



Addis Ababa University
Addis Ababa Institute of Technology
Center of Renewable Energy Technology

***Field-Based Performance Evaluation of Three Household Biogas
Digesters: the Case of Holeta, West of Addis Ababa, Ethiopia***

A Thesis Submitted to the School of Graduate Studies, at Addis Ababa Institute of Technology, Center of Renewable Energy, in Partial Fulfillment of the Requirements for the Degree of Master of Science in Renewable Energy Technology.

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Dec/2022
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DECLARATION

I hear by declaring that this MSc thesis, titled “*Field-Based Performance Evaluation of Three Household Biogas Digesters: the Case of Holeta, West of Addis Ababa, Ethiopia*” was completed independently by me **Tariku Messele** under the supervision of **Dr. Ebrahim Tilahun** (Assistant professor). This MSc thesis was not submitted for the purpose of receiving any other degree or professional qualification.

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ABSTRACT

Biogas is one of clean, and alternative renewable energy source obtained through anaerobic digestion of readily available organic waste materials. Ethiopian government have been actively engaged in disseminating biogas technologies into the country since 2009. Until Jan, 2022, total of 35,626 domestic biogas digesters were constructed through consecutive three phases. The biogas digester functionality rate is 79%, however only 30% of the constructed biogas digesters were functioning without significant problem. The performance of a biogas plant is mainly dependent on the input feedstock characteristics, the microbial activity (condition inside the bio-digester), and process conditions and parameters including pH, temperature, and etc. This study evaluated the performance of three household anaerobic bio-digester to which generates biogas from cattle dung. The bio-digesters selected through purposive sampling in Holeta west of Addis Ababa. The finding of the study indicated that the biochemical theoretical methane potential was 60%, while the actual methane percentage was 51%. The total solid, volatile solid, and chemical oxygen demand removals resulted as 37.7%, 26.7%, and 70.7%, respectively. The result shows lower digestibility, this is due to unstable alkalinity, temperature, and pH level. Sulfate-reducing bacteria had also an effects in the methanogenic bacteria's performance. The maximum hydrogen sulphide amount contained in the biogas was 651 ppmv, which is caused by high sulfur content on the feedstock. The study concluded that improper management, lack of monitoring of installed biogas digesters, poor construction quality, are among the challenges that have derailed the sustainable implementation of, and household biogas production in the country. Unless these problems are addressed, the functionality rate of bio-digesters in Ethiopia could not be improved.

Keywords: Anaerobic digestion, cattle dung, methanogenesis, performance, volatile fatty acid.

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LIST OF ABBREVIATIONS AND ACRONYMS

AD	Anaerobic Digestion
APHA	American Public Health Association
BAL	Balance
BOD	Biochemical oxygen demand
C	Carbon
CH ₄	Methane
CO ₂	Carbon dioxide
COD	Chemical oxygen demand
COD _{AD}	Chemical oxygen demand after anaerobic digestion
COD _{BD}	Chemical oxygen demand before anaerobic digestion
DiBiCoo	Digital global Biogas Corporation
DO	Dissolved oxygen
FA	Free ammonia
FAO	Food and agricultural organization
FS	Fixed solid
GC	Gregorian Calendar
GHG	Greenhouse gas
H	Hydrogen
H ₂ S	Hydrogen sulfide
HPLC	High pressure liquid chromatograph
HRT	Hydraulic retention time
IEA	International Energy Agency
K	Potassium
kg	kilogram
LR	Loading rate
ltr	liter
m	meter
m ³	Cubic meter
Mg/L	Milligrams per Liter
g/l	Gram per liter
mm	millimeter
N	Nitrogen
NBPE+	National biogas program in Ethiopia
NH ₃	Ammonia
NH ₃ -N	Ammonia nitrogen
NPK	Nitrogen, phosphorous and potassium
O	Oxygen
OLR	Organic loading rate

OM	Organic Matter
UN	United Nations
P	Phosphorus
pH	Power of hydrogen
ppm	Parts Per Million
S	Sulfur
T°	Temperature
TKN	Total kjeldahl nitrogen
TS	Total solid
VFA	Volatile fatty acid
VS	Volatile solid
°C	Degree Celsius
µg/L	Micro gram per liter

CHAPTER ONE: INTRODUCTION

1.1. Background

Due to the industrialization and population growth, the world energy consumption is spontaneously increasing [1]. Non-renewable energy sources fossil fuels, such as coal, natural gas and oil are rapidly depleting, despite their negative impact on human health, global climate change and environmental degradation. The commercial production of biogas and other alternative energy sources such as solar, wind, hydropower, and geothermal promotes the economic development of developing countries [2, 3].

In Ethiopia, there is a shortage of energy particularly in the rural areas. While the availability of traditional fuels such as wood, agricultural residues, and charcoal is declining, commercial fuels are more expensive and their availability is unreliable. Therefore, the energy problem is more prominent in the country. In response, the Ethiopian government is developing a strategy to address these energy trouble issues through a variety of intervention mechanisms, including the use of solar energy, hydropower, wind, biogas, biodiesel and bioethanol.

Biogas is a renewable energy source that can substitute fossil fuels. It can be generated from biomass resources such as agricultural wastes, animal wastes, crops and their residues, household, and industrial wastes [3]. The energy produced from biogas can be used in the form of heat, electricity, etc., and it's desirable to create, zero-carbon emission and sustainable energy system.

Biogas is produced through anaerobic digestion (AD). Which is a bio-chemical process used to generate mainly methane (CH_4) and carbon dioxide (CO_2), it also produces other minor gases and bio-slurry through breakdown of organic compound by micro-organism in the absence of oxygen [4].

National biogas program in Ethiopia (NBPE+) had been introduced since 2009. Two phases are already accomplished and now it's on the third phase. In the first two phases the program constructed a total of 35,626 household size bio-digesters till Jan 2022 in nine regions of the country. Several studies have been conducted on statues of biogas plants in Ethiopia. NBPE+ [2], studied the status of household biogas plants in four regions of Ethiopia and reported that 40% of the plants are fully functional without any significant problem, 20% with minor problems and 27% with major problems. The remaining 13% of plants are not functional. Eshete and Sonder [5] reported that 60% of the biogas plant addressed in the study was not functional. Tadesse Luel [6] reported that from institutional biogas plant constructed in Ethiopia 48.8 % of the biogas plant were not functional, and also Bogale et al [7] reports showed that

out of the non-functional biogas plants 56% stop functioning within less than three years of the construction time.

Various reasons have been given for the failure of the biogas plants, i.e. mismanagement of facilities, either due to lower demand for biogas sector or a lack of ownership and responsibility and other, but up to now detailed study of the properties of the feedstock material, the biogas production process parameters, microbial activity, the quality of methane gas produced and sludge characterization have not yet been carried out.

This study examined the performance of a three household level biogas digesters in Holeta area, taking into account the characterization of raw materials (feedstock) and bio-slurries, investigation of process parameters in the digester that may affect the production biogas such as (temperature, pH., retention time, loading rate. Mixing, C/N ratio, etc..) the microbial activity inhabitants, and gas composition. This study conducted through field tests and experimental analysis. Three plants were chosen based on their efficiency to identify the issue in the operational biogas digester. The first plant chosen has a higher efficiency, the second has a medium efficiency, and the third has a lower efficiency. These decisions were made based on rough field observations, questionnaires given to the digester owner and interviews with various stakeholders and experts from Holeta town and regional biogas program coordinators.

1.2. Problem Statement

Ethiopian government had launched consecutive 5-year biogas programmes since 2009 with the aim of promoting biogas energy for domestic uses, and in order to improve the living standards of farmers, and their families. The program completed NBPE-I and NBPE-II, and now undergoes Biogas Dissemination Scale-up Program (NBPE+) in 9 regions of the country, with the aim of ensuring continuity, scale-up, and expansion of efforts. Under the program 35,626 household biogas digesters constructed until Jan 2022. In this regard, from the total household biogas digester constructed across the country only 30% of the systems are functioning without significant problem, and 22% are functioning with minor problems, and other 27% are functioning with major problems, and 21% of the plants are not functional at all [8]. Bogale et al. [7] study also reported that 56% of non-functioning plants has stopped functioning in less than three years. For the failure, the study mentioned several reasons including, technical problems, dung and water shortage, problem with appliances, abandonment, lack of interest, and others, but the operational parameters of bio-digester and microbial activity has not been revealed yet.

The performance of a biogas plant is mainly dependent on the input feedstock characteristics, the microbial activity (condition inside the reactor), and process conditions and parameters including pH., temperature, and etc. This paper aims to evaluate the performances of anaerobic digester in order to determine the reason for the failure of the biogas digesters taking into account the, substrate and bio-slurry characterization, effects of parameters, and inhabitants in AD, of three household level biogas digesters. The first plant having higher efficiency, the second have medium efficiency, where-as the third one is approached to failure. The performance also evaluated through COD removal efficiency, TS, and VS removal efficiency and throughout the comparison of estimated theoretical methane production potential, with the actual.

1.3. Objectives

1.3.1. General objective

The general objective of this thesis is to investigate, and evaluate the operational performance of three biogas digesters located in Holeta, Waste of Addis Ababa, Ethiopia.

1.3.2. Specific objective

- ✓ To characterize the composition of feedstocks.
- ✓ To evaluate operational parameters of the household biogas digester.
- ✓ To determine the biogas composition and methane yield.
- ✓ To characterize the bio-slurry.

1.4. Significance of the study

Energy plays a vital role in the economic development of the country, and in improving living standards, biogas dissemination program had been implemented since 2009 by Ethiopian government, but the functionality rate was lower. This study tried to determine the reasons for non-functionality of household level biogas digesters through determining the causes for the drop performance of biogas digesters and appliances, through identifying the characteristics of cattle dung, and classifying the major process inhabitants in the system, and user side problems.

1.5. Scope of the study

The study primarily focuses on the performance analysis of three household-scale biogas digesters, with an emphasis on the characterization of the raw feedstock, and the bio-slurry, as well as the process parameters and microbial inhabitants, estimation of theoretical methane potential, and compared it with the actual of methane production, and the biogas analysis.

1.6. Organization of the study

This study encompassed five major chapters, the first chapter includes background of the study, problem statements, and objectives, significance and scope of the study. The second chapter incorporate the literature review. The third chapter covers the scientific methods and materials. The fourth chapter consist the result and discussion, and the last chapter deals about the conclusion, and recommendation.

CHAPTER TWO: LITERATURE REVIEW

2.1. Introduction

Energy is an important requirement for human life. It affects all aspects of human well-being, including food preparation, agricultural productivity, water access, healthcare, education, job creation, climate change, and environmental sustainability [9].

Ethiopia has convincing reasons to promote biogas technologies, because of its high number of livestock's, high requirement of fertilizer, and consumption of traditional biomass energy resources [10]. With approximately 35.4 million cattle exist as a result, 10.6-14.2 million m³ of biogas can be produced and utilized for cooking and lighting. In addition, about 78,000 m³ of liquid fertilizer can be generated during the production of the biogas energy [11]. Despite these, resources most of Ethiopian community still suffers from a lack of clean energy, and they are exposed to several health problems due to pollution.

2.2. Biogas production

Biogas is an eco-friendly energy which is produced from mono-digestion and co-digestion of organic matters. It can be used as electricity, heat, and vehicle fuel, moreover the bio-slurry used for fertilizer and soil conditioner. Biogas produced from biomass includes livestock manure, food waste, industrial waste, energy crops, and agricultural residue, sewage sludge, through anaerobic biological breakdown of organic matter (OM) in the absence of oxygen [12, 13].

Biogas is a composition of mainly methane (CH₄), carbon dioxide (CO₂) and small amount of carbon monoxide, hydrogen, ammonia, hydrogen sulfide, and oxygen etc. The production of biogas follows four process steps which are: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

Biogas is produced through anaerobic digestion (AD). Anaerobic digestion is a biochemical process in which different kinds of microbes break down organic materials into a gaseous mixture that primarily contains methane and carbon dioxide in an environment free from oxygen [14]. Due to two primary factors, the production of biogas might be encouraged. The first is related to the emission of greenhouse gases (methane and carbon dioxide) released to the environment and the release of pathogens into water bodies through the introduction of manures in the landfill. The second is that the generated biogas becomes a source of renewable energy [15].

2.3. Bio-slurry

According to SNV/Ethiopia (2005), bio-slurry is an organic material that has been anaerobically digested, and expelled as a waste product from the biogas plant after producing combustible methane gas. Bio-slurry is composed of 93% water, and 7% dry matter, essential elements for the healthy growth of crops present in the dry matter which are, Nitrogen (N), phosphorus (P), and potassium (K) [14, 15].

Furthermore, trace elements i.e., zinc, iron, manganese, and copper may exist in the bio-slurries. As a result of the fermentation process, these nutrients are kept in the bio-slurry, which may then be used as complete liquid fertilizer.

If the substrate fully digested, the co-product (bio-slurry) may not have smell, nearly free of pathogens, and don't draw flies. Termites and other pests that are typically drawn to raw fertilizers are repelled by it. The biogas digester's procedure can be used to destroy plant-disease-causing organisms in vegetable and fruit crops. Bio-slurry is the best soil conditioner, and organic fertilizer. It improves the soil's water holding capacity while adding humus [16].

2.4. The Four Stages of Anaerobic Digestion

2.4.1. Hydrolysis

Hydrolysis is the first stage in AD, it occurs as extracellular enzymes produced by hydrolytic microorganisms for example (cellulose, amylase, protease, and lipase) decompose complex organic polymers into simple, soluble monomers. Proteins are reduced into amino acids, lipids into long-and short-chain fatty acids, starch into glucose, and carbohydrate into sugars.

Here higher organic polymers are reduced into monomers like sugar, amino acids, and fats. However, if acetate and hydrogen exist could be used directly by methanogens [18]. Hydrolysis process involves the most complex series of syntrophic reaction, and the largest molecule sizes this makes it to be considered as rate limiting step [19].

2.4.2. Acidogenesis

The remaining components of the hydrolysis steps then degraded by fermentative bacteria. Such a process results in the generations of volatile fatty acids (VFA), hydrogen (H), hydrogen sulfide (H₂S),

ammonia (NH₃), carbon dioxide (CO₂), and other by-products [18]. Acidogenesis is the fastest step in anaerobic conversion compared to other stages.

2.4.3. Acetogenesis

The products of acidogenesis are then converted to acetate, CO₂, and hydrogen. This process preferably take place at low concentrations of hydrogen gas. Therefore, acetogenic bacteria live in symbiosis with methanogenic bacteria, which consume hydrogen, and converted to methane [18].

2.4.4. Methanogenesis

Methanogenesis is the critical step in the AD process, the acetate and other products from the previous three stages are converted into biogas. It looks like the speed limitation step. Methanogenesis is sensitive to temperature, and pH levels, it generally occurs at pH level ranging between 6.5 - 8. At the completion this step, an indigestible material called a digestate is created [18].

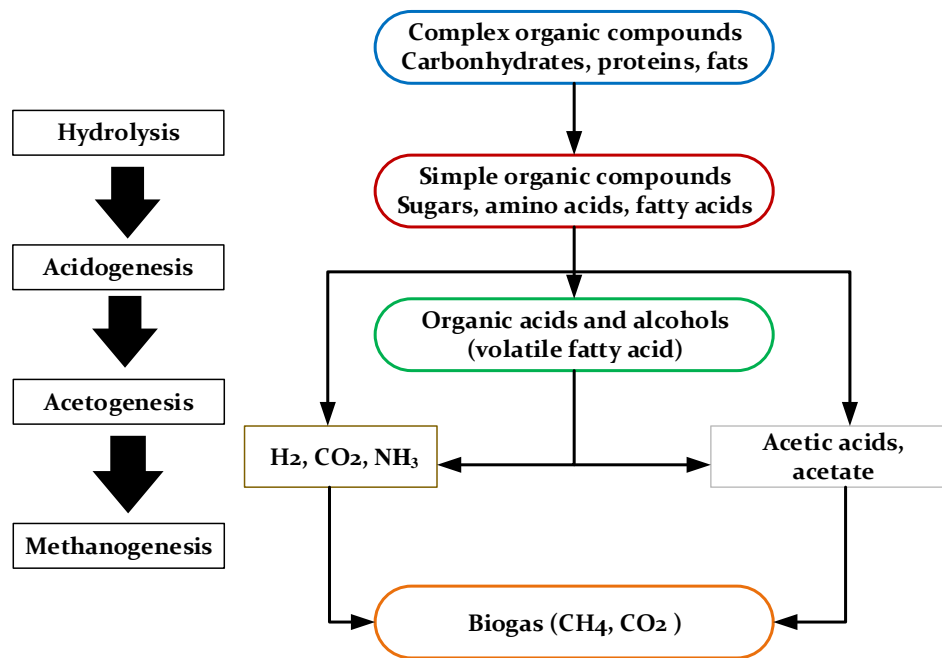


Figure 1. The simplified scheme of pathways in anaerobic digestion [20]

2.5. Parameter affecting anaerobic digestion

There are several factors that affect the production of biogas which includes temperature, pH, retention time, loading rate, mixing/agitation, carbon nitrogen ratio (C/N ratio), moisture content, chemical oxygen demand (COD), organic loading rate (OLR).

2.5.1. Temperature

Temperature impacts the structure, composition, and activity of anaerobic bacteria, as well as the metabolic degradation processes of organic molecules, because they are temperature sensitive [21]. When the temperature rises, the rate of growth of microorganisms accelerates, resulting in more methane generation per unit volume of the digester.

Temperature classification for anaerobic digestion fall in three regime which is psychrophilic, mesophilic, and thermophilic. Psychrophilic temperature ranges $<10^{\circ}\text{C}$, mesophilic ranges within $20\text{--}45^{\circ}\text{C}$, and the optimum temperature for this range is 35°C and thermophilic is greater than 50°C . At psychrophilic regime the biogas production yield lower due to the lower activity of the microorganism in this temperature regime. Nevertheless the thermophilic gives a higher yield, but it costs higher than the others, hence mesophilic regime is the common, and optimum temperature condition for most of the anaerobic digestion plants [12, 20].

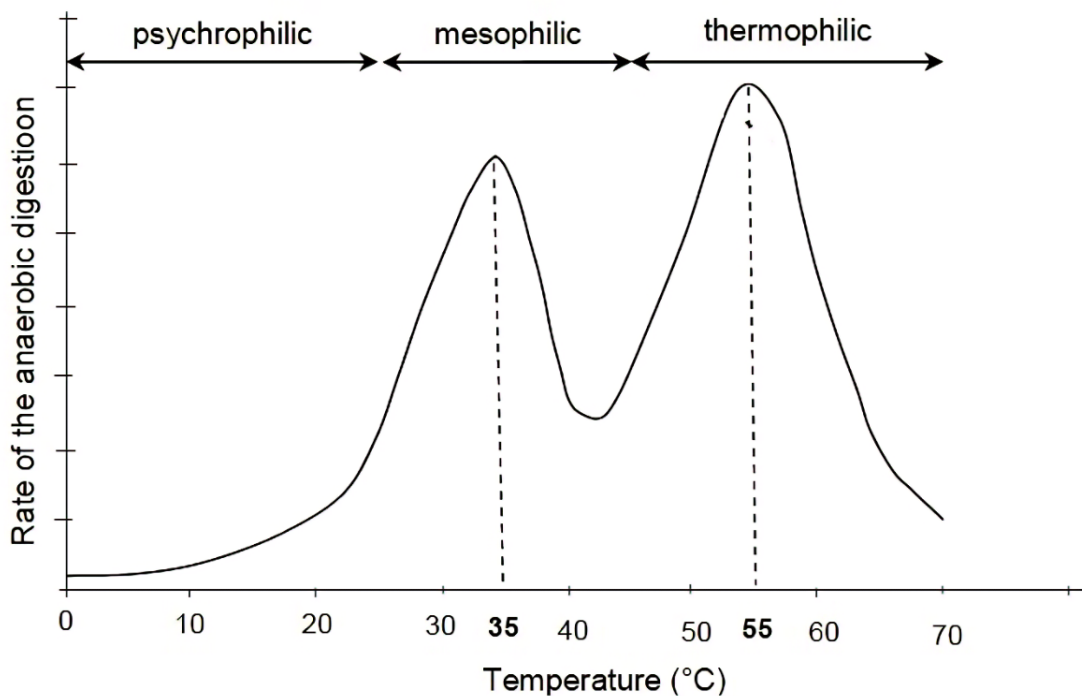


Figure 2. Influence of temperature in anaerobic digestion [23]

According to Mitchell and Gu, [24], the efficiency of AD decreases dramatically at psychrophilic temperatures, due to poor anaerobic consortium bacteria growth rates, and exposure to temperature fluctuations caused by seasonal variations. Temperature sensitivity is also increased during the

acetogenesis, and methanogenesis stages. As a result, obtaining a steady volume of gas from the system is difficult at this temperature regime.

