# MODELING OF BIOGAS PRODUCTION EFFICIENCY FROM DIFFERENT SOURCES OF WASTE BY ANAEROBIC DIGESTION

BY

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A DISSERTATION SUBMITTED TO THE DEPARTMENT OF CIVIL
ENGINEERING, POSTGRADUATE SCHOOL,
FEDERAL UNIVERSITY OF TECHNOLOGY, OWERRI

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE
AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY (PhD) IN CIVIL
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**JULY 2025**

# CERTIFICATION

This is to certify that this dissertation "Modeling of biogas production efficiency from different sources of waste by anaerobic digestion" was carried out by Udechukwu John Abaraogu (20194199708) in Partial fulfillment of the requirements for award of Doctor of Philosophy (PhD) in Water Resources Engineering in the Department of Civil Engineering, Federal University of Technology Owerri (FUTO).

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# DEDICATION

I dedicate this work to my Lord and Saviour Jesus Christ for counting me worthy and giving me the grace to carry out this research work.

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# LIST OF NOTATIONS FOR ABBREVIATIONS

| **Abbreviation** | **Full Form** |
|---|---|
| A | Maximum biogas production potential |
| AD | Anaerobic Digestion |
| ADM1 | Anaerobic Digestion Model No. 1 |
| BOD | Biochemical Oxygen Demand |
| BP | Biogas Production |
| C/N | Carbon to Nitrogen ratio |
| $CH_4$ | Methane |
| COD | Chemical Oxygen Demand |
| $CO_2$ | Carbon Dioxide |
| CSTR | Continuous Stirred-Tank Reactor |
| EC | Electrical Conductivity |
| ECN | Energy Commission of Nigeria |
| FAO | Food and Agriculture Organization |
| GHG | Greenhouse Gas |
| $H_2O$ | Water (as vapor) |
| $H_2S$ | Hydrogen Sulfide |
| I | Industrial Wastewater or Influent |
| INDC | Intended Nationally Determined Contribution |
| Ks | Monod constant (half-saturation constant) |
| $\lambda$ | Lag time |
| MC | Maize cob |
| MBR | Membrane Bioreactor |
| MFC | Microbial Fuel Cell |
| MSK | Modified Stover-Kincannon |
| MSW | Municipal Solid Waste |
| $NH_3$ | Ammonia |

| | |
|---|---|
| $N_2$ | Nitrogen |
| OFMSW | Organic Fraction of Municipal Solid Waste |
| P | Atmospheric pressure (kPa) |
| PD | Pig waste |
| PM | Pig dung and maize cob |
| PMW | Pig dung, maize cob and water hyacinth |
| PSA | Pressure Swing Adsorption |
| PW | Pig dung and water hyacinth |
| R | Biogas production rate (in modeling equations) |
| S | Substrate concentration |
| SS | Sewage Sludge |
| SSTS | Subsurface Sewage Treatment Systems |
| T | Temperature (°C) |
| TDS | Total Dissolved Solids |
| TK | Total Potassium |
| TN | Total Nitrogen |
| TOC | Total Organic Carbon |
| TP | Total Phosphorus |
| TS | Total Solids |
| TSS | Total Suspended Solids |
| U.M. | Unit of Measurement |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VFA | Volatility Fatty Acid |
| VS | Volatile Solids |
| VSS | Volatile Suspended Solids |
| WH | Water hyacinth |
| WWTP | Wastewater Treatment Plant |
| X | Biomass concentration |
| $\mu$, $\mu_{max}$ | Specific and maximum specific growth rates |

