Addis Ababa University
Addis Ababa Institute of Technology
School of Mechanical and Industrial Engineering

Experimental Analysis of Biogas Compression and Purification from Biogas Digester: A Case Study at Sidist Killo Campus

A Thesis Submitted to the School of Graduate Studies of Addis Ababa Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Mechanical Engineering
(Thermal Engineering Stream)

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ABSTRACT

The study encourages a way to recover energy from food wastes with the objective of producing clean biogas fuel (methane) from a food waste by using anaerobic digestion (biological decomposition). This waste to fuels technology reduces the amount of waste to be sent to the living areas, recovers energy from bio waste, helps to generate income from the selling of the produced biogas fuel (methane) and solves the energy problems. This thesis assesses the compression and purification of biogas mainly methane through anaerobic digestion, using a $10m^3$ digester installed at Sidist killo campus.

Biogas which is a clean and environmental friendly fuel emerged as one of the potential alternative fuels. Raw biogas contains about 60-70% methane (CH_4), 30-40% carbon dioxide (CO_2), traces of hydrogen sulfide (H_2S) and fractions of water vapors. But its wide spread use is disadvantaged by the associated problems like low energy density due to the presence of impurities, generation at low pressures and the absence of means for storing and transporting. Biogas is widely used for cooking and lighting, but its commercial use has not been realized due to difficulties in its storage and transportation.

This work intends to establish a facility at the site of biogas production in the sidist killo campus for purifying, compressing, bottling and making it transportable. Solution identified to the problem is to increase the energy density of the gas through removal of incombustible and corrosive gas and consequent compression which is experimented on this paper. This paper presents all the results of removal of impurities of biogas which are mainly carbon dioxide gas, hydrogen sulphide and water from biogas using reasonable chemicals selected. Sodium hydroxide, activated carbon powder and silica gel are chemicals selected to remove carbon dioxide, hydrogen sulphide and moisture respectively from the raw biogas.

Experimental results are evaluated by ever-changing the amount of chemical used from 0 up to 10 gm. As a result, the purity of biogas increases with increasing the amount of chemicals. The gas purified after the scrubbing unit constitutes 61% of methane which is in the acceptable range of methane content in the biogas. Further, compression of biogas was carried out by a commercial compressor and stored into a 500lt biogas bag and tire inner tube at a pressure of 2 and 1 bar respectively. And finally the stored biogas is bottled in to 2lt commercial gas cylinder using modified cycle pump at a pressure of 5 to 8 bar which a normal person can exert.

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ACRONYM'S

AD	Anaerobic digestion
CH_4	Methane
CO_2	Carbon di Oxide
N_2	Nitrogen
H_2S	Hydrogen Sulphide
P	Phosphorus
K	Potassium
pH	Potential of Hydrogen
CO	Carbon mono Oxide
VFA	Volatile Fatty Acids
TS	Total Solids
VS	Volatile Solids
C/N	Carbon to Nitrogen ratio
HRT	hydraulic retention time
SRT	solids retention time
OLR	Organic Loading Rate
Q	substrate flow rate in m^3/day,
S	substrate concentration in kg/m^3
V	reactor volume
BMP	biological methane potential
COD	chemical oxygen demand
GC	Gas chromatography
LPG	Liquefied Petroleum Gas
GHGs	Greenhouse gases
FW	Food waste
VFA	Volatile Fatty Acids
TS	Total Solid
VS	Volatile Solid
NRV	Non Return Valve
BV	Ball valve

PG	Pressure Gauge
STP	Standard Temperature and Pressure
MC	moisture content
ECETOC	European Centre for Ecotoxicology and Toxicology of Chemicals
ISO	International Organization for Standardization
TCD	Thermal Conductivity Detector
FID	Flame Ionization Detector

CHAPTER ONE

1.0. Introduction

1.1. Background

Biogas is a valuable renewable energy produced from biodegradable organic materials through anaerobic digestion. Anaerobic digestion is a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. One of the end products is biogas, which is combusted to generate electricity and heat, or can be processed into renewable natural gas and transportation fuels.

Anaerobic digestion is a scalable technology widely used around the world to safely manage organic waste while allowing for the capture of marketable byproducts (biogas) through the treatment of wastes and wastewater. It has a low energy requirement, used to convert organic material from a wide range of biological waste types into biogas.

Biogas is produced by anaerobic degradation of organic compounds and could be the substitute for natural gas and fossil fuels. It contains mostly three components, which are methane (CH_4), carbon dioxide) (CO_2) and nitrogen (N_2), However, other trace species exist as well, which are hydrogen sulphide (H_2S), hydrogen (H_2), nitrogen (N_2), ammonia (NH_3), oxygen (O_2) and carbon monoxide (CO). Furthermore, typical biogas is saturated with water, dust particles, siloxanes, aromatic and halogenated compounds [1], but the amounts of these trace compounds are very low compared to CH_4 and CO_2. Various biogas sources with their impurities levels are shown in Table 1.

Table 1 various biogas sources with their impurities level [1]

Biogas	CH_4 (%)	CO_2 (%)	N_2 (%)	O_2 (%)	H_2S(ppm)	Benzene(mg/m^3)
Landfills	45-62	24-40	1--17	1--2.6	15-427	0.6-35.6
Sewage Digesters	58-65	33-40	1--8	<1	0-24	0.1-0.3
Organic waste Digesters	60-70	30-40	1	1--5	10-180	0.1-1.1

The gases methane, hydrogen, and carbon monoxide (CO) can be combusted or oxidized with oxygen. This energy release allows biogas to be used as a fuel; it can be used for any heating purpose, such as cooking. It can also be used in a gas engine to convert the energy in the gas into electricity and heat. We can use this biogas for the purpose of cooking food, lighting and fuel gas for vehicle running too.

Biogas can play a major role in the developing market for renewable energy and it is assessed that biogas usage in the world will be doubled in the future years from 14.5 gigawatts (GW) in 2012 to 29.5 GW in 2022[1]. The demand for renewable fuels is increasing with growing concern about environmental problems due to the high greenhouse gases (GHGs) emission from fossil fuel combustion [4].

Also many farmers can use biogas production to establish a second economic support, in that way ensuring that their agricultural enterprises continue. Because energy generated from biogas is not subject to price fluctuations, it represents a reliable source of revenue.

Namely, anaerobic digestion can be the most feasible technology, since there are so many places where biological wastes and animals can be used for this purpose, and waste accumulations leading to a positive, environmental, and economical outcome for the society.

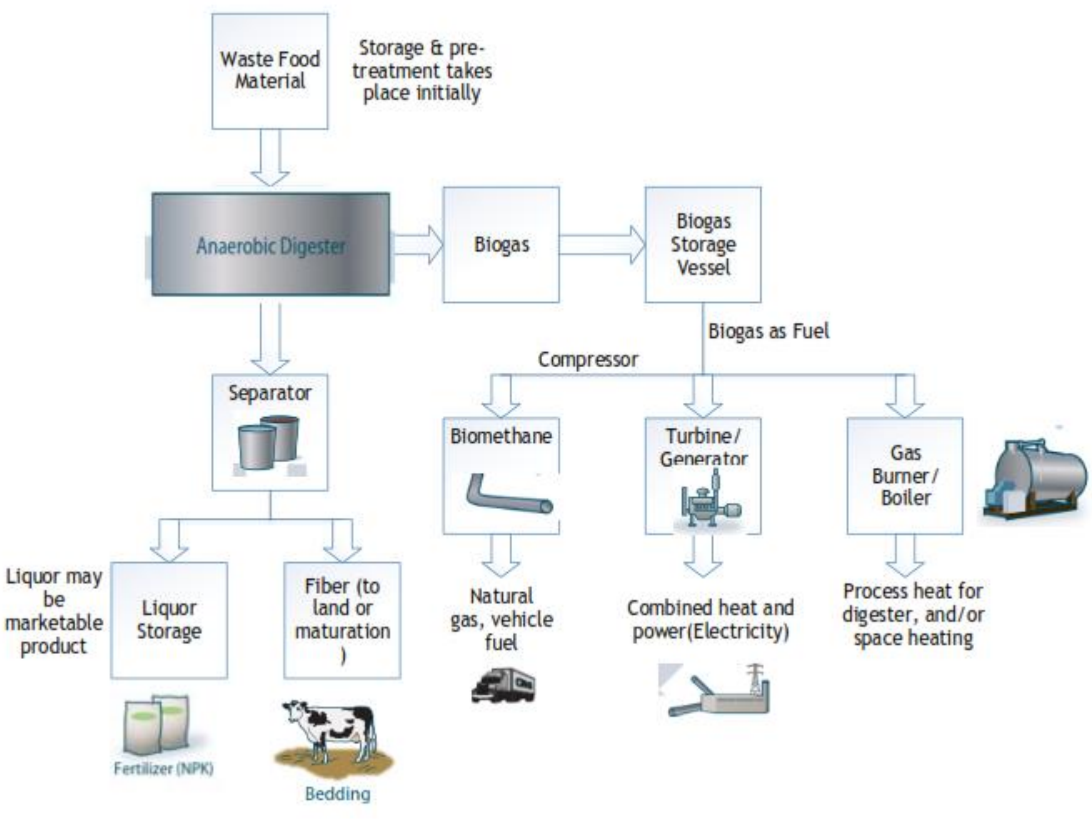


Figure 1 Anaerobic Digestion Flow Chart [5]

This technology can be applied at the household level, in small neighbor hoods or for the stabilization of sludge at large bio waste treatment plants, for which biogas reactors provide energy for cooking, lighting and heating as well as fertilizing sludge for soil improvement. In rural areas, they are often used for the digestion of animal manure, kitchen waste optionally toilet wastes.

Furthermore, biogas is also improving the environment indoors and outdoors. The indoor environment is enhanced by reduction in the incidents of illness from burning of firewood and dung, outdoor by reduction in carbon dioxide and methane emission [8]. Biogas is also a proven technology that contributes to the reduction of the deforestation rate and helps to save the trees to sequester more carbon from the atmosphere and the local effects of trees being cut down that otherwise cause soil erosion, desertification, loss of soil fertility, and landslides [4].

Biomass resources comprise of residues from agriculture, harvests from forest (in the form of firewood, charcoal, residues), crop residue, energy crops, animal manure, residues from agro-industrial and food processes, municipal solid wastes, and other biological resources [10]. These resources could be directly utilized for basic energy needs (e.g. firewood, charcoal, dung cake etc.) or transformed into invaluable renewable energies (e.g. biogas, biofuel, bioelectricity, hydrogen energy etc.) for household as well as industrial and transportation sector.

Gas production is dependent upon controlling anaerobic digester temperature, fermentation or retention time and the feedstock material. The gas production from the manure is dependent on the feeding of the animals, and the age of the manure when it is fed into the digester [7].

Anaerobic Digestion

Anaerobic digestion is a process of controlled decomposition of biodegradable materials under managed conditions where free oxygen is absent, at temperatures suitable for naturally occurring mesophilic or thermophilic anaerobic and facultative bacteria and archaea species, that convert the inputs to biogas and whole digestate. It consists in the biochemical degradation of complex organic matter resulting in the bio, which has as main constituents' methane (CH_4) and carbon dioxide (CO_2), and trace amounts of hydrogen (H_2), nitrogen (N_2), ammonia (NH_3) and hydrogen sulfide (H_2S). The significant amount of biodegradable components (carbohydrates, lipids and proteins) present in the microalgae biomass makes it a favorable substrate for the anaerobic microbial flora that can be converted into biogas rich in (CH_4) [20, 23].

Merits and Demerits of anaerobic digestion

Disadvantages

- Requires expert design and skilled construction
- Substrates need to contain high amounts of organic matter for biogas production
- Incomplete pathogen removal, the digestate might require further treatment
- Limited gas production below 15°C

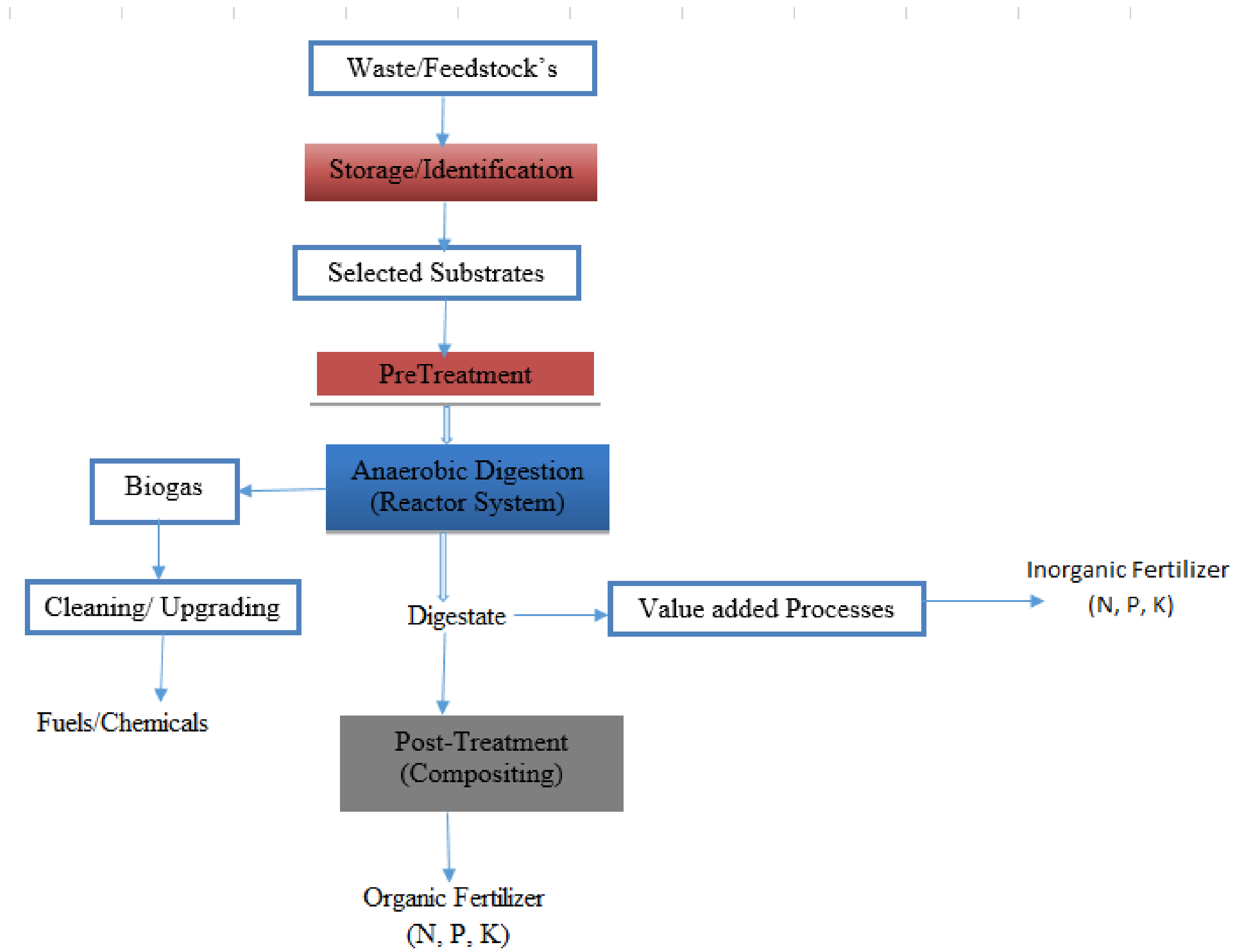


Figure 2 Overview of Anaerobic Digestion Technology [18]

Advantages

- Generation of renewable energy
- Small land area required (most of the structure can be built underground)
- Can be built and repaired with locally available materials
- No electrical energy required
- Combined treatment of animal, human and solid organic waste
- Conservation of nutrients
- Long service life
- Low to moderate capital costs; low operating costs

Major Processes of Biogas Production in an Anaerobic Digestion

The anaerobic digestion (AD) process involves four stages that successively break down matter until only simple molecules remain methane (CH_4), carbon dioxide (CO_2) and water [6]. AD begins with hydrolysis, which deconstructs complex organic matter into simple sugars, amino acids and fatty acids. Acidogenesis breaks down these sugars and acids further into alcohols and volatile fatty acids, creating carbon monoxide (CO), hydrogen sulphide. Acidogenesis is the third stage which produces hydrogen, CO acetic acid. The final stage, methanogenesis, involves specialized microorganisms that convert the remaining hydrogen and acetic acid into biogas, which consists of roughly 60% methane, 40% carbon dioxide, water vapor and various trace gasses.

Microbial Processes in anaerobic digestion occurs in four processes and is carried out by various groups of bacteria working together. Figure 3 below shows a general graphic representation of the processes involved in producing biogas from raw organic feedstocks. The basic processes are described below.

- *Hydrolysis (or liquification):* Microbial breakdown of the input feedstocks (such as corn, grain, sawdust, food waste, or manure) results in simple sugars, fatty acids, and amino acids, which are then available to other bacteria.
- *Acidogenesis:* Bacteria transform the products of hydrolysis into short chain volatile acids, ketones, alcohols, hydrogen, and carbon dioxide.
- *Acetogenesis:* Microbial conversion of organic acids into acetic acid, ammonia, hydrogen, and carbon dioxide
- *Methanogenesis:* Methane-producing microbes utilize acetic acid, hydrogen, and carbon dioxide to methane.