2.5.2. PH

The other important parameter in AD is pH, which has the capability to control the stability and performance of AD. The bacteria involved in biogas production consist of hydrolytic bacteria, fermentative bacteria, and methane producing archaea. These anaerobic bacteria's are sensitive to pH and require different pH range for better growth [25].

In anaerobic digestion process higher yield is obtained between 6 – 7 pH levels. Due to the nature of microbes, they can't grow at a high acidity condition, and may result with less biogas yield. To maintain the pH, the alkalinity level should be available at about 3000 mg/L to do this internal or external alkalinity may be required to be supplemented and kept [26]. Onaji et al, [27] studied the effect of pH on the production of biogas from cow dung, they conducted at pH levels of 5, 7, and 9, and found that the maximum methane yield was obtained at pH 7.

Different studies have been conducted to determine the optimum pH value for anaerobic bacteria some of them are listed in the Table 1 below.

Table 1. Optimum pH concentration in AD

No	Methanogenic bacteria	Optimal range	Reference
1	5.5–8.5	6.5–8.0	[28]
2	4.0–8.5	5.0–6.0	[29]
3	-	7	[27]
4	-	5-6	[30]
5	4	5.5- 6.5	[31]
6	6.6-8.2	-	[32]

2.5.3. Retention time

Retention time is the average interval of time which biodegradable substrate kept in the digester. Retention time varies depending on temperature, for example at mesophilic temperature the retention time may ranges between 15–40 days, and at thermophilic temperature the retention period varies within 12–14 days [33].

2.5.4. Organic loading rate

Loading rate is a quantity substrate fed in to the reactor volume at a given time [34]. It is a crucial parameter that influences the production of biogas during anaerobic digestion, especially when the digestion is carried out in continuous flow mode.

OLR is a measure of how well the anaerobic digestive system can convert biological substances. OLR is expressed as the total amount of raw material added in to the digestion tank (kg of volatile solids per unit volume per day, kg VS/m³.d) [35]. In anaerobic digestion the methane yield decreases as the substrate fed increases because the bacteria is unable to decompose [33]. Overloading easily affects the anaerobic digestion process due to accumulation of acids. According to Khoiyangbam et al. [35] the optimum loading rate varies between 0.5 kg - 2 kg VS/m³.d, which can be chosen based on the process temperature type of raw material feed to the reactor, retention time etc.

2.5.5. Mixing/agitation

Mixing is the process of blending fresh feedstock material with digestate to lag microbes with fresh material. It helps to kept uniform substrate concentration, uniform temperature, and avoid occurrence of scum [31, 32]. Additionally, it stops solids from building up at the digester's bottom. Both mechanical stirrers, and centrifugal pumps can be used for direct mixing, and recirculating the digester slurry in the system [36].

2.5.6. C/N ratio

The carbon to nitrogen ratio (C/N) represents the ratio between the carbon, and nitrogen content in the organic substrate. In the last two to three decades, several studies have been conducted to determine the effect of influent carbon nitrogen ratio in anaerobic digestion. According to early study [35–38] the C/N is regarded as a useful and relevant measure for evaluating the AD process efficiency.

The most ideal C/N ratio for AD processes is between 20–30, while too high or too low C/N ratios are likely to create acidification or ammonia inhibition in the digester, resulting in biogas generation failure [41]. As carbon creates energy for microorganisms, excess nitrogen causes ammonia to form. When the C/N ratio is higher, the nitrogen (N) used by methane-producing bacteria will be rapidly consumed to meet their needs of protein, causing a decrease in biogas production. When the ratio of C/N is low the pH value is above 8.5, it will promote the toxic environment where methanogenic bacteria exist. To

operate the anaerobic digester with the best C/N ratio, biodegradable materials with a high C/N ratio must be mixed with biodegradable materials with a low C: N ratio [33].

Furthermore, the C/N can be utilized to design the anaerobic co-digestion with substrates having different C, and N contents [40, 41]. Wang et al. [37] studied the effect of C/N on biogas production through co-digesting of swine manure, dairy manure, and wheat straw. They discovered that the most stable carbon to nitrogen ratio for anaerobic co-digestion is between 25, and 30, and at C/N of 27 biogas generation becomes the highest. Haider et al. [44] also studied effects of mixing on rice husk, and food waste, and found that the maximum biogas creation can be achieved when the C/N of the combination liquor becomes 20.

2.5.7. Moisture content

Water is very important for optimal digestion because it helps the digestion process to produce high-quality methane. The literature recommends that the moisture content in optimal conditions be 90%. However, digestion process to fail if there is extremely excess moisture content [45].

Fujishima et al [46] studied effect of MC in anaerobic digestion with different moisture content level under mesophilic condition and, they found out that, VS removal efficiency dropped from 45.6% - 33.8% when moisture content decreases from 97% to 89%, and also the removal efficiency of carbohydrate decreased from 71% to 27.8%. Generally, their study proved that the lowering the moisture content affects glucose consuming acidogenic bacteria's negatively, and causes reduction in methane production were observed.

2.5.8. Total solid

Total solid (TS) describes dry matters of a substrate and it is expressed as the percentage of the total weight solid materials in the substrate after water has been removed from the feedstock sample. Several studies have been conducted to determine the optimum amount of TS content to get maximum methane content in anaerobic digestion. As reported by Wang et al [47], Tsunatu et al [48], and Kelly Orhorhoro [49] the optimum biogas production obtained at 9.2%, 9% and 10.16% respectively and Sajeena et al [50] also reported that the optimum biogas yield obtained on their study was at 10% of total solid. Tsunatu et al [48] concluded that the water volume decreases as the concentration of total solid increases this reduces the activity of microbial communities in anaerobic digestion consequently drops the biogas yield.

Masinde et al [51] also study the effect of total solid on a biogas production from cow dung at 35 °C, they found that maximum methane produced observed at 8% of TS concentration, below, and above this value the methane production is lower.

2.5.9. Volatile solid

The organic fraction of TS is defined as volatile solid (VS) concentration, which is generally measured as a percentage of TS in grams per kilogram. Volatile solid concentration used to assess AD system efficiency. The volatile solid is the solid remaining after ignited at 550°C. Kelly Orhororo, [49] studied the effects of Total Solid (TS) and Volatile Solid (VS) on biogas yield and found that the quantity of biogas yield from these substrates increase with increasing percentage volatile solid and an optimum total solid observed on the study were 10.6%.

2.5.10. Biochemical Oxygen Demand

Biochemical Oxygen Demand (BOD) is 5 days experiment that is used to determine the amount of dissolved oxygen (DO) consumed by bacteria or other organisms, when they degraded organic substrates in anaerobic conditions at optimum temperature. (BOD) provides measurements of biodegradable organic matter present in sludge and can be used as a measure of the overall effectiveness of anaerobic fermenter. BOD reflects the value of microbial metabolism of dissolved oxygen in a particular sludge sample over a 5-day period [52].

2.5.11. Chemical Oxygen Demand

Chemical Oxygen Demand (COD) is a measure of the oxygen present in the substrate that can be consumed in the reaction with oxidizing agent [52]. It indirectly measures the amount of organic matter in a sample, and represents the theoretical maximum methane produced from a substrate. This test can measure virtually any organic compound that can be digested with digestive reagents [53].

Since COD measures all organic matter in sludge, its value is naturally higher than the BOD value. Therefore, the ratio of BOD to COD can be used to represent the biodegradable fraction of sludge [54].

2.6. Process Inhibitors

2.6.1. Ammonia nitrogen

Ammonia is produced from the nitrogenous substances in the raw material (feedstock), from the breakdown of proteins, and urea in manure. Total ammonia nitrogen (TAN) is the sum of ammonium

nitrogen ($\text{NH}_4^+\text{-N}$), and free ammonia nitrogen (FAN, $\text{NH}_3\text{-N}$), as the concentration of the nitrogen increases in the reactor, it affects the process stability negatively, and causes ammonia formation [55]. The majority of the ammonia is produced during the hydrolysis stage, and the type of nitrogen products created influenced by factors such as pH, temperature, inoculum, or microbial communities [56]. Free ammonia is a strong candidate for the inhibition of methanogens.

There are several factors that control ammonia inhibition Chen et al [57], reported on their study that temperature has a direct impact on a growth rate of microbes, and the concentration of free ammonia. The metabolic rate of microorganisms was positively affected by increasing the process temperature, which leads to high ammonia concentrations.

2.6.2. Volatile fatty acid

VFA concentration is the most sensitive parameter that needs to be monitored during anaerobic digestion, it may lead to system failure. VFA is mainly composed of acetic acid, butyric acid, propionic acid, caproic acid, valeric acid, and enanthic acid, with acetic acid being the most predominant [58]. Labatut & Gooch, [58], stated that properly designed, and operated anaerobic digester could have VFA concentration of less than 500 mg/L, but a concentration above 1,500-2,000 mg / L cause biogas production inhibition. Monitoring VFA regularly is important for better biogas production and to avoid system failure.

Selection of the appropriate reactor type, pH, operating temperature, hydrogen partial pressure, organic load factor, and chemical additives are considered to be the accelerator of conversion of VFA into methane [59].

2.6.3. Hydrogen sulfide

Removal of hydrogen sulfide is very important for the long-term operation of anaerobic digestion. Hydrogen sulfide (H_2S) is a major cause of corrosion in fermenters and is basically formed as a by-product of anaerobic digestion. The H_2S content in biogas ranges from 0.1% to 2% [60]. High hydrogen sulfide concentrations affect fermentation and reduce the quality of biogas production. These odorous gases are also harmful to the human body through direct irritation and psychopathological mechanisms [61].

In anaerobic digestion, sulfate is reduced to sulfide, and usually, it is the product of sulfate-reducing bacteria [58, 63]. The formation of sulfide in AD causes inhibition of methane-producing bacteria

(MPB), it causes fluctuations in pH level and reduces methane formation through efficiency reduction of the methanogenesis process [60].

2.6.4. Light and Heavy Metals

Light and heavy metals can be present in significant concentrations during anaerobic digestion, it may release through breakdown of organic material. Light metals include sodium, potassium, calcium, and magnesium. Heavy metals such as chromium, iron, cobalt, copper, zinc, cadmium, and nickel may be created. The presence of this metal in high concentrations causes toxicity to the system [57]. This reduces the performance of anaerobic digestion.

Metals are required for the growth of microorganisms in AD, thereby affecting specific bacterial growth. Medium concentrations of light metal stimulate microbial growth, but excessive and high concentrations can cause serious inhibition or toxicity and slow down microbial growth [63].

Table 2. The inhibitory and beneficial concentration of metals in AD

Metals	Unit	Stimulating concentration	Inhibitory level
K	mg/l	200-400	2500-4500
Ca	mg/l	100-200	2500-4500
Mg	mg/l	75-150	1000-1500
Na	mg/l	100-200	3500–5500
Al	mg/l		1000

Source; data compiled by author sourced from [55, 62, 63]

Summary of Inhabitants in AD

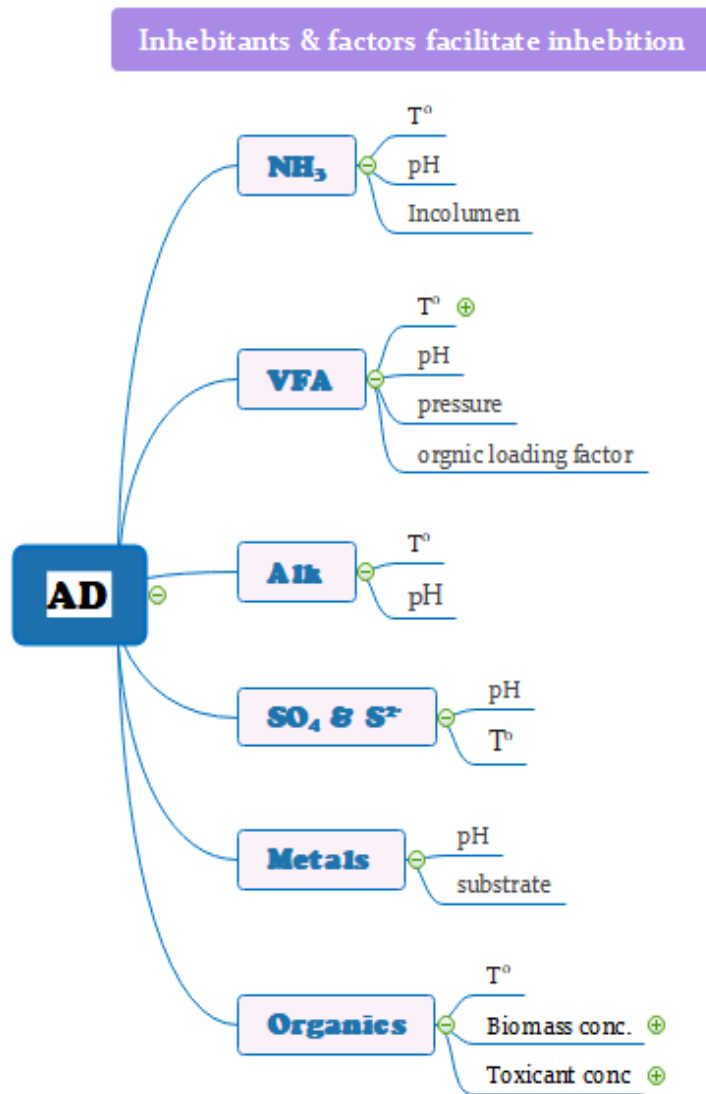


Figure 3. Inhabitants and factors facilitating inhibition

Compiled by: author sourced from literatures.

2.7. Purification of biogas

Purification of biogas performed to remove harmful trace components, and enrich the biogas methane content. Biogas purification is the operation of reducing unwanted biogas components before they are used in the combustion process. No matter what the final way of using biogas is, it is not preferable to use it in its original form. To use biogas through cogeneration, the substances that must be removed are: water, organic halogens, carbon dioxide, and hydrogen sulfide.

2.8. Types of Digesters

2.8.1. Fixed Dome Digester

Fixed dome digester is mainly composed of a dome-shaped closed digester, rigid gas holder, an inlet for feedstock, and a displacement pit to remove digestate. Mostly this reactor is constructed underground to maintain the temperature at night time and cold season. In a fixed dome digester, the gas produced and stored in the upper part of the digester (dome). As the gas outlet valve closed the pressure inside the reactor elevates and pushes the digestate out of the reactor [64].

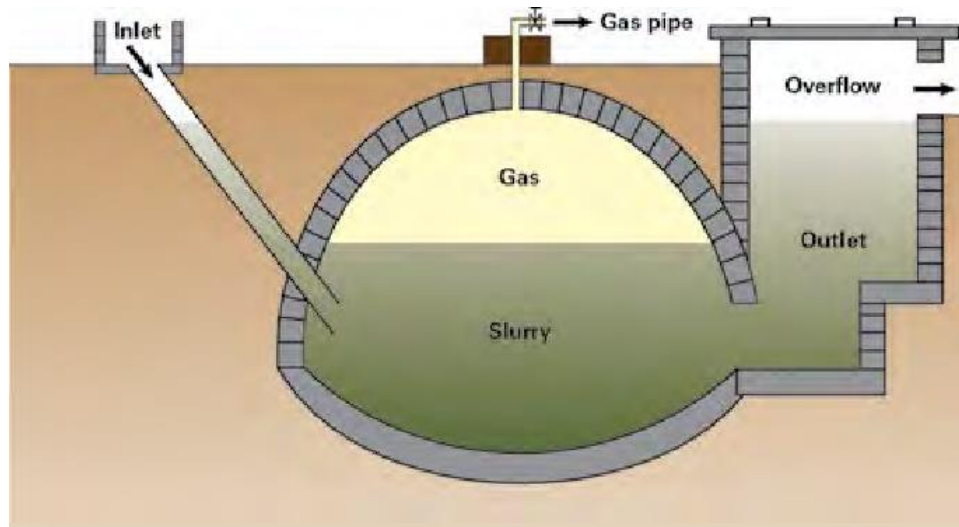


Figure 4. The schematic diagram of fixed dome anaerobic digester, [34]

2.8.2. Floating Drum Digester

The floating-drum biogas digester is mainly composed of a cylindrically shaped digester and floating gasholder (drum). This type of digester constructed underground whereas the gasholder lay above the ground surface. The gas drum used to collect the produced gas, and it shows the level of gas produced in the digester, through rise and fall the drum.

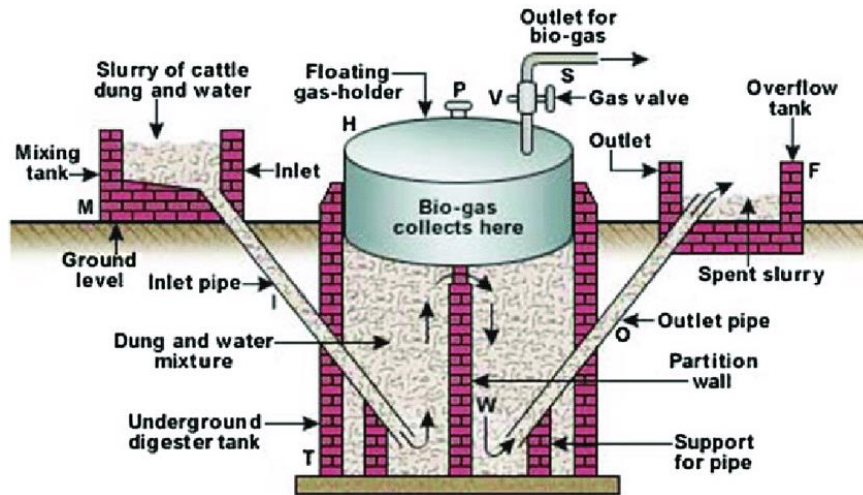


Figure 5. The schematic diagram of floating drum anaerobic digester, [65]

2.8.3. Tubular/Balloon Digester

A tubular biogas plant is made of weather-resistant plastic or rubber bag. It is used as both a digester and gas holder. The upper part of the balloon utilized for storing gas, and the inlet and outlet of part of the digester are directly attached to the balloon.

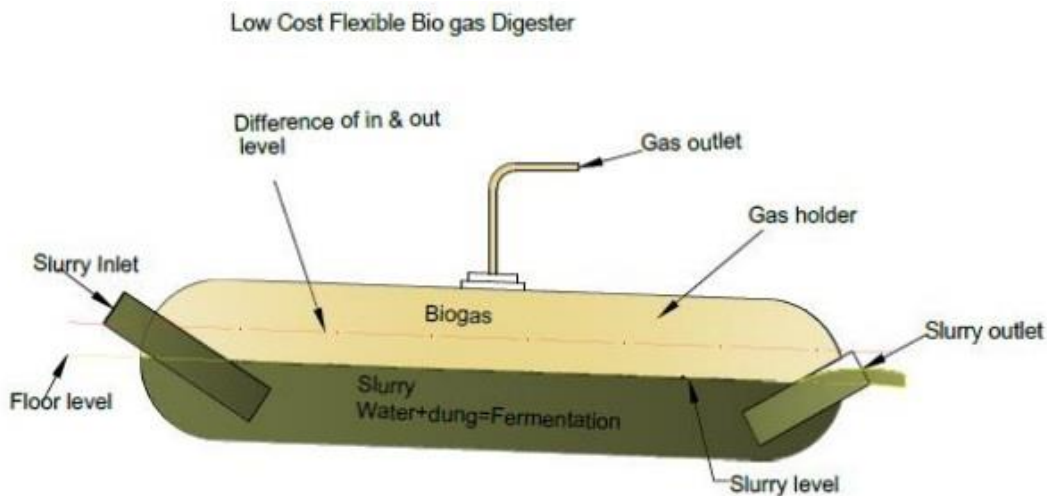


Figure 6. The schematic diagram of balloon type anaerobic digester, [66]

2.8.4. Plug Flow Digester

Plug flow digester is a continuous type digester and classified as a low-rate system and no need to have substrate longitudinal mixing from the inlet to outlet and the substrate flows as a plug. As a new substrate flowing in to the digester an equal amount of digested flows out. This substrate is thick enough to prevent the particles from settling to the bottom, and there is little mixing, so the substrate travels through the

digester as a plug. This digester type has a constant capacity but produces biogas at variable pressure. This digester cannot perform as a dry digestion due to its low fluidity [65, 66].