# ABSTRACT

This research focused on the modeling of biogas production efficiency from different sources of waste using anaerobic digestion. The objectives of the work are to determine the biogas production capacities of the selected feedstocks (organic wastes), determine the compositions of the biogas produced, and derive/validate a model that optimizes the biogas production. The process of producing the biogas from the mini-biodigester involves sourcing the feedstocks, mixing them with water to a suitable proportion, pouring the slurry mixture into the mini-biodigester while ensuring that the mini-biodigester is airtight, and allowing anaerobic bacteria to break down the waste. The study was conducted in a controlled laboratory environment employing mini-biodigesters with capacities of 120 and 40liters respectively. Four different feedstocks—sewage, pig waste, poultry waste, and homemade waste (a mixture of watermelon and pineapple)—were used as substrates to feed the biodigesters singly and in various combinations. The experimental results over a 14-day peak production periods indicated average daily biogas production rates of 0.0329, 0.0372, 0.0354, 0.0296, 0.0344, 0.0336, 0.0362,0.0356, 0.0328, 0.0319, 0.0384, 0.0332, 0.0326, 0.0340 and 0.0381 liters per day for the following substrate samples: Sample 1, Sample 2, Sample 3, Sample 7, Sample 8, Sample 9, Sample 10, Sample 11, Sample 12, Sample 13, Sample 14, and Sample 15 respectively. The percentage methane content in the biogas produced from these substrates (Samples) was found to be 54.80%, 58.70%, 56.60%, 51.70%, 68.10%, 66.84%, 68.20%, 69.18%, 66.24%, 64.98%, 65.50%, 68.04%, 65.24%, 66.50% and 66.73%, respectively. To optimize biogas production, a mathematical model was formulated with the variables X1, X2, X3, and X4 subjected to retention time, moisture content, carbon/nitrogen, temperature, and pH constraints. The Simplex Method was employed to solve the model, resulting in an objective function value of 2.6669. The optimal values of the variables were X1 = 0.0075, X2 = 1.1981, X3 = 0.0027, and X4 = 0.0227, indicating the most efficient combination of feedstocks for biogas production. The developed optimization model serves as a valuable tool for maximizing biogas yields using small scale biodigester in an anaerobic environment, thereby contributing significantly to the field of renewable energy and environmental sustainability.

**Keywords:** Anaerobic digestion, biogas production, methane content, sewage waste, pig waste, poultry wastes, watermelon wastes, pineapple wastes, mini-biodigester, optimization model.

# CHAPTER ONE

# INTRODUCTION

## 1.1 BACKGROUND INFORMATION

The use of biogas for energy production has a long and fascinating history that dates back to ancient civilizations. While biogas technology as we know it today emerged in the 19th and 20th centuries, its origins can be traced to much earlier periods (Nabuuna, and Okure. 2005). The first documented observations of biogas production occurred around the 10th century BCE in Assyria, where decaying organic matter was noted to produce flammable gases. In the 17th century, Jan Baptista Van Helmont, a Flemish chemist, documented the combustible nature of gas emitted by decomposing organic materials. These early observations set the stage for understanding the potential of biogas as an energy source (Bajpai, 2021).The scientific study of biogas began in earnest during the 17th and 18th centuries. In 1776, Alessandro Volta, the Italian physicist, was the first to identify a quantitative relationship between decaying organic matter and the production of combustible gas. This discovery laid the groundwork for future research on biogas production.

In 1808, Sir Humphry Davy demonstrated that methane was a major component of biogas, derived from cattle manure. His work confirmed the energy potential of biogas and marked the beginning of its systematic study as a renewable energy source (Faaij, 2020). The first practical applications of biogas production were developed in the 19th century. In 1859, the first anaerobic digester was built in Bombay (modern-day Mumbai), India, to manage waste and produce gas for heating and lighting. By 1895, biogas produced from sewage treatment was used to light streetlamps in Exeter, England. These early adopters demonstrated the feasibility of biogas as an energy source and waste management solution (Zhou, He, & Wu, 2020). The development of modern biogas technology began in the mid-20th century, spurred by global energy crises and the need for sustainable waste management solutions. During the 1970s, biogas systems became a focus of research and development, particularly in developing countries where decentralized energy solutions were needed. Today, biogas technology is recognized as a critical component of renewable energy systems, with applications ranging from small-scale household digesters to large-scale industrial plants (Kinyua, Wanyoike & Ngugi, 2019).