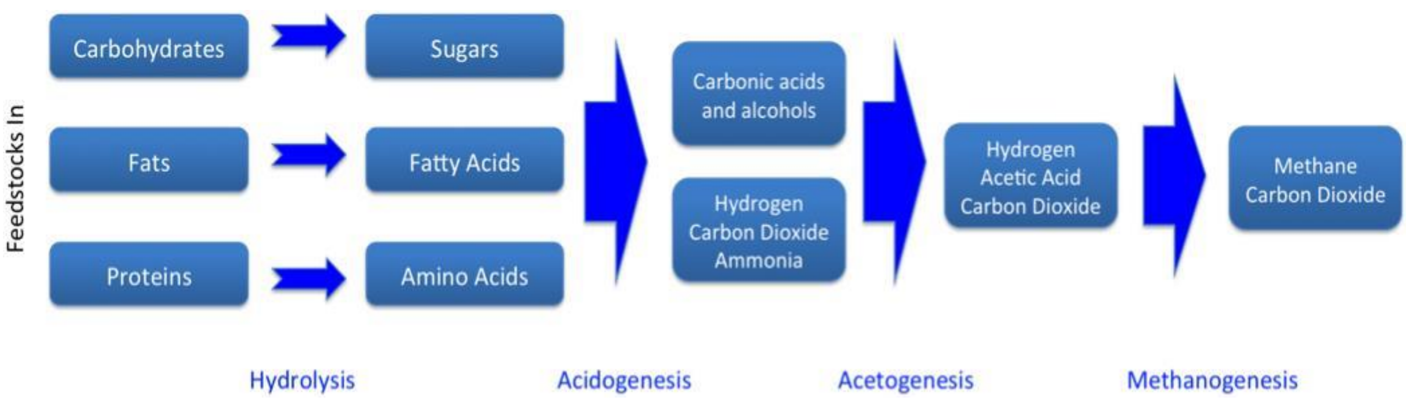


Figure 3 anaerobic digestion pathway follows four major steps [24]

Main parameters that can influence biogas production

Anaerobic digestion (AD) of food waste (FW) is a complex process that should simultaneously digest all organic substrates (e.g. carbohydrate and protein) in a single-stage system. It is governed by different key parameters such as temperature, volatile fatty acids (VFA), pH, ammonia (NH), total solid(TS), volatile solid(VS), nutrients, trace elements, and others: a good nutrient and trace element balance, and a stable environment are required for microbial growth. It is therefore, extremely important to maintain the key parameters within the appropriate range for long term operation of anaerobic digestion.

- *PH value:* The pH value of the reacting material is an essential factor in the anaerobic digestion of food waste. The importance of the pH is due to the fact that methanogenic bacteria are very sensitive to acidic conditions and their growth and methane production are inhibited in acidic environment
- *Composition of food waste:* It is important to know the composition of food waste in order to be able to predict both the biomethaniztion potential and the most efficient anaerobic digestion facility design. The biomethaniztion of the waste depends on the concentration of the four main components: protein, Lipids, carbohydrate and cellulose. This is due to the different bio-chemical characteristics of these components [23, 11].
- *Loading rate:* It is the measure of the biological conversion capacity of anaerobic digestion system. It determines the number of volatile solids feasible as an input in the anaerobic digestion system. Overloading of the system can result in low biogas yield. This happens due to the accumulation of inhibiting substances such as fatty acids in the digester slurry [23].
- *Retention time (residence time),* It refers to the time that feedstock stays in the digester.
- *Mixing:* It allows enhanced contact between bacteria and material being consumed.
- *Temperature:* Anaerobic digestion can occur in three different temperature ranges, with most reactors using the second and third ranges [25, 2]:
    1. *Psychrophilic Digestion*: occurs temperature below 25 ^{0}C.
    2. *Mesophilic Digestion:* occurs between 25 ^{0}C and 45 ^{0}C.
    3. *Thermophilic Digestion*: occurs above 45 ^{0}C.

Table 2 below shows the effects of different parameters like temperature, pH, inoculum, particle size, stirring intensity and Headspace flushing which can influence the biogas production potential

Table 2 Effects of some process parameters that influence the biogas production potential [17, 21]

Effects of some process parameters that influence the Biogas production potential	
Parameter	Effects
Temperature	Increasing digestion temperatures increase CH_4 yield
	A sharp rate of temperature rise can diminish CH_4 production
	There are two ranges of temperature for optimal bacterial activity, defined as mesophilic (25-40 °C) and thermophilic (50-65 °C)
pH	Neutral pH between 7.0 and 7.8 are favorable for BMP (Biomethane potential) test
	The optimal range of pH for obtaining maximal biogas yield is 6.5-7.5
	AD is severely inhibited if the pH decreases below 6.0 or rises above 8.5
Inoculum	Origin of inoculum determines the initial activity of the microorganisms
	Inoculum source brings about differences in bacterial populations, substrate adaptation, and residual anaerobically-biodegradable substrate
Substrate per inoculum ratio (S/I)	Significantly affects BMP(Biomethane potential) assays, mainly the kinetics
	S/I ratio exceeding 0.1 is recommended for the AD process of piggery slaughterhouse wastes
	S/I ratios of 0.5 to 1.0 provided maximal CH_4 yields in anaerobic batch digestion of herbaceous and woody feedstock, and municipal wastes.
Particle size	Suitable S/I ratios to maintain efficient AD vary with the amount of labile organic matter in the substrate
	Decomposition is faster with decreasing particle size but does not necessarily increase methane yield
	Particle size reduction of agro-byproducts from 5.0, 2.0, 0.5, and 0.2 cm increased methane yields by more than 80%
	Methane yields increased by 21% when the substrates were pretreated by grinding into very fine particles compared with the chopped substrate
Stirring intensity	Homogeneity and interaction among bacteria/enzyme and microorganism in AD are facilitated by increased stirring intensity or mixing
	Mixing also prevents the accumulation of substrate and intermediates such as fatty acids in the digestion medium
Headspace flushing	Removing the oxygen is crucial to avoid aerobic respiration
	Aerobic respiration hinders activity of methanogens and causes loss of methane potential
	20% of CO_2 in the flush gas increased significantly methane production by over 20% compared with flushing with pure N_2

Comparison of biogas production from different kinds of wastes

There are different types of anaerobic systems: farm based food processing and other centralized waste systems. Each type of anaerobic system will have different gas productions due to the difference in the feedstock for the digesters. Figure 4 below demonstrates how different waste materials affect biogas production.

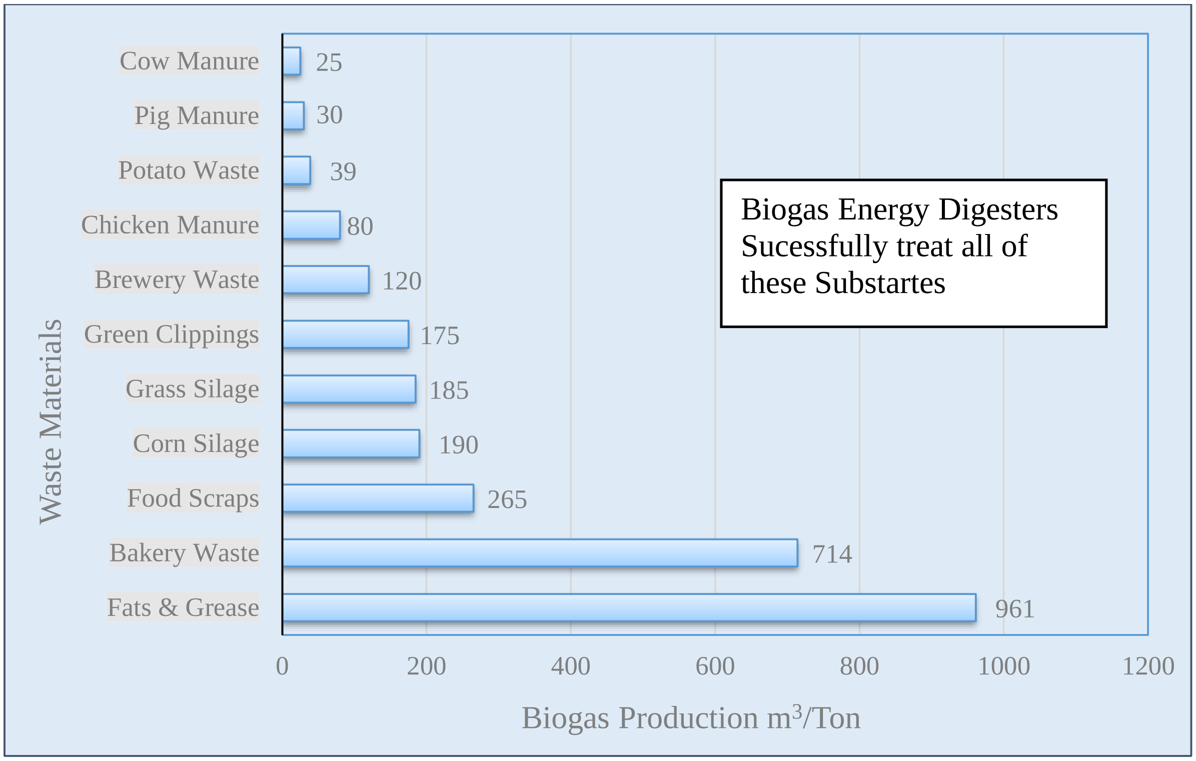


Figure 4 Comparison of Biogas Production by Feedstock [30]

Table 3 Composition of biogas

Compound	Chemical Symbol	Content (Vol %)
Methane	CH_4	50-75
Carbon dioxide	CO_2	25-45
Water vapor	H_20	$2(20^0C) - 7(40^0C)$
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Hydrogen sulfide	H_2S	<1

Food wastes have higher compositions which encourages to use as a sources of biogas. Table 4 below indicates the properties and compounds found in food waste comparing with slurry feedstock's

Different properties and compounds found in food waste feedstock vs. slurry feedstock [34]

Compositions	Food Waste Feedstock			Slurry Feedstock		
	Mean	Min	Max	Mean	Min	Max
DS (%)	4,5	2,7	6,8	4,9	3,5	9,3
VS (%)	69,0	68,3	69,6	73,2	73,2	73,2
pH	8,4	8,3	8,4	8	7,6	8,8
Nutrient content in percentage						
Nitrogen, N (%)	15	11,9	20,5	16,1	6,7	24,9
Readily available N (% of total N)	61,9	38,7	86,8	65,4	39,3	85,6
Potassium, K (%)	4,7	1,4	9,3	3,2	1,5	5,9
Phosphorous, P (%)	0,7	0,3	2,0	0,9	0,2	5,0
Calcium, Ca (%)	0,34	0,0	1,70	2,6	0,0	4,8
Magnesium, Mg (%)	0,19	0,0	0,69	0,3	0,0	3,7
Sulfur, S (%)	0,33	0,0	0,57	0,9	0,0	1,7
Heavy metal content in milligram per kilogram						
Copper, Cu (mg/kg)	31,5	18,6	24,6	82,1	20,3	180,7
Zinc, Zn (mg/kg)	105,1	71,0	142,3	240,0	4,4	631,0
Lead, Pb (mg/kg)	46,3	3,6	114,7	1,0	0,0	17,9
Cadmium, Cd (mg/kg)	1,2	0,2	2,2	1,5	0,6	2,3
Mercury, Hg (mg/kg)	1,1	1	1,1	0,1	0,0	0,6
Nickel, Ni (mg/kg)	43,2	5,5	137,3	8,6	0,0	18,8
Chromium, Cr (mg/kg)	50,2	7,8	157,5	12,4	0,3	38,2
Fluorine (F)	209,5	200,0	219,0	118,0	118,0	118,0
Aluminum (Al)	-	-	-	4141	131	11812
Iron (Fe)	-	-	-	14059	1551	37701

Table 4 Different properties and compounds found in food waste feedstock vs. slurry feedstock [34]

Kinetics of Biogas production

In a tank reactor, reactants A and B are put into the digester at a certain rate (in the model, this value is specified by a user input). Once in the digester, A and B break down into products C and D at a rate based on reaction coefficients. Some of A and B don't break down all the way, and leave through the outlet - the amount that leaves instead of being broken down depends upon digester size and feeding rate, which determine the residence time of the feedstock.

If the volume fractions of principal components of the biogas produced are analyzed simultaneously [29],

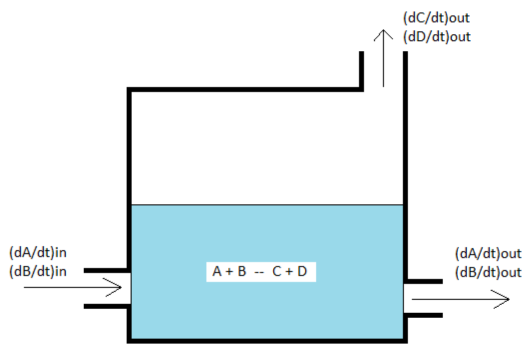


Figure 5 Basic input-output model of a tank reactor used for the kinetic model of an AD [29]

$$(C_nH_aO_b)+(n-\frac{a}{4}-\frac{b}{2})(H_2O) = (\frac{n}{2}-\frac{a}{8}-\frac{b}{4})(CO_2) + (\frac{n}{2}-\frac{a}{8}-\frac{b}{4})(CH_4)\text{......... ....Eq 1}$$

Or $$C_nH_aO_b + (C_1)(H_2O) = (C_2)(CO_2) + (C_3)(CH_4) \text{ ....Eq 2}$$

With $$C_1 = n \frac{-a}{4} \frac{-b}{2} \text{ ....Eq 3}$$

$$C_2 = \frac{n}{2} - \frac{a}{8} - \frac{b}{4} \text{ .... Eq 4}$$

$$C_3 = \frac{n}{2} - \frac{a}{8} - \frac{b}{4} \text{ .... Eq 5}$$

Table 5 Balance of biochemical reaction from equation two

	Left	Right
C	n	n/2 + n/2 = n
H	a +2*(n- a/4 -b/2) = 2n + a/2 -b	4*(n/2 + a/8 - b/4) = 2n + a/2 -b
O	b+(n - a/4 -b/2) = n - a/4 + b/2	2*(n/2 -a/8 + b/4) = n- a/4 + b/2

Biogas Upgrading and Purification Technologies

The basic concept of biogas upgrading is to concentrate the CH_4 in the raw biogas stream (~65%) by separating CO_2 (~35 %) and other minor gases (H_2S, H_2O, H_2, N_2, O_2 and others) from the inlet gas [2]. This process can be carried out by applying different kind of separation technologies, which utilize the different chemical and physical behavior of these gases. Accordingly, these technologies can also be grouped depending on which type of chemo-physical mechanisms they mainly utilize for the separation. These mechanisms are [2, 25]:

- Adsorption
- Absorption (physical and chemical)
- Gas permeation
- Cryogenic distillation

In the Adsorption, the selective affinity of CO_2 onto a surface of a media (adsorption) at different pressures is used for controlling the separation. The technology is thus also called pressure swing adsorption (PSA).

The Absorption (physical and chemical) is using the difference in selective affinity of solving gas into a liquid media (absorption). In this group, several different technologies have been developed based on different liquid absorption, medias in which the CO_2 is dissolved and the CH_4 is not, depending on pressure and temperature. The temperatures and pressures utilized for controlling the absorption and desorption (stripping) process are subject to which media is used. Examples of medias are water, different kind of amines, as well as organic solvent and thus the main biogas upgrading techniques using *absorption for separation are water scrubbing, amine scrubbing and organic physical scrubbing.*

The Gas permeation is using the fact that CO_2 and CH_4 gas molecules travel with different ease (permeates) through membranes. The permeability is higher for CO_2 than for CH_4, and membranes can thus separate this mixture.

Cryogenic distillation is using the fact that CH_4 and CO_2 have different boiling points (- 164 °C for CH_4 and -78 °C for CO_2 at 1 atm). When biogas is cooled to these low temperatures, cryogenic distillation is possible and thus allows for separation of CH_4 and CO_2.

CO_2 removal technologies

The following processes can be considered for CO_2 removal. The processes are presented roughly in the order of their current availability for and applicability to biogas upgrading:

- Water scrubbing (NAOH and POH)
- Pressure swing adsorption
- Chemical scrubbing with amines
- Chemical scrubbing with glycols (such as Selexol)
- Membrane separation
- Cryogenic separation

H_2O removal chemicals

Biogas always contains water vapors that have to be removed to avoid corrosion in pipelines and equipment.

H_2S removing techniques

H_2S concentration in the biogas can be reduced by preventing its migration to biogas during digestion process or by treating the gas stream [21, 23].

Table 6 H_2S & H_2O treatment and removal methods

H_2S pretreatment and removal methods	H_2O Removal methods
Air/O_2 dosing to biogas reactor	Condensation
Iron sponge	Demister
Iron Oxide	Cyclone
Iron chloride dosing to digester slurry	Moisture trap
Air stripping and recovery	Adsorption dryer
Biological removal on a filter bed membranes	Silica Gel
Adsorption on activated carbon	Aluminum
Physical and chemical absorption	Physical absorption with glycol
Zinc oxide sorbents	Absorption with hygroscopic salts

Biogas compression technologies

The biogas compression and bottling process consist of different steps such as biogas purification, compression and bottling. Fig 6 below represents the typical arrangement of biogas compression and bottling process. It consists of three basic units are scrubbing unit, compressor unit and storage unit. The raw biogas from the digester is first allowed to pass through a set of three scrubbing units for removal of removal of impurities. The methane rich content biogas is now allowed to be compressed by passing it through a compressor.

The compressed gas is finally stored into small cylinders with the help of manifold system and adapter. The manifold system has an input and double output. Gas cylinder is connected to one output port where as a pressure gauge (PG) is connected to the other output port. The reverse flow of the biogas is avoided by using Ball valve (BV) and Non return valve (NRV).

If biogas is stored, it will be at the digestion site in large impermeable bags [28]. These are impractical to transport and require direct connection to cooking/lighting apparatus. In regions where piping systems are unachievable, biogas systems prove to be unsustainable and such systems may fail. So it is necessary to compress the biogas & store it in bottles/cylinders so that it can be used in place of LPG (Liquefied Petroleum Gas) and can be transported as per requirements. Even it can be used in place of CNG (Compressed natural gas) cylinders as a clean & green fuel to the vehicles.