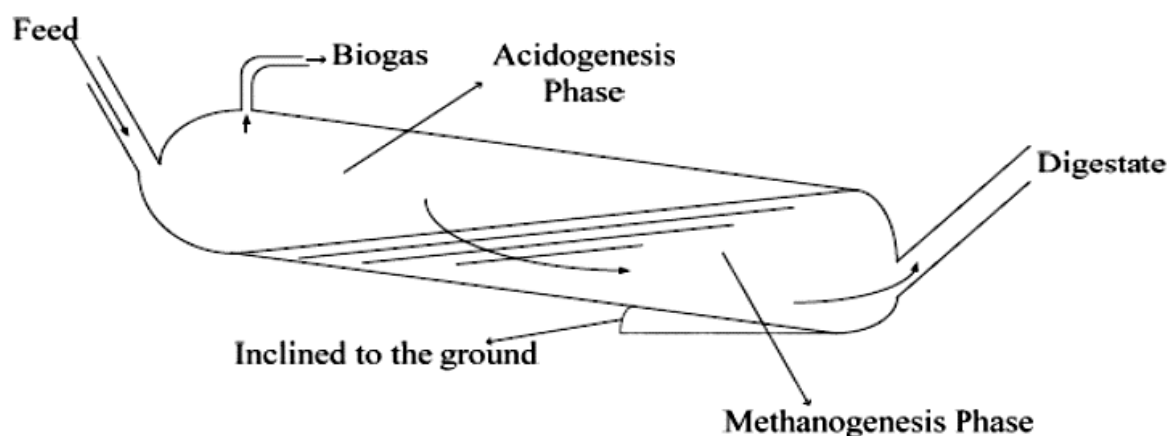


Figure 7. Schematic diagram of plug flow anaerobic digester [69]

2.9. Performance of AD

The performance of anaerobic digestion evaluated based on the volume of gas produced, the volatile solid removal efficiency and chemical oxygen demand (COD) removal efficiency. According to the Ethiopia 2015 bio-digester model construction manual the SINDU 2008 bio-digester model have been modified to have the following characteristics.

Table 3. Construction, and user manual for SINDU 2008 bio-digester model [70].

Volume	Max average daily feeding* (Dung + Water)	Max daily gas prod. [ltr]	Digester volume [ltr]	V _{effec. gas} storage [ltr]	V Buffer [ltr]	Total bio-digester volume [ltr]
4 m ³	30 + 30	1050	2360	685	485	3530
6 m ³	50 + 50	1750	3740	900	600	5240
8 m ³	70 + 70	2450	5300	1350	850	7500
10 m ³	100 + 100	3500	7270	1935	1165	10370

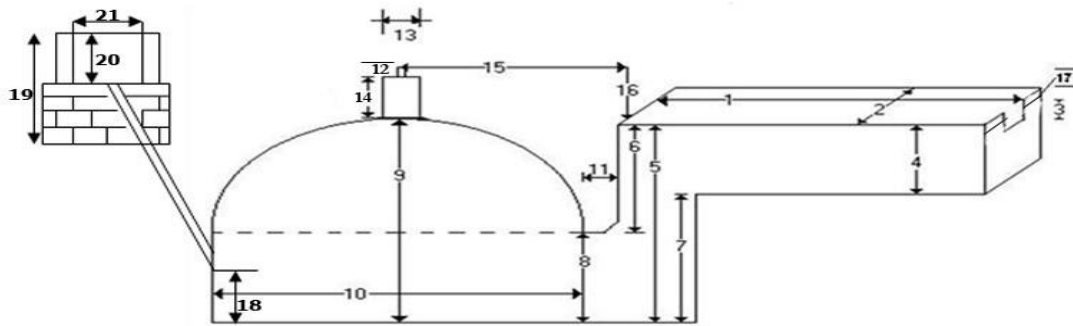


Figure 8. SINDU model biogas plant drawing [70].

2.10. Research Approach to Enhance Performance of AD

Anaerobic digestion is a well-known recognized process of organic waste reduction and bio-energy recovery (CH_4) [71]. Anaerobic digestion can be seen as a useful tool for producing renewable energy. The theory of anaerobic digestion has been established for decades. However, anaerobic digestion still faces several challenges that prevent it from reaching its full potential, such as low biogas production efficiency, long digestion period, limited volumetric efficiency, high capital cost [72], high concentration of hydrogen sulfide production, and slow volatile solid destruction [73]. Additionally, the microbial composition affected by several factors including operational parameters (pH, temperature...), volatile fatty acids (VFAs), ammonia, concentration, and salinity.

There are several techniques recommended for enhancing anaerobic digestion which includes pre-treatment, usage of additives, operational parameter control.

2.10.1. Pre-treatment

A general tendency towards pretreatment is to improve the biodegradability of substrate materials, for particle size reduction and solubilisation, but some pre-treatment techniques can adversely affect processes, including the formation of recalcitrant compounds, and the mineralization of organic matter [74]. According to the Carlsson et al [74], report the primary effects of pre-treatments on various substrates are stated as (i) particle size reduction, (ii) biodegradability augmentation, (iii) solubilisation, (iv) loss of organic material, and (v) production of refractory compounds

The efficiency of anaerobic digestion can be improved through substrate pre-treatment. Pre-treatment can be classified as mechanical (reduction of the particle size) it helps to increase the specific surface

area of the reactor, and it makes it easier for bacteria to break down the substrate, and prevent clogging of the digester. Thermal (heating feedstock at 220 °C for a given pressure) helps to remove pathogens, and helps to improve dewatering performance, and reduce viscosity of the digestate. The other is biochemical pre-treatment which can remove the biodegradable material by using alkalis, strong acids in a digestion process, and helps to adjust pH [37]. Review made by Orlando & Borja,[75] stated that a biological, physical and chemical pretreatment of lignocellulos animal manure improves the anaerobic digestion, and increase methane yield by 74, 30, and 41% respectively.

2.10.2. Applying additives

Substances used to improve biogas output are referred to as additives. Several researches have been conducted in order to improve the performance of anaerobic digestion process. The additives used includes chemical additives such as enzymes, and inorganic salts, biological additives including (microbial culture, crop residue, etc.) which are available in the natural surroundings. Additionally, Gunaseelan [76] claimed that the use of additives in biogas plants could considerably increase the performance of the system.

2.10.3. Operational parameter control

In order to obtain better anaerobic digestion process, the action of bacteria must be converted biodegradable organic matter into intermediate compounds used by methanogenic bacteria. Reaction medium conditions should be suitable for each bacterial population to allow simultaneous growth of all involved bacteria. It is necessary to maintain the optimum state of the reaction medium, to maintain the slow growth and reaction rate of anaerobic bacteria, [77].

2.10.4. Co-digestion

Co-digestion is a way to increase methane production and minimize HRT. Co-digestion of raw materials, biomass residues can produce more methane than manure, but the challenge in this process is to achieve complete decomposition of organic matter during hydrolysis [12].

Several studies were conducted on anaerobic co-digestion. Matheri et al [12] pointed out that co-digestion can give better amount of biogas as compared to mono-digestion, and it helps to control process parameters such as carbon-nitrogen ratio, and temperature. El-Mashad, and Zhang [78] also proved that ammonia inhibition reduced, and buffer capacity can improved by applying co-digestion of two or more substrates. After Jorgense [79] investigation of corn stover and chicken manure the methane

yield from co-digestion was 90%, whereas from mono digestion methane obtained was only 55.4% and 64.8% for corn stover and chicken manure.

2.11. Research Gap and Summary of Literature Review

Anaerobic digestion is the process where organic matter is broken down by a group of microorganisms without the use of oxygen, resulting in digestate (bio-slurry) and biogas that mostly contains methane (CH₄), and carbon dioxide (CO₂). Organic matter breakdown involves a number of sequential and concurrent reactions, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The majority of anaerobic digestion regulation is carried out directly by the microbes; however, operating factors including pH, temperature, hydraulic retention time, vital trace nutrients, and toxicants (VFA, NH₄, ALK, sulfide and sulfate) can significantly alter the reaction rates of specific sub-processes. The characteristics of the feedstock have a significant impact on the stability of the anaerobic digestion process and the production of biogas. Substrate characterization including proximate ultimate analysis, identifying the concentration of light and heavy metals, BOD and COD are important in order to have an efficient anaerobic digestion. Toxicants should also be studied for a better AD. The optimal concentration of parameters which affect the anaerobic digestion and their effect had been given in the above section.

Leul [6], Gebretsadik [80], Leta [81], and Eshete & Sonder [5] studied the status of biogas in Ethiopia in various years from a theoretical perspective, and mentioned various causes for the anaerobic digesters' failure, including user side management issues, and construction issues, but no one had been studied the technical issues from the existing biogas digesters in Western Addis Ababa, Holeta. This study focuses on identifying the issues that cause the anaerobic digesters to experience difficulties from the technical aspects, and offers scientific recommendations to deal with the issues. The detailed technical issues, in the field, and laboratory scale study, the parameters, and the inhabitants of the anaerobic digestion are all taken into consideration.

Research gaps and study coverage

To the best of our knowledge previous studies mentioned the following reasons for non-functionality of anaerobic digesters in Ethiopia, this study addresses the points which is not covered in the studies.

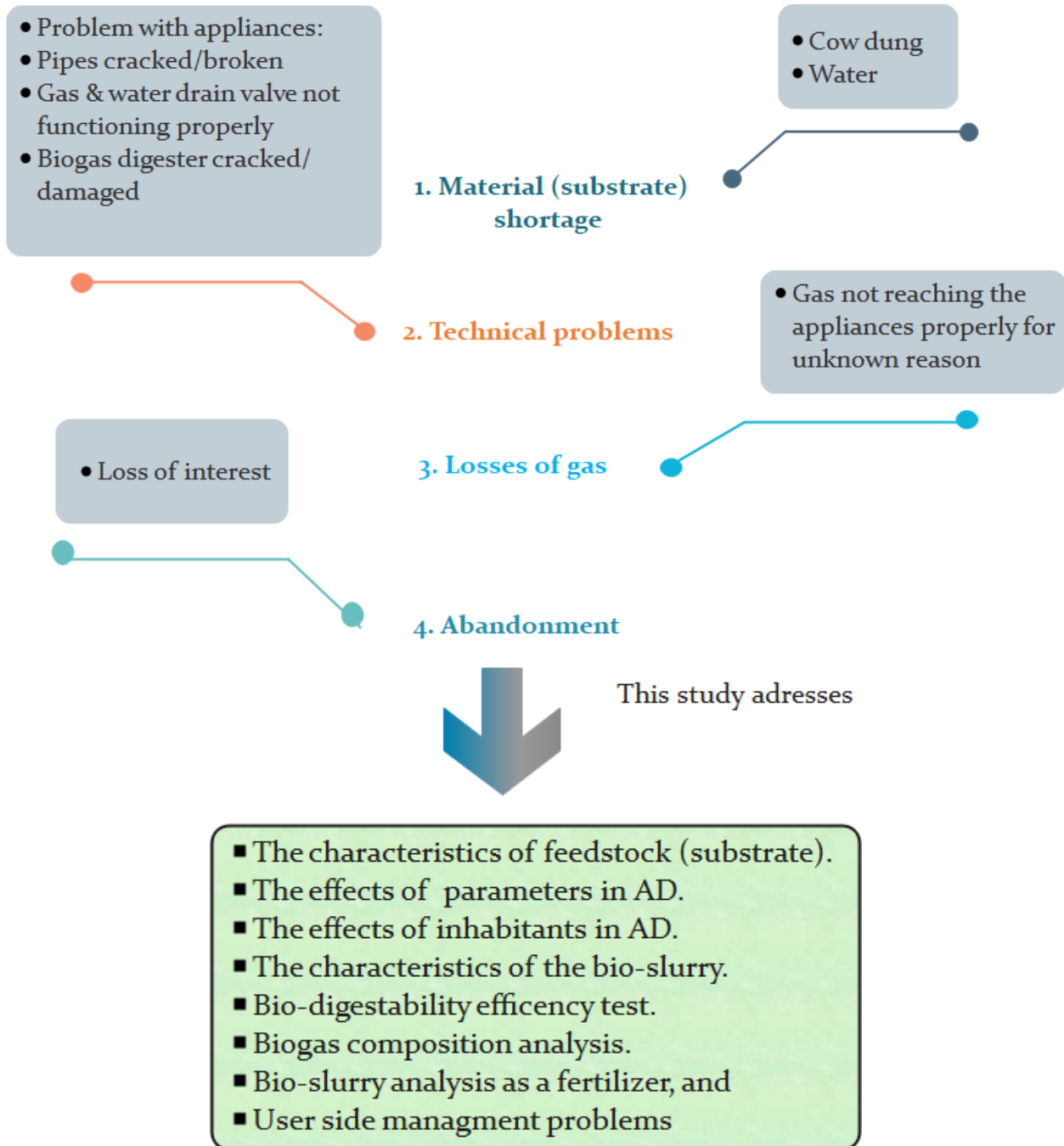


Figure 9. Research gap, and the study coverage

CHAPTER THREE: MATERIAL AND METHOD

The research area, the sampling method, the experimental design, and the data processing method were addressed in this section.

3.1. Description about the Study Area

This research was carried out at Holeta town and its surrounding in central parts of Ethiopia. It is located in the Oromia special zone surrounding Addis Ababa, with a latitude of $9^{\circ} 4' 0''$ N and a longitude of $38^{\circ} 30' 0''$ with an elevation of 2391 meters above sea level.

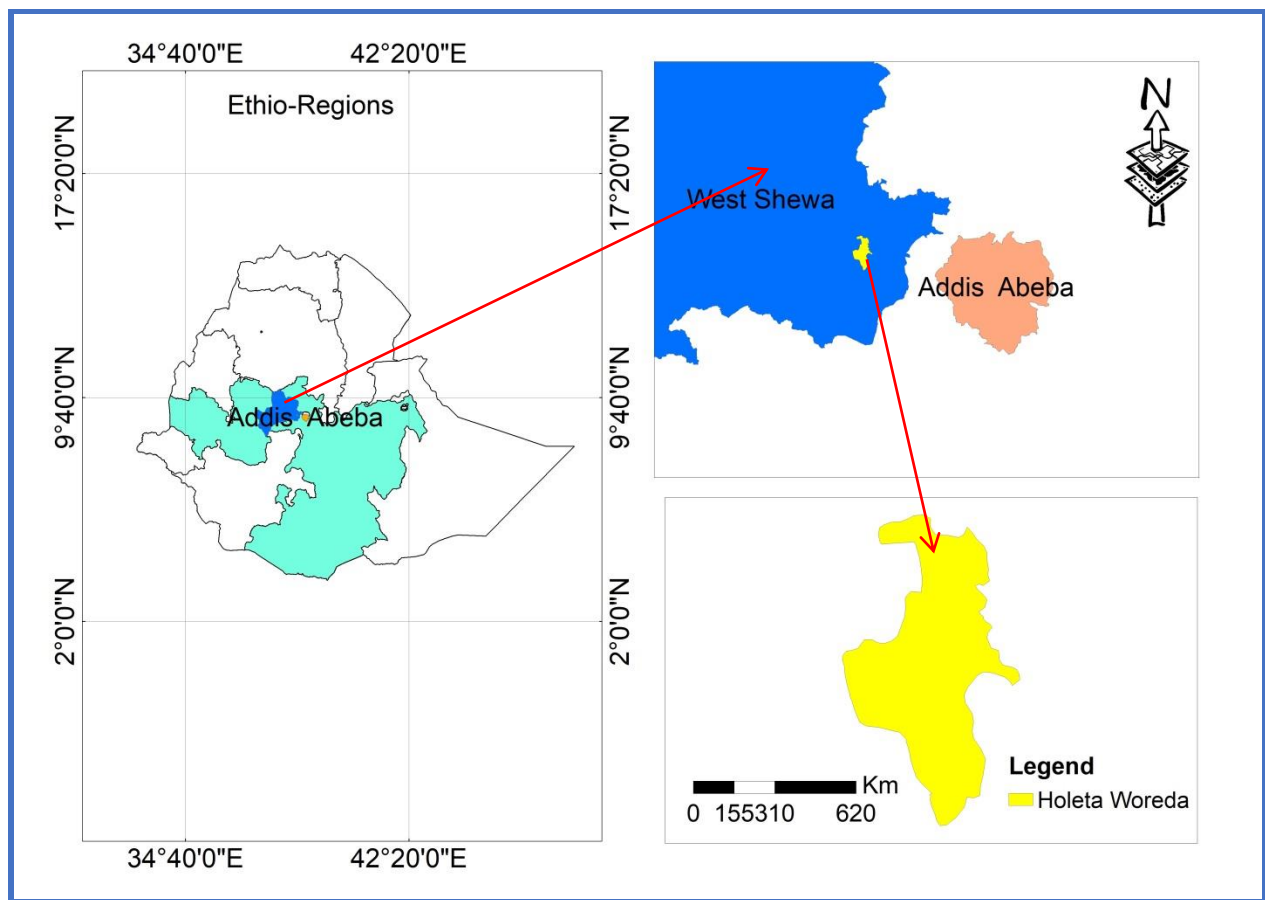


Figure 10. Geographical map of the study area

Weather condition

The table 4 below shows the maximum, minimum, and average temperatures, the precipitation / rainfall mm (in), humidity, rainy days from 1991-2021. According to the recorded data, Holeta's climate is classified as warm and temperate. The summers here have a good deal of rainfall, while the winters have

very little. The temperatures are highest on average in April, at around 16.0 °C | 60.9 °F. August is the coldest month, with temperatures averaging 13.6 °C | 56.5 °F. (Climate data.org)

Table 4. Weather condition of Holeta from (1991 – 2021)

		Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Avg. Temperature	°C	14.2	15.5	16	16	15.8	14.5	13.6	13.6	13.7	13.9	13.9	13.6
	°F	57.6	59.8	60.9	60.9	60.5	58	56.5	56.5	56.7	57	57.1	56.5
Min. Temperature	°C	7.9	8.9	10.1	10.8	10.8	10.2	10.2	10.1	9.5	8.5	8.1	7.5
	°F	46.2	48	50.3	51.4	51.4	50.3	50.3	50.2	49	47.4	46.5	45.5
Max. Temperature	°C	21.3	22.6	22.5	22 °C	21.5	19.9	18.6	18.6	19	19.7	20.6	20.6
	°F	70.3	72.7	72.5	71.6	70.7	67.9	65.5	65.5	66.1	67.4	69	69.2
Precipitation / Rainfall	mm	17	27	71	128	159	291	412	438	309	60	14	7
	in	0	1	2	5	6	11	16	17	12	2	0	0
Humidity	%	51	44	50	60	63	78	87	88	83	62	51	51%
Rainy days	d	3	4	8	11	11	18	22	22	19	6	2	1
avg. Sun hours	hr.	9.5	10	9.8	9.7	9.4	7.7	6	5.8	7	9.4	9.7	9.5

Source: climate data.org [82]

3.2. Sampling method

The biogas digesters were selected using purposive sampling, the researcher's judgment and understanding of the situation are key factors in this sampling process [83]. The total number of constructed biogas digesters in Holeta was 45. In this study semi-structured questionnaire were administered for 17 household digester owners in four woredas, and an interview with area technical supporter in order for selection of biogas digesters based on their performance. In addition, direct observations were also carried out to support the information generated from the households. Three household biogas digesters were selected based on their efficiency, the first reactor have higher efficiency, whereas the second have medium, and the third one with lower efficiency.

3.3. Research Design

The data were collected from field and further analyzed in the laboratory.