The feedstock used for biogas production plays a critical role in determining the efficiency, yield, and quality of biogas. Feedstocks vary in terms of chemical composition, degradability, and availability. Understanding these characteristics is essential for optimizing biogas production and ensuring the sustainability of biogas systems. Biogas feedstocks are broadly categorized into agricultural residues, livestock manure, municipal solid waste (MSW), industrial organic waste, and energy crops. Each type has unique characteristics that influence its suitability for biogas production. Agricultural residues, such as crop stalks, husks, and leaves, are commonly used feedstocks for biogas production. These residues are abundant and inexpensive, making them ideal for large-scale biogas systems. However, they often contain high lignocellulosic content, which can reduce degradability and require pre-treatment to improve biogas yield (Siddique, Zahoor & Khokhar, 2021). Livestock manure is a widely used feedstock for biogas production due to its high biodegradability and availability. Manure typically contains a balanced mix of nutrients and microorganisms that facilitate anaerobic digestion. However, its high moisture content can dilute biogas yields, and it is often co-digested with other feedstocks to enhance efficiency (Onwosi, Chikere, & Ibhafidon, 2019). Municipal solid waste, including food waste and other organic fractions, is a valuable feedstock for biogas production. It is rich in biodegradable materials but often requires sorting and pre-treatment to remove non-organic contaminants. MSW is especially important in urban areas where waste management is a challenge (Kinyua et al., 2019). Industrial organic waste, such as waste from food processing and breweries, is another significant feedstock. These wastes are often high in organic content and readily biodegradable, making them ideal for biogas production. However, the presence of inhibitors such as fats, oils, and grease can affect the efficiency of anaerobic digestion (Pereira, Silva, & Costa, 2018). Dedicated energy crops, such as maize silage and grass, are used as feedstocks in regions where agricultural residues and waste materials are insufficient. These crops have a high energy yield per hectare but can compete with food crops for land use, raising concerns about food security (Faaij, 2020). The C/N ratio is a critical factor in maintaining the balance of microorganisms in the digester. An optimal C/N ratio (20–30:1) ensures efficient digestion. Feedstocks with a low C/N ratio, such as livestock manure, are often co-digested with high-carbon materials, such as crop residues, to achieve balance (Bajpai, 2021). Feedstocks with high lignin and cellulose content, such as crop residues, are less biodegradable and require pre-treatment to enhance digestibility. Pre-treatment methods, including mechanical, chemical, and biological processes, can break down lignocellulosic structures and improve biogas yields (Siddique et al., 2021). The moisture content of feedstocks affects the consistency of the substrate and the efficiency of anaerobic digestion. Feedstocks with very high moisture content, such as livestock manure, may dilute the digester contents and reduce biogas yield. Balancing moisture levels through co-digestion with drier materials is a common practice (Onwosi Nwosu & Ekwe, 2019). Certain feedstocks may contain inhibitors such as ammonia, sulfides, or heavy metals, which can negatively impact microbial activity. Understanding and mitigating these inhibitors is essential for maintaining stable biogas production (Pereira et al., 2018). To optimize biogas production, feedstocks often undergo pre-treatment to improve their biodegradability and enhance methane yield. Common pre-treatment methods include:

i. **Mechanical Pre-treatment:** Shredding or grinding feedstocks to reduce particle size and increase surface area.

ii. **Chemical Pre-treatment:** Using acids, alkalis, or enzymes to break down lignocellulosic materials.
iii. **Thermal Pre-treatment:** Heating feedstocks to disrupt complex organic structures.
iv. **Biological Pre-treatment:** Using microbial or enzymatic treatments to degrade resistant materials (Siddique et al., 2021).

## 1.2 PROBLEM STATEMENT

The two major problems that are increasingly threatening the good life of many developing and under-developed nations are the issues of inadequate and inefficient waste management systems, as well as severe shortage of energy supply. Waste not well disposed-off, is a major cause of environmental pollution capable of resulting in environmental hazards. Such hazards range from contamination of groundwater to air pollution.

For most parts of the world, fossil fuels constitutes the primary source of energy production and have been used for centuries to generate power (Courtney and Dorman. 2003); but there are many disadvantages associated with their use. These are as follows:

i. Fossil fuels pollute the environment,
ii. Fossil fuels are non-renewable and unsustainable,
iii. Drilling for fossil fuels is a dangerous process, etc.

The production of biogas, a renewable and sustainable energy source, has gained significant attention as an alternative to fossil fuels and can serve as a very great tool for the efficient management of the different types of waste (Nzeadibe, Olorunfemi, & Adefolalu, 2018). However, several challenges and limitations exist in the current biogas production processes, which hinder its widespread adoption and efficient utilization. Such problems include the following:

i. Feedstock selection and pre-treatment for optimum yield of biogas.
ii. Process optimization and small reactor design for family use.
iii. Digestate management and environmental impact.