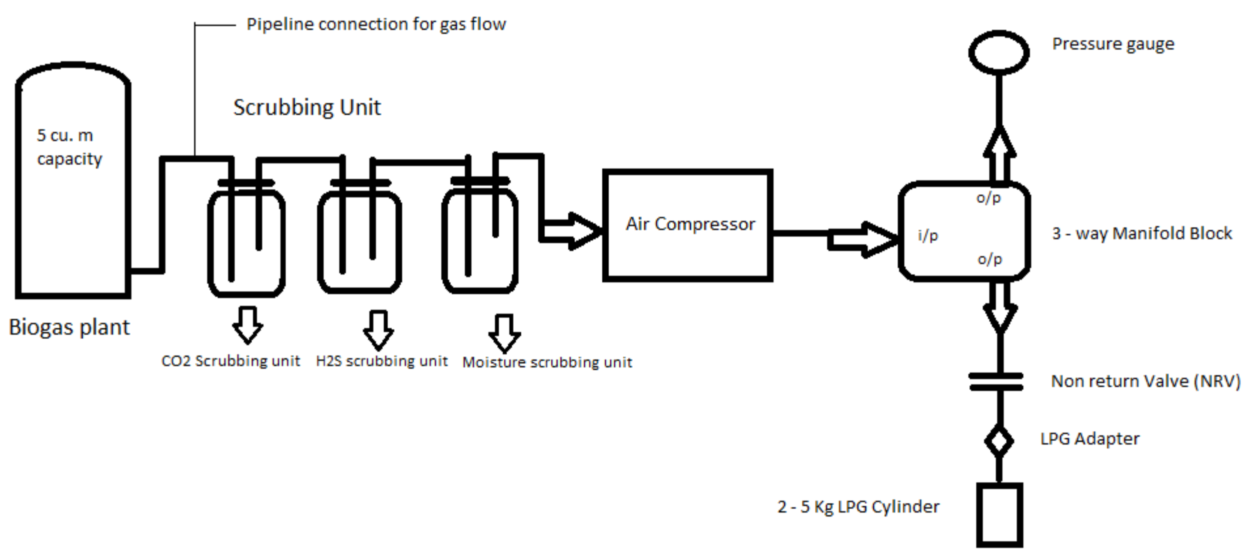


Figure 6 Typical Arrangement of Biogas Compression and Bottling Process [28]

1.2. Problem statement

The ever increasing demand of electrical energy due to industrialization and urbanization has led to concentrate on the use renewable energy sources at the fullest. Under the renewable energy sources the biogas energy source is the most challenging one to cope up with the scarcity of electrical energy. The biogas from the biogas digesters can be compressed and bottled. This stored biogas can be put in use to the extent where it is required and it also reduces transportation costs, which is a major difficulty in the biogas usage and upgrading of biogas is very important.

Upgrading of biogas has gained increased attention due to rising oil and natural gas prices and increasing targets for renewable fuel quotes. Renewable energy plays a vital role in improving the country's economy by supplying the industries energy demand. Fuel is one of the highest costs paid in foreign currency. Good quality of biogas using upgrading technologies can replace this fuel import and can be used as fuel for transport as well as industrial energy sources. Without any effective treatment measures, the disposal of food waste (FW) has caused severe environmental pollution in many countries [3, 4].

The traditional approach for food waste disposal was mainly landfill, incineration and aerobic composting. Whereas land filling food waste has been largely forbidden in many countries, burning is energy-intensive (due to the high moisture content (MC)) and often creating air pollution. Both environmentally unfriendly approaches are gradually discarded. The application of food waste as animal feed also bears a lot of risks since the propagation of diseases will be higher if food waste is directly used as animal feed as a result of the shorter food chain. Laws are hence increasingly more severe with respect to environmental protection and to ensure food safety. An alternative method for food waste disposal is needed to tackle the waste crisis in which anaerobic digestion of food waste can be option.

Anaerobic digesters provide potential solutions to: acceleration of methane released into the atmosphere, and reduced amount of residuals for disposal, compared with aerobic treatment, poor indoor air quality and subsequent chronic health problems, unequal exposure to hazards by gender, the need for a fuel, deforestation for fuel use, lack of treatment of food waste, expensive inorganic fertilizers.

1.3. Objectives

1.3.1. Main objectives

The main objective of the study is producing clean biogas fuels from food wastes by using anaerobic digestion (biological decomposition).

1.3.2. Specific objectives

- The project aims to compress biogas from the digester for natural gas usage.
- The compressed biogas will also have to purified for higher efficiency and usage as an energy source.
- Measuring and analyzing the scrubbing capability of chemicals per amount of chemicals used.
- Storing purified gas in tire inner tube and compressor cylinder
- Bottling the purified biogas in the gas cylinder

1.4. Scope of the project

The project conducted considering the food wastes collected from Addis Ababa University main campus Sidist killo. The study conducted using experimental laboratory test. Compression of biogas from 10m^3 biogas digester to the cylinder is analyzed mainly. Improve the use of the digester by a comprehensive analysis of all possible parameters that impact the anaerobic digestion process. Use the best upgrading method of biogas from anaerobic digester to purify compressed gas from the digester.

1.5. Significance of the Research

Compression of biogas is very important to reduce the size of the gas storage facility or to transport the biogas to a pipeline. Compressing biogas reduces storage requirements. Purifications of biogas increase the methane concentrations and increase the heating ability of biogas.

CHAPTER TWO

2.0. Literature Review

2.1. Biogas Compression

Compressing the biogas is very important because biogas containing mainly methane could not be stored easily, it does not liquefy under pressure at ambient temperature (critical temperature and pressure required are 82.5 ^{o}C and 47.5 bar, respectively) [32].

Significance of Compressing the biogas: -

- It reduces the storage requirements,
- It concentrates energy content,
- It increases pressure to the level required overcoming resistance to gas flow. and
- It is better in the scrubbed biogas.

In addition, Compression can eliminate the mismatch and guarantee the efficient operation of the equipment. Moreover, large biogas systems rely on compression to reduce the size of the gas storage facility or to transport the biogas to a pipeline. Compressing biogas reduces storage requirements since the production pressure of a biogas source does not match the pressure requirements of the gas utilization equipment [38].

Combined units with facilities for scrubbing, compressing and storing have been developed in certain developed countries. For instance,

- ➢ A water scrubber coupled with a gas compressor is being promoted for uniform use in New Zealand [35].
- ➢ The biogas produced from poultry manure is being dried, scrubbed, compressed and stored at a pressure of 4 bars in 0.2 m^3 steel tanks in Belgium [32, 35].
- ➢ Khapre conducted a study on scrubbing and compression of biogas and subsequently used it for domestic cooking. He found reduced requirement of scrubbed and compressed biogas (0.353 m^3) than raw biogas (0.591 m^3) for cooking a day's meal of a six-member family. He stored the scrubbed and compressed biogas at a pressure of 7 bars in cylinder of 0.1 m^3 capacity [35].
- ➢ Similar results have also been reported from Netherlands, UK, Australia, New Zealand and USA [32].

Here we have different researches which reviewed the most current technologies available in the world to compress biogas from the digester and identify the gap each research states.

- **Vinayak R. Gaikwad, P K Katti, and Dr. Babasaheb (2015), Biogas Compression and Bottling: A Solution to Energy Crises.**

Vinayak, Katti and Babasaheb reported a working model to bottle biogas which can be carried out at the required site as a source of supply for heat and power. The model of biogas compression and bottling process they used consist of different steps such as biogas purification, compression and bottling. The proposed method had; Biogas digester, Scrubbing unit, Compressor unit and Manifold block.

The research had a process of the raw biogas from the digester was first allowed to pass through a set of three scrubbing units for removal of impurities. The methane rich content biogas is then allowed to compress by passing it through a compressor. The compressed gas is finally stored into small cylinders with the help of manifold system and adapter. The manifold system used in the prototype is of single input and double output. Gas cylinder is connected to one output port where as a pressure gauge is connected to the other output port. The reverse flow of the biogas is avoided by using ball valve and non-return valve. Below is representative arrangement of biogas compression and bottling process used in the research.

Figure 7 Typical arrangement of biogas compression and bottling process [31, 41]

- ***Shyam Sunder Kapdi, Virendra Kumar Vijay, Rajesh S Kempegowda and Rajendra Prasad (2005); Biogas Scrubbing, Compression and Storage.***

They had carried out trials to compress the biogas by a number of earlier investigators working on the subject. They reviewed the efforts made to improve the quality of biogas by scrubbing CO_2 and the results obtained. Different methods of scrubbing are reviewed in the research and found that water scrubbing is simple, continuous and less expensive method for CO_2 removal from biogas. It simultaneously also removes H_2S.via two general categories namely: (1) dry oxidation process (by converting it either into sulfur or oxides of sulfur which is used where the sulfur content of gas is relatively low and high purities are required) and (2) liquid phase oxidation process (used for the treatment of gases containing relatively low concentration of H_2S).

- ***Prof B.V. Appa Rao, Abyot Teferra, & Ramesh Babu Nallamothu (2013), Biogas Purification, Compression and Bottling***

They had stated about biogas purification, compression and bottling in an experimental analysis. They compressed the gas in cylinders after removing its CO_2, H_2S and water vapor components. To increase the energy density of the gas, different experiments were conducted in removing incombustible and corrosive gas. To remove this impurities steel wool, water and silica gel was used. The experiment showed that, the methane concentration available in the raw and purified biogas was 68 ± 2.52 % and 90 ± 1.53 % respectively. Compression of purified biogas was carried out by using a hermetic reciprocating type refrigerant compressor and bottled into normal LPG cylinder. Compression of biogas was carried out up to an absolute pressure of 5 bars in total of 12-14 minutes. In order to evaluate the impact of biogas purification on heating value, purified and raw biogas was used to heat 500 ml of water and took 4.54 ± 0.03 and 5.62 ± 0.02 minutes respectively. Below figure 8 is layout of biogas purification, compression and bottling unit they used in the experiment.

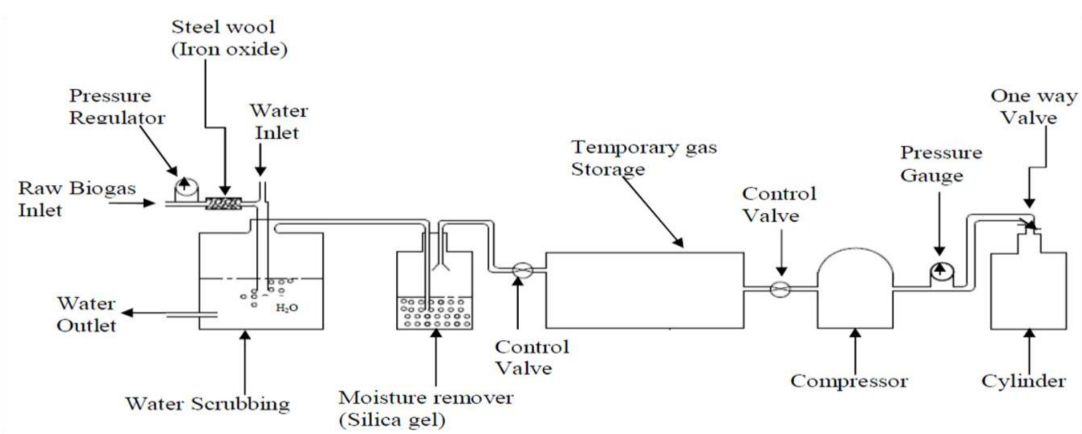


Figure 8 Layout of Biogas Purification, Compression and Bottling Unit [34]

- ***N.H.S. Ray, M.K. Mohanty, R.C. Mohanty (2016), Biogas Compression and Storage System for Cooking Applications in Rural Households***

Here in the study, the biogas was produced in a floating drum type digester by the anaerobic digestion of kitchen wastes and collected by an elastic balloon. A foot lever compressor also designed, which allows the users to stand and compress using foot lever and a valve system. The final prototype was able to compress the biogas to approximately 4 bars in a 0.5m^3 tank.

In addition to the compressor, a container with silica gel is used for removal of water vapor from biogas and there is also a fiber container with steel wool to act as a hydrogen sulfide scrubber in-line with the inlet of the biogas to the compression system. The study showed that the system could compress biogas into a container, 4 bar pressure and operating time of 30 min.

Figure 9 Foot compressor [36]

2.2. Storage Options for Biogas

Callum Ross discussed the types of systems available for the storage of biogas and modes of biomethane transportation. The below table 7 summarizes storage options for biogas.

Table 7 Storage Options for Biogas [37]

Storage Options for Biogas				
Purpose of Storage	Pressure (mbar)	Storage Device	Material	Size (m^3)
Short And Intermediate Storage	< 7	Floating Cover	Reinforced And Non-Reinforced Plastics, Rubbers	Variable Volume Usually Less Than One Day's Production
	< 137	Gas Bag	Reinforced And Non-Reinforced Plastics, Rubbers	4.2 up to 311.5
	137 up to 413	Water Sealed Gas Holder	Steel	325.00
		Weighted Gas Bag	Reinforced And Non-Reinforced Plastics, Rubbers	99 up to 792
		Floating Roof	Plastics, Reinforced Plastic	Variable Volume Usually Less Than One Day's Production
Possible Means of Storage for Late on or off Use	700 up to 200,000	Propane Or Butane Tanks	Steel	56.6
	> 200,000	Commercial Gas Cylinder	Alloy Steel	9.9

The study also reported that important considerations for storage of biogas include: -

1. The needed volume (typically, only small amounts of biogas need to be stored at any one time),
2. possible corrosion from H_2S or water vapor that may be present, even if the gas has been partially cleaned, and
3. Cost (since biogas is a relatively low-value fuel).

2.3. Compressors used for biogas compression

- N.H.S. Ray, M.K. Mohanty, R.C. Mohant [36], suggested Two types of compressors
  - Automatic Biogas Compressor.
  - Manual or Hand Compressor.

  1. Automatic biogas compressors are readily available in the local market. They are available in the pressure range of 2.5 bars up to 200 bars. So depending on the capacity of biogas plant and storage systems appropriate compressor should be chosen.
  2. On the other hand, if the capacity of biogas plant & storage systems is small a suitable hand compressor can be used. The hand compressor works on the principle of suction and compression similar to that of a bicycle pump.
- Vinayak R. Gaikwad, Dr. P. K. Katti [41] uses biogas compressors which readily available in the local market in the range of 2.5 bar up to 200 bars. Depending on the application a suitable compressor can be chosen. The study proposed a suitable compressor with a compressibility of 4-5 bars. The compressor work on the principle of suction and compression similar to that of a bicycle pump. The compressor consists of one inlet for biogas to enter in and one outlet for compressed biogas. The compressor consists of specific valve at its base which consists of two ports, one port for suction and other for compression.
- Abyot Teferra , Prof B.V. Appa Rao and Ramesh Babu Nallamothu

  The compressor used in the experiment is a hermetic reciprocating type compressor used in the manufacture of commercial refrigerators with a hydrocarbon refrigerant. The pressure of the gas at various points of compression can be noted using a pressure gauge. For storing the gas after compression, a normal LPG cylinder used [36].

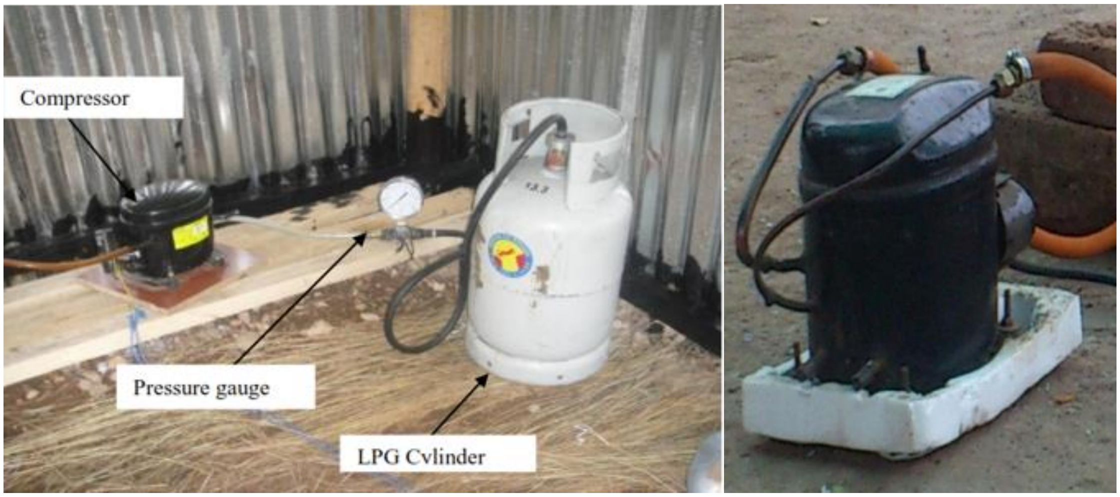


Figure 10 Cylinder and Compressor used [36]

2.3. Biogas Storage and Bottling Systems

The biogas is usually used soon after generation without storage [39]. However, should gas storage be necessary to balance the mismatch between gas production and its use and there are two basic reasons for storing biogas [37, 42]:

- storage for later on-site usage and
- Storage before and/or after transportation to off-site distribution points or systems.

Table 8 most commonly used biogas storage options [32]

Pressure	Storage Device	Material
Low (0.138-0.414 bar)	Water Sealed Gas Holder	Steel
Low	Gas Bag	Rubber, Plastic, Vinyl
Medium (1.05-1.97 Bar)	Propane or Butane Tanks	Steel
High (200 Bar)	Commercial Gas Cylinders	Alloy

The least expensive and easiest to use storage systems are low-pressure systems; these systems are commonly used for on-site, intermediate storage of biogas. The energy, safety, and scrubbing requirements of medium- and high-pressure storage systems make them costly and high-maintenance options [37].

Low-pressure storage generally will be the most practical alternative. Old water tanks or other salvaged containers should not be used; a weak tank at high pressure can be dangerous. It is important to ensure that the storage tank is safe at the pressure being used.

If the gas is used as it is generated (no storage), any excess should be flared off [39].

High-pressure storage of compressed biomethane can be stored to save space. Gas scrubbing is even more important at high pressures because impurities such as H_2S and water are very likely to condense and cause corrosion. The gas is stored in steel cylinders such as those typically used for storage of other commercial gases. Storage facilities must be adequately fitted with safety devices such as rupture disks and pressure relief valves. The cost of compressing gas to high pressures between 2,000 and 5,000 psi is much greater than the cost of compressing gas for medium-pressure storage. Because of these high costs, the biogas is typically upgraded to biomethane, a more valuable product, and prior to compression. Compression to 2,000 psi requires nearly 14 kWh per 1,000 ft of biomethane. If the biogas is upgraded to 97% methane and the assumed heat rate is 12,000 Btu/kWh, the energy needed for compression amounts to 17% of the energy content of the gas [39].

- ***Mr. Arulanandam Kajavatan BSc Eng.(Mora), MSc (Soton), Mr. Uthayakumar Nitharsan; Containerizing Biogas: Design and development of portable low cost Biogas bottling system [40]***
  - Masters students in university of Nottingham - Michael A, Jason A, Peter E and James F designed and developed a low cost bottling system as shown in the figure 11(a). Their prototype of biogas bottling system cost 75 sterling pounds which is equal to 15 000 Sri Lankan rupees (2445 ETB). According to the study, compressor head with motor is used in most of the biogas bottling systems. The following figure 11(b) shows the low cost biogas bottling system constructed in Thailand. Figure 11 depicts the low cost small-scale compression and bottling unit constructed.