To investigate the performance of the selected biogas plants. The research was carried out using numerous parameters, including substrate characterization (a sample taken and tested prior to feeding to the reactor), operational parameters such as temperature and pH, frequently monitored, digestate analysis (a sample taken in the middle of the retention time to study microbial conditions such us ammonia, alkalinity, and volatile fatty acid), and bio-slurry characterization at the end of HRT.

The process flow diagram of the research design was provided in figure 11 is below; -

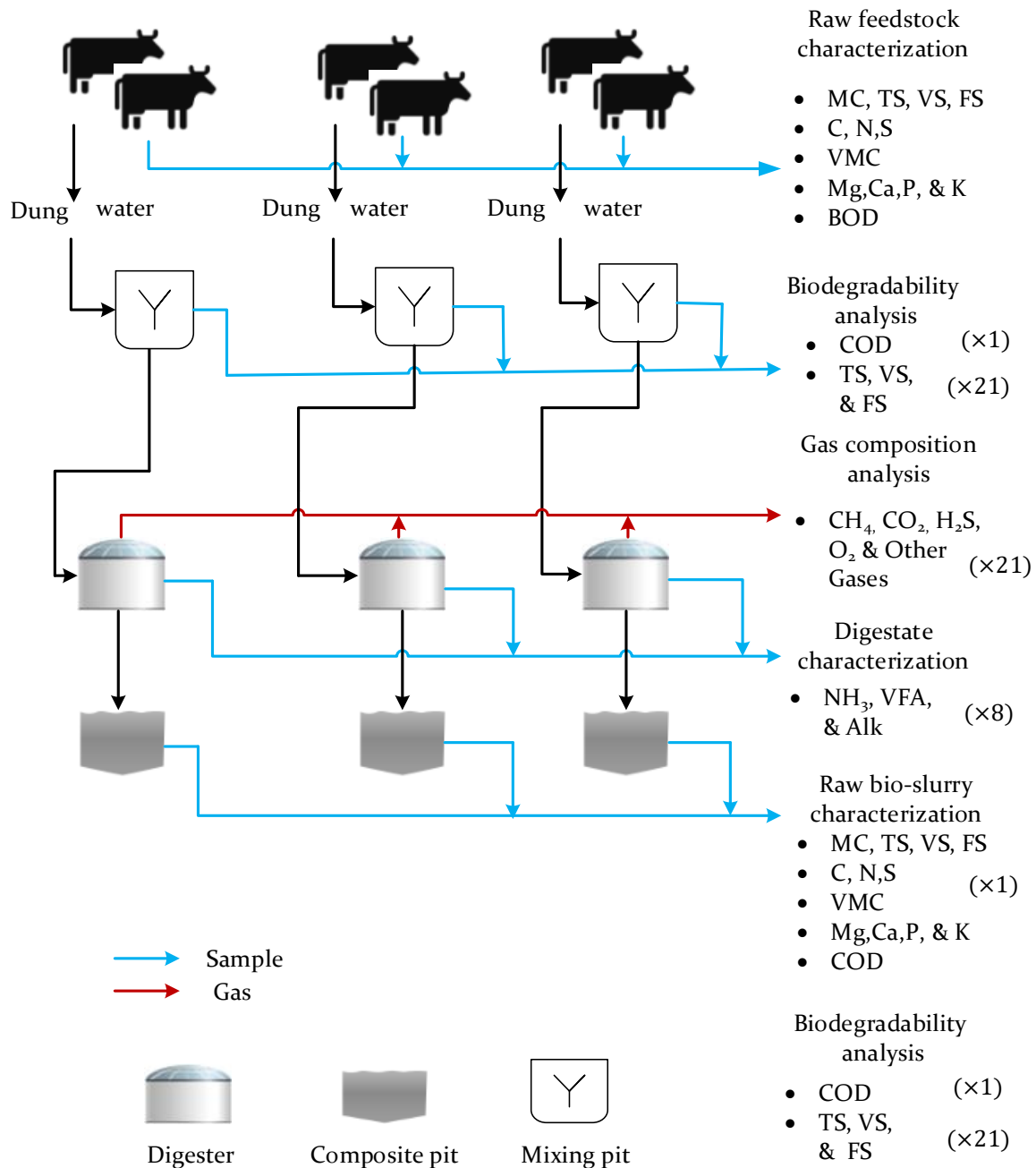


Figure 11. Process flow diagram of the research

3.4. Household anaerobic digester selection

The digesters were chosen based on its performance, depending on the questioner with digester owners, interviews with regional biogas coordination offices, and field observations.

Bio-digester (A)

Reactor A was owned by Holeta Agricultural Research Center, which was built in 2021 GC with a $10m^3$ volume SINDU2008 model reactor and is utilized for lighting and cooking. Which has one stove and three biogas lamps. The research center has a large number of livestock. This reactor has been selected due to the unburnt gas produced from the reactor at the time of observation and the production of a pungent (rotten egg-like) odour from the gas. According to the interview, questionnaire, and field observation the researcher named it the lowest-performer reactor.

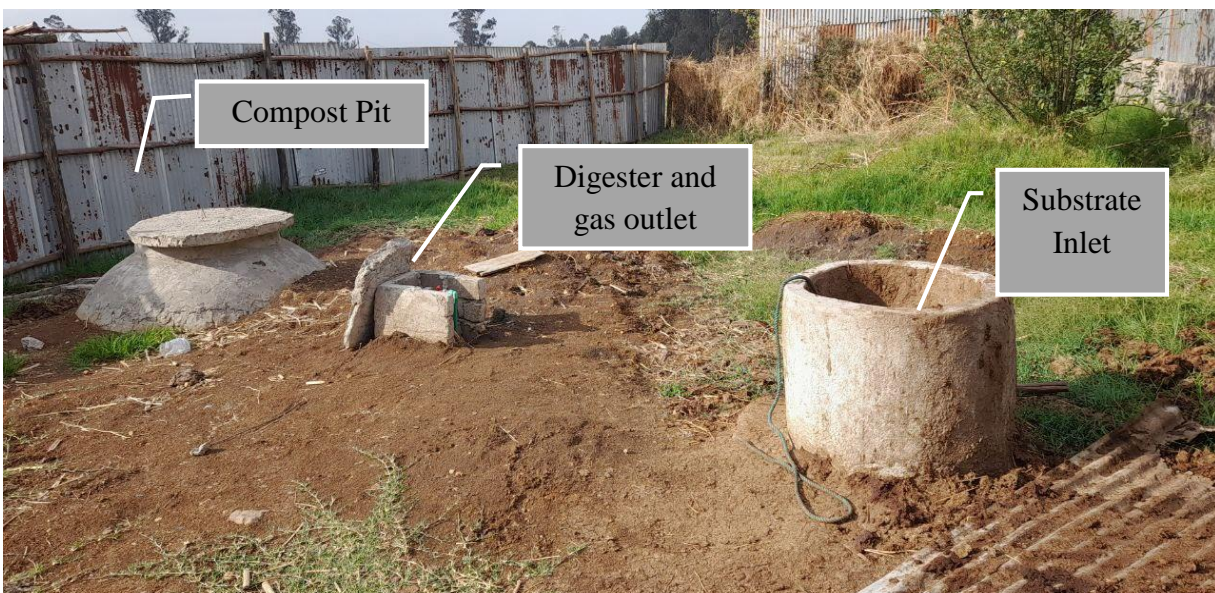


Figure 12. Bio-digester (A)

Bio-digester (B)

Reactor B is a $6m^3$ fixed dome digester that belongs to a farmer and was built in 2014 GC. The gas is utilized for cooking and lighting. This reactor has connected with one biogas lamp and one stove. At the time of the field observation, the biogas was produced well, however a small quantity of an odor resembling rotten eggs, issues with the biogas pipe fittings, and multiple instances of biogas lamp explosions were reported by the digester owners due to this they were stopped using the biogas lump. Reactor B has been chosen as the study's medium-performing anaerobic digester based on information gathered through interviews, questionnaires, and field observations.



Figure 13. Bio-digester (B)

Bio-digester (C)

Reactor C is owned by a farmer and is an $8m^3$ volume SINDU2008 model reactor built in 2020. It is functional and connected to one stove and one light, but the owner only uses it for cooking as they are wired into the grid. Reactor C worked admirably without any difficulties being noticed at the time of the field observation and interview from the owner. Reactor C has been chosen as the digester with the best performance based on the information gathered through interview, questionnaire, and field observation.



Figure 14. Bio-digester (C)

3.5. Equipment's and Chemicals used in the study

The major apparatus and chemicals used in the study were listed in the Table 5, and 6 below.

Table 5. Equipment's used during the study

No	Apparatus	No	Apparatus
1	Muffle furnace	10	pH meter
2	Dry oven	11	Thermometer
3	Portable gas analyzer	12	Glass like beaker, bottles ...
4	Gas chromatography	13	Erlenmeyer flask, spoon
5	Ion chromatography	14	Magnetic stirrer
6	Spectrophotometer	15	Ceramic crucibles
7	Stirrer bar	16	Desiccator
8	Autoclave	17	Colorimeter
9	Analytical balance	18	HPLC

Table 6. Chemicals used during the study

No	Chemicals	No	Chemicals
1	Sulfuric acid (H_2SO_4)	7	COD reagent
2	Potassium dichromate solution ($K_2Cr_2O_7$)	8	Sodium hydroxide
3	Orthophosphoric acid (H_3PO_4)	9	Ferrous ammonium sulfate
4	Mercury sulfate	10	Barium diphenylamine sulphonate
5	Potassium sulfate (K_2SO_4)	11	Concentrated orthophosphoric acid (H_3PO_4)
6	Copper sulfate		

3.6. Field and laboratory experiments

Several field testing and laboratory experiments were undertaken as part of the research. The type of analysis, time/period and place of the test were indicated the Table 7.

Table 7. Field and laboratory experiments

Field tests, and laboratory experiments				
No		Types of analysis	Experiments	Description
Feedstock characterization				
1	Influent characterization (cattle manure)	Proximate analysis	MC, TS, VS & FS	Once for raw feedstock, sample collected from livestock house.
2			BOD & COD	
3			Ash	
4			C, N, & S	
5			Total solid	Sample taken after mixed with water. Every three days for a two month (60 Days of retention period).
6			Volatile solid	
7			Fixed Solid	
8			COD	Once after dung mixed with water
9		Light Metal analysis	Potassium	Once, sample taken, and measure before feeding to the reactor.
10			Calcium	
11			Magnesium	
12			Phosphorous	
Field measurements				
13	Continuous measurement's	Gas analysis	Ph. and Temperature	Every three days for two months
14			Gas analysis (CH ₄ , CO ₂ , H ₂ S, O ₂ , & other gases)	
15			Volume of gas	
Digestate characterization				
16	From the inside of digester	AD process inhibitors	Sulphide	Sample taken from the inside of the digester once a week for two months
17			Sulfate	
18			VFA (volatile fatty acid)	
19			NH ₃ (Ammonia)	
20			Alkalinity	
Bio-slurry characterization				
21		Proximate analysis	Moisture Content	Sample taken after mixed with water. Every three days for a two month (60 Days of retention period).
22			Total solid	
23			Volatile solid	
24			Fixed Solid	
25			Carbon, Nitrogen	
26		Light metal analysis	Potassium	
27			Calcium	
28			Magnesium	
29			Phosphorous	
30			Total nitrogen	Once for liquid, and dry bio-slurry after filtration and oven dry
31			Phosphorous	

3.7. Sample preparation

In this study, samples were taken from the field (digesters), pH and temperature were monitored instantly and then the required data (liquid or gas samples) brought to the laboratories for further analysis.

Field measurement and sample collection

Inlet of the digester

The sample was taken at the entrance (inlet pit) of the digester after the raw material (feedstock) was completely mixed with water and ready for supply. Samples were taken from the inlet using a plastic cup. After temperature and pH readings were taken, samples were prepared for laboratory measurements using labeled plastic bags.

Inside the digester

A 2-meter-long wire was coupled with a small plastic bottle sufficient for inserting it into the digester through the inlet hole, and then the bottles collected the required sample from within the digester. Temperature and pH readings were measured immediately from the collected sample. This was done prior to the daily feed manure being added to the digesters.

Outlet side of the digester

With the exception of the sampling location, both the inlet (feedstock) and outflow (slurry) were sampled using the same methodology. By removing the slab cover from the upper portions of the composite pit, the bio-slurry sample was collected. The sample was collected, packed, and labeled for laboratory studies after the pH and temperature readings were taken.

NB. All the sample taken from the field were directly taken to the laboratory, when it was necessary the prepared sample was stored at 4 °C prior to use.

Gas sample collection

Gas samples for analysis in this study were obtained using glucose gas bags. The gas line must first be separated from the biogas burner at a specific place, after which it may be quickly connected to the gas collector bag using a screwdriver and locked when it is full. The sample was brought to the lab, where a gas analyzer was used to determine the composition of the gas.

3.8. Experimental analysis

To characterize the sample before and after AD process, and evaluate the household anaerobic digester ultimate and proximate analysis were performed.

3.8.1. Ultimate analysis

The nitrogen content of the influent and effluent were determined using Total kjeldahl nitrogen method. The carbon content was determined by using Walkley-Black method.

Potassium, calcium, magnesium, were measured by reading the sample using Flame atomic absorption spectrophotometry. Germany (analytikjena) novAA400P. Phosphorous content measured by Ammonium molybdate HACH (spectrometric Method DR/6000)

3.8.2. Proximate analysis

3.8.2.1. Total, fixed and volatile solid

The total solid was determined using APHA 2540B method. Before starting the test ceramic crucibles washed and dried in an oven set at 105 °C for 30 min to remove any adhering moisture. Vigorously mix the sample by hand until homogenous. 5g of well-mixed sample were placed to a pre-weighed crucible. The 5g homogenized sample placed in oven set at 105°C for 24 hrs. After that, the samples were placed in a desiccator to avoid moisture contamination, cooled, and weighed.

After weighing, dried samples it was again ignited in a muffle furnace at 550 ± 50 °C for an hour. Then the samples were cooled in a desiccator and weighed. The ignition, cooling, and weighing were repeated until constant weight or until below 4% weight difference were obtained. Finally, the percentages were determined using the following equations of which the total solid (equations 1), volatile solid (equations 2), and fixed solid (equations 3).

Total solids

$$TS(\%) = \frac{W_{\text{total}} - W_{\text{dish}}}{W_{\text{sample}} - W_{\text{dish}}} \times 100 \quad (1)$$

Volatile solid

$$VS(\%) = \frac{W_{\text{total}} - W_{\text{volatile}}}{W_{\text{total}} - W_{\text{dish}}} \times 100 \quad (2)$$

Fixed solid

$$FS(\%) = \frac{W_{\text{volatile}} - W_{\text{dish}}}{W_{\text{total}} - W_{\text{dish}}} \times 100 \quad (3)$$

Where;

W_{total} = weight of dried residue (105°C) + dish, in g

W_{dish} = weight of dish in g

W_{sample} = weight of wet sample + dish, in g

W_{volatile} = weight of residue + dish after ignition, at (550°C) in g

3.8.2.2. Moisture content

Water content in the animal dung was determined by using oven dry. 5 gm. of sample was taken and dried in an oven at a temperature of 105±3°C for 24 hr. then after the weight difference were measured using analytical balance. The moisture content determined as per the standard of (ASTM standard D 3173 – 03, 2013), and calculated as equation 4 below.

$$MC(\%) = \frac{M_{\text{wet}} - M_{\text{dried}}}{M_{\text{dried}}} \times 100 \quad (4)$$

Where:

MC = Moisture content

M_{wet} = Mass of wet sample

M_{dried} = Mass of dried sample

3.8.3. Biochemical Oxygen Demand determination

The 5-day biochemical oxygen demand (BOD₅) test was carried out for the raw waste water using the standard method set by (APHA, 1999). Section 5210B was used in particular. As stated in the standard method, the major apparatus used were a DO (dissolved oxygen) meter and an incubator set at 20±1°C. The initial dissolved oxygen and the final dissolved oxygen after 5-day incubation were measured and recorded. The BOD was then calculated in the given equation 5 below [52].

$$BOD = \frac{D_1 - D_2}{P} \text{ (mg/l)} \quad (5)$$

where D_1 = is the initial dissolved oxygen of the raw dung (mg/L)

D_2 = is the final dissolved oxygen after 5 – day incubation of the dung (mg/L)

P = is the decimal volumetric fraction of the sample used

3.8.4. Chemical Oxygen Demand determination

The chemical oxygen demand determined using 5220D closed reflux (calorimetric) method. COD digester in DR6000 UVVIS Spectrophotometer. For analysis reagents mercury sulfate, potassium dichromate, and sulfuric acid were utilized. The digestate taken from the digesters and the required reagents were added on the tube then placed on the COD digester by setting the heating block at 150 °C for reaction time of 2 hrs. After cooling the digested sample, the concentration of COD was measured using multi-photometer. During analysis, 1 ml of sample to be analyzed was diluted with 5 ml of distilled water. After dilution, 2 ml of the diluted sample was transferred to COD reagent, and digested for 2 hours using a digestion vessel set at 150 °C. After digestion, the mixture was cooled and transferred to vials for multi-photometer reading. Measurements were performed on raw samples and bio-digestate. COD removal efficiency was calculated using Equation 6 below.

$$\text{COD}_{\text{Removal efficiency}} = \frac{\text{COD}_{\text{BD}} - \text{COD}_{\text{AD}}}{\text{COD}_{\text{BD}}} \times 100\% \quad (6)$$

Where;

COD_{BD} = Chemical oxygen demand before AD

COD_{AD} = Chemical oxygen demand after AD

3.8.5. Process monitoring parameter

Selected parameters (pH and T°) which affect the process of anaerobic digestion were determined. The pH value and the temperature of the sample were measured using the standard method APHA 4500-H⁺ and APHA 2550 B respectively.

3.8.6. Inhabitant determination

The concentration of volatile fatty acid was determined by simple titration with spectrometric method DR/6000, and esterification method by using sulfuric acid standard solution. The ammonia nitrogen was determined using Nessler method and DR/6000 spectrophotometer. In order to determine the alkalinity buret titration method 8221 were utilized. For determination of sulfate sulfaVer 4 method were utilized.

3.8.7. Gas volume and composition determination

3.8.7.1. Volume of gas

Bioreactor process performance can be evaluated based on biogas production and its composition. It is questionable whether the biogas produced can meet the energy needs of the family. In this study, back-calculation was used to determine the amount of gas produced.

3.8.7.2. Gas composition

The gas produced by anaerobic digestion is mainly composed of methane and carbon dioxide, and contains a minor amount of hydrogen, hydrogen sulfide, nitrogen and oxygen. In this study, gas composition is measured using a portable gas analyzer and the gas sample was taken to the laboratory using glucose, and urine bag. The gas analyzer used in this study is Geo gas meters.

CHAPTER FOUR: RESULT AND DISCUSSION

This chapter presents the results obtained during the course of the work and research findings including (field and laboratory results) as well as their respective discussions, and various justifications.

4.1. Demographic Analysis of Respondents

Among the surveyed 17 households during the study 71% (12 persons) of respondents from the biogas users were females and 29 % (5 persons) were males. The average age of respondent's is above 41 and the average family size were 7 persons including servant.

Table 8. Demographic and Socio-economic status

Marital Status	Freq.	% Of marital status		
Married	17	100%		
Unmarried	0	0		
		100%		
Gender (who manage the bio-digester)	Freq.	% Of Gender		
F	12	71%		
M	5	29%		
		100%		
Age of respondent	Freq.	Age		
		Min	Max	Ave
		20	71	41
Family members of respondent	Freq.	Family size		
		Min	Max	Ave
		5	9	7

4.1.1. Source of feedstock, water, and sizes of the digesters

Majority of the respondent 65% used cattle dung, and toilet together as feedstock for biogas production the rest 35% uses cattle dung alone as a substrate. 53% of respondent also used public tap for dilution of raw feedstock while 35% uses public tap, ground water, pond, and streams based on conditions and public tap availability. 76% of household have an 8m³ biogas digester followed by 10 m³ and 6m³. Majority of respondents 76% feeds the digester in a daily biases while 18% in one interval.