There is need to address these challenges to optimize biogas production and improve its overall efficiency.

## 1.3 OBJECTIVES OF THE STUDY

The main objective of this work is modeling of biogas production efficiency from different sources of waste by anaerobic digestion.

The specific objectives are as to:

i. Determine the biogas production capacity of each of the selected feedstocks as well as the capacity when the feedstocks are combined.
ii. Determine the compositions of the biogas produced.
iii. Derive an optimization model that determines the optimum combinations of the selected feedstocks.
iv. Calibrate and verify the developed model.

## 1.4 JUSTIFICATION OF STUDY

The following are the justifications for this research work:

a. Renewable Energy Source: Biogas is a renewable energy source that can be produced from various organic waste materials such as animal manure, food waste, and sewage sludge. It can be used as a substitute for fossil fuels like coal, oil, and natural gas, which are finite resources and are harmful to the environment during their extraction process or when they are burned.

b. Greenhouse Gas Emissions Reduction: Biogas production can help reduce greenhouse gas emissions, particularly methane. Methane is a potent greenhouse.

gas that contributes to global warming (Jaynes, 2009).. When organic waste materials decompose in landfills or open pits, they release methane into the atmosphere. Biogas production can capture this methane and convert it into a useful energy source, reducing greenhouse gas emissions and mitigating climate change.

c. Waste Management: Organic waste materials, if not managed properly, can pose environmental and health hazards. They can contaminate water sources, emit foul odors, and attract pests. Biogas production provides an efficient and sustainable method of managing organic waste materials, as it not only produces energy; but also reduces waste volumes and eliminates the need for traditional waste disposal methods.

d. Economic Benefits: Biogas production can provide economic benefits to communities, particularly in rural areas. It can create jobs, generate income, and reduce energy costs for households and businesses. Additionally, biogas production can help reduce reliance on imported fossil fuels, which can improve energy security and reduce dependence on volatile global energy markets.

## 1.5 SCOPE OF STUDY

The scope for this study covers the analysis of biogas production capacities for individual and combined feedstocks (the four feedstocks used were as follows: sewage, pig waste, poultry waste, and homemade waste - a mixture of watermelon and pineapple), an assessment of the biogas compositions and qualities, an optimized mathematical model for maximizing the biogas production, and the calibration and verification of the model's accuracy. The research was limited to the use of mini-biodigesters with capacities of 60 and 120-liter capacities. The experiments were conducted in a controlled laboratory environment.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 BIOGAS PRODUCTION TECHNOLOGIES AND TECHNIQUES

Biogas production is primarily achieved through anaerobic digestion (AD) (Hernandez, Garcia, & Sandoval. 2015), where microorganisms break down organic matter in the absence of oxygen. While anaerobic digestion remains the primary biogas technology, various reactor designs and operational techniques have been developed to optimize the process, improve yields, and enhance efficiency. These technologies can vary depending on the scale of operation, the type of feedstock used, and the desired outcome. Anaerobic digestion occurs in specialized bioreactors that create optimal conditions for microorganisms to decompose organic materials. The main types of anaerobic digesters used for biogas production include batch digesters, continuous stirred-tank reactors (CSTR), plug-flow digesters, and membrane reactors.

i. **Batch Digesters**: In this system, feedstock is added in one go and allowed to digest over a set period. The process continues without the addition of new substrate until the batch is complete. Batch digesters are simple and cost-effective, making them suitable for smaller-scale applications. However, they may not be the most efficient for continuous or large-scale production due to their time-consuming nature (Tomei, Liu and Zhang 2019).

ii. **Continuous Stirred-Tank Reactors (CSTR)**: The CSTR is one of the most widely used systems for biogas production, especially in large-scale operations. This system allows for continuous feedstock input and biogas output. The reactor has a stirring mechanism that keeps the substrate well-mixed to enhance microbial activity. CSTRs offer good flexibility in terms of feedstock type and can operate at various temperatures and loading rates, making them suitable for both industrial and agricultural waste (Bajpai, 2021). The advantage of CSTRs is their ability to provide consistent gas yields, but they also require careful management of parameters like pH and temperature to ensure optimal microbial activity.