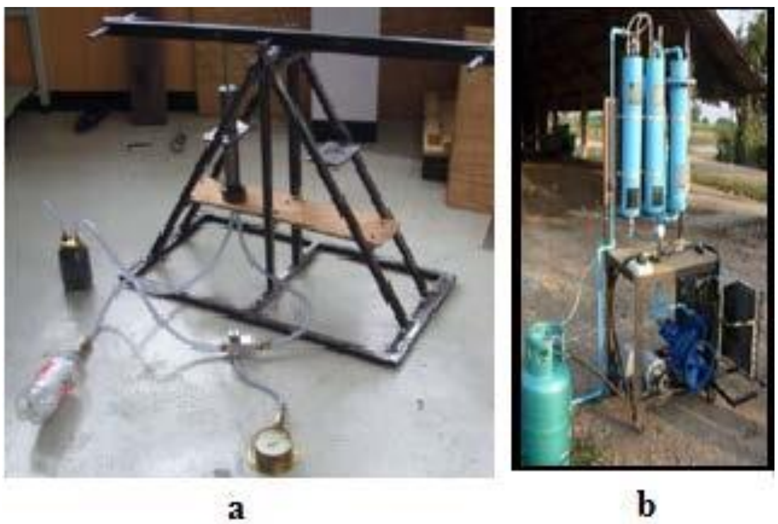


Figure 11 (a) Biogas bottling system and (b) Biogas upgrading system [40]

- The following figure 12 depicts the design of the biogas bottling tool. Raw biogas from plant's gas holder inflate into compressor via inlet valve and compressed and intake into cylinder via outlet valve. The valve system controls the biogas intake and compression.

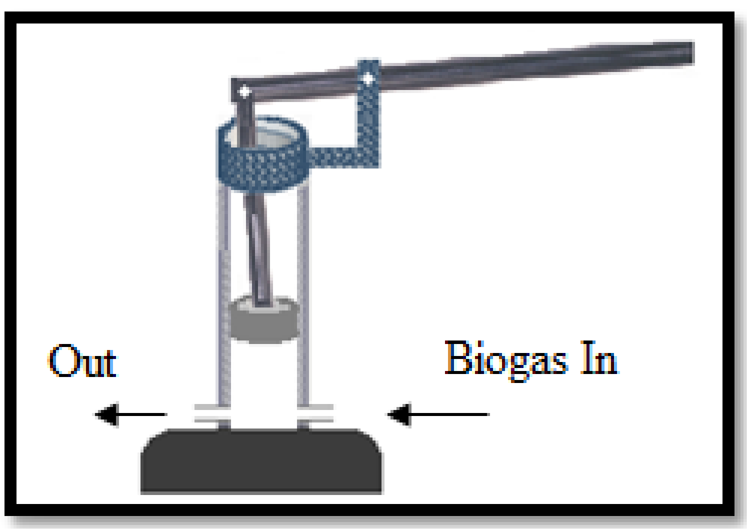


Figure 12 Designed Biogas Bottling System [40]

2.4. Biogas scrubbing unit

2.4.1. Removal of Water

Biogas always contains water vapors that have to be removed to avoid corrosion in pipelines and equipment's. Water can be eliminated by physical separation (cooling and compression) and chemical drying (absorption and adsorption). Refrigeration or cooling preceded or not by compression, is the simplest way of removing excess water vapor. The condensed water can be then separated using demisters, cyclones or water traps [2]. Adsorption using alumina, silica gel or zeolites is the most common technique [20]. Also, hygroscopic salts or triethylene glycol can be used.

A. Techniques Using Physical Separation of Condensed Water Include:

- Demisters in which liquid particles are separated with a wired mesh (micropores 0.5-2 nm). A dew point of 2-20 ^{o}C (atmospheric pressure) can be reached;
- Cyclone separators in which water droplets are separated using centrifugal forces;
- Moisture traps in which the condensation takes place by expansion, causing a low temperature that condenses the water;
- Water taps in the biogas pipe from which condensed water can be removed [11].

B. Methods Based on Chemical Drying Method (Absorption or Adsorption)

I. Adsorption of water vapor on silica, alumina or equal chemical components that can bind water molecules (adsorption dryer): - Usually two columns are used in parallel: one column adsorbs water, while the other is being regenerated. Regeneration is achieved by evaporating the water through decompression and heating.

   A part of the dried gas is led through the column and recycled to the compressor inlet. Silica, activated carbon, aluminum oxide or magnesium oxide can be used for the drying process. Using adsorption dryers, a dew point from -10 to -20 ^{o}C (atmospheric pressure) can be achieved [21,11].

II. Absorption of water in triethylene glycol**:** - (Drying takes place by using the water binding component triethylene glycol. Used glycol is pumped into a regeneration unit, where a temperature of 200 ^{o}C is used to regenerate the glycol. Dew points from -5 to -15^{o}C (atmospheric pressure) can be reached [11].

III. Absorption of water with hygroscopic salts: - The salt is dissolved as it absorbs water from the biogas. The saturated salt solution is withdrawn from the bottom of the vessel. The salt is not regenerated and new salt granules have to be added to replace the dissolved salt [21].

2.4.2. Removal of H_2S

H_2S concentration in the biogas can be reduced by preventing its migration to biogas during digestion process or by treating the gas stream [21, 23]. In the first case, the addition of iron ions to the digester precipitates the iron sulfide that will leave the rector with the digestate. In the second case, adsorption on activated carbon, iron oxide or hydroxide [24], washing with sodium hydroxide or biological treatment [25] are all well-known options.H_2S can be also separated from the biogas by leading the gas by a semi-permeable membrane [26].

I. Air/oxygen dosing to the biogas system

This technique is based on the biological aerobic oxidation of H_2S to elemental sulfur by a group of specialized microorganisms. Most of those sulfides oxidizing micro-organisms (Thiobacillus) are autotrophic and use CO_2 from the biogas to cover their carbon need. They grow on the surface of the digestate or on the framework of the digester and do not require inoculation. The following reaction occurs in the biogas:

$$2H_2S + O_2 \rightarrow 2S + 2H_2O \quad \text{………………. Eq 6}$$

Not only elemental sulfur, but also sulfate is formed, which can cause corrosion in solutions. A small amount (2-6%) of O_2 needed for the reaction to occur is introduced in the biogas System by an air pump. A reduction of H_2S concentrations down to 20-100 cm^3 and a removal efficiency of 80-99% can be achieved [27, 28]. However, the remaining concentrations may still be too large to enable use of the biogas as a substitute for natural gas [22]. Safety measures have to be taken to avoid overdosing of air: biogas in air (6-12%) is an explosive mixture. Care has to be taken that anaerobic conditions remain present in order to keep the digestion process from being inhibited.

II. Addition of iron chloride into the digester

Iron chloride can be dosed directly into the digester or through the influent mixing tank. It reacts with the H_2S present in the biogas to form FeS (particles). The precipitation reaction of the iron salt can be written as follows: -

$$2Fe^{3+} + 3S^{2-} \rightarrow 2FeS + S \quad \text{……………………. Eq 7}$$

$$Fe^{2+} + S^{2-} \rightarrow FeS \quad \text{………………………… Eq 8}$$

Due to the precipitation of FeS, the presence of H_2S in the biogas is avoided. This method is very efficient in reducing high concentrations of H_2S, but less efficient in achieving a low and stable level of hydrogen sulfide necessary for vehicle fuel quality or pipeline quality biomethane [28].

III. Adsorption using iron oxide or hydroxide

Hydrogen sulfide reacts easily with iron oxide, iron hydroxide and zinc oxide and forms iron sulfide or zinc sulfide respectively. This process is often referred to as "iron sponge" because rust-covered steel wool may be used to form the reaction bed. Steel wool, however, has a relatively small surface area, which results in low binding capacity for the sulfide. For this reason, wood chips impregnated with iron oxide have been used as preferred reaction bed material since they have a larger surface-to-volume ratio. Iron oxide or hydroxide can also be bound to the surface of pellets made from red mud, a waste product of the Bayer process gaining aluminum out of Bauxite. With these pellets an even larger surface-to-volume ratio can be reached [28].

Iron oxide, iron hydroxide and sodium hydroxide react with H_2S in the biogas according to following reactions: -

$$Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O \text{……………………. Eq 9}$$

$$2Fe(OH)_3 + 3H_2S \rightarrow Fe_2S_3 + 6H_2O \text{………………. Eq 10}$$

$$Na(OH)_2 + H_2S \rightarrow NaS + 2H_2O \text{………………… Eq 11}$$

The reaction is slightly endothermic: a minimum temperature of about 12°C is required to provide the necessary energy. The reaction is optimal between 25 and 50°C.Condensation of water on the iron oxide should be avoided since the iron oxide material will stick together with water which reduces the reactive surface [27]. The iron oxide can be regenerated with oxygen according to the following reaction: -

$$2Fe_2S_3 + 3O_2 \rightarrow 2Fe_2O_3 + 6S \text{……………………. Eq 12}$$

This reaction is exothermic and therefore a large quantity of heat is released during regeneration. This may lead to self-ignition of the wood chips, if air flow and temperature are not carefully controlled. Typically, two reaction beds are installed. The former elementary sulfur remains on the surface and blocks the active iron oxide or hydroxide, restricting the number of cycles that can be performed [27].

IV. Absorption with liquids

Absorption of H_2S in liquids can be either physical or chemical. Physical absorption involves dissolving the trace component in the solvent, whereas chemical absorption involves dissolving the component followed by a chemical reaction of the trace component and the solvent. Physical absorption removes H_2S by absorption in water or an organic solvent [22]. The most common solvent is water scrubbing being a robust technique although operational disturbances due to the growth of micro-organisms on the packing occur. Two types of water absorption processes are commonly used for the upgrading of biogas: single pass absorption and regenerative absorption [29]. A high consumption of water is needed if there is no regeneration step involved. Adding chemicals in water can improve the absorption process, resulting in lower water and energy consumption due to reduced pumping. Chemical absorption liquids that can be used are:

- Diluted NaOH-solution: NaOH reacts with H_2S to form Na_2S or NaHS which precipitates. The formed sodium salts are not regenerative and have to be disposed off.
- $FeCl_2$-solution: This process is based on the formation of insoluble FeS that needs to be removed
- Fe (OH) $_3$-solution: H_2S is removed using Fe (OH) $_3$ resulting in the formation of Fe_2S_3. Regeneration is done with oxygen or air (closed system) [22]. Horikawaet al investigated chemical absorption of H_2S in a Fe (III) catalyst solution. In this process, H_2S is dissolved in an aqueous solution and catalytically removed by a chelated iron according to the following reaction.

$$S^{2-} + 2Fe^{3+} \leftrightarrow S + 2Fe^{2+} \text{ ………………………. Eq 13}$$

The sulfur produced is easily separated by sedimentation or filtration from the Fe-solution. Regeneration of the aqueous Fe-solution is done by oxygenation, followed by conversion of the pseudo-catalyst into its active form Fe^{3+}

$$1/2O_{2\,(aqu)} + 2Fe^{2+} \leftrightarrow 2Fe^{3+} + 2OH^{-} \text{…………. Eq 14}$$

Due to the regeneration the Fe-solution can be retained entirely and a large consumption of chemicals is avoided. The process can be carried out at ambient temperature and is very specific in removing H_2S: the volumes of the other biogas components CH_4 and CO_2 remain nearly constant. Moreover, a removal of 90 -100% can be obtained for biogas containing 2.2% H_2S at a gas flow of 1 dm^3 min^{-1}, the catalytic solution flowing at 83.6 cm^3 min^{-1} and an inlet biogas pressure of 220 kPa [30]. At lower catalytic solution flow, lower absorption efficiency is obtained. At lower inlet H_2S concentration higher absorption efficiency is obtained. Therefore, the total removal of H_2S depends on the use of the adequate ratio of gas to liquid flow rates [30].

V. Adsorption on activated carbon

H_2S can also be removed by using activated carbon, which is often dosed with KI or sulfuric acid (H_2SO_4) to increase the reaction rate. In biological filters the H_2S is catalytically converted to elemental sulfur and water.

$$2H_2S+O_2 \leftrightarrow 2S+2H_2O \text{ .... Eq 15}$$

Before entering the carbon bed air is added to the biogas. The former elementary sulfur is adsorbed by the activated carbon. Best efficiency is obtained at pressures of 700-800 kPa and temperatures of 50-70^{o}C. This temperature is easily achieved through heat generation during compression. If a continuous process is required the system can consist of two vessels [21, 27, and 31]. Regeneration can be performed with hot nitrogen (inert gas) or steam. The sulfur is vaporized and, after cooling, liquefied at approximately 130^{o}C. Typically, the activated carbon is replaced rather than regenerated [24, 34, and 32].

1.3.1. Removal of CO_2

Upgrading biogas to natural gas quality is a multiple step procedure. After removal of water (vapor), H_2S, siloxanes, carbon hydrates and NH3, the removal of CO_2 is necessary in order to obtain the quality that meets the Wobble Index [31]. Depending on its intended use (pipeline or vehicle fuel), biomethane consists of 97- 99% methane and 1-3% CO_2. Typical pipe line specifications require a CO_2 content of less than 3% whereas vehicle fuel specifications require a combined CO_2 and N_2 content of 1.5 - 4.5% [32]. One of the following techniques can be used to remove CO_2 from the biogas:

- Physical and chemical CO_2-absorption,
- Pressure Swing Adsorption (PSA) and Vacuum Swing Adsorption (VSA),
- Membrane separation,
- Cryogenic separation and
- Biological methane enrichment

Table 9 below explains different techniques used to remove carbon dioxide from a biogas. The advantage and disadvantage of each method are also explained in the table 9.

Table 9 Techniques for removal of CO_2 [23]

Method	Advantage	Disadvantage
Absorption with water	High efficiency (>97% CH_4) Simultaneous removal of H_2S when H_2S<300cm^{3}m^{-3}, easy in operation Capacity is adjustable by changing pressure or temperature Regeneration possible Low CH_4 losses (<2%) Tolerant for impurities	Expensive investment Expensive operation Clogging due to bacterial growth Foaming possible Low flexibility toward variation of input gas
Absorption with polyethylene glycol	High efficiency (>97% CH_4) Simultaneous removal of organic S components, H_2S, NH_3, HCN and H_2O Energetic more favorable than water Regenerative Low CH_4 losses	Expensive investment and operation Difficult in operation Incomplete regeneration when stripping/vacuum (boiling required) Reduced operation when dilution of glycol with water
Chemical absorption with amines	High efficiency (>99% CH_4) Cheap operation Regenerative More CO_2 dissolved per unit of volume (compared to water) Very low CH_4 losses (<0.1%)	Expensive investment Heat required for regeneration Corrosion Decomposition and poisoning of the amines by O_2 or other chemicals Precipitation of salts Foaming possible
PSA/VSA Carbon molecular sieves Alumina silicates	Highly efficient H_2S is removed, Low energy use: high pressure, but regenerative Compact technique Also, for small capacities, Tolerant to impurities	Expensive investment Expensive operation Extensive process control needed CH_4 losses when malfunctioning of valves
Cryogenic separation	90-98% CH_4 can be reached CO_2 and CH_4 in high purity Low extra energy cost to reach liquid biomethane (LBM)	Expensive investment and operation CO_2 can remain in the CH_4
Biological removal	Removal of H_2S and CO_2 Enrichment of CH_4 No unwanted end products	Addition of H_2 Experimental not at large scale

The biogas scrubbing system consists of three units, the hydrogen sulfide (H_2S) removing unit, Carbon dioxide (CO_2) removing unit, and moisture trapping unit. The three units are interconnected with plastic hoses. The steel wool or sodium hydroxide, pure water or charcoal activated carbon and an adsorbent material (silica gel) could be use [34].

- The steel wool is to react with the hydrogen sulphide,
- The water is to reduce the percentage of carbon dioxide and
- The silica gel is to reduce the presence of water vapor in the purified biogas.

The experiment can be done by taking the raw biogas with pressure builds up in the digester head and forced through the steel wool on its way to the biogas scrubber unit to remove hydrogen sulphide. After the hydrogen sulphide was removed by the steel wool, the raw biogas passes into the water scrubbing unit for further purification. When carbon dioxide dissolved in water carbonic acid (H_2CO_3) is formed. It is a weak acid. Then the biogas pass throgh the silca gel to reduce the presence of water vapor in the purified biogas.

Figure 13 Scrubbing Units [34]

The function of each unit is as follows,

1.3.2. H_2S separation Unit

First the raw biogas is passed through a H_2S separation unit. Hydrogen sulphide is removed by using catalyst iron oxide in the form of oxidized steel wool or iron turning from any workshop. Once biogas comes in contact with this wool, iron oxide is converted into elemental Sulphur. The chemical equations are as follows [31];

$$2Fe_2O_3 + 6H_2S \;\ldots\ldots\; 2Fe_2S_3 + 6HO_2 \;\ldots\ldots\; \text{Eq 17}$$

$$Fe_2S_3 + 3O_2 \;\ldots\ldots\; 2Fe_2O_3 + 6S \;\ldots\ldots\; \text{Eq 18}$$

Figure 14 H_2S scrubbing mechanism [36] H_2S scrubbing unit [40]

An operation that removes H_2S from raw biogas results the hydrogen sulphide to convert into black iron Sulphide by the steel wool. The steel wool used before and after scrubbing is shown in figure [36]

A) Steel wool before scrubbing   B) Steel wool after scrubbing [36]

Figure 15 Hydrogen Sulphide Remover

1.3.3. CO_2 separation Unit; -

Then biogas is passed through a CO_2 separation unit. Limestone crystals are used to remove carbon dioxide. Limestone reacts with carbon dioxide to form calcium carbonate. The chemical reaction is as follows [31];

$$CaO + CO_2 \;\ldots\ldots\; CaCO_3 \;\ldots\ldots\; \text{Eq 19}$$

Pure water can also be used to remove carbon dioxide, when carbon dioxide dissolved in water carbonic acid (H_2CO_3) is formed. It is a weak acid [34];

$$H_2O + CO_2 \text{ ---> } H_2CO_3 \qquad \text{Eq 20}$$

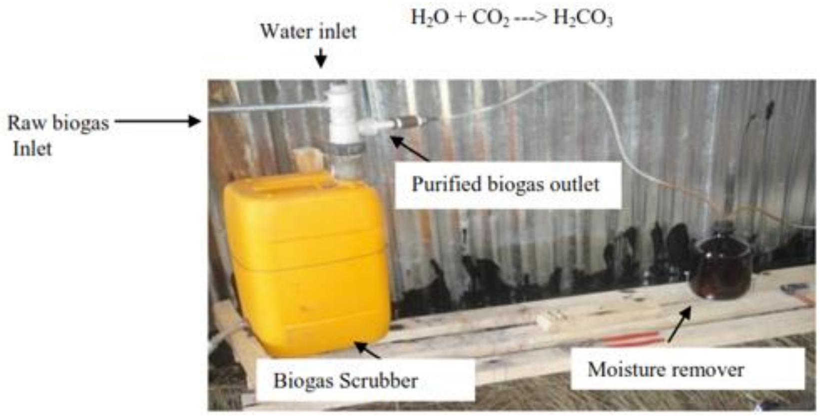


Figure 16 Carbon dioxide separation unit in the scrubbing system [34]

1.3.4. Moisture separation Unit –

Finally, the biogas is passed through a moisture separation unit. Here silica gel crystals are proposed to separate moisture. Silica gel crystals should be replaced after a specific time according to the rate of purification.