Table 9. Source of feedstock, water, and sizes of the digesters

Source of feedstock	Freq.	% Feedstock used
Cattle dung	6	35%
Cattle dung and toilet	11	65%
		100%
Source of water	Freq.	% Source of water
Public tap water	9	53%
Ground water/ponds	2	12%
Public tap water & Ground water/pond	6	35%
Size of the digester	Freq.	% Size of the digester
6 m ³	2	12%
8 m ³	13	76%
10 m ³	2	12%
		100%
Feeding interval	Freq.	% Loading interval
Daily	13	76%
Every two day	3	18%
Two times a week (randomly)	1	6%
Total	17	100%

All of the respondents uses the produced biogas for cooking, and lighting purpose, but they are connected to the grid they use the biogas for lighting when electricity is off.

4.1.2. Utilization of the biogas

Table 10. Utilization of biogas

Utilization of biogas	Freq.	% Utilization
Electricity	0	0
Stove and Lamp	17	100%
Total	17	100%
Grid connection	Freq.	% Grid connection
Yes	17	100%
No	0	0
Total	17	100%

4.1.3. Problems faced in the system

Majority of respondents 65% have faced technical problems before. 53% of the respondents observed rotten egg-like smells from the produced biogas frequently, while 17% of the respondents observe the rotten egg smells sometimes.

Table 11. Biogas digester technical performance

Have you faced technical problems	Freq.	% Technical problems faced
Yes	11	65%
No	6	35%
Total	17	100%
Experience of rotten egg-like smells	Freq.	% experienced rotten egg-like smells
Yes	9	53%
No	5	30%
Sometimes	3	17%
Total	17	100%

4.2. Characteristics of the feedstock

The characteristics of the feedstock have a significant impact on the stability of the anaerobic digestion process and the production of biogas. The characteristics of the feedstock includes, the carbon and nitrogen contents, moisture content, total solid, volatile solid (ignition at 550°C), particle size, pH, biological oxygen demand (BOD), chemical oxygen demand (COD). The characteristics of the feedstock and loading rates heavily influence the concentration of volatile fatty acids and ammonia, both of which could lead to toxicity and process failure at high concentrations [84].

4.2.1. Substrate characterization before mixing

In order to improve the outcome of anaerobic digestion and to optimize the process for both the scientific and industrial levels, it is necessary to characterize the substrate in detail before and during the anaerobic digestion process [85]. In addition to the proximate and ultimate analyses this study examines the concentration of COD, BOD, alkalinity, and level of temperature, pH, and other inhibitors.

The TS, VS, FS, COD, and BOD values shows the amount of biodegradable matter available in the samples. According to different studies fresh cattle dung consists approximately 80% of water and 20% of solid materials, out of the total solid material approximately 70% of it encompasses the volatile solid,

and the remaining 30% is fixed solid although the non-volatiles are not affected during digestion, and come out of the digester unchanged.

In order to get better anaerobic digestion, for easy mixing and handling dilution is required. Literatures recommended 8-10% of TS for better anaerobic digestion. The NBP+ Ethiopia trainee's manual stated that to get 8-10% of total solid the raw feedstock could be mixed with water at 1:1 ratio. In this study the moisture content of the raw feedstock was found to be $87.6\% \pm 1.2$, $84.5\% \pm 0.9$, and $86.3\% \pm 1.1$ for substrate A, B, and C respectively and the TS obtained in the study was $12.4\% \pm 1.2$, $15.5\% \pm 0.9$, and $13.7\% \pm 1.1$ for sample A, B, and C respectively. Masinde et al [51] stated that the optimum methane obtained from cow dung was at 8% of TS this implies that the raw substrate requires further dilution with water in order to get the optimum amount of biogas from the AD process. The volatile solid content of the raw feedstock were $72.13\% \pm$, $81.6\% \pm$, and $80.2\% \pm$ for A, B, and C respectively.

The C/N ratio obtained from the study shows that 30.827 ± 0.76 , 30.367 ± 1.02 , and 29.45 ± 0.87 for A, B and C respectively. According to earlier studies the most optimal C/N ratio for AD processes is between 20–30 and the value of C/N ratio ranging between 20-30 was supported by (Chandra et al [40], Sievers and Brune [39], Molinuevo-Salces et al., [38], X et al. [37]., and Bolzonella et al [41]) studies,. The C/N obtained in this study agrees with the previous reports.

Table 12. Characteristics of raw cattle dung

Parameters	Unit	Substrate A	Substrate B	Substrate C
Moisture content	%	87.6 ± 1.2	84.5 ± 0.9	86.3 ± 1.1
Total solid	%	12.4 ± 1.2	15.5 ± 0.9	13.7 ± 1.1
Fixed solid	%	27.87 ± 2.1	18.4 ± 2.5	19.8 ± 3.1
Volatile solid	%	72.13 ± 2.5	81.6 ± 2.5	80.2 ± 3.1
Ash content	%	18.5	18.5	18.7
BOD	mg/l	111.5 ± 1.14	81.515 ± 1.24	104.4 ± 1.74
Calcium (Ca)	mg/l	23.112 ± 0.018	25.228 ± 0.021	24.64 ± 0.011
Phosphorus (P)	mg/l	6.93 ± 0.014	8.82 ± 0.042	8.47 ± 0.056
Magnesium (Mg)	mg/l	10.316 ± 0.03	10.188 ± 0.001	10.231 ± 0.014
Potassium (K)	mg/l	7.45	6.521	7.34
Sulphur (dry biases)	%	0.10	0.09	0.09

4.2.2. Substrate characterization after mixing with water

According to the user's manual provided by NBPE+, [70] the collected raw feedstock should be mixed with water at a 1:1 ratio prior to feeding. This study also conducted the characterization of substrates after dilution to feed into the anaerobic digester i.e., moisture content, total solid, volatile solid, and

chemical oxygen demand (COD). The water used for diluting the feedstock was tested for sulfide and showed 36 $\mu\text{g}/\text{l}$ for reactor A and 25 $\mu\text{g}/\text{l}$ for reactor B and C. The overall characteristics given in the table 13 below.

The biochemical oxygen demand (BOD) is a measurement of the amount of biodegradable organics in a sample. From the experiment, the amount of BOD in the influent obtained to be is 111.5, 81.515, and 104.4 mg/l for sample A, B, and C respectively. The chemical oxygen demand (COD) is a measurement of how much oxygen is present in a sample of sludge that can be consumed by oxidizing agents in a reaction. The result obtained from the experiment showed 1892 mg/l, 2280 mg/l, and 2060 mg/l of COD for sample A, B and C respectively. According to the study made by [86] the raw cow dung COD obtained to be 2200mg/l as compared to this study the result didn't show significant difference.

Table 13. Characteristics of substrate after mixing with water

Parameters	Unit	Substrate A	Substrate B	Substrate C
Moisture content	%	90.7±2.9	91±2.14	92.07±1.6
Total solid	%	9.2±2.93	9.0±2.14	7.9±1.6
Volatile solid	%	72.3±12.1	81.5±14.5	80.3±5.89
Fixed solid	%	27.87±2.1	18..5±14.5	19.5±5.89
COD	mg/l	1892	2280	2060
Carbon	%	36.5	37.2	37.4
Nitrogen	%	1.184	1.225	1.27
C/N		30.827	30.367	29.45
Sulfide (water)	$\mu\text{g}/\text{l}$	36	25	25

4.3. Process stability of the anaerobic digestion

4.3.1. Effect of pH in anaerobic digestion

All biological processes take place during anaerobic digestion at pH levels that are predetermined. A lower pH value in the reactor is caused by fast acidification from the generation of volatile fatty acids (VFA), and it is a significant barrier to the anaerobic digestion process [87].

Study made by Valvilin et al, [88], Castillo et al, [89], and Veeken et al, [90], stated that the pH of the optimal hydrolytic stage in anaerobic digestion was between 5 – 6, and Converti et al [91] also indicated that for the methane production stage, the optimal pH value varies between 6.5 – 8. If the pH value decreases below 6, methane production is severely restricted and inhibited. Due to its negative effect on the activity of methanogenic bacteria.

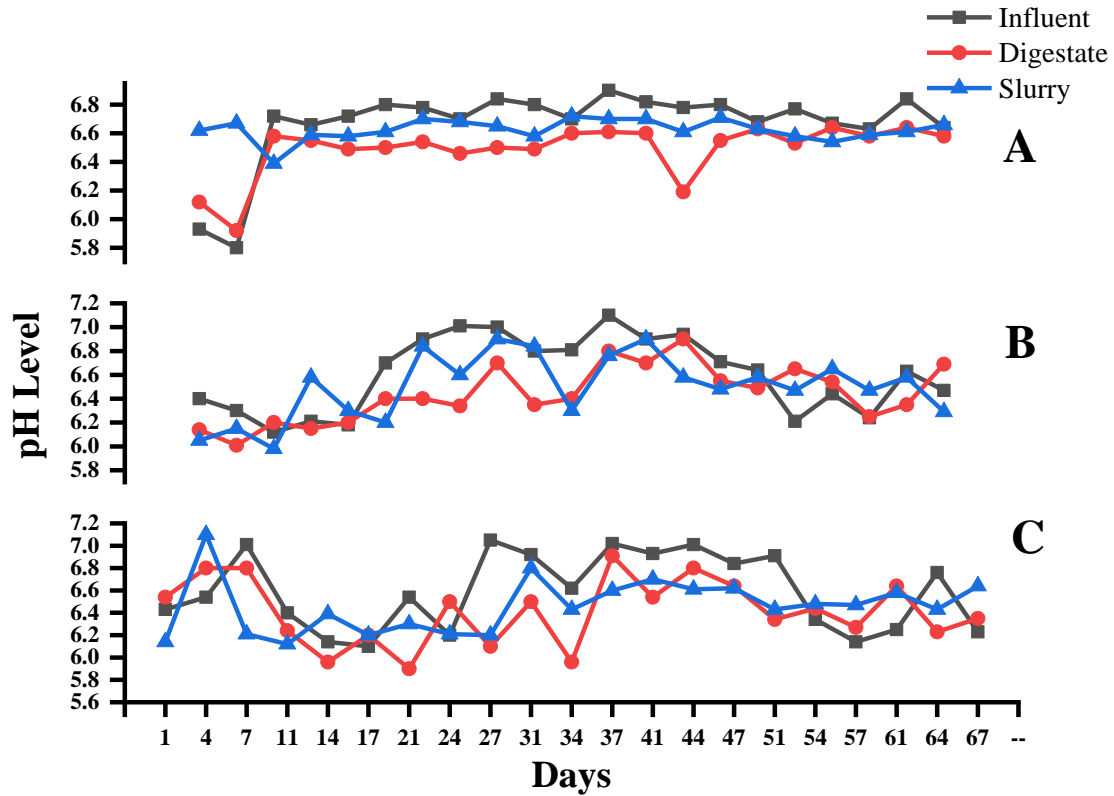


Figure 15. pH level while monitoring the AD process

According to the interview with technical supporter and digester owner, reactor A the digester gas production was well but, it was not burning, was also like smelling rotten egg, it was because of the reactor was new and the substrate was not properly feed with the required amounts of inoculum. According to El-Fadel et al. [92] report, for an appropriate microbial seed of new digester the substrate should be exposed with an existing inoculum of similar substrate, if this is not done it results a longer startup period for the new reactor. Due to this and higher volatile fatty acid accumulation and lower alkalinity from day one up to seven the pH value in reactor A dropped below 6 as indicated in Figure 14. Other report by Karakashev et al. [93], also stated that a lower pH leads to a higher hydrolysis rate due to increasing VFA concentration and causes a lower efficiency of anaerobic digestion. After day 11 the biogas could burn but still the pH value was unstable, its majorly due to the lower amount of alkalinity in the reactor. Alkalinity levels must be sufficient for optimal pH management. Earlier works

also revealed that alkalinity acts as a buffer to stop rapid changes in pH level during anaerobic digestion [94].

4.3.2. Effect of temperature in anaerobic digestion

For better biogas production the digester's temperature must be controlled. A 20°F drop in temperature results in a 50% reduction in gas production [84]. The necessity to maintain a constant temperature is even more important because methane formers are temperature-sensitive. The weather in Holeta is categorized as warm and temperate.

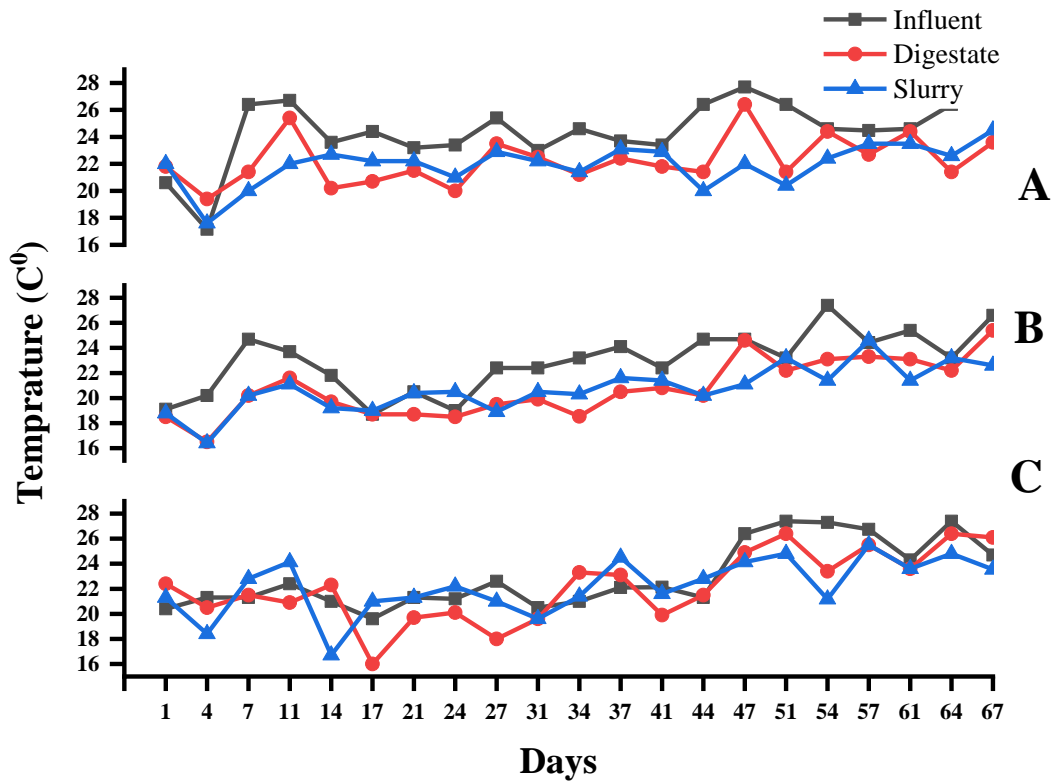


Figure 16. Temperature levels influent, digestate and slurry

According to figure 15 the recorded result showed that the temperature regime falls in the mesophilic temperature region for all of the three reactors with an average temperature of the digestate (sample taken from the reactor and an immediate measurement) 22.3, 20.7, and 22.2°C for reactor A, B and C respectively, but this value may vary seasonally.

It is challenging to maintain constant biogas production throughout the year because of this seasonal temperature change [95]. The mesophilic and thermophilic zones are where methanogens thrive best, which leads to a higher rate of biogas generation [96]. According to Alvarez et al. [43] the biogas

productivity of AD diminishes when temperature variations occurs. Garba [97], stated that the methane-producing bacteria are extremely sensitive to quick fluctuation in temperature, thus it is advised to avoid any extreme alterations. According to Rahman et al. [98] observation when temperature is lower the pH becomes lower, and causes a low rate of organic matter conversion in to biogas, and also Karakashev et al. [93], stated that a lower pH leads to a higher hydrolysis rate due to increasing VFA concentration and causes a lower efficiency of anaerobic digestion.

4.3.3. Effect of alkalinity in anaerobic digestion

Alkalinity serves as a buffer to stop a sudden change in pH. It's critical for the system to function properly that happens when the digester maintains an acceptable pH. In the first days of anaerobic digestion the pH might initially decrease due to the volatile fatty acids production. However the generated VFA immediately consumed by methane-forming bacteria, and alkalinity will produced, then the pH in the digester will increase and the system becomes stabilized [99].

In this study the average alkalinity level obtained were 225.7, 292.4, and 331.2 mg/l for A, B, and C respectively in reactor A lower alkalinity concentration was recorded as compared to B and C, in all cases the concentrations of alkalinity were fluctuating (Figure 16), due to poor management of the reactors. As compared to other literatures the value obtained in this study was very small to maintain the buffering capacity this leads to accumulation of VFA and reduce the methane production.

Chen et al., [94] studied effect of alkalinity source such as LMP, CaCO_3 , WES and NaHCO_3 , from food waste which have an initial 825 ± 50 mg/l alkalinity concentration with an addition of an inoculum with 980 ± 50 mg/l alkalinity concentration and alkalinity level reached 7820, 7307, 6782, 9504 and 5906 mg/l respectively, due to this the pH buffering capacity were improved, and the VFA concentration were dropped, and the methane production were significantly improved.

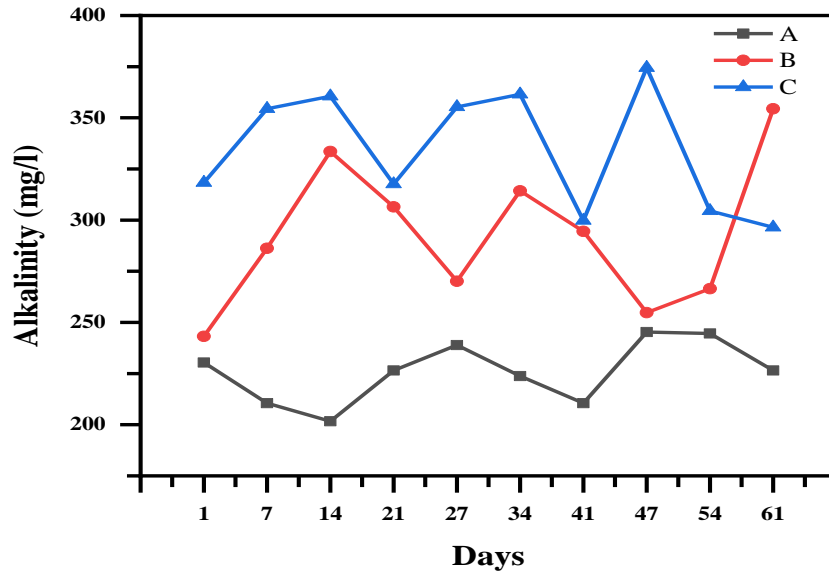


Figure 17. Alkalinity concentration in the anaerobic digestion

4.3.4. The effect of volatile fatty acid

It is generally recognized that the VFA concentration serves as a crucial signal for keeping track of anaerobic digestion. Acid producing bacteria created VFA during the steps of acidogenesis. Two volatile fatty acids (acetic acid, and butyric acid) are among the anaerobic digestion's intermediate products that are most favorable for the creation of methane, with acetic acid making up more than 70% of the methane gas [16].

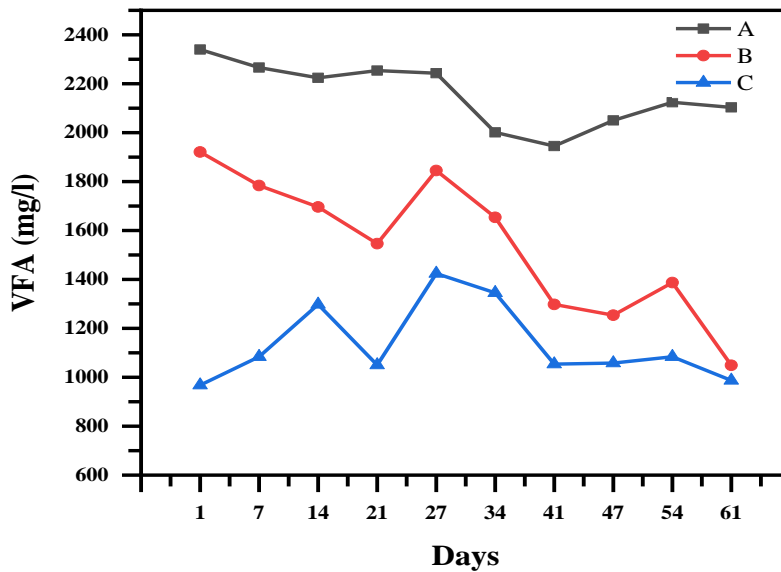


Figure 18. VFA concentration in anaerobic digestion

As shown in Figure 17 the concentration of VFA vary for all of the three reactors. Reactor A shows a higher amount of VFA concentration as compared to B and C, the higher amount of VFA accumulated in the reactors might affects the biogas production negatively. In a steady AD process, methanogens were used to transform this VFA into biogas. According to Sneath et al [100], the value of VFA should be below 2 g/l for the AD to function properly.