iii. **Plug-Flow Digesters**: In plug-flow digesters, the substrate moves through the reactor in a linear direction. These digesters are best suited for feedstocks with high solid content, such as manure, crop residues, and other fibrous organic materials. The substrate is gradually converted to biogas as it flows through the system, with little or no mixing. While plug-flow digesters can be more efficient than batch digesters for solid feedstocks, they require precise management to avoid the formation of blockages and ensure uniform flow (Sprecher, Muench & Sych, 2020).

iv. **Membrane Reactors**: Membrane bioreactors (MBRs) combine biological treatment with filtration technologies. They are used in some biogas production processes to separate methane from the biogas mixture after digestion. This technique improves the methane concentration in the biogas produced and allows for higher energy yields from the same volume of gas (Kim, Jung & Koo, 2021). Membrane reactors are more complex and expensive than traditional systems but provide higher efficiency, especially for biogas upgrading and purification.

Biogas is a renewable, high-quality fuel, which can be produced from a lot of different organic raw materials and be used for various energy services. Biogas technology has been developed and widely used around the world, because it has a lot of advantages, including reducing the dependence on non-renewable resources; high energy efficiency; preventing environmental pollution; available and cheap resources to feedstock; relatively easy and cheap technology for production; and extra values of digestate as fertilizer, etc. But the status of biogas production and utilization largely varies among the different continents. Biogas is produced when microorganisms degrade organic materials in the absence of oxygen (Van-Nes and Nhete, 2007).

Biogas can be used as fuel for heating, cooking, and electricity generation. It can be burned directly in boilers and engines or upgraded to natural gas quality and injected into the gas grid. Biogas is considered a renewable energy source because the organic matter used to produce biogas can be replenished through agricultural and food waste streams (Jorgensen, 2009). The production of biogas has several environmental benefits, such as reducing greenhouse gas emissions, providing a sustainable waste management solution, and contributing to energy independence. However, the production of biogas also requires careful management to ensure proper operation of the anaerobic digestion process and to prevent environmental impacts such as odor emissions and nutrient runoff (Van Nes et al., 2007).

This process of producing Biogas is known as anaerobic digestion and it produces a gas mixture that is composed primarily of methane ($CH_4$) and carbon dioxide ($CO_2$), with small amounts of other gases such as hydrogen sulfide ($H_2S$) and ammonia ($NH_3$). The feedstock can derive from agricultural, industrial, or municipal sources. To date, to obtain a higher biogas yield, a lot of agricultural biodigesters digest manure with some additional co-substrates for increasing the content of organic materials. Besides input materials, biogas yield and anaerobic processes are affected by several other factors. There are a lot of different types of biodigesters all over the world, and they are accepted and widely used by different countries. For example, floating drums and fixed dome biodigesters are two major types of small to medium-scale biogas digesters used in African countries.

The microscopic organism that produces biogas is known as Archaea. Archaea are among the oldest life forms on Earth. They are much less oxygen-breathing and $CO_2$-absorbing plant life that preexisted on planet Earth 3.5 billion years ago. They are not bacteria but are genetically closer to humans and other animals (eukaryotes) and form their own animal kingdom. As the earth's atmosphere became predominantly oxygen about 500 million years ago, Archaea became isolated in the few remaining airless places, such as stagnant swamps, deep oceans, caves, hot springs, and of course the stomachs of vertebrates. To create biogas, the conditions in which Archaea thrive in nature must be recreated. Biogas is reproduced in a special air-tight tank called an anaerobic digester (Van Nes et al., 2007).

Natural biodegradation of organic matter contributes approximately 590-800 million tons of methane to the atmosphere (Bond and Templeton, 2011). Wastewater and landfills constitute 90% of waste sector emissions and about 18% of global anthropogenic methane ($CH_4$) emissions (Bogner, Pipatti, Hashimoto, Diaz, Mareckova, Diaz, Kjeldsen, Monni, Faaij and Gao, 2008). Methane ($CH_4$) which has a high potential for global warming can either be tapped or released freely into the atmosphere. The latter situation takes place when organic matters are illegally disposed of or thrown away in vacant places. The tapped methane (Biogas) is used as a source of energy, while the un-tapped methane is very harmful to the environment (Bond et al., 2011).