Figure 17 Removal of water vapor from Biogas [36]

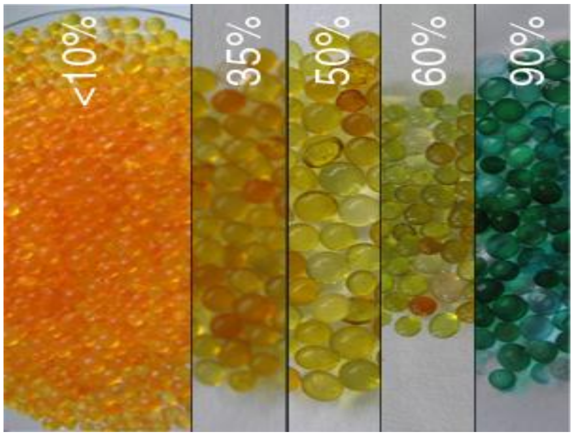


Figure 18 Silica gel turns pink once it has soaked up moisture [36]

1.4. Gas Measurement and Techniques

Monitoring of biogas production is the most common method adopted in most of the research as the level of CO_2 and CH_4 gives important information about the state of the anaerobic degradation process. The comparison of biodegradability data from different scientific papers can be a complex task. This is not only due to the difference in environmental conditions and protocols, but also due to the variety of equipment used. The basic protocol for anaerobic gas measurement and biodegradability tests is defined in the European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) and the International Organization for Standardization (ISO) [44].

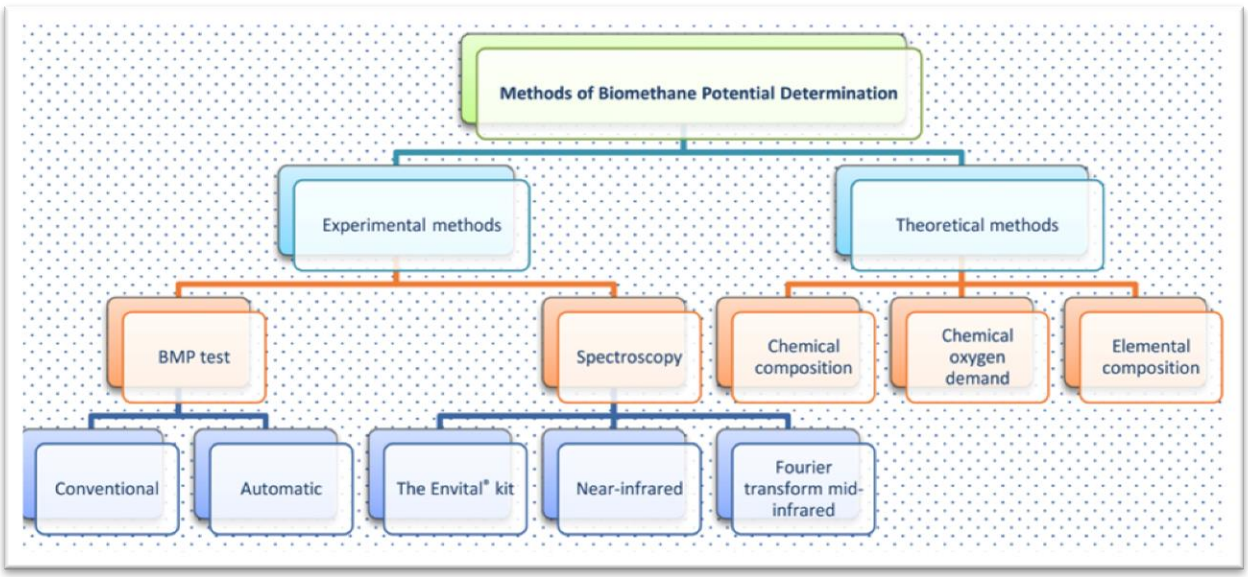


Figure 19 Gas Measurement Techniques [44]

A. Volumetric and Manometric Gas Measurement

Biogas measurement is done either manometrically by keeping the volume constant and measuring the pressure increase, or volumetrically by providing constant pressure conditions allowing measurement of the biogas volume [43]. The rate and volume of biogas produced from anaerobic biodegradability assays include different techniques such as lubricated syringes, volume displacement devices, pressure manometers or transducers, manometer assisted syringes, or low pressure switch meters. Measurement of gas at low headspace pressure is an important requirement to all manometric or volumetric determinations of anaerobic biodegradability [44].

Different researchers have developed different types of displacement gas measurement devices depending upon the research requirements [28, 31]. The general working principle of these automatic displacement gas meters is the difference of pressure between the inlet and outlet of the meter which causes the periodic filling and emptying a defined volume of gas in the measurement chamber. The sensor operates the closing and opening of a two- way or three-way solenoid valve in order to release the collected gas and resets the whole system. The total volume of gas is the product of the number of fillings or emptying's (recorded by a counter system) times the defined volume of the chamber. The measurement of gas is independent of the flow profile.

B. Liquid Displacement Gas Measurement

The majority of laboratory volumetric gas meters are based on the liquid displacement method. These meters can be constructed with simple materials like glass/plastic jars or cylinders. Liquid displacement meters are simple, economic and they can work for a long period of time without maintenance. The preservation and collection of gases is the most important operation for any liquid displacement gasometers [34].

Gasometers are the classical gas measuring unit which works with the principle of gas storing and does not provide the flow rates directly. The collection of the gas is usually done with the use of vessels containing a suitable liquid which is displaced as the gas gets collected.

Conversion procedures of biogas from Normal conditions to Standard conditions are presented below. Fluctuation of room temperature and atmospheric pressure during the measurement of gas can contribute errors in volume calculations. Therefore, to apply corrections, the record of change of atmospheric pressure and temperature is important. The gas pressure inside the tube collected over the liquid solution is the sum of the biogas pressure and the vapor pressure. The pressure of biogas, (P) can be obtained by subtracting the vapor pressure of liquid (Pw) at the temperature of measurement from the pressure of collected moist gas (P).

$$P_{bio} = P - P_w \qquad \text{Eq 21}$$

If the gas is collected over liquid, static pressure acts due to the difference of level (P_{level}),

$$P_{bio} = P - P_w - P_{level} \quad \text{or } P_{bio} = P - P_w + P_{level} \qquad \text{Eq 22}$$

The produced biogas volume in normal condition can be converted to STP using Combine

Gas law:

$$Vo = V * \frac{To}{T} * \frac{Pbio}{Po} \qquad \text{Eq 23}$$

Here, V is the measured gas volume, V_o is the volume of gas in standard temperature and pressure, P_o is the standard pressure, T is gas temperature at the time of measurement, and T_o is the standard temperature. Modified Arden Buck Equation (1996) can be suggested for the calculation of vapor pressure [44].

$$Pw = 6.1121\exp\left(\left(18.678-\frac{Tc}{234.5}\right)*\frac{Tc}{234.14+Tc}\right) \quad \text{Eq 24}$$

Tc is the temperature of gas in degrees Celsius. Pw is pressure in Hecto Pascal hP

Gasometers are usually height or weight types. In the height gasometers, biogas can be introduced into the liquid column directly from the digester or by emptying a gas bag. Gas volume is calculated from the measurement of change in barrier solution height.

Equation for gas volume calculation by height measurement using height meter:

$$Vo = \frac{To}{T\,Po}\left[\left((P - Pw - \rho g.b1)A.a1\right) - \left((P - Pw - \rho g.b2)A.ha2\right)\right] \quad \text{Eq 25}$$

Equation for gas volume calculation by weighting dispalced solution in bottle meter:

$$Vo = \frac{To(mb-ma)}{T\,\rho Po}\left[\left((P - Pw + \rho g(a1 + a2 + Va/A)\right)\right. \quad \text{Eq 26}$$

Equation for gas volume calculation by weighting dispalced solution in column meter:

$$Vo = \frac{To}{T\,Po}\{\left[\left(P - Pw + \rho g\left(b1 - \frac{m}{\rho.A}\right)A.(a1 + \frac{m}{\rho.A})\right] - \left[(P - Pw + \rho g.b1).A.a1\right]\right) \quad \text{Eq 27}$$

Here, a and b represent heights of gas and liquid. m represents mass of liquid measured. Subscripts 1, 2 represent condition before measurement and after measurement. ρ is the density of liquid. A is cross sectional area. g is acceleration due to gravity.

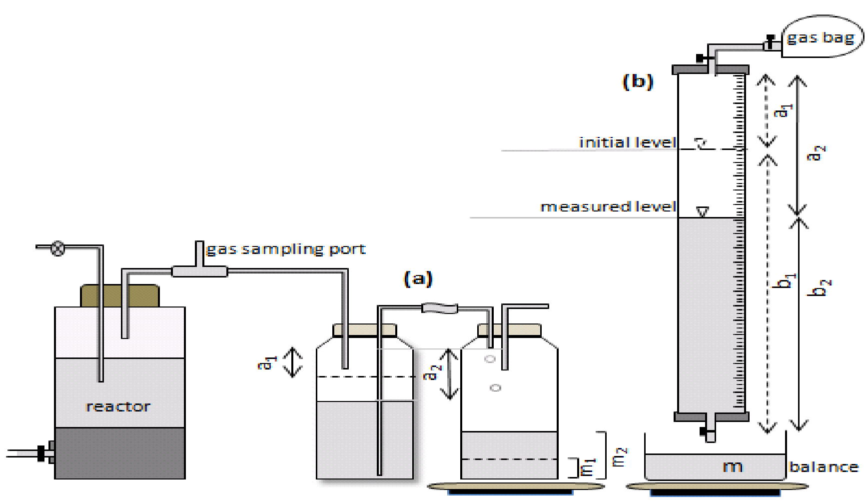


Figure 20 Measurement of gas [44]

The major drawback of the liquid displacement gas collecting and measuring system is inaccuracy due to biogas solubility/diffusion through the barrier solution. Liquids such as simple tap water, oil, acidified water and carbonated water are widely used as barrier solutions. The solubility and diffusion varies with type of liquid, atmospheric pressure, temperature, density of liquid, gas composition. Therefore, the same correction factor cannot be applied for every time of gas measurement. A study reported that underestimations of CO_2 in the biogas could be as high as 30% with the use of Warburg liquid displacement gas measurement system [15]. The evaporation of barrier solutions after a long period of time can also result in inaccuracies. Gas solubility errors can be eliminated by collecting gas in gas bags and measuring the gas volume with liquid column meters. CO_2 is a sensitive parameter and its analysis is important for the monitoring of the anaerobic digestion process. The increase and subsequent stabilization of CO_2 content represents the progress of the process during the start-up. The CO_2 measurement during the routine operation is also important as it suggests the specific digester's operational background value.

Simple basic solutions can be used for determining the CO_2 and CH_4 concentration without chromatography analysis. This is done by allowing a known volume of biogas in contact with a saturated solution of sodium hydroxide. The CO_2 will get dissolved rapidly in the solution and the remaining gas can be assumed to be methane [36].

Most scientific publications and standards suggest the use of either a highly acidic, saline or acidified saline solution to avoid the diffusion of CO_2 in the liquid displacement measuring gasometers [17, 37, 38, and 39]. The accuracy of automatically operated displacement instruments also depends on the nature of the sealing liquid.

C. Gas Chromatography

Gas chromatography (GC) is a popular instrument and has several advantages such as high resolution, high speed, high sensitivity and good quantitative results. GC is an ideal method since it is well suited for the measurement of gas which is in contact with its liquid phase [39].

Samples are inserted into the GC after running the prepared calibration standards of CO_2 and CH_4. The thermal conductivity detector (TCD) is widely used for the detection of light hydrocarbons and compounds that respond weakly to the flame ionization detector (FID). The FID analysis is important when measurement is required for small amounts of hydrocarbons as it can give larger signals and hence better precision than TCD [40].

Gas Chromatography (GC) is an optimal analytical instrument for the analysis of components such as CH_4, CO_2, H_2S and siloxanes which are present in the gas. The most important factors affecting the precision of biogas volume measurement and sensitivity are errors due to varying temperatures, vapor content, solubility and pressure. The gas measurement technique and process itself can result in the inhibition of anaerobic digestion. This is because the high amounts of dissolved CO_2 can affect the pH of the medium and, consequently, can alter the microbial activity [44].

Standard Temperature and Pressure Conversion

The important parameters for gas to standard temperature and pressure (STP) conversion are the biogas temperature and pressure, temperature of anaerobic environment and ambient temperature and pressure. Most of the scientific papers in the field of anaerobic digestion simply quote gas production volumes without mentioning any correction applied to standard conditions. However, the results reported as corrected to standard temperature and pressure (STP) more often do not provide the information of the standard conditions [17].

Correction of the measured volume of a standard temperature and pressure (STP) volume of dry gas is important. Different organizations have different definitions for the standard reference conditions of temperature and pressure. The standards of the International Union of Pure and Applied Chemistry (IUPAC) and the National Institute of Standards and Technology (NIST) are most common in use. Since there is no universally accepted set of reference conditions, the information about reported gas volumes without stating reference temperature and pressure cannot be considered accurate. The current definition of IUPAC for standard reference conditions of absolute pressure and temperature is 100 kPa (1 bar) and 0 °C (273.15 K) [44]. Similarly, for NIST the reference conditions are absolute pressure of 101.325 kPa (1atm) and temperature of 20 °C (293.15 K). Generally, gas volumes are reported as IUPAC original standard reference conditions of 101.325 kPa (1 atm) and 0 °C (273.15 K) [44].

Interrelation between Gas Measurement and Anaerobic Degradation

The anaerobic digestion process is carried out by the involvement of different types of microorganisms which possess a very close syntrophic relationship. The production of CH_4 is a slow and sensitive process. Favorable environmental conditions such as temperature and pH are very essential factors for the growth of micro-organisms. The steady conversion and utilization of organic acids are essential as the accumulation of these acids or decrease of pH can lead to the inhibition of the methanogenesis process.

The solubility of gases increases with an increase in pressure and decreases with an increase in temperature. CH_4 can be considered a less soluble hydrocarbon in water because of its smaller size and because it has the potential of causing minimum disruption to water's hydrogen bonds. This effect is so low that its solubility in water can be considered virtually zero [44]. On the other hand, CO_2 is very polar and its solubility is high in water. The difference in the solubility of two gases in water at different temperatures is given in Figure 21.

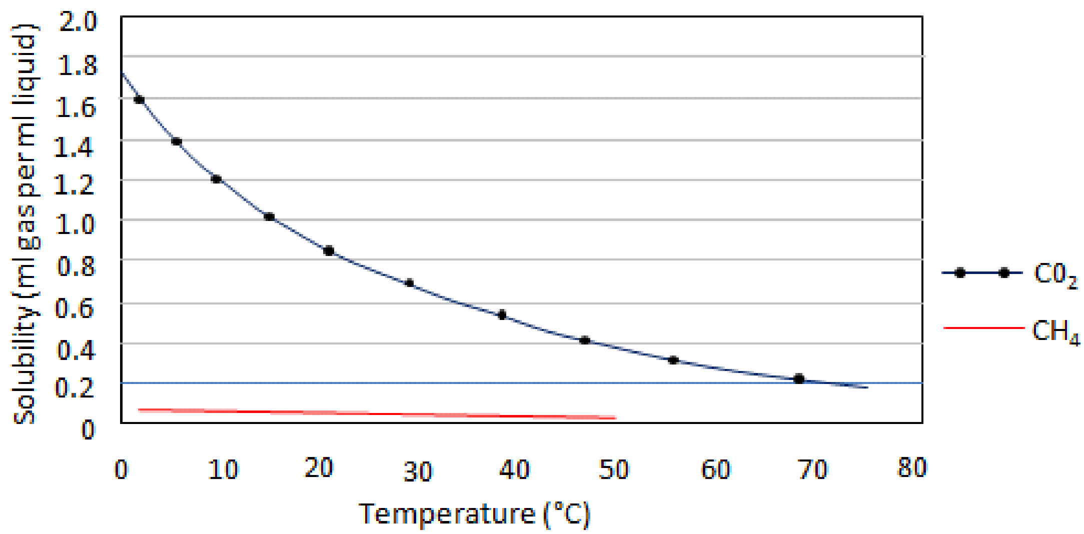


Figure 21 solubility of CO_2 and CH_4 [44]

The partial pressure of gas in the headspace can be held within a constant range. But CO_2 can hydrate and dissociate in the aqueous phase and vary the function of pH and other factors. The reaction scheme can be expressed as;

- When pH value is less than 8, the concentration of carbonate ions may be neglected
- When alkalinity is less than 1000 mg/L, pH starts to change rapidly.

The CO_2 concentration in the reactor head space, temperature, alkalinity and volatile acids can alter the pH which can influence the anaerobic process either directly by affecting the enzymes' activity by changing their protein structure or indirectly by affecting the toxicity of the compounds. Figure 22 shows that the methanogens have optimum growth within the pH range of 6.6 to 7.4 or in a wider range of 6.0 to 8.0 [44].

The pH value outside this range is very lethal for the survival of microorganisms. However, the acid forming bacteria can still be active even for pH values as low as 4.5. Therefore, continuous acid production can occur even when the methane production gets interrupted due to low pH [44].