4.3.5. The effect of ammonia concentration

The primary nitrogen component is derived from nitrogenous substances found in organic matter, most commonly in the form of proteins, and urea. Proteins, and urea are hydrolyzed to create ammonia. Even if the production of VFA (mainly acetic acid) reduces buffer capacity, the production of NH_4^+ boosts bicarbonate concentrations and process stabilities [101]. This investigation found that reactors A, B, and C had average $\text{NH}_3\text{-N}$ concentrations of 20.32, 21.7, and 22.8 mg/l, respectively. This value is lower than the stimulating concentration (50-200 mg/L) suggested by Chen et al. [57]. According to the previous study volatile fatty acids (VFAs) concentration increment due to process instability was the cause for the drop in pH level and also for the declining in free ammonia concentration [102]. An "inhibited steady state," or a situation where the process is running steadily but with a decreased methane production, may result from the interaction between free ammonia (FA), VFAs, and pH [103]. Wendland, [104] although stated that methanogenesis is mostly inhibited by high ammonia concentration. Concentrations of TAN greater than 1.5 g/L are normally considered to be inhibitory for AD [105]. The concentrations of ammonia recorded in all the anaerobic digesters used in this study was, too low to inhibit the microbial activities. The figure 18 below shows the ammonia nitrogen concentration in the AD.

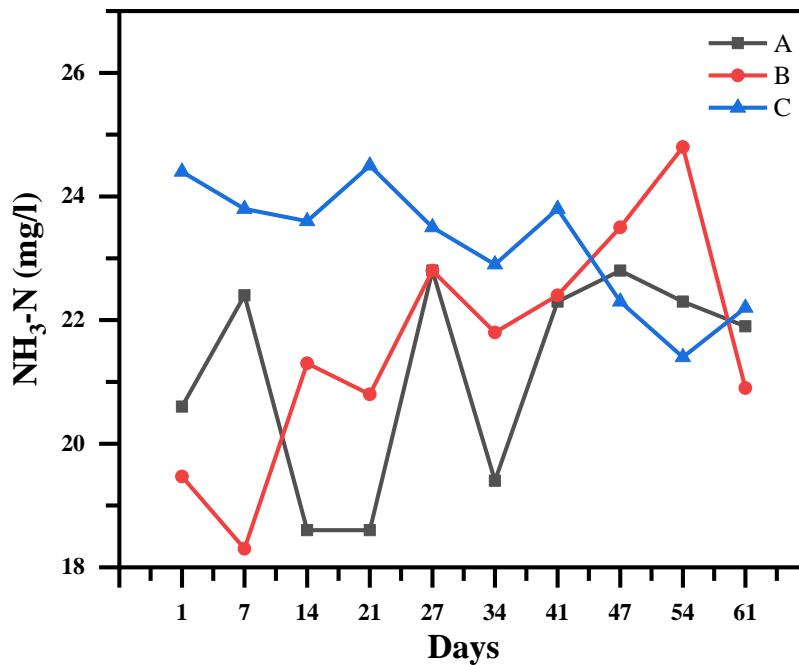


Figure 19. Ammonia nitrogen ($\text{NH}_3\text{-N}$) concentration inside the digesters

4.3.6. Effects of Sulfide concentration in AD

Previous studies stated that sulfate-reducing bacteria (SRB) converts sulfate to sulfide in anaerobic reactors [106, 107]. Anaerobic digestion results in the simultaneous production of sulfide, and methane. Since hydrogen, and acetate are both used as sources of electron donors by methane-producing bacteria (MPB), and sulfate-reducing bacteria (SRB) there could be a competition [58, 108]. The sulfate concentration found in this study was 68 ± 1.2 , 60 ± 0.9 , and 52.5 ± 0.78 mg/l, for reactor A, B, and C. The value obtained in this study may be lower due to sampling problems, and the system was uncontrolled. The concentration of sulfate in reactor A is comparatively higher as compared to B, and C this may contribute to the higher concentration of H_2S in the biogas and lower methane percentage.

4.4. Removal efficiency

4.4.1. COD removal efficiency

According to the research done by Ibn Abubakar, and Ismail [86], the average COD removal efficiency obtained through anaerobic digestion of cow dung was 48.5%. Other study by Castrillón et al [109] showed a COD removal varied between 54.8 and 79.7% for HRT of 7.3, and 22.5 days from cow dung,

hence the maximum COD removal efficiency obtained from the study was 79.7%. According to the Table 14 the COD removal efficiencies of reactor A, B, and C were 70.7%, 77%, and 78% respectively, this implies that reactor B, and C had shown a better COD removal efficiency as compared to reactor A. Chollom et al. [110] stated that acidity and alkalinity of a system inhibits the COD removal efficiency this may be the reason for the reduction of COD removal efficiency for reactor A . The result recorded in thesis work nearly consistent with earlier literatures.

Table 14. COD removal efficiency in the anaerobic digestion process

Code	COD _{BD} (mg/l)	COD _{AD} (mg/l)	COD removal efficiency (%)
A	1896.5	556	70.68
B	2280	524	77.02
C	2060	453	78.01

4.4.2. VS and TS removal efficiency

As illustrated in Figure 19 the average TS removal efficiency were 37.7, 44.7, and 43.7% for reactor A, B, and C, respectively. Whereas the reactor A shows an average lower TS removal efficiency as compared to B and C. According to the research done by Ibn Abubakar and Ismail [86] the TS removal efficiency obtained from cow dung was 47% which is a bit higher than the average TS removal result found in the current study. Wang and Wan [111], stated that the efficiency of organic compound degradation improved as temperature rose from 20 °C to 40 °C. However, as the temperature rose above 40 °C, the degrading efficiency began to diminish. When Leven et al. [112] examined the impact of temperature on several bacterial communities for the AD of organic household waste, they discovered that the degradation capability at mesophilic temperature was greater than that at thermophilic temperature. A higher level of microbial diversity was seen in mesophilic conditions, which may have contributed to an improved degradation efficiency [112].

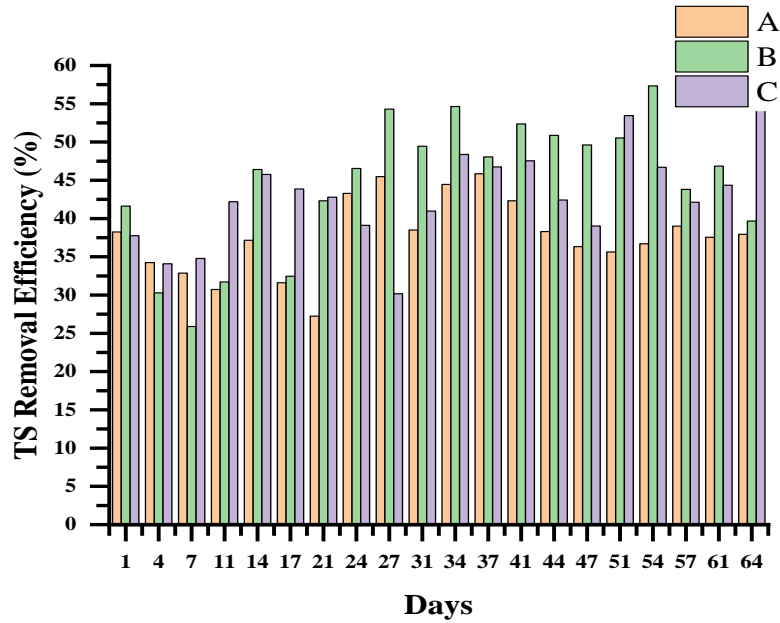


Figure 20. TS removal efficiency

The average VS removal efficiency of reactor A, B, and C were 26.7, 31.4, and 30.2% for A, B, and C. The work done by Ibn Abubakar and Ismail [86], showed a 49% of VS removal efficiency. According to Figure 20 the VS removal efficiency varies between 22-45%, this difference may happens due to improper feeding. Excess feeding leads the undigested materials to flow out of the digester, and improper mixing also cause for the lower VS removal efficiency.

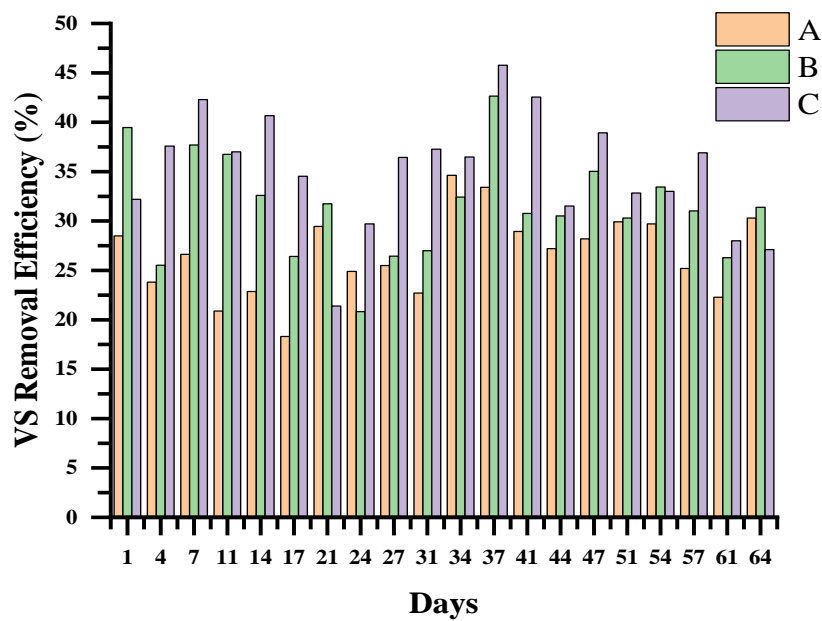
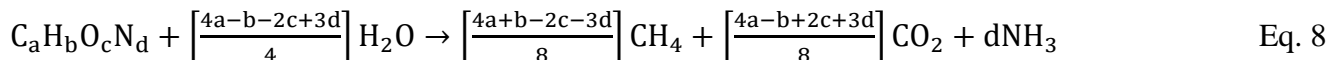


Figure 21. VS removal efficiency

4.5. Theoretical and actual methane percentage in AD process

In order to estimate the substrate theoretical methane production potential, the study used Buswell formula given in Equation 8. The detailed calculation was given in appendix I.



The result obtained from the study shows that the theoretical methane potential of substrate A, B, and C are 60.01, 58.3, and 58% respectively, and the actual average methane percentage is 51, 50.5, and 51% respectively, this shows a drop in 9.01, 7.8, and 7% of methane production as compared with the theoretical potential respectively.

Table 15. Deference in theoretical, and actual methane production percentage

Code	Theoretical		Actual		Difference	
	CH ₄ (%)	CO ₂ (%)	CH ₄ (%)	CO ₂ (%)	CH ₄ (%)	CO ₂ (%)
Substrate A	60.01	39.9	51	48	9.01	-5.4
Substrate B	58.3	41.7	50.5	48.2	7.8	-3.2
Substrate C	58	42	51	48	7	-6

4.6. Gas analysis

The composition and concentration of produced biogas had been analyzed in this study, and the results including methane, carbon dioxide and hydrogen sulfide presented in this section, also the whole gas composition measured during the experiment were given in the appendix VII.

4.6.1. Composition of produced biogas

The composition of the produced biogas was analyzed using portable gas geo-meter and the result showed that the methane percentage rages from 48.5 to 54.5 for all of the three reactors. Figure 21, shows the methane (CH₄) concentration of the produced biogas.

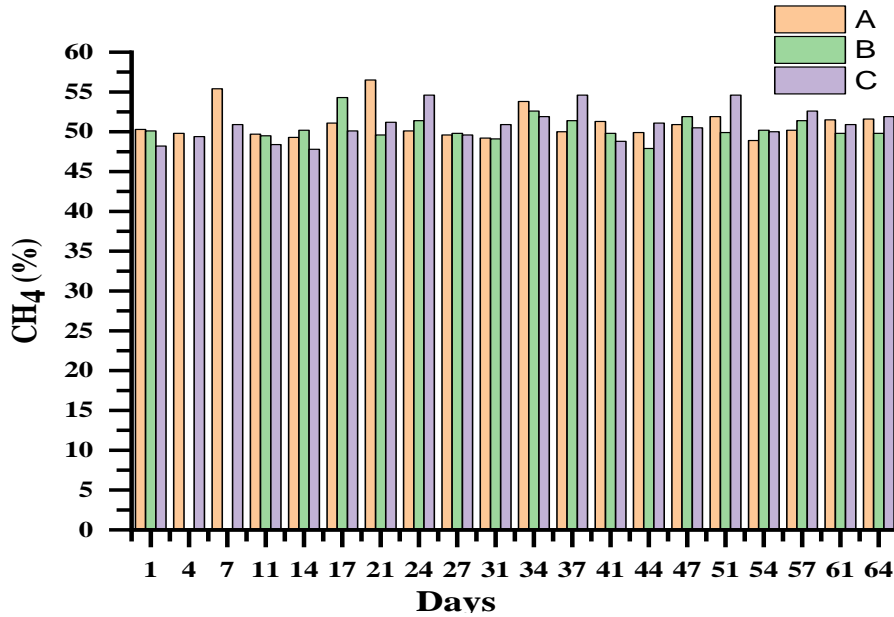


Figure 22. Methane percentage of the biogas generated from the digesters

Carbon dioxide (CO₂)

The carbon dioxide (CO₂) concentration of the produced biogas showed that it ranges between 45-50% in the three digesters. Figure 22 below shows the concentration of carbon dioxide produced in the anaerobic digesters.

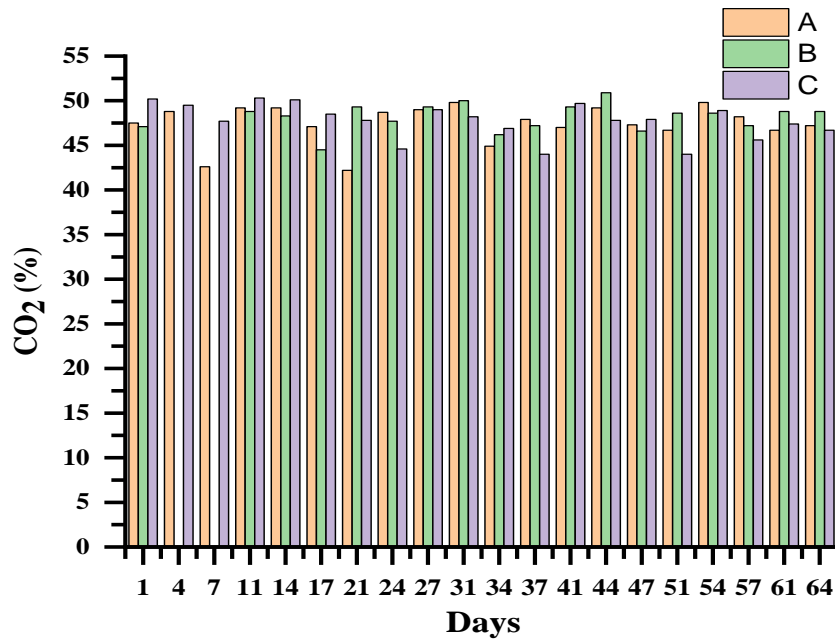


Figure 23. Carbon dioxide percentage of the biogas generated from the digesters

Hydrogen sulphide (H₂S)

According to the investigation the concentration of hydrogen sulfide significant variation in the digesters. The biogas produced from reactor C shows an average of 20.6 ppm of hydrogen sulfide, during time of sample collection period from the reactor C no smell (rotten egg) was detected, but reactor A showed a higher amount of hydrogen sulfide on average of 528 ppm and pungent (rotten egg) smell were detected throughout the experiment time. On the other hand reactor B showed an average of 144.5 ppm of hydrogen sulphide, in the Figure 23 below the concentration hydrogen sulphide in the digesters was illustrated.

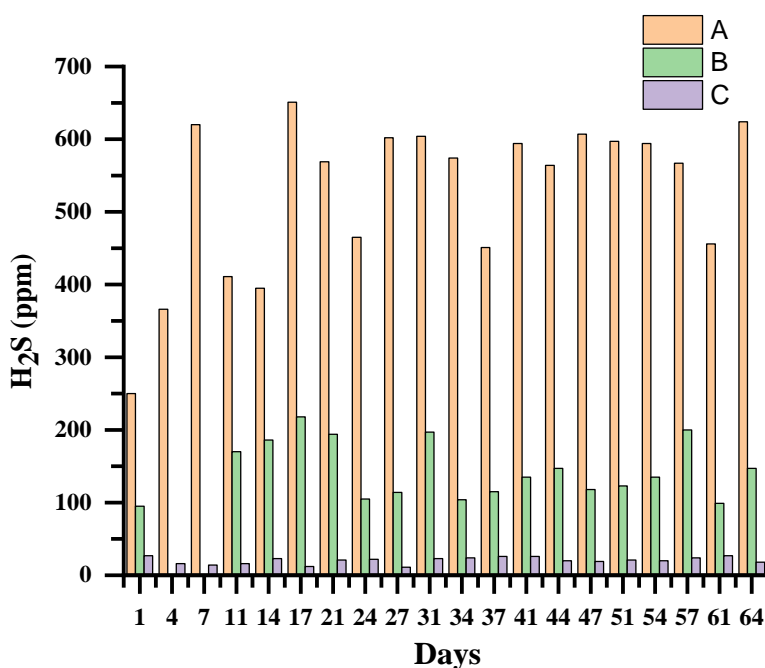


Figure 24. Hydrogen sulfide concentration of the biogas generated from digesters

The sulfur content of the feedstock A was higher compared to B and C and the concentration of sulfide sulfate in the water also higher in A, this may be the reason for the higher concentration of hydrogen sulfide in digester A. Peu et al [113] stated that the organic or inorganic sulfur concentration in the feedstock could have an effect in AD, it reduces the fermentation result by formation of dissolved sulphides which then transformed to biogas in the form of hydrogen sulphide gas. This leads to toxic, bad smell and cause corrosion in the appliances. Wellinger and Linberg, [114] stated that when the concentration of hydrogen sulphide of above (65–330 ppm) was harmful. The concentration of H₂S in digester A exceeded this limit, reached above 600 ppm, since digester A built recently despite its toxic and bad smell corrosion of appliances not observed. While in digester B worked for a long time it

negatively affect the appliance and corroded, especially the valves were broken on the time of investigation. The picture in the Figure 24 below shows the broken pipe while trying to maintain the corroded and stacked valve.

The amount of H₂S also impacts the methanogenic bacteria, [115],. The study also discovered that sulphur precipitation into the AD is reduced by chemically pretreating the substrate. However, the pre-treatment H₂S removal efficiency was just 75%. Although post-treatment is expensive to perform, it can lower H₂S by 95% but, it cannot mitigate its toxicity to methanogens.



Figure 25. The picture of broken pipe when trying to maintained the stacked valve

4.6.2. The volume of biogas produced during the AD process.

Daily household gas use for cooking (breakfast, lunch, and dinner), preparing tea, coffee, and milk, and boiling water for various purposes was used to compute the daily gas production. According to the data gathered only household B, uses the gas appropriately for cooking and lighting. A mainly used gas for lighting, with occasional usage for boiling water and milk. Household C utilized gas regularly for cooking purpose only, and the lamp when the electricity was off.

Institute "A" uses the gas in a biased manner because it is an institute, and nobody regularly monitored and feeds the influent to the reactor. Although when enough gas was generated, no one used it, and when it gets full, it pushes the feedstock back flow through the inlet, and sometimes it get unfed for a days and becomes lagged and no gas accessible at the time of observation. Due to excessive biogas produced in the case of reactor "C," consumers fed the reactor on a three days interval.

In all three reactors, the concentration of methane percentage in the biogas was lower, but the volume of gas produced was greater than what the owners needed, making up for the lower methane percentage in the biogas. $8m^3$ of reactor space may be sufficient for two homes with correct system management and regular feeding. The detail calculation was given in appendix II.