Anaerobic digestion is the process and technique of decomposition of organic matter by a microbial process in an oxygen-free environment (FAO, 1996). Controlled anaerobic digestion of organic waste has multiple benefits. On the one hand, it provides a renewable source of clean energy, while on the other side; the digestates can be used as organic fertilizers in the agriculture sector (Vasudeo, 2005). The electricity and fuel production from the biogas might strengthen the national energy supply, as well as reduce greenhouse gas (GHG) emissions (Yadvika, Sreekrishnan, Kohli and Rana, 2004).

### 2.1.1 Advantages and Disadvantages of Biogas

The following are the Advantages of Biogas:

i. Renewable energy source: Biogas is a renewable energy source that is produced from organic waste materials such as agricultural waste, food waste, and sewage sludge, among others.
ii. Reduced greenhouse gas emissions: Biogas production helps to reduce greenhouse gas emissions as it captures and utilizes methane that would otherwise be released into the atmosphere, which is a potent greenhouse gas.
iii. Waste management: Biogas production can help to address waste management issues, as it provides a way to convert organic waste into a useful energy source and reduce the amount of waste sent to landfills.
iv. Localized energy production: Biogas production can be done at a local scale, reducing the need for long-distance transportation of fuel, and promoting energy independence.
v. Multiple uses: Biogas can be used for a variety of applications such as heating, electricity generation, and transportation fuel.

The following are the Disadvantages of Biogas:

i. Initial cost: The initial cost of setting up a biogas production system can be high, which can make it unaffordable for some individuals or communities.
ii. Feedstock availability: The availability of suitable feedstocks for biogas production can be limited, particularly in urban areas.
iii. Energy intensity: The process of producing biogas requires energy inputs, particularly for the operation of pumps and other equipment, which can offset some of the energy benefits of biogas production.
iv. Maintenance requirements: Biogas production systems require regular maintenance and monitoring to ensure efficient operation, which can be time-consuming and expensive.

Odor and other environmental impacts: Biogas production can produce odors and other environmental impacts, particularly if not properly managed (Sialve, Bernet and Bernard 2009).

### 2.1.2 History of Renewable Energy

The history of renewable energy, dates back thousands of years, when humans first began to harness the power of the wind, water, and sun to grind grains, pump water, and dry crops. Ancient civilizations used wind and water to power grain mills and other machinery. The ancient Greeks and Romans also used passive solar design in their buildings.

i. In the 8th century, the Chinese developed the first windmill, which was used to pump water and grind grain.
ii. In the 19th century, hydropower became a major source of energy as water wheels were used to power factories and mills.
iii. In the late 1800s, solar power was used to produce steam to power engines and generate electricity.
iv. In the early 20th century, the first wind turbines were developed for electricity generation. The first geothermal power plant was also built in Italy in 1904.
v. In the mid-20th century, the use of renewable energy declined as fossil fuels became cheaper and more widely available.
vi. In the 1970s, the oil crisis and growing concerns about pollution and climate change sparked renewed interest in renewable energy. Governments and organizations around the world began investing in renewable energy research and development.
vii. In the 1980s and 1990s, wind and solar power became more cost-effective and began used on a larger scale.

viii. In the 2000s and 2010s, renewable energy continued to grow rapidly, driven by falling costs, government incentives, and public demand for cleaner energy sources. Today, renewable energy accounts for a significant and growing share of global energy production. However, many countries have set ambitious targets for increasing their use of renewable energy in the coming years.

### 2.1.3 Biogas in Nigeria

Nigeria has considerable potential for biogas production due to its large agricultural sector, high livestock population, and substantial volumes of organic waste generated from municipal solid waste and food processing industries. The adoption of biogas technology in Nigeria is still at a relatively early stage but is gradually gaining traction, particularly in rural areas where waste management practices are limited, and access to energy is scarce. The availability of feedstocks is one of the major factors that influence biogas production in Nigeria. Agricultural residues, including rice husks, maize stover, and sugarcane bagasse, are abundant and provide a significant source of organic matter for biogas generation. Similarly, livestock manure, particularly from cattle, poultry, and pigs, is widely available, particularly in rural areas where farming and animal husbandry are the primary economic activities (Akinbomi, Adewumi & Okorie, 2020). Additionally, municipal solid waste (MSW) is a significant potential feedstock for biogas production in Nigerian urban centers. The rapid urbanization in Nigeria has led to increased waste generation, and the organic fraction of MSW presents an opportunity for waste-to-energy projects (Kinyua et al., 2019).