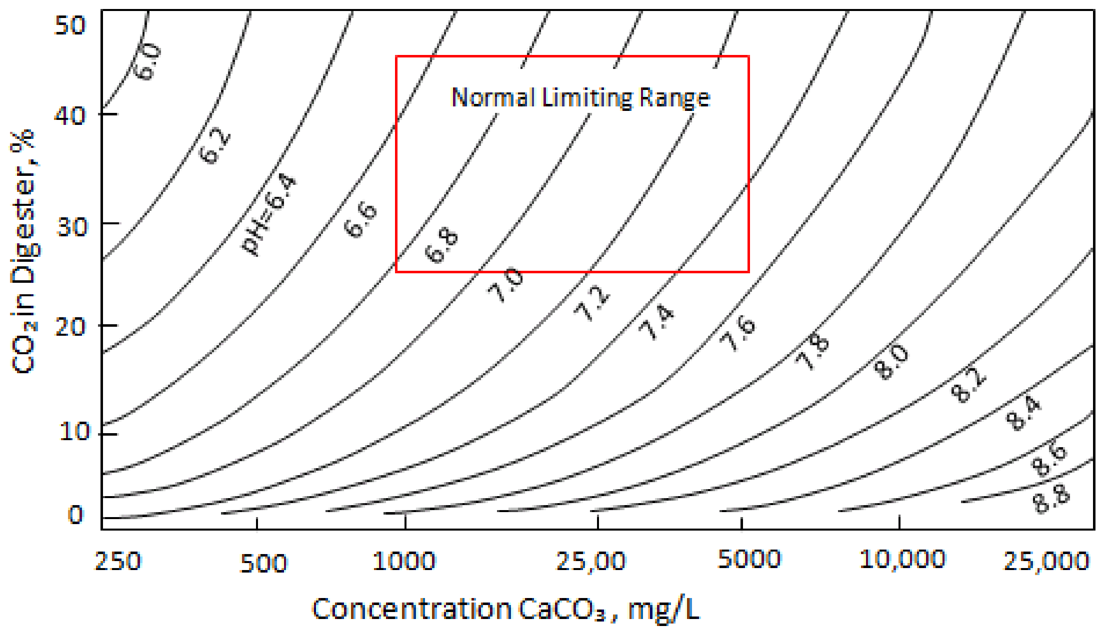


Figure 22 Relationship between pH, calcium carbonate concentration, and carbon dioxide [26]

The two important factors that can influence the pH of the system are carbonic acid and volatile acids. Within the pH range of methogenic bacteria, the buffering capacity is closely dependent on CO_2/alkalinity. The concentration of the CO_2 in the gaseous phase directly influences the carbonic acid in the solution when the balance is established between the CO_2 in liquid and gaseous phase. It is also related with Henry's law which states the solubility of a gas in a liquid is directly proportional to the pressure of that gas above the surface of the solution.

The gas measurement technology is very much interlinked with the buildup of gas pressure. As CO_2 is about 40 to 60 times more soluble than CH_4 in water under anaerobic conditions, the increase in digester pressure results in the increase of CO_2 concentration in the liquid resulting in a change in pH. This can stimulate the methane production rate by changing the concentration of free ammonia.

Ammonia is always found in equilibrium with ammonium (NH_4^+) in the aqueous solution. Ammonium is not as toxic as ammonia to the microorganisms and this equilibrium is determined by several factors such as acidity, pH and temperature.

The equilibrium of the reaction shifts to the right under the influence of high pH or high temperature resulting in a toxic environment for the anaerobic microorganisms.

This is why the thermophilic digestion process is more sensitive to ammonia inhibition than a mesophilic digestion process [27].

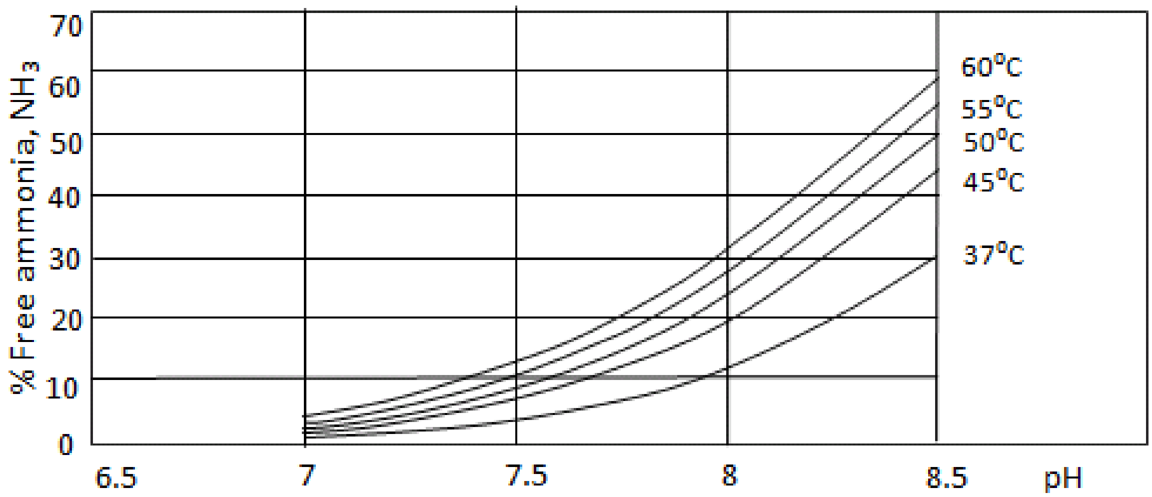


Figure 23 Effect of pH and temperature [27]

Development of negative pressure in the biogas could drag the outside air into the anaerobic system which should not be allowed. The oxygen in the air inhibits methanogens and results in a drop in the biogas methane production rate. Negative pressure occurs when the pressure of the atmosphere (outside the anaerobic system) is greater than the inside gas pressure. Therefore, anaerobic gas collection, sampling and the feeding process should not allow the atmospheric diffusion of air with the reactor. This is why the thermophilic digestion process is more sensitive to ammonia inhibition than a mesophilic digestion process [27].

CHAPTER THREE

3.0. Material and Method

Biogas Purification and Compression

Production of biogas could be a continuous process. The utilization of biogas as an efficient energy source depends strongly on its methane concentration. Therefore, biogas purification is essential in order to have more energy per unit volume of compressed biogas and to get rid-off the corrosive effect of hydrogen sulfide (H_2S). This can be done by compressing the gas into the cylinders, which is possible only after removing carbon dioxide (CO_2), hydrogen sulfide (H_2S) and water vapor (H_2O).

Biogas purification increases the concentration of methane in biogas, in order to have fuel of higher calorific value. This can be achieved mainly by decreasing the concentration of carbon dioxide (CO_2). Elimination of carbon dioxide from the biogas helps to increase its calorific value as well as to eliminate the greenhouse gas.

The purification of biogas is carried out in the scrubber unit which consists of the following sub units;

A. CO_2 separation Unit

B. H_2S separation Unit

C. Moisture separation Unit

The biogas scrubbing and storage facility is composed of two units, namely – the scrubbing unit and the storage unit. The entire biogas scrubbing and storage facility is schematically represented in figure 24.

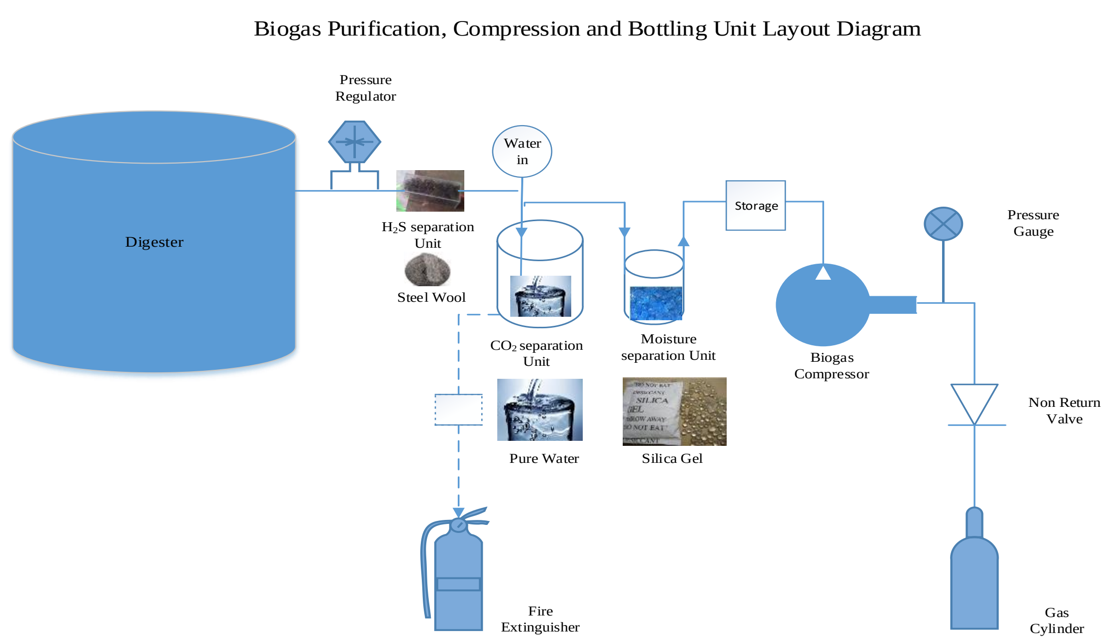


Figure 24 biogas purification compression and bottling unit layout

Generally, the system has;

3.1. Biogas Digester unit
3.2. Scrubbing unit
3.3. Compressor unit
3.4. Storage unit

3.1. Biogas Digester unit

In this process biogas digester is prepared 10m^3 closed container in which the separation and feeding of the organic fraction takes place. In this digester, the biodegradation of separated waste takes place under anaerobic conditions and in the presence of methanogenic bacteria, and as a result produces a methane-rich biogas. The type of digester used is called floating cover digester in which biogas is floating over the waste.

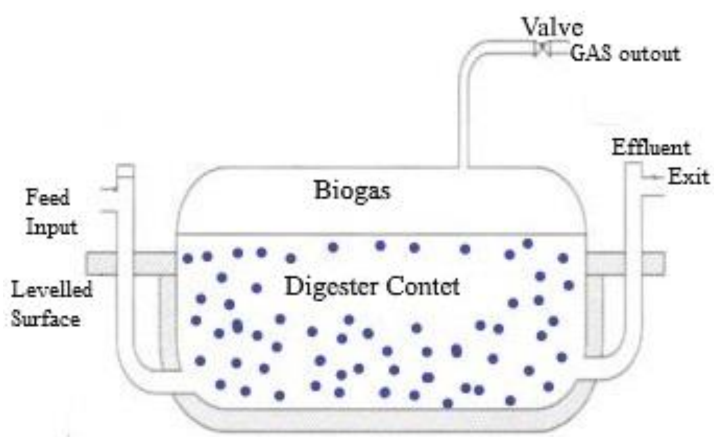


Figure 25 cross- sectional view of digester

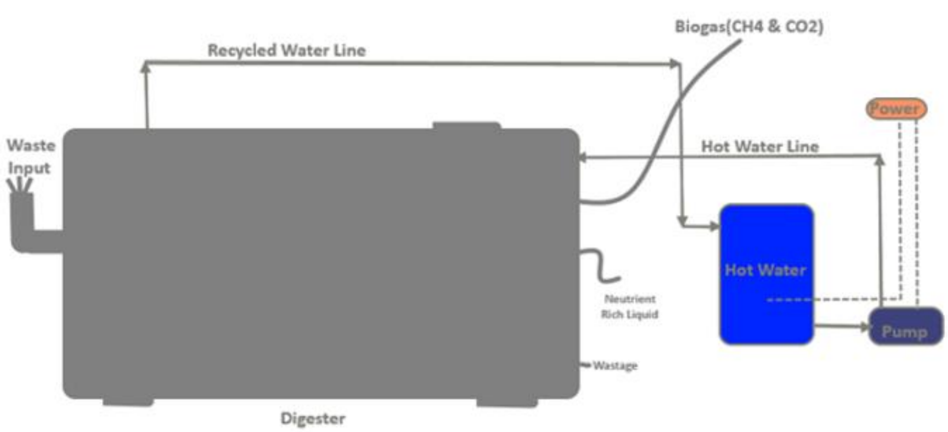


Figure 26 Biogas Digester Unit

Biogas digester unit has parts which facilitates working process to produce biogas.

- Food waste Input

Food waste is usually obtained as "bio waste" from households, restaurants, big kitchens as well as stores. This type of waste needs a pre-treatment including shredding, separating plastics and metals from it as well as mixing with water. In general, it has a high biogas production but its quality is dependent on the sorting and pre-treatment. Good sorted food waste has generally a high amount of easily biodegradable organic waste which increases the risk of sinking pH and accumulation of fatty acids. Food wastes are used in the digestion feed stock, namely cafeteria waste including vegetable wastes, and fruit wastes which were collected from Addis Ababa university sidist kilo campus cafeteria and the cow manure was collected and introduced in to the digester so that bacterial fermentation is assisted. The prepared stocks were fed by a volume of $10m^3$ biogas digester. The estimation procedure and the biogas production process involve breaking down of food waste into its elemental compositions, C, H, O, N, and S.

Table 10 Elemental Compositions of Food Waste [11]

Food Waste Elemental	%
C	45.405
H	7.655
O	42.915
N	3.945
S	0.4

Figure 27 Cow Manure Input as Catalyst to Biodegradability of Food Waste

- Hot water tank

Water tank is used to maintain the temperature of biogas digester for bacterial decomposition. It has two heaters maintained up to 60^0C. Water is recycled via the digester pipeline to the water tank.

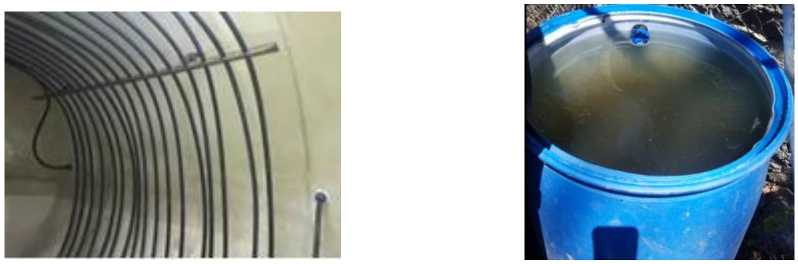


Figure 28 Hot Water Tank

- Water Pipe line (Hot and Cold)

The pathway from water tank to digester as well as from digester to water tank circulations.

- Pump

Pump is used to circulate hot water in to the digester from the water tank. Hot water maintains temperature in the digestate for bacterial decomposition.

Figure 29 Pump and Specification

Table 11 Pump Specification

Pump Specification	
Product	Peripheral pump
Type & Inlet	APm 75, 1”
Power & Max. flow rate	750W, 50L/h
Max. delivery height & Gross weight	65m, 10,5Kg
EC directive(s)	2014/35/EU Low voltage
EC standard(s)	EN 60335-2-41:2003; EN 60335-1:2012; EN 62233:2008

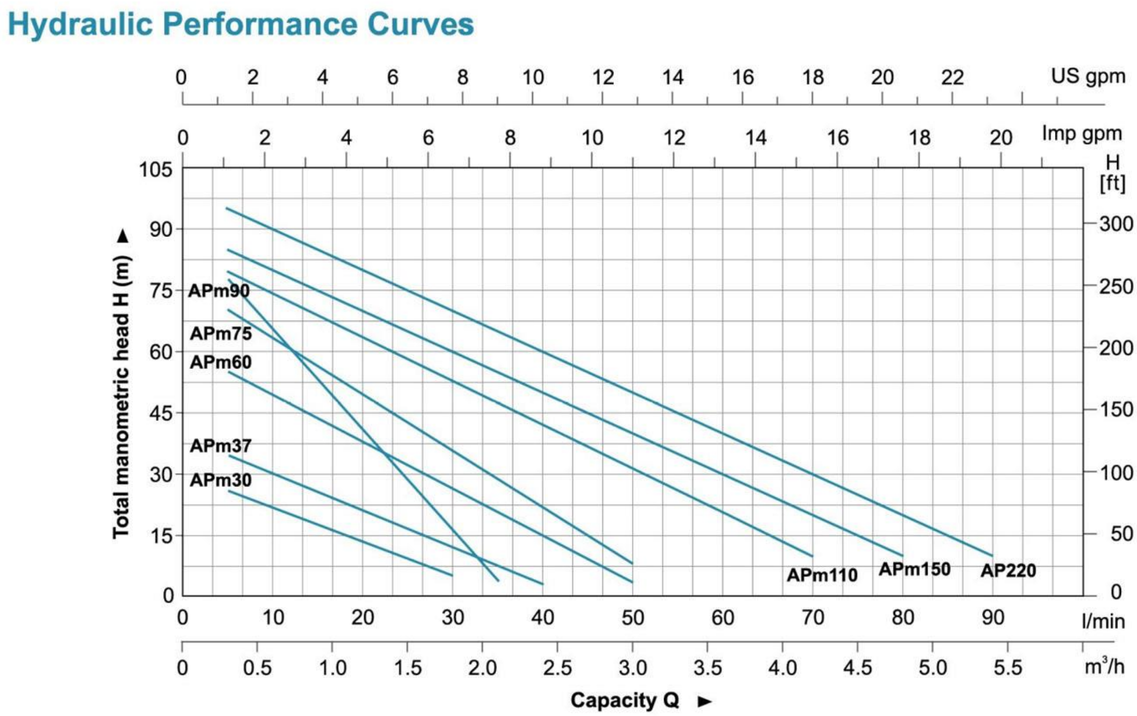


Figure 30 Pump Performance Curves

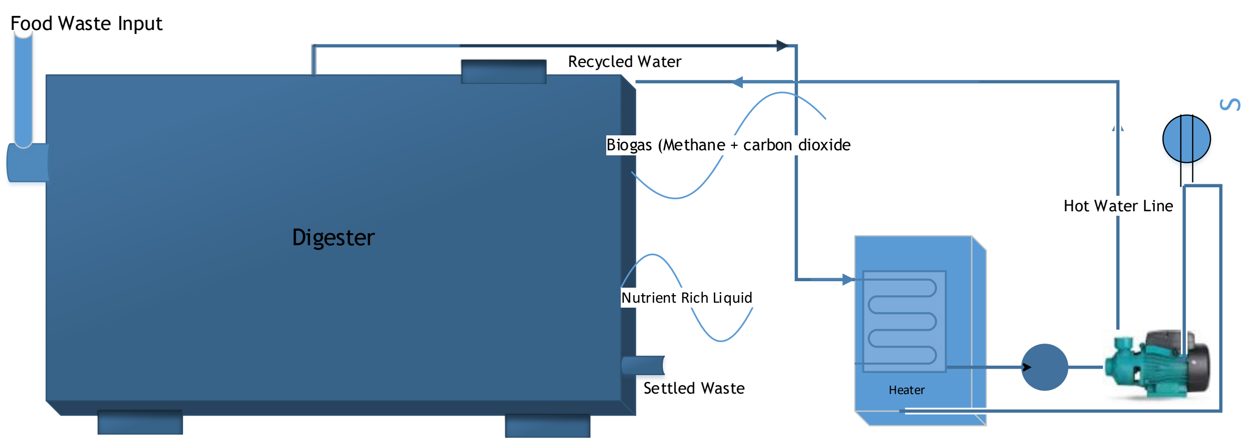


Figure 31 Biogas Digester Unit

3.2. Biogas scrubbing unit

The biogas scrubbing system consists of three units, the hydrogen sulfide (H_2S) removing unit, Carbon dioxide (CO_2) removing unit, and moisture trapping unit. The three units are interconnected with plastic hoses. The sodium hydroxide, or charcoal activated carbon and an adsorbent material (silica gel) are used. From the literature review it's more accurate to use the chemical absorption method uses aqueous chemical solution (NaOH solution, charcoal, activated carbon powder and silica gel).