4.7. The concentration of metals in AD process

Influent contains light metal ions such as potassium, sodium, magnesium, and calcium. They might be released as organic material breaks down, or through introduced as chemicals for pH adjustment [116]. They are essential for microbial development and, as a result, affect a particular growth rate just like any other nutrient [117]. Despite the fact that moderate doses encourage microbial development, and excessive levels restrict it, and even greater concentrations can be poisonous or severely inhibit the AD [63]. In this investigation the concentration of light metals (such as calcium, magnesium, and potassium) in the influent obtained as 23.112 ± 0.018 , 10.316 ± 0.03 , and 7.45 mg/l, for digester A and 25.228 ± 0.021 , 10.188 ± 0.001 , and 6.521 mg/l for digester B, and 24.64 ± 0.011 , 10.231 ± 0.014 , and 7.34 for digester C respectively. This result proved that the concentration of these metals in the digesters not exceed the inhibitory level [55, 62, 63].

Excess concentration calcium may lead to precipitation of phosphate, and carbonate, this causes scaling on digesters, and pipes, deteriorate methanogenesis activity by scaling of biomass, and causes a buffer capacity loss and losses of important nutrients [118]. According Jackson-Moss et al. [119], statement the concentrations calcium up to 7000 mg/L had no inhibitory effect on AD, the value obtained in this study was too small to inhibit. Previous researches reported that the optimal concentration of magnesium for AD was between 400 to 720 mg/L [120], the result obtained in this study was below the optimal level. Studies shows that potassium concentration below 400 mg/l shows an enhancement in anaerobic digestion [121], the result found in this study shows a lower value than previous studies, the detail value was given in table 7.

4.8. Bio-Slurry Characterization

After anaerobic digestion, the leftover mixture of solution, and solids is known as digestate. The digestate is referred to as bio-slurry when manure is employed as the feedstock. The characteristics of the bio-slurry was determined and reported in Table 16 below. The dry matter obtained to be an average

of 6.58, 5.27, and 5.45%. The moisture content 93.42, 94.72, and 94.54% for A, B, and C respectively. The C/N ratio becomes 6.5, 6.8, and 6.6 for A, B, and C respectively this shows drop in 80.6, 81.7 and 81.7 % from the influent respectively. The COD concentration obtained to be 556 ± 2.5 , 524 ± 1.7 , and 453 ± 1.64 mg/l for A, B, and C respectively, according to previous studies [86], the values of COD, TS, and VS could be dropped below the values obtained in this study, this caused by improper feeding and process instability in the AD, and the sulfate reducing bacteria also affect the COD removal efficiency and consequently affect the methane production. The amount of nitrogen out of the reactor is approximately equal to the input.

Table 16. Characteristics of bio-slurry

Parameters	Unit	Sample A	Sample B	Sample C
Moisture content	%	93.42	94.72	94.54
Total solid	%	6.58	5.27	5.45
Volatile solid	%	62.9	75.63	54.80
Fixed solid	%	37.09	24.36	45.19
pH		6.5 ± 0.15	6.4 ± 0.2	6.8 ± 0.3
COD	mg/l	556 ± 2.5	524 ± 1.7	453 ± 1.64
Calcium	mg/l	$18.11.112\pm 0.003$	16.174 ± 0.005	18.22 ± 0.003
Phosphorus	mg/l	10.1938	10.758	11.244
Magnesium	mg/l	7.623 ± 0.011	7.554 ± 0.023	7.265 ± 0.013
Potassium	mg/l	9.194 ± 0.045	7.095 ± 0.02	8.46 ± 0.034
Carbon	%	6.89	7.536	7.31
Nitrogen	%	1.064	1.106	1.104
C/N Ratio		6.5	6.8	6.6
NH ₃	mg/l	1.36	0.61	0.8

4.9. Field Observation and User Side Management Problems

Based on the observations of the researcher the following user's side, management problems stated.

- ⇒ Lack of proper feeding causes a reduction on the volume of gas produces, and causes lag phase in the AD process.
- ⇒ Due to not using of the generated biogas, it cause higher accumulation in the digester, and resulted push back of the digestate with the inlet.
- ⇒ Blockage of the composite pit outlet causes a high accumulation of bio-slurry in the composite pit and causes crack in the pit (reactor A).
- ⇒ Due to higher pressure of the biogas the light bulb explodes.

- ⇒ Due to higher hydrogen sulphide concentration in the biogas, it causes corrosion on appliances, and valves stacks (reactor A and B).
- ⇒ Pipe breakage when trying to identify, and maintain the failed part of the pipe.
- ⇒ Improper mixing, and feeding leads to flow out undigested feedstocks and increases concentration of intermediate products.
- ⇒ Slurry management problem was observed in A and C.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study examined the performance of a three household level biogas plants in Holeta area, taking into account the characterization influent, and effluent, through investigation of process parameters (temperature, pH.), investigation of effects of inhabitants such as (volatile fatty acid, ammonia, alkalinity, sulfide, and metals), and bio-slurry as a fertilizer were examined. The theoretical methane percentage obtained in this study were 60% while the, actual methane percentage obtained to be is 51%, this shows 9% difference. The COD removal efficiency obtained to be 70.7%, the TS and VS removal efficiency becomes 37.7, and 26.7%, respectively which is lower comparative to other studies. The concentration of inhabitants becomes the reason for the drop of the methane production, the lowering alkalinity, and ammonia nitrogen level, and increment of VFA concentration. Higher concentration of sulfate affects the methanogenic bacteria through competition with sulfate reducing bacteria. The drop in alkalinity, pH and temperature level causes instability in the anaerobic digestion. The H₂S concentration in the biogas contained 651 ppm, caused by high sulfur content in the feedstock. The bio-digestate was, finally, assessed for its suitability for organic fertilizer use. The concentration of NPK is lower, blending with materials such as, banana peel, banana stalk, and cow urine could enhance the fertilizer potential of the digestate.

5.2. Recommendation

In order to improve the biogas production, the author suggested that:

- ⇒ The theoretical methane potential obtained in the study was lower as compared to other studies which can be improved by 10 to 15%, [122], through anaerobic co-digestion with an available organic materials, straws and agricultural residues.
- ⇒ The VFA concentration were higher, and the alkalinity, and ammonia nitrogen concentration were below the stimulating level this causes instability in the system. In order to maintain the VFA concentration, the alkalinity, pH and temperature level should be maintained, so the reactor surrounding should be free from trees to naturally maintain the temperature.
- ⇒ An increase in H₂S in the gas, and causes a pungent rotten like egg smell, a temperature, and pH control could improve the H₂S concentration.
- ⇒ The reactor's poor build quality leads the surrounding water to percolate inside it, which results in an excessive buildup of water in the reactors and disrupts the anaerobic digestion process.

- ⇒ Since most digester owners are not aware of the benefits of using bio-slurry as fertilizer, education and training for the digester owners is required in order to handle the bio-slurry properly, and to prevent the bio-slurry from flowing into the rivers, and harming the environment.
- ⇒ Excess production of manure were recorded in all cases, and they were producing dung cake in order to handle it, and the biogas production were also observed beyond the demand of the households this can be maintained by merging multiple households into a single reactor.

In order to further refine the current study, the following recommendations are suggested

- ⇒ The microbial analysis
- ⇒ At lab scale level, maintain the decreased pH, through addition of sodium hydroxide, calcium carbonate, or calcium hydroxide.
- ⇒ Anaerobic co-digestion with other organic materials.
- ⇒ Assessment, and characterization of the food that the cattle's feed.
- ⇒ Test on hydrogen sulfide content from digestate (sample inside the reactor)

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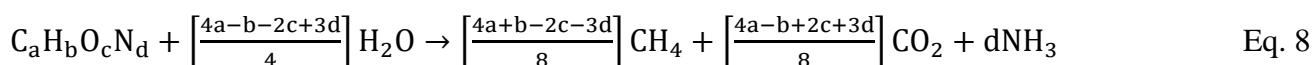
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APPENDIX

Appendix I. Theoretical methane percentage calculation

The theoretical methane percentage was determined using Buswell formula Eq. 8 [123]. The carbon, nitrogen percentage were measured in the laboratory, while the O, H & S concentrations was taken from literatures, [123, 124].



Ultimate analysis

		Elemental analysis (%)					
Code	Component	C	H	O	N	S	Ash
A	Cattle manure	36.5	5.86	38.68	1.184	0.37	17.4
B	Cattle manure	37.2	5.35	38.53	1.225	0.29	17.4
C	Cattle manure	37.4	5.91	37.47	1.27	0.25	17.7

Density of methane, and carbon dioxide

$$CH_4 = 0.657 \text{ kg/m}^3$$

$$CO_2 = 1.978 \text{ kg/m}^3$$

Percentage by weight in kg

		Composition (Kg)								
Code	Wet weight (kg)	MC (%)	Dry weight (kg)	Water (H ₂ O)	C	H	O	N	S	Ash
A	100	87.6	12.4	87.6	4.526	0.72664	4.79632	0.146816	0.04588	2.1576
B	70	84.5	10.85	59.15	4.0362	0.58048	4.180505	0.132913	0.031465	1.8879
C	70	86.3	9.59	60.41	3.58666	0.56677	3.593373	0.121793	0.023975	1.69743

In order to determine the oxygen and hydrogen pound in the dung sample the following formula were used;

$$H = \left[\frac{\text{Total moisture in kg}}{\text{molecular weight of water}} \right] \times \text{molecular weight of H}$$

Similarly for oxygen

$$O = \left[\frac{\text{Total moisture in kg}}{\text{molecular weight of water}} \right] \times \text{molecular weight of O}$$

The amount of Hydrogen and Oxygen should be added to the H and O in the sample when calculating chemical composition with water.

Theoretical methane potential determination for substrate A

Component	A				
	Weight (kg)		Atomic weight (g/mole)	Moles	
	W/O H ₂ O	W H ₂ O		W/O H ₂ O	W H ₂ O
C	4.526	4.526	12.01	0.3768526	0.3768526
H	0.72664	10.46	1.01	0.7194455	10.356409
O	4.79632	82.663	16	0.29977	5.1664367
N	0.146816	0.14682	14.01	0.0104794	0.0104794
S	0.04588	0.04588	32.07	0.0014306	0.0014306
Ash	2.1576	2.1576			

→ Determination of approximate chemical formula
Normalizing the mole ratio

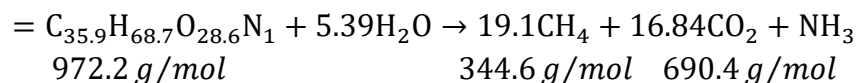
Component	Mole ratio (N=1)		Mole ratio (S=1)	
	W/O H ₂ O	W H ₂ O	W/O H ₂ O	W H ₂ O
C	35.961375	35.9614	263.419	263.42
H	68.653499	988.266	502.89055	7239.1
O	28.605722	493.01	209.53845	3611.3
N	1	1	7.3250535	7.3251
S			1	1

The chemical formula without sulfur

Without water = C_{35.9}H_{68.7}O_{28.6}N₁

$$\begin{aligned}
 & C_{35.9}H_{68.7}O_{28.6}N_1 + \left[\frac{(4 \times 35.9) - 68.7 - (2 \times 28.3) + (3 \times 1)}{4} \right] H_2O \\
 & \rightarrow \left[\frac{(4 \times 35.9) + 68.7 - (2 \times 28.3) - (3 \times 1)}{8} \right] CH_4 \\
 & + \left[\frac{(4 \times 35.9) - 68.7 + (2 \times 28.3) + (3 \times 1)}{8} \right] CO_2 + dNH_3
 \end{aligned}$$

→ Resulting Equation



→ Estimation of the amount of CH₄, and CO₂, which can be produced using the resulting equation

$$CH_4 = (344.6/972.2) \times 12.4kg = 4.39 kg$$

$$CO_2 = (690.4/972.2) \times 12.4kg = 8.8 kg$$

→ Converting the weight of gas to volume by dividing it's with density.

$$\text{CH}_4 = (4.39\text{kg}/0.657\text{ kg/m}^3) = 6.7\text{ m}^3$$

$$\text{CO}_2 = (8.8\text{kg}/1.978\text{ kg/m}^3) = 4.45\text{ m}^3$$

→ Percentage composition of the of the gas

$$\text{CH}_4(\%) = (6.7\text{ m}^3/(6.7\text{ m}^3 + 4.45\text{ m}^3)) \times 100\% = 60.01\%$$

$$\text{CO}_2 = (4.45\text{ m}^3/(6.7\text{ m}^3 + 4.45\text{ m}^3)) \times 100\% = 39.9\%$$

→ Theoretical biogas generation per kg of organic TS

$$(6.7\text{ m}^3 + 4.45\text{ m}^3)/12.4\text{ kg} = 0.89\text{ m}^3/\text{kg of organic TS}$$

Theoretical methane potential for feedstock B, and C were computed accordingly the result had given in table 10.

Appendix II. Biogas consumption back calculation

Daily gas consumption had been calculated (back calculation from the questioner and interview)

Breakfast

Total time used for cooking breakfast = cooking + tea/milk

Time for cooking = 40 min

Time for tea/milk = 20 min

Time used for cooking breakfast = 40 min + 20min = 60min = 1hr

Lunch

Total time used for cooking lunch = cooking + coffee + Water boiling

Time for cooking = 70 min (it may vary depending on food)

Time for coffee = 20 – 30 min

Water boiling for different purpose = 30 min

Hours used for lunch = 70 min + 30min + 30min = 130 min = 2.167 hr

NB: boiling water performed before or after the lunch, when hot water required for different purpose.

Dinner

Total hours used for cooking dinner = cooking + coffee

Time for cooking = 50 min

Time for coffee = 30 min

Hours used for cooking breakfast = 50 min + 30 min = 80 min = 1.33 hr

Total hours used per day by burner

Total hours used for cooking = For breakfast + for lunch + for dinner

Total hours used for cooking = 1hr + 2.167hr + 1.33hr

= 4.5 hr

Consumption of gas by burner per hour

Household burners consume approximately 200-450 liters of biogas per hour. (energypedia, [126]) an average value 325 liter per hour is taken for this study.

Volume of gas by burner = hours of used × burner consumption per hour

$$= 4.5 \text{ hr} \times 325 \text{ lit/hr}$$

$$= 1462.5 \text{ lit} = 1.46\text{m}^3$$

$$\text{Efficiency of burner} = 55\%$$

$$\text{Total volume of gas by burner} = 1.46\text{m}^3 + 0.653\text{m}^3$$

$$\underline{\underline{= 2.1\text{m}^3}}$$

Consumption of gas for lighting

$$\text{Gas consumption for lighting per day} = \text{Number of lamp} \times \text{operating time} \times 0.15 \text{ m}^3/\text{hr}$$

$$\text{Number of lamp} = 1$$

$$\text{Operating time} = 4\text{hr}$$

$$\text{Gas consumption for lighting per day} = 1 \times 4\text{hr} \times 0.15 \text{ m}^3/\text{hr} = 0.6 \text{ m}^3$$

$$\text{Efficiency of biogas lump} = 3\%$$

$$\text{Total volume of gas by lamp} = 0.6\text{m}^3 + 0.582\text{m}^3$$

$$\underline{\underline{= 1.282\text{m}^3}}$$

$$\text{Total gas consumption per day} = \text{gas for cooking} + \text{gas for lighting}$$

$$= 2.1\text{m}^3 + 1.182\text{m}^3$$

$$\underline{\underline{= 3.282\text{m}^3}}$$

For the calculation of the biogas demand Gas consumption of lamp and the consumption rate of gas burner are taken from energypedia [126] the burner used approximately 200 – 450 lit/hr of gas, and the lamp use a maximum of 0.15 m^3 . Efficiency of biogas stove, and biogas lamp taken in the calculation was 55 and 3% respectively [126].

Appendix III. Questioner for household digester owners

A. Location and General Information

- ✓ Area Name: _____
- ✓ Family Number: _____
- ✓ Bio digester Type: _____
- ✓ Year and date of Installation: _____
- ✓ Sex of respondent: Male Female
- ✓ Age of respondent
- ✓ Position as a family member: _____

B. Information about the reactor

- 1 Substrate used
 - a) Cow dung b) Pig dung c) Cow dung + toilet d) Grass
 - e) Waste materials f) If other _____
2. The number of cattle available?
 - a) 4 b) 5 c) 6 d) 7 e) >7
3. Type of feed for animals
 - a) Molasses b) Grass c) Fig d) Chid e) other_____
4. Source of water
 - a) Government pipe b) Pond c) Groundwater d) Stream
5. Distance to the water source
 - a) 10-30 meter b) 30-100 meter c) > 100meter d) Other _____
6. Size of the digester?
 - a) 4m³ b) 6m³ c) 8m³ d) 10m³
7. Loading interval?
 - a) Daily b) Twice a week c) Three times a week c) Weakly
8. What are the uses/purposes of biogas?
 - a) Cooking b) Lighting c) Electricity d) Other _____
9. A number of stoves available?
 - a) One b) Two c) Three d) No
10. A number of bulbs available?

- a) One b) Two c) Three d) No

11. Do you have connected to the grid?

- a) Yes b) No

C. Daily gas consumption?

		Breakfast	Lunch	Dinner	Tea/coffee	Milk	Boiling water	Lighting
12	Meals cooked per day							
13	Numbers of people consumed							
14	Times take to cooking							

D. What is the Existence/condition of the biogas plant and its system components?

No	Components	Condition			
		Bad (a)	Good (b)	Very good (c)	No Idea (d)
1	Inlet + mixer				
2	Outlet+ compensation				
3	Chamber				
4	Digester				
5	Dome				
6	Stirrer				
7	Water drain				
8	Gas flow meter				
9	Pressure gauge				
10	Gas pipe				
11	Main gas valve				
12	Hose pipe				
13	Stove				
14	Bulbs				

E. Bio-digester technical performance

1. Have you faced technical problems?

- a) Yes b) No

2. If the answer is yes for question number 1, what kinds of problems you have faced?

Type of problems	Frequency

--	--

3. Which components have frequently failed?
a) Pipes b) Valves c) Gauge d) _____
4. Who is responsible for fixing problems?
a) Yourself b) Area technical supporter c) NGOs d) Other _____
5. Have you experienced rotten egg-like smells from the biogas?
a) Yes b) No
6. If the answer is yes for question no 5, how frequently is that?
a) Every day b) Sometimes c) _____
7. Have you experienced the production of unburned gas?
a) Yes b) No
8. Are there any non-functional parts currently?
a) Yes b) No
9. If the answer is yes for question number 8 which part is non-functional?
a) Digester b) Pipelines c) Appliances d) If other _____

F. Bio-digester owner Satisfaction Level

10. What is your level of satisfaction?
a) Excellent b) Very Good c) Good Satisfactory d) Not happy
- Bio-slurry usage
11. For what purpose do you use the bio-slurry?
a) Used as fertilizer
b) Offered to others
c) Sold for money
d) Not used for any purpose
e) Other _____
12. Does the bio-slurry have a bad smell?
a) Yes b) No
13. If you use it as a fertilizer how did you use it?
a) As semi-solid bio-slurry b) after drying
14. If you use it as a fertilizer how much you are satisfied with it?
a) Excellent b) Very Good c) Good Satisfactory d) Not happy