In Nigeria, biogas production is primarily practiced on a small scale, with a few pilot projects implemented by local and international organizations. Many of these projects aim to address both waste management and energy supply challenges, particularly in off-grid rural areas.

- **Rural Biogas Projects**: In rural areas, biogas systems are often implemented as part of integrated waste management systems that aim to reduce reliance on traditional biomass (e.g., firewood and charcoal) while providing a cleaner and more sustainable source of energy. These systems are generally small-scale, family-based digesters that use agricultural residues, animal manure, and kitchen waste as feedstocks (Onwosi et al., 2019).
- **Biogas from MSW**: In urban centers, some initiatives are beginning to focus on biogas production from municipal solid waste, particularly in Lagos and other major cities. These projects are typically aimed at reducing the volume of waste going to landfills and providing renewable energy for local use (Kinyua et al., 2019).

Despite the considerable potential for biogas production in Nigeria, several challenges hinder widespread adoption of this technology:

- **Lack of Infrastructure and Funding**: Many rural areas in Nigeria lack the necessary infrastructure to support large-scale biogas production, including reliable waste collection systems, digesters, and upgrading technologies. Furthermore, the high upfront costs associated with biogas projects are a significant barrier, particularly in a country with limited access to financing and technical expertise (Akinbomi et al., 2020).
- **Technical Capacity and Knowledge**: There is a lack of technical capacity and expertise in biogas technology among local stakeholders. This limits the ability to design, build, and maintain biogas plants effectively. Training and capacity-building programs are essential to ensure that biogas projects are operated efficiently and sustainably (Bajpai, 2021).
- **Regulatory and Policy Support**: Although biogas production offers significant environmental and economic benefits, the lack of a comprehensive national policy

framework for renewable energy, including biogas, is a barrier to large-scale development. Policy support and incentives are necessary to encourage private sector investment and foster the growth of the biogas industry (Pereira et al., 2018).

According to a research work by Akinbami et al. (2001), Renewable energy has a long history in Nigeria, with traditional sources such as biomass and hydropower being used for centuries. However, the modern renewable energy industry in Nigeria began to take shape in the 1990s, when the government launched several initiatives to promote the use of renewable energy sources. In 1990, the Nigerian government established the Energy Commission of Nigeria (ECN) to promote and coordinate the development of renewable energy and energy efficiency in the country. The ECN has played a key role in promoting renewable energy in Nigeria through research, development, and demonstration projects. In the early 2000s, the Nigerian government introduced policies and incentives to encourage the use of renewable energy, including a feed-in tariff for solar power and tax breaks for renewable energy investments. However, progress in the renewable energy sector was slow, due to limited funding, lack of political will, and a challenging business environment. In recent years, there has been renewed interest in renewable energy in Nigeria, driven by a growing demand for electricity, the declining cost of renewable energy technologies, and increasing concern about the environmental and health impacts of fossil fuels. In 2015, Nigeria submitted its Intended Nationally Determined Contribution (INDC) to the United Nations Framework Convention on Climate Change (UNFCCC), committing to increase the share of renewable energy in its energy mix to 13% by 2030.

Biogas is a relatively new form of renewable energy in Nigeria, but it is gaining momentum. In 2017, the Nigerian government launched the National Biogas Policy and Program to promote the development of biogas as a source of renewable energy and to address the challenges of waste management and rural electrification. The policy aims to deploy 1 million household-scale biodigesters and 10,000 large-scale biodigesters by 2025. Overall, the renewable energy and biogas industries in Nigeria are still in their early stages of development, but there is significant potential for growth and investment in these sectors in the coming years.

Biogas production in Nigeria is still in the early stages, but there is a growing interest in technology as a means of providing clean energy and addressing waste management challenges. Biogas can be produced from a variety of organic waste sources, including agricultural residues, livestock manure, food waste, and sewage sludge.

