(1):38-52," 2019.

[31] S. Mucyo, Analysis of Key Requirements for Effective Implementation of Biogas Technology for Municipal Solid Waste Management in Sub-Saharan Africa. A Case Study of Kigali City, Rwanda., November 2013 .

[32] Edward Meller, Grzegorz Jarnuszewski, Patrycja Rogalska, Marcin Baran,, "CHARACTERISTICS OF MUNICIPAL WASTE BIODEGRADABLE FRACTION AND EVALUATION OF ITS PROCESSING. DOI: 10.12911/22998993/60469," *Journal of Ecological Engineering,* vol. 16, no. 5, pp. 133-137, 2015.

[33] Sithara Mary Sunny, Kiran Joseph , "“REVIEW ON FACTORS AFFECTING BIOGAS PRODUCTION” International Journal For Technological Research In Engineering Volume 5, Issue 9, May-2018".

[34] "Okonkwo P.C, Aderemi B.O ,Okoli C.S “Factors Affecting Biogas Production during Anaerobic Decomposition of Brewery effluent- wastewater in a Fluidized Bed Digester.”Journal of Environment and Earth Science ,".