Appendix VII. Field measurement results

Table: Daily field measurement data result

Date	Code	pH			Temperature (°C)		
		Influent pH	Digestate pH	Slurry pH	Influent Temp.	Digestate Temp.	Slurry Temp
D1	A	6.8	6.08	6.32	20.6	21.8	22
	B	6.4	6.14	6.05	19.1	18.5	18.8
	C	6.43	6.54	6.14	20.4	22.4	21.3
D4	A	6.9	6.34	6.47	17.15	19.4	17.6
	B	6.3	6.01	6.15	20.2	16.5	16.4
	C	6.54	6.8	7.1	21.3	20.5	18.4
D7	A	6.64	6.3	6.11	26.4	21.4	20
	B	6.12	6.2	5.98	24.7	20.2	20.2
	C	7.01	6.8	6.21	21.3	21.5	22.8
D11	A	6.66	6.15	6.21	26.7	25.4	22
	B	6.21	6.15	6.8	23.7	21.6	21.1
	C	6.4	6.24	6.12	22.4	20.9	24.14
D14	A	6.72	6.4	6.58	23.6	20.2	22.7
	B	6.18	6.2	6.3	21.8	19.7	19.2
	C	6.14	5.96	6.39	21	22.3	16.7
D17	A	6.8	6	6.22	24.4	20.7	22.2
	B	6.7	6.4	5.8	18.7	18.7	19
	C	6.1	6.2	6.2	19.6	16	21
D21	A	6.8	6.5	6.74	23.2	21.5	22.2
	B	6.9	6.4	6.84	20.5	18.7	20.4
	C	6.54	5.9	6.3	21.3	19.7	21.3
D24	A	6.7	6.4	6.94	23.4	20	21
	B	7.01	6.34	6.6	19	18.5	20.5
	C	6.2	6.5	6.21	21.2	20.1	22.2
D27	A	6.94	6.5	6.8	25.4	23.5	22.9
	B	7	6.7	6.9	22.4	19.5	18.9
	C	7.05	6.1	6.2	22.6	18	21
D31	A	6.8	6.22	6.18	23	22.5	22.2
	B	6.8	6.35	6.84	22.4	19.9	20.5
	C	6.92	6.5	6.8	20.5	19.6	19.6
D34	A	6.7	6.6	6.82	24.6	21.2	21.4
	B	6.81	6.4	6.3	23.2	18.54	20.3
	C	6.62	5.76	6.43	21	23.3	21.4
D37	A	6.9	6.8	6.7	23.7	22.4	23.1
	B	7.1	6.8	6.76	24.1	20.5	21.6

	C	7.02	6.91	6.6	22.1	23.1	24.5
D41	A	6.82	6.6	6.7	23.4	21.8	22.9
	B	6.9	6.7	6.9	22.4	20.8	21.4
	C	6.93	6.54	6.7	22.13	19.9	21.6
D44	A	6.78	6.43	6.31	26.4	21.4	20
	B	6.94	6.9	6.58	24.7	20.2	20.2
	C	7.01	6.8	6.61	21.3	21.5	22.8
D47	A	6.8	6.45	6.71	27.7	26.4	22
	B	6.71	6.55	6.48	24.7	24.6	21.1
	C	6.84	6.64	6.62	26.4	24.9	24.14
D51	A	6.68	6.63	6.31	26.4	21.4	20.4
	B	6.64	6.49	6.58	23.2	22.2	23.2
	C	6.91	6.34	6.43	27.4	26.4	24.8
D54	A	6.77	6.23	6.41	24.6	24.4	22.4
	B	6.21	6.65	6.47	27.4	23.1	21.4
	C	6.34	6.44	6.48	27.3	23.4	21.17
D57	A	6.67	6.64	6.54	24.47	22.7	23.5
	B	6.44	6.54	6.65	24.42	23.3	24.6
	C	6.14	6.27	6.47	26.74	25.5	25.5
D61	A	6.63	6.73	6.41	24.6	24.4	23.5
	B	6.24	6.25	6.47	25.4	23.1	21.4
	C	6.25	6.64	6.58	24.3	23.6	23.6
D64	A	6.84	6.64	6.31	26.4	21.4	22.6
	B	6.63	6.35	6.58	23.2	22.2	23.2
	C	6.76	6.23	6.43	27.4	26.4	24.8
D67	A	6.64	6.18	6.56	26.8	23.6	24.5
	B	6.47	6.69	6.29	26.6	25.4	22.6
	C	6.23	6.35	6.64	24.7	26.1	23.54

Appendix 5. Laboratory measurement results (MC, TS, VS and FS)

Days	Code	W(dish)	W2(D+S)	Wtotal.	Wvolatile	MC	TS	VS	FS
1	A Feedstock	28.7	68.8	33.0	29.6	89.4	10.6	79.4	20.6
	A Slurry	31.9	71.9	34.5	33.1	93.4	6.6	55.2	44.8
	B Feedstock	32.1	72.5	35.0	33.0	92.9	7.1	69.5	30.5
	B Slurry	31.3	63.0	32.6	32.2	95.8	4.2	33.3	66.7
	C Feedstock	31.9	71.9	35.4	32.5	91.2	8.8	81.1	18.9
	C Slurry	50.3	100.4	53.0	51.5	94.5	5.5	54.6	45.4
4	A Feedstock	28.7	68.7	30.9	29.9	94.4	5.6	45.2	54.8
	A Slurry	32.1	72.2	33.6	33.2	96.3	3.7	28.0	72.0
	B Feedstock	39.5	89.5	43.9	39.8	91.2	8.8	94.2	5.8
	B Slurry	31.3	71.7	33.8	32.1	93.9	6.1	68.8	31.2
	C Feedstock	31.9	71.9	35.2	32.3	91.7	8.3	87.8	12.2
	C Slurry	50.3	100.4	53.0	51.5	94.5	5.5	54.8	45.2
7	A Feedstock	28.7	68.8	31.9	30.0	92.1	7.9	58.9	41.1
	A Slurry	31.9	71.9	34.0	33.1	94.7	5.3	43.2	56.8
	B Feedstock	32.1	72.5	35.0	33.9	92.8	7.2	36.4	63.6
	B Slurry	31.3	63.0	33.0	32.7	94.7	5.3	16.0	84.0
	C Feedstock	39.5	79.5	42.8	40.0	91.7	8.3	84.5	15.5
	C Slurry	50.3	100.3	53.0	51.7	94.6	5.4	48.8	51.2
11	A Feedstock	28.7	68.8	32.9	29.6	89.5	10.5	77.1	22.9
	A Slurry	31.9	71.9	34.8	33.1	92.7	7.3	57.3	42.7
	B Feedstock	32.1	72.5	36.9	33.9	88.1	11.9	62.6	37.4
	B Slurry	31.3	63.0	33.9	33.0	91.8	8.2	33.2	66.8
	C Feedstock	39.5	79.5	42.9	39.9	91.6	8.4	86.5	13.5
	C Slurry	50.3	100.3	52.7	51.4	95.1	4.9	54.5	45.5
14	A Feedstock	28.7	68.8	32.1	30.0	91.5	8.5	61.5	38.5
	A Slurry	31.9	71.9	34.0	33.0	94.7	5.3	47.4	52.6
	B Feedstock	32.1	72.5	36.7	33.0	88.7	11.3	81.4	18.6
	B Slurry	31.3	63.0	33.2	32.2	93.9	6.1	54.9	45.1
	C Feedstock	39.5	79.5	42.7	39.9	91.9	8.1	88.4	11.6
	C Slurry	50.3	100.3	52.5	51.3	95.6	4.4	52.5	47.5
17	A Feedstock	28.7	68.8	33.0	29.5	89.2	10.8	82.0	18.0
	A Slurry	31.9	71.9	34.8	32.9	92.6	7.4	67.0	33.0
	B Feedstock	32.1	72.5	35.0	32.5	92.9	7.1	84.7	15.3
	B Slurry	31.3	63.0	32.8	31.9	95.2	4.8	62.4	37.6
	C Feedstock	39.5	79.5	43.0	40.0	91.3	8.7	86.7	13.3
	C Slurry	50.3	100.3	52.8	51.4	95.1	4.9	56.8	43.2
21	A Feedstock	28.7	68.8	33.0	29.6	89.3	10.7	79.6	20.4
	A Slurry	31.9	71.9	35.0	33.3	92.2	7.8	56.1	43.9
	B Feedstock	32.1	72.5	35.8	32.4	90.9	9.1	93.3	6.7

	B Slurry	31.3	63.0	33.0	31.9	94.7	5.3	63.7	36.3
	C Feedstock	39.5	79.5	42.3	40.0	92.9	7.1	83.2	16.8
	C Slurry	50.3	100.3	52.3	51.0	95.9	4.1	65.4	34.6
24	A Feedstock	28.7	68.8	32.5	29.5	90.6	9.4	78.6	21.4
	A Slurry	31.9	71.9	34.0	32.8	94.7	5.3	59.0	41.0
	B Feedstock	32.1	72.5	36.0	32.9	90.4	9.6	79.6	20.4
	B Slurry	31.3	63.0	32.9	31.9	94.9	5.1	63.0	37.0
	C Feedstock	39.5	79.5	42.7	40.0	91.9	8.1	84.5	15.5
	C Slurry	50.3	100.3	52.8	51.3	95.1	4.9	59.4	40.6
27	A Feedstock	28.7	68.8	32.6	29.8	90.3	9.7	72.2	27.8
	A Slurry	31.9	71.9	34.0	32.9	94.7	5.3	53.8	46.2
	B Feedstock	32.1	72.5	36.7	32.6	88.6	11.4	90.3	9.7
	B Slurry	31.3	63.0	33.0	31.9	94.8	5.2	66.4	33.6
	C Feedstock	39.5	79.5	41.7	39.9	94.4	5.6	83.8	16.2
	C Slurry	50.3	100.3	52.3	51.2	96.1	3.9	53.3	46.7
31	A Feedstock	28.7	68.8	33.2	29.3	88.7	11.3	86.9	13.1
	A Slurry	31.9	71.9	34.7	32.8	93.1	6.9	67.2	32.8
	B Feedstock	32.1	72.5	35.5	32.7	91.5	8.5	83.9	16.1
	B Slurry	31.3	63.0	32.7	31.8	95.7	4.3	61.3	38.7
	C Feedstock	39.5	79.5	43.0	40.0	91.2	8.8	85.8	14.2
	C Slurry	50.3	100.3	52.9	51.5	94.8	5.2	53.8	46.2
34	A Feedstock	28.7	68.8	32.5	29.1	90.4	9.6	87.9	12.1
	A Slurry	31.9	71.9	34.0	32.8	94.7	5.3	57.5	42.5
	B Feedstock	32.1	72.5	36.5	32.5	89.1	10.9	90.0	10.0
	B Slurry	31.3	63.0	32.9	31.9	95.1	4.9	65.8	34.2
	C Feedstock	39.5	79.5	42.8	39.3	91.6	8.4	107.1	-7.1
	C Slurry	50.3	100.3	52.5	51.0	95.7	4.3	68.0	32.0
37	A Feedstock	28.7	68.8	33.3	29.1	88.5	11.5	92.0	8.0
	A Slurry	31.9	71.9	34.4	32.8	93.8	6.2	61.2	38.8
	B Feedstock	32.1	72.5	35.5	32.3	91.7	8.3	92.7	7.3
	B Slurry	31.3	63.0	32.7	32.0	95.7	4.3	53.2	46.8
	C Feedstock	39.5	79.5	43.0	39.7	91.1	8.9	95.4	4.6
	C Slurry	50.3	100.3	52.7	51.4	95.3	4.7	51.7	48.3
41	A Feedstock	28.7	68.8	33.4	29.3	88.4	11.6	87.7	12.3
	A Slurry	31.9	71.9	34.6	32.9	93.3	6.7	62.3	37.7
	B Feedstock	32.1	72.5	35.7	32.4	91.1	8.9	93.0	7.0
	B Slurry	31.3	63.0	32.7	31.8	95.8	4.2	64.4	35.6
	C Feedstock	39.5	79.5	43.1	39.9	91.0	9.0	90.0	10.0
	C Slurry	50.3	100.3	52.7	51.4	95.3	4.7	54.7	45.3
44	A Feedstock	28.7	68.8	33.1	29.1	89.0	11.0	91.0	9.0
	A Slurry	31.9	71.9	34.6	32.8	93.2	6.8	66.3	33.7

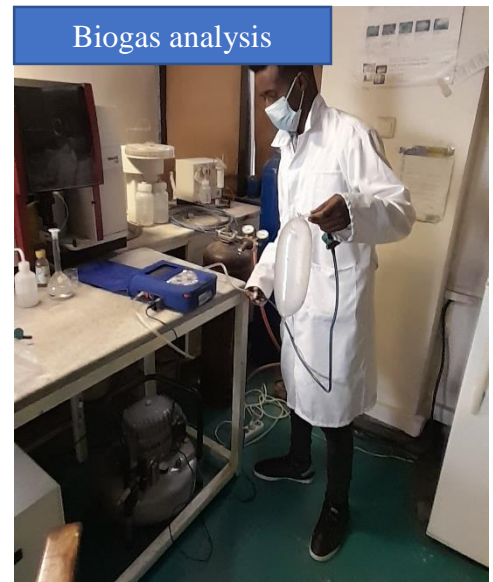
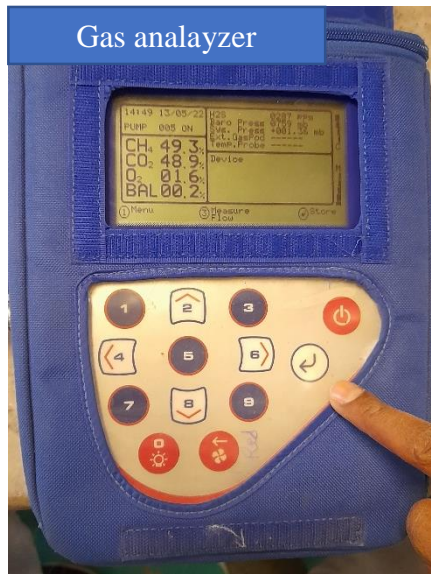
	B Feedstock	32.1	72.5	35.7	32.6	91.1	8.9	87.2	12.8
	B Slurry	31.3	63.0	32.7	31.9	95.6	4.4	60.6	39.4
	C Feedstock	39.5	79.5	43.1	39.7	90.9	9.1	95.6	4.4
	C Slurry	50.3	100.3	52.9	51.2	94.8	5.2	65.5	34.5
47	A Feedstock	28.7	68.8	33.2	29.3	88.7	11.3	86.9	13.1
	A Slurry	31.9	71.9	34.8	33.0	92.8	7.2	62.4	37.6
	B Feedstock	32.1	72.5	35.7	32.2	91.1	8.9	96.4	3.6
	B Slurry	31.3	63.0	32.7	31.9	95.5	4.5	62.6	37.4
	C Feedstock	39.5	79.5	43.0	39.5	91.2	8.8	99.9	0.1
	C Slurry	50.3	100.3	53.0	51.3	94.7	5.3	61.0	39.0
51	A Feedstock	28.7	68.8	33.0	29.0	89.2	10.8	92.6	7.4
	A Slurry	31.9	71.9	34.7	32.9	93.1	6.9	64.9	35.1
	B Feedstock	32.1	72.5	35.6	32.7	91.3	8.7	84.3	15.7
	B Slurry	31.3	63.0	32.7	31.9	95.7	4.3	58.8	41.2
	C Feedstock	39.5	79.5	43.9	39.4	89.0	11.0	102.2	-2.2
	C Slurry	50.3	100.3	52.9	51.1	94.9	5.1	68.6	31.4
54	A Feedstock	28.7	68.8	33.1	29.1	89.0	11.0	90.2	9.8
	A Slurry	31.9	71.9	34.7	32.9	93.1	6.9	63.4	36.6
	B Feedstock	32.1	72.5	35.8	32.9	90.9	9.1	78.9	21.1
	B Slurry	31.3	63.0	32.5	31.9	96.1	3.9	52.5	47.5
	C Feedstock	39.5	79.5	43.1	39.6	91.0	9.0	96.1	3.9
	C Slurry	50.3	100.3	52.7	51.1	95.2	4.8	64.4	35.6
57	A Feedstock	28.7	68.8	33.2	29.3	88.9	11.1	86.2	13.8
	A Slurry	31.9	71.9	34.6	32.8	93.2	6.8	64.5	35.5
	B Feedstock	32.1	72.5	35.7	32.2	91.1	8.9	97.8	2.2
	B Slurry	31.3	63.0	32.9	31.8	95.0	5.0	67.5	32.5
	C Feedstock	39.5	79.5	43.1	39.9	91.0	9.0	88.7	11.3
	C Slurry	50.3	100.3	52.9	51.4	94.8	5.2	56.0	44.0
61	A Feedstock	28.7	68.8	33.1	29.5	88.9	11.1	81.8	18.2
	A Slurry	31.9	71.9	34.7	32.9	93.1	6.9	63.5	36.5
	B Feedstock	32.1	72.5	35.7	32.4	91.2	8.8	93.0	7.0
	B Slurry	31.3	63.0	32.8	31.8	95.3	4.7	68.5	31.5
	C Feedstock	39.5	79.5	43.2	39.8	90.7	9.3	93.0	7.0
	C Slurry	50.3	100.3	52.9	51.2	94.8	5.2	66.9	33.1
64	A Feedstock	28.7	68.8	33.1	29.3	88.9	11.1	87.1	12.9
	A Slurry	31.9	71.9	34.6	33.0	93.1	6.9	60.7	39.3
	B Feedstock	32.1	72.5	35.4	32.8	91.9	8.1	78.8	21.2
	B Slurry	31.3	63.0	32.9	32.0	95.1	4.9	54.1	45.9
	C Feedstock	39.5	79.5	43.4	40.4	90.2	9.8	77.1	22.9
	C Slurry	50.3	100.3	52.4	51.2	95.9	4.1	56.2	43.8

Table: Laboratory gas analysis result

Day	Code	CH4 (%)	CO2 (%)	O2 (%)	BAL (%)	H2S (ppm)
1	A	50.3	47.5	0.66	1.1	250
	B	50.1	47.1	0.9	1.2	95
	C	48.2	50.2	0.5	0.7	27
4	A	49.8	48.8	0.9	0.3	366
	B	-	-	-	-	-
	C	49.4	49.5	0.7	0.3	16
7	A	55.4	42.6	0.7	1.2	620
	B	-	-	-	-	-
	C	50.9	47.7	0.7	0.6	14
11	A	49.7	49.2	0.7	0.2	411
	B	49.5	48.8	0.8	0.7	170
	C	48.4	50.3	0.8	0.4	16
14	A	49.3	49.2	0.5	0.8	395
	B	50.2	48.3	0.7	0.7	186
	C	47.8	50.1	0.8	1.2	23
17	A	51.1	47.1	0.6	1.1	651
	B	54.3	44.5	0.6	0.4	218
	C	50.1	48.5	0.5	0.7	12
21	A	56.5	42.2	0.7	0.5	569
	B	49.6	49.3	0.5	0.4	194
	C	51.2	47.8	0.7	0.2	21
24	A	50.1	48.7	0.9	0.2	465
	B	51.4	47.7	0.5	0.3	105
	C	54.6	44.6	0.6	0.1	22
27	A	49.6	49	0.5	0.7	602
	B	49.8	49.3	0.6	0.2	114
	C	49.6	49	0.6	0.7	11
31	A	49.2	49.8	0.7	0.1	604
	B	49.1	50	0.6	0.2	197
	C	50.9	48.2	0.4	0.3	23
34	A	53.8	44.9	0.4	0.7	574
	B	52.6	46.2	0.6	0.5	104
	C	51.9	46.9	0.8	0.2	24
37	A	50	47.9	0.8	0.6	451
	B	51.4	47.2	0.9	0.3	115
	C	54.6	44	0.6	0.6	26
41	A	51.3	47	0.7	0.8	594
	B	49.8	49.3	0.4	0.4	135
	C	48.8	49.7	0.7	0.7	26

44	A	49.9	49.2	0.3	0.4	564
	B	47.9	50.9	0.6	0.5	147
	C	51.1	47.8	0.3	0.6	20
47	A	50.9	47.3	0.7	0.9	607
	B	51.9	46.6	0.6	0.8	118
	C	50.5	47.9	0.7	0.8	19
51	A	51.9	46.7	0.7	0.5	597
	B	49.9	48.6	0.6	0.8	123
	C	54.6	44	0.6	0.6	21
54	A	48.9	49.8	0.5	0.6	594
	B	50.2	48.6	0.7	0.4	135
	C	50	48.9	0.5	0.5	20
57	A	50.2	48.2	0.7	0.8	567
	B	51.4	47.2	0.7	0.6	200
	C	52.6	45.6	0.9	0.8	24
61	A	51.5	46.7	0.7	0.9	456
	B	49.8	48.8	0.6	0.7	99
	C	50.9	47.4	0.7	0.9	27
64	A	51.6	47.2	0.7	0.4	624
	B	49.8	48.8	0.7	0.6	147
	C	51.9	46.7	0.5	0.8	18

Appendix VIII. Photos during the study





Lab testes



Oven



Dry sample



Biogas Burning



Biogas Burning

Improper bio-slurry management