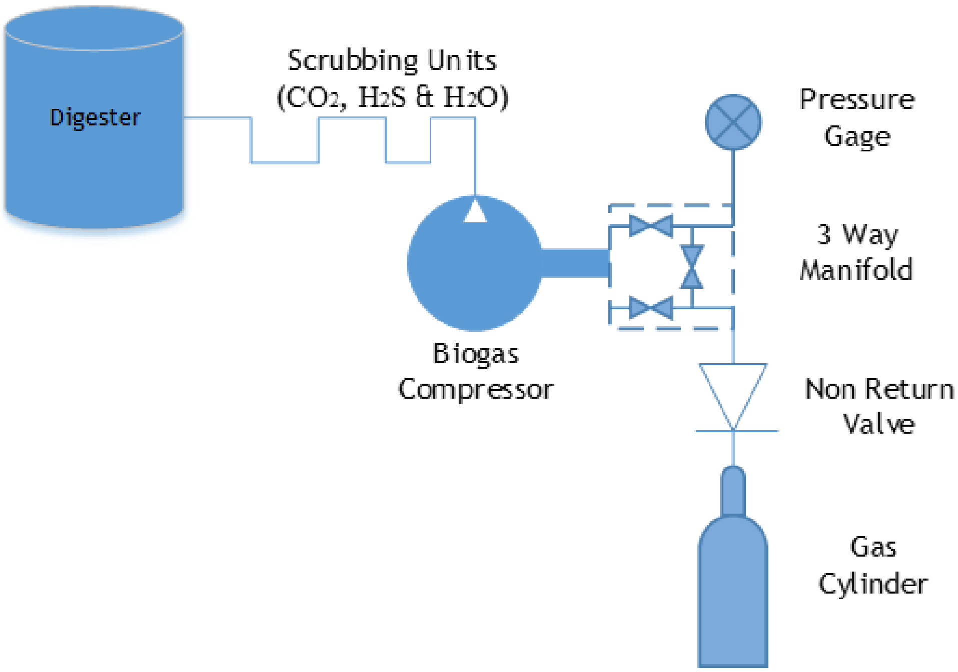


Figure 32 Digester, Scrubbing Unit, Compressor and Gas Cylinder layout

- The charcoal, activated powder is to react with the hydrogen sulphide,
- The sodium hydroxide is to reduce the percentage of carbon dioxide and
- The silica gel is to reduce the presence of water vapor in the purified biogas.

The experiment is done by taking the raw biogas with a compressor sacked from the digester through the activated carbon on its way to the biogas scrubber unit to remove hydrogen sulphide. Then, the carbon dioxide was removed by sodium hydroxide, the biogas passes into the scrubbing unit for further purification. Then the biogas pass throgh the silca gel to reduce the presence of water vapor in the purified biogas.

Tube pipe lines are connected for each flasks to take samples and analyze the constitites of biogas . each has also control valves so that its possible to open and close the flow. Leakages are controlled by plaster and forced hoses used to the input and out put points of the scrubbing units.

Silica gel used was bigger in size which needs to minimize the size into smaller so that it has better ability to absorb moisture in the biogas passing through the scrubbing unit.

The amount of chemicals used are weighted by weighing scale. 1 upto 10 gm of activated powder, NAOH solution and silica gel used to purify raw biogas passes through the scrubbing units.

Figure 33 Scrubbing Units

The function of each unit is as follows,

A. *H_2S separation Unit* –first the raw biogas is passed through a H_2S separation unit. Hydrogen Sulphide is removed by using Charcoal, activated carbon. Once biogas comes in contact with Charcoal activated carbon this is converted into elemental Sulphur. Hydrogen sulphide removed by using activated carbon is often dosed with KI or sulfuric acid (H_2SO_4) to increase the reaction rate. In biological filters the H_2S is catalytically converted to elemental sulfur and water. The chemical equations are as follows [31];

$$2H_2S+O_2 \leftrightarrow 2S+2H_2O \text{ .... Eq 28}$$

Hydrogen sulfide adsorb on the internal carbon surface where it can be oxidized in presence of oxygen to Sulphur. Ash constituents like iron oxide, can accelerate and improve the H_2S removal. The H_2S removal capacity of plain activated carbon is usually not attractive due to the low removal capacities.

Figure 34 Hydrogen Sulphide Remover

CO_2 separation Unit; - then biogas is passed through a CO_2 separation unit. Sodium hydroxide (NAOH) is used to remove carbon dioxide. Sodium hydroxide solution (caustic soda) is an alkali, and carbon dioxide is an acid gas, and the two react to form sodium carbonate (washing soda). The chemical reaction is as follows;

$$2NaOH + CO_2 \text{ ……………} Na_2CO_3 + H_2O \text{……………………} \quad \text{Eq 29}$$

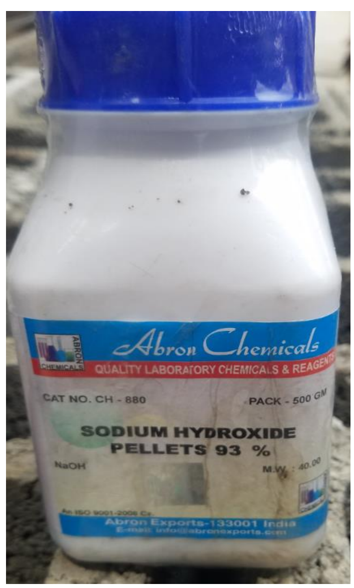


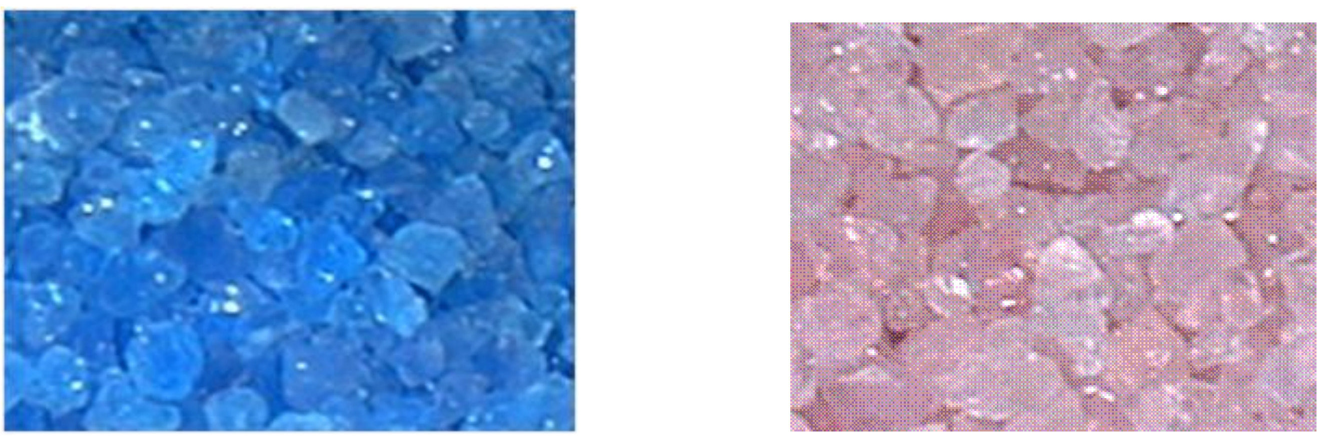
Figure 35 Carbon dioxide separation unit in the scrubbing system

B. *Moisture separation Unit* – Finally the biogas is passed through a moisture separation unit. Here silica gel crystals are proposed to separate moisture. Silica gel crystals should be replaced after a specific time according to the rate of purification.

Figure 36 Removal of water vapor from Biogas

It consists of one inlet for raw biogas to enter the unit and one outlet for clean biogas. The glass jar is tightly closed with a lid or plaster and hose attachment in order to prevent gas leakage. Finally, the clean biogas from scrubbing unit is allowed to pass through a compressor.

The color of the silica gel would change from blue to pink color after absorbing the moisture from the purified biogas.



A) Ready to use silica gel B) Silica gel turns pink once it has soaked up moisture.

Figure 37 Moisture Absorber

Now the out coming biogas from the scrubbing unit is pure.

3.3. Compressor unit

The least expensive and easiest to use storage systems are low-pressure systems; these systems are commonly used for on-site, intermediate storage of biogas. The energy, safety, and scrubbing requirements of medium- and high-pressure storage systems make them costly and high-maintenance options.

Commercial compressor is a low-pressure storage which should be the most practical alternative. It is important to ensure that the storage tank is safe at the pressure being used.

Pure methane should be compressed and stored in small cylinders or bottles which make it easy to transport at the point of application for the purpose of biogas.

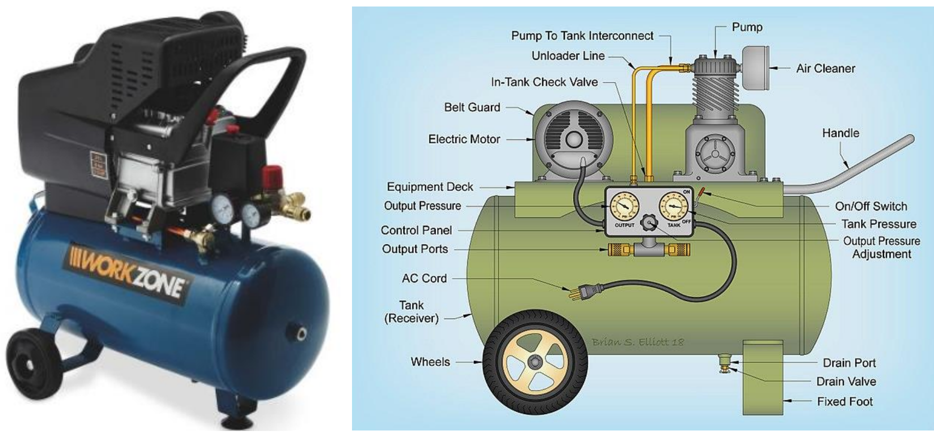


Figure 38 Compressor unit [25]

Table 12 Compressor Specification [25]

Compressor Specification	
Model	ZB-1047
Voltage	220V
Electric Current	13.2A
Frequency	50/60HZ
Rated Revolving Speed	2800RPM
Grade of Insulation	B
Volume of Insulation	$0.13m^3$/min
Designed Temperature	80 ^oC
Working Pressure	0.8MPa
Cylinder	Dim 47mmxl
Volume of Gas Tank	50L
Power	5HP

3.4. Gas Storage

The biogas is usually used soon after generation without storage. However, gas storage should be necessary to balance the mismatch between gas production and its use. LPG gas cylinder-bottle pressure is dependent upon temperature. The higher the temperature, the higher the LPG gas cylinder-bottle pressure within the cylinder. LPG gas cylinder pressure, or larger vessel pressure, is dependent upon the temperature of the vessel.

Table 13 Gas Cylinder-Bottle Pressure Table [43]

Temp	Pressure	Pressure
ºC	kPa	Bar
70	2482	24.8
60	2013	20.1
54	1794	17.9
43	1358	13.6
38	1186	11.9
32	1027	10.3
27	883	8.8
16	637	6.4
-1	356	3.6
-18	152	1.5
-29	74	0.7
-43	0	0

Figure 39 Biogas Cylinder

Biogas can be stored in the biogas compressor cylinder (50 lt volume) at a pressure up to 8 bar as shown in the figure 40. Biogas is also stored in a biogas bag and tire inner tube. The biogas compressor has 50 lt volume capacity cylinder with a flow rate of 0.13m^3/min.

Figure 40 Biogas Compressor

Biogas storage bags are selected based on the availability and cost incurring. In this experiment tire inner tube 12R20 and biogas bag are used to store the compressed biogas from the digester.
The biogas has compressed at a pressure of 2 bar I the 500 lt Volume biogas bag. The compression pressure for the tire inner tube is 1 bar having 13 lts in volume.

Figure 41 Tire inner tube used for biogas storage option

Figure 42 Biogas bag used as biogas storage option

Table 14 below describes the size and specifications of tire inner tube used for storing biogas from the digester,

Table 14 Tire Inner Tire Tube Specifications [34]

Size	*12.00R20*
Profile	*XZM*
Load / Speed Index	*176A5*
Diameter (mm)	*1136*
Width (mm)	*324*
Tread (mm)	*40*
Standared Rim	*8.5*
Pressure (Kpa)	*830*

Figure 43 Tire Inner Tube for biogas storage

Figure 44 Tire Inner Tube before and after biogas storage

- Gas Analyzer: used to measure the chemical composition of the biogas produced in the form of methane (CH_4), carbon dioxide (CO_2), oxygen (O_2), hydrogen sulfide (H_2S) and ammonia NH_3.

Figure 45 Gas Analyzer

- Air bags: holds the biogas produced from the food waste anaerobically

Figure 46 Air bag

- Vacuum Pump: this pump was used to purge the air inside the air bag. The vacuum pump has a great contribution for anaerobic digestion of the food waste.
- Flask: works as an aerobic digester for a laboratory purpose
- Weighing Scale: used to measure the mass of food wastes and scrubbing chemicals used for purifications.

Figure 47 Weighing Scale

CHAPTER FOUR

4.0. Results and Discussions

4.1. Purifications

4.1.1. CO_2 Removal

Experimental studies on carbon dioxide removal were carried out. NaOH solution was used as CO_2 absorbent. Effects of different operating and design parameters, NaOH solution and total gas flow rate on CO_2 removal efficiency were investigated. Experimental results showed that the higher concentration of NaOH solution, lower flow rate of total gas were beneficial to promote CO_2 removal efficiency. In order to have high removal efficiency of CO_2, the mole ratios of absorbent to CO_2 should be larger than values for NaOH solution. With higher concentration of NaOH, the higher CO_2 removal which Carbon dioxide reacts with the sodium hydroxide based absorbent and undergoes a complete chemical change.

Results obtained during CO_2 removal using NaOH are figured as follows.

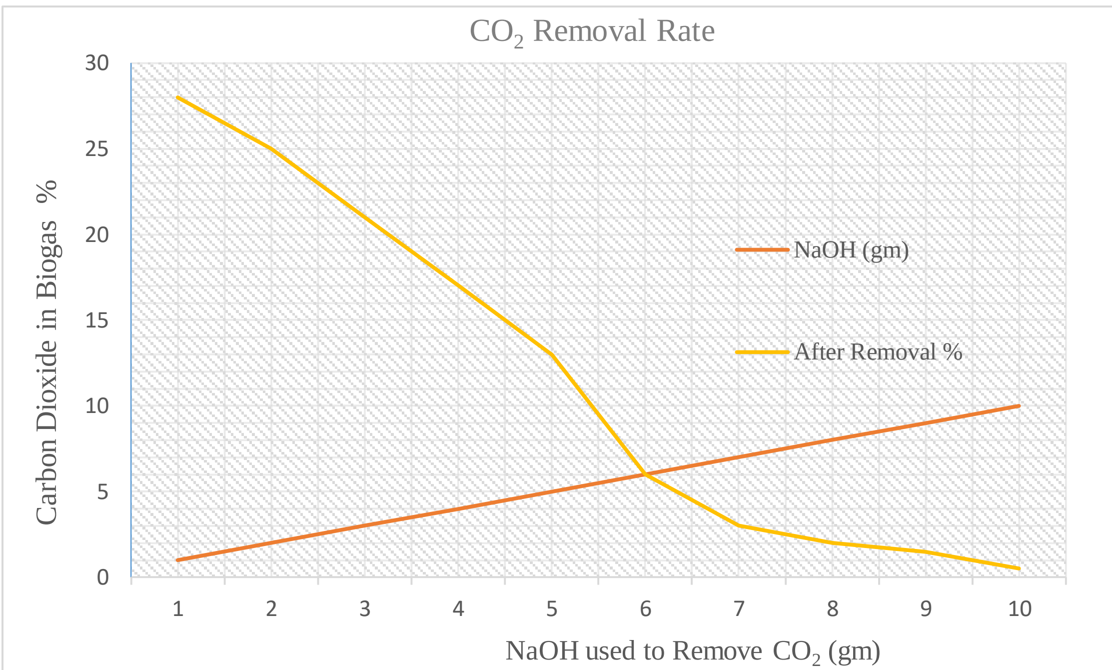


Figure 48 Effect of NaOH solution to remove CO_2

The reaction rate and capture efficiency were strongly dependent on the NaOH concentration in the production range. The amount of CO_2 absorbed in the solution was slightly less than the theoretical value, which was ascribed to the low power production during the reaction and the consequent decrease in CO_2 absorption in the NaOH solution.

4.1.2. H_2S removal

Hydrogen sulfide also adsorbs on the internal carbon surface where it oxidized in the presence of oxygen to sulphur. Ash constituents like iron oxide, can accelerate and improve the H_2S removal. The H_2S removal capacity of activated carbon is increasing with its higher proportions. The effect of amount of activated carbon toward adsorption capacity was investigated; the result indicated that adsorption capacity increases with the amount of activated carbon and decreases with flow rate of gas stream.