The Nigerian government has recognized the potential of biogas as a source of renewable energy and has launched several initiatives to promote its development. In 2017, the government launched the National Biogas Policy and Program, which aims to deploy 1 million household-scale biodigesters and 10,000 large-scale biodigesters by 2025. The policy also aims to promote the use of biogas for cooking, lighting, and electricity generation in rural areas. Several private companies and non-governmental organizations (NGOs) are also involved in promoting biogas in Nigeria. For example, the NGO SNV Netherlands Development Organization is working with smallholder farmers to set up biogas digesters on their farms, using livestock manure and other organic waste as feedstock. The company, 'Biogas Africa' is also developing large-scale biogas projects in Nigeria, using municipal solid waste and agricultural residues as feedstock. Despite the potential of biogas in Nigeria, there are several challenges to its widespread adoption (Oparinde, Ayodele, & Falade. 2020). These include a lack of awareness and understanding of the technology, limited financing options for biogas projects, and a lack of infrastructure for collecting and transporting organic waste to biodigesters. However, with continued government support and private sector investment, biogas has the potential to play an important role in Nigeria's energy mix and contribute to the country's sustainable development goals.

### 2.1.4 Types of Biogas

There are different types of biogases that can be produced from various organic sources through anaerobic digestion. Here are some of the common types of biogases:

i. Landfill gas: This is biogas that is produced from decomposing organic waste in landfills. Landfill gas is typically composed of around 50% methane and 50% carbon dioxide, as well as trace amounts of other gases.

ii. Sewage gas: This is biogas that is produced from the anaerobic digestion of sewage sludge, which is the solid waste produced during wastewater treatment. Sewage gas is typically composed of around 60% methane and 40% carbon dioxide, as well as trace amounts of other gases.

iii. Agricultural biogas: This is biogas that is produced from agricultural waste such as animal manure, crop residues, and food processing waste. Agricultural biogas can vary in composition depending on the type of feedstock and the anaerobic digestion process used, but it typically contains around 50-70% methane and 30-50% carbon dioxide, as well as trace amounts of other gases (Stürmer, Leiers, Anspach, Brügging, Scharfy and Wissel, 2021).

iv. Industrial biogas: This is biogas that is produced from industrial waste such as food processing waste, brewery waste, and paper mill waste. Industrial biogas can vary in composition depending on the type of waste and the anaerobic digestion process used, but it typically contains around 50-70% methane and 30-50% carbon dioxide, as well as trace amounts of other gases (Arvola, Belt, Harkonen, Kess and Imppola, 2012).

v. Biogas from energy crops: This is biogas that is produced from crops such as corn, sugarcane, and switchgrass that are specifically grown for energy production. Biogas from energy crops, can vary in composition depending on the type of crop and the anaerobic digestion process used, but it typically contains around 50-70% methane and 30-50% carbon dioxide, as well as trace amounts of other gases (Tommaso, Lidia & Giorgio, 2015).

### 2.1.5 Types of Biodigesters and Their Advantages and Disadvantages

A biodigester is a device that uses anaerobic digestion to break down organic waste and produce biogas, which is a mixture of methane and carbon dioxide that can be used as a renewable energy source. Biodigesters can be used to process a variety of organic waste materials, including agricultural waste, food waste, animal manure, and sewage sludge.

Biodigesters typically consist of a sealed tank or container in which the organic waste is mixed with water and bacteria and then left to ferment for a period. During this fermentation process, the bacteria break down the organic waste and produce biogas, which can then be collected and used for energy production.

There are several different types of biodigesters, including batch digesters, continuous-flow digesters, and plug-flow digesters, each with its own advantages and disadvantages. Biodigesters can be used for small-scale or large-scale applications, depending on the amount and type of organic waste being processed.

Batch biodigesters: These are small-scale biodigesters that process organic waste in batches. The organic waste is added to the biodigester, left to ferment for a period, and then the biogas is collected. Once the biogas has been collected, the leftover waste can be removed, and the process can start again with a new batch of organic waste (Mahmudul, Rasul, Akbar, Narayanan and Mofijur, 2021).

a) Batch biodigesters: These are small-scale biodigesters that process organic waste in batches. The organic waste is added to the biodigester, left to ferment for a period, and then the biogas is collected. Once the biogas has been collected, the leftover waste can be removed, and the process can start again with a new batch of organic waste.

   Below are the Advantages of Batch Biodigester:

   i. Simple and low cost
   ii. Can be operated manually.
   iii. Can handle a variety of organic waste.
   iv. Easier to control the fermentation process.

   Below are the Disadvantages of Batch Biodigester:

   i. Less efficient compared to continuous flow biodigesters.
   ii. Longer