Results obtained during H_2S removal using activated carbon are figured as follows,

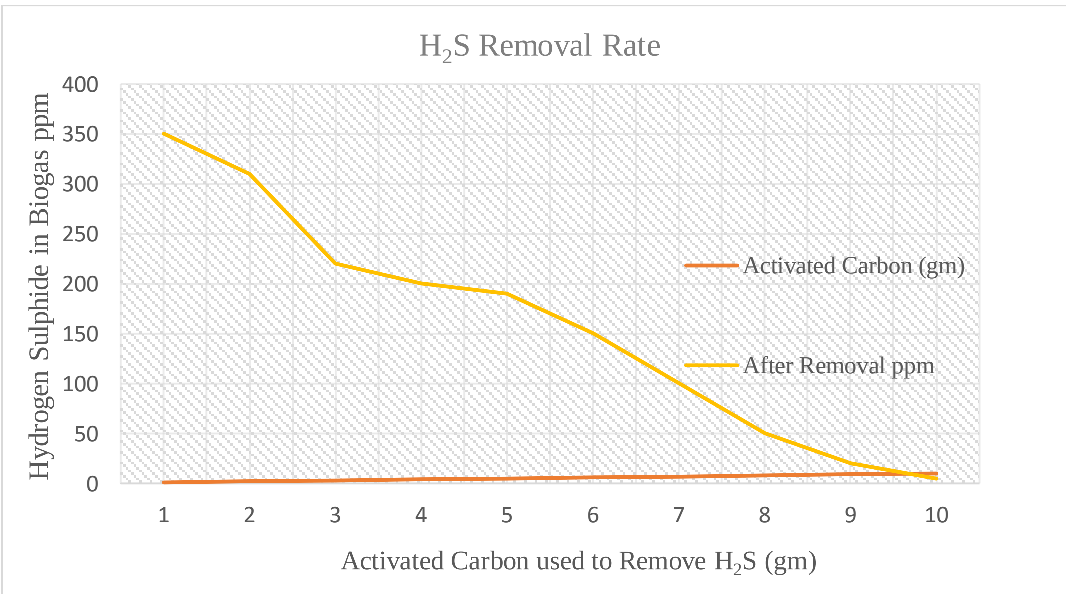


Figure 49 Effect of activated carbon solution to remove H_2S

4.1.3. Moisture Removal

Silica gel, naturally, has a high surface area. When gas is passed through these moisture absorbers, the water molecules present attach themselves to the gel surface as it has a lower vapour pressure compared to the air around. When the desiccant reaches the point of equal pressure then the adsorption stops, so we can safely conclude that more the levels of humidity in the surrounding air, larger amounts of water will be adsorbed before equilibrium is achieved.

Results obtained during water removal using silica gel are figured as follows,

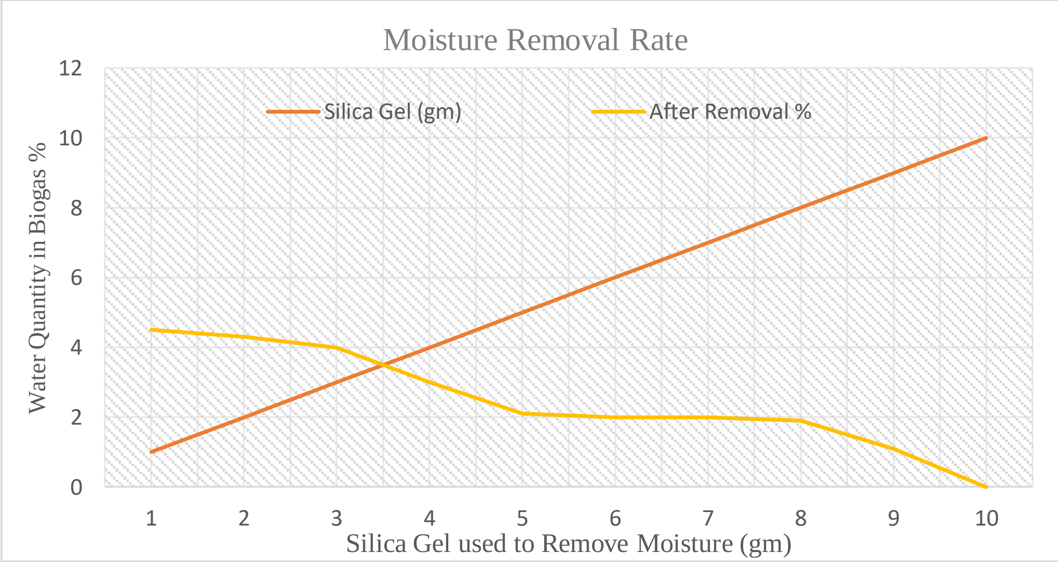


Figure 50 Effect of Silica gel to remove Moisture

Generally, Purification of the biogas was done using scrubbing units and relative purity of the gas was tested by biogas analyzer. From these experimental results the amount of methane available in purified biogas was approximately 61%.

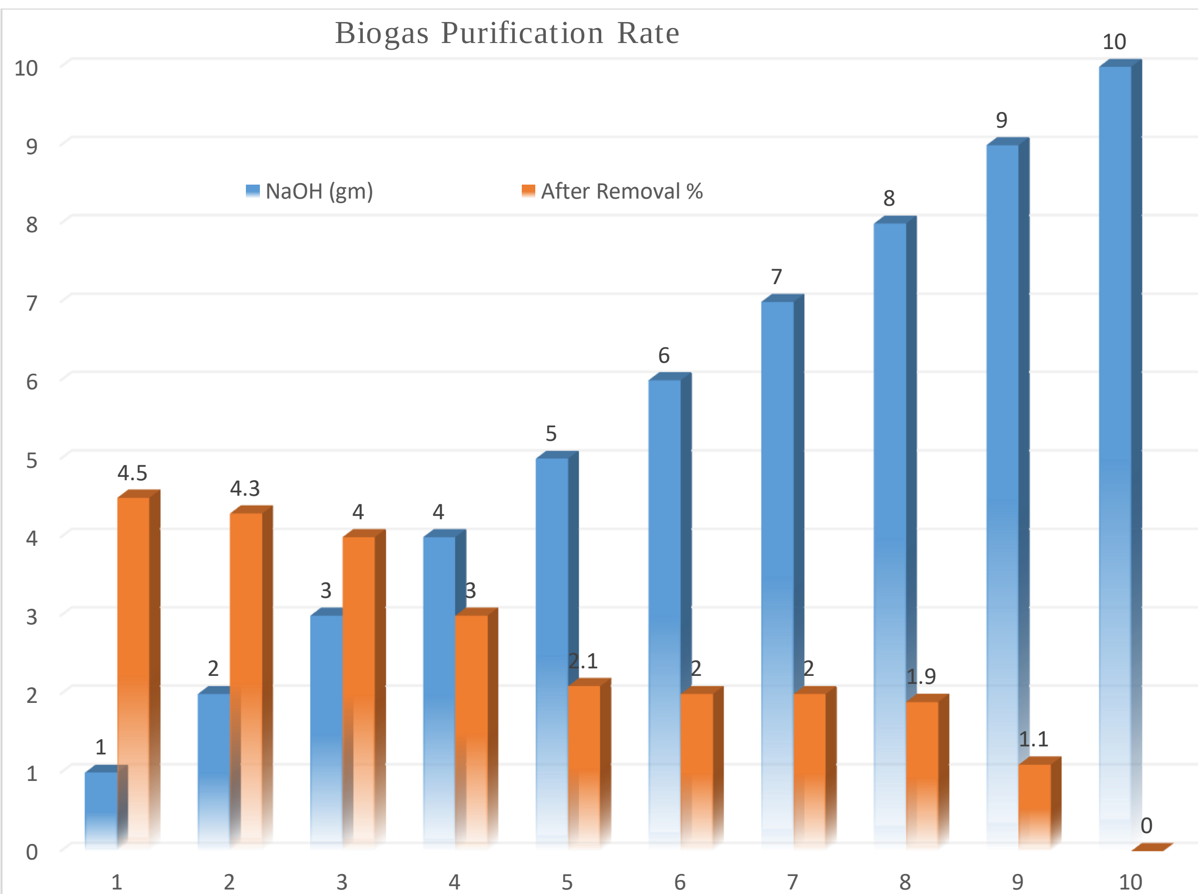


Figure 51 Effects of Chemicals used to purify biogas

4.2. Biogas Compression

Commercial compressor is used to compress biogas from the digester which has been used repeatedly in different ways to compress biogas from the digester. Biogas stored in the biogas storage bag has an internal pressure not more than 50mbar. Food waste input to the digester is 230kg per day, digester temperature is controlled by the heater to be 40 – 60 ^{0}C, Biogas flow rate to the scrubber is 0.13m^3/min and working pressure of the scrubber 1.013Pa and total solid TS= (Daily input) *0.3033 and measured methane concentration after overall analysis is 61% tested by the biogas analyzer. Comparing with the theoretical value the biogas content the result is optimum (60-70%).


Figure 52 Biogas compressed and stored into ballon and biogas bag

Suction pressure: -The pressure at the compressor inlet expressed, P_s= 1.06 bar

Discharge pressure: - The pressure at the compressor discharge expressed, P_d= 2 bar

Suction temperature $(T_s) = 300\ K$

Power: -

R= $\frac{P_d}{P_s}$, $P_s = 1.106bar + 1.01325bar = 2.093\ bar$

$\mathrm{P_d} = 2\text{ bar} + 1.013\text{ bar} = 3.01\text{bar}$

$$R = \frac{3.0133}{2.093} = 1.44, \text{single stage compressor is best suited}$$

Calculate the discharge temperature ($\mathrm{T_d}$)

$$\mathrm{T_d} = \mathrm{T_s}\left(\frac{\mathrm{P_d}}{\mathrm{P_s}}\right)^{\frac{n-1}{n}} = \mathrm{T_s}\mathrm{R}^{\frac{n-1}{n}}$$

R = compression ratio = 1.44

n = specific heat ratio of the gas = 1.3 for biogas

T_d = Discharge temperature calculated = 326 K

Figure 53 Biogas compressor connected to line on a gas stove

The biogas heating ability can be tested by connecting the tube piped from the digester to the compressor and into the gas stove. As it is shown in the figure below the biogas can give spark in the stove. The boiling ability can be tested using water in a given time.

Figure 54 Biogas heating test

The boiling ability of biogas bag from the digester can be compared with the result from the normal gas. The purification will improve the ability more.

4.3.Biogas Bottling

For bottling a gas after compression, gas cylinder has been used with a volume of 2 liters and the cylinder requires a pressure of 5 bars while stored in the cylinder. In order to bottle the cylinder a hand (cycle) pump is used. To store the gas in the cylinder pressure requires in which a normal person can exert 5-8 bar pressure.

Figure 55 Hand (cycle) pump used to bottle gas in to a cylinder

A hand pump is converted by little modification to suck and release biogas under high pressure. Two washers are mounted as in figure and its holes are closed using silica. A valve system developed to inlet the gas when the pump sucks biogas and to outlet the biogas during filling it into a cylinder. Modified connecter is mounted to the cylinder which enables the gas cylinder to be fillable. A pressure gauge can be mounted at the end of the pipe which is used to fill biogas into cylinder. During up-stroke, the piston draws biogas through a one-way valve into the pump from biogas bag. During down-stroke, the piston then displaces the gas from the pump into the cylinder.

Figure 56 Configuration of hand pump used to bottle biogas in the cylinder

CHAPTER FIVE

5.0. Conclusion

Biogas plants convert food wastes to biogas and the biogas is a clean renewable energy which will be used in different forms of environmentally friendly energy sources. The study facilitates the technology to get an environmentally friendly energy sources by converting the food waste to biogas.

Converting food wastes to biogas indeed will make the atmosphere free from environmental pollution that could be caused because of the food wastes. Converting the food waste to biogas and this production of biogas will reduce cost of gas which is used for cooking stoves and ovens.

Even if biogas is widely used for cooking and lighting, but its commercial use has not been realized due to difficulties in its storage and transportation. Solution identified to the problem is to increase the energy density of the gas through removal of incombustible and corrosive gas and consequent compression which was experimented on this paper.

This paper presents all the results of removal of impurities of biogas which are mainly carbon dioxide gas, hydrogen sulphide and water from biogas using different chemicals and relative purity with raw gas. Further, compression of biogas and bottling was carried out by a compressor and stored into biogas bag which can be easily bottled into a normal gas cylinder. Compression of biogas into compressor cylinder was carried out under near isothermal and adiabatic conditions 5 to 8 bar absolute pressure. Later, purification of the biogas was done using different methods and relative purity of the gas was tested by biogas analyzer. From this experimental result the amount of methane available in the purified biogas was 61%. Comparing with the theoretical value of methane constitute the biogas content in the study result is optimum.

Generally, compression of biogas from a digester at sidist killo campus was carried out by a 5lt commercial compressor and stored into a 500lt biogas bag and tire inner tube at a pressure of 2 and 1 bar respectively. And finally the stored biogas is bottled in to 2lt commercial gas cylinder using modified cycle pump at a pressure of 5 to 8 bar which a normal person can exert.

CHAPTER SIX

6.0. Recommendations or Further Development

There are many ways in which the present research could be continued to investigate in the near future. This study recommends upgrading and purifying the raw biogas as it is continuous and it’s possible to get a better and more refined biogas with methane content up to 98%. Especially absorption and adsorption upgrading methods can be seen further in the future.

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APPENDIXES

- Typical compounds found in biogas and their effects on the gas value as well as content and cause

Component	Content	Effect	Cause
Carbon dioxide	25 – 50 Vol%	Lowers heating value, corrosion, damages alkali fuel cells	High C/N, low pH, O_2 contamination of slurry, in the beginning of digestion process as well as with any disturbances of it
Hydrogen sulfide	0 – 0.5 Vol%	Corrosion, sulfur dioxide (SO_2) emission, spoils catalysts	Low pH, rise in temperature, any disturbances of digestion process, protein or sulfate in substrate, long digestion time
Ammonia	0 – 0.05 Vol%	Nitrogen oxides (NO_x) emission, corrosion	Low C/N, thermophile temperatures
Water vapor	1 – 5 Vol%	Corrosion, condensation, risk of freezing equipment	Increases with temperature increase
Dust	> 5 µm	Blocks nozzles and fuel cells	---
Siloxanes	0 – 50 mg/m^3	Act like abrasive and damages equipment	Siloxanes in substrate

(Deublin & Steinhauser, 2008, p.52; House, 2006, p. 86-87)

- Table 2: Different properties and compounds found in food waste feedstock vs slurry feedstock

	Food Waste Feedstock			Slurry Feedstock		
	Mean	Min	Max	Mean	Min	Max
DS (%)	4,5	2,7	6,8	4,9	3,5	9,3
VS (%)	69,0	68,3	69,6	73,2	73,2	73,2
pH	8,4	8,3	8,4	8	7,6	8,8
Nutrient content in percentage						
Nitrogen, N (%)	15	11,9	20,5	16,1	6,7	24,9
Readily available N (% of total N)	61,9	38,7	86,8	65,4	39,3	85,6
Potassium, K (%)	4,7	1,4	9,3	3,2	1,5	5,9
Phosphorous, P (%)	0,7	0,3	2,0	0,9	0,2	5,0
Calcium, Ca (%)	0,34	0,0	1,70	2,6	0,0	4,8
Magnesium, Mg (%)	0,19	0,0	0,69	0,3	0,0	3,7
Sulfur, S (%)	0,33	0,0	0,57	0,9	0,0	1,7
Heavy metal content in milligram per kilogram						
Copper, Cu (mg/kg)	31,5	18,6	24,6	82,1	20,3	180,7
Zinc, Zn (mg/kg)	105,1	71,0	142,3	240,0	4,4	631,0
Lead, Pb (mg/kg)	46,3	3,6	114,7	1,0	0,0	17,9
Cadmium, Cd (mg/kg)	1,2	0,2	2,2	1,5	0,6	2,3
Mercury, Hg (mg/kg)	1,1	1	1,1	0,1	0,0	0,6
Nickel, Ni (mg/kg)	43,2	5,5	137,3	8,6	0,0	18,8
Chromium, Cr (mg/kg)	50,2	7,8	157,5	12,4	0,3	38,2
Fluorine (F)	209,5	200,0	219,0	118,0	118,0	118,0
Aluminum (Al)	-	-	-	4141	131	11812
Iron (Fe)	-	-	-	14059	1551	37701

(Rigby & Smith, 2011, A1-A9)

Table 2a: Critical Point of Various Gases (Constant & Naveau, 1989)

	H_2	N_2	NH_3	O_2	CH_4	CO_2	H_2S	C_3H_8	C_4H_{10}
Temperature (C°)	-239.9	-147.1	132.4	-118.57	-82.5	31	100.4	96.6	152
Pressure (bar)	13.1	34.2	113.9	50.8	46.7	73.85	90.1	42.5	37.9

(According to Weast and Astle, 1980) [43]

Table 2b: Energy Content of Various Gases (Constant & Naveau, 1989)

Combustible	$MJ\ kg^{-1}$	$MJ\ m^{-3}$
Methane	50.0	35.9
Purified biogas (90%)	45.0	32.3
Mean biogas (60%)	30.0	21.5
Butane	45.7	118.5
Propane	46.4	90.9
Methanol	19.9	$15.9\ 10^3$
Ethanol	26.9	$21.4\ 10^3$
Gasoline	45.0	$33.3\ 10^3$
Diesel	42.1	$34.5\ 10^3$

*At 1 atm and 0°C

APPENDIX 1: BIOGAS PLANT CALCULATION TABLES

Table 10: Estimated volume of a fixed dome plant (hemisphere design) by plant diameter

Diameter (m)	Total plant volume (m^3)	Digester volume (m^3)	Gas storage volume (m^3)	Rated daily gas production (m^3/day)
2.0	2.09	1.68	0.42	0.70
2.2	2.79	2.23	0.56	0.93
2.4	3.62	2.90	0.72	1.21
2.6	4.60	3.68	0.92	1.53
2.8	5.75	4.60	1.15	1.92
3.0	7.07	5.65	1.41	2.36
3.2	8.58	6.86	1.72	2.86
3.4	10.29	8.23	2.06	3.43
3.6	12.21	9.77	2.44	4.07
3.8	14.37	11.49	2.87	4.79
4.0	16.76	13.40	3.35	5.59
4.2	19.40	15.52	3.88	6.47
4.4	22.30	17.84	4.46	7.43
4.6	25.48	20.39	5.10	8.49
4.8	28.95	23.16	5.79	9.65
5.0	32.72	26.18	6.54	10.91

Note: these figures assume that the gas storage volume is 20% of total volume and that it can hold 60% of daily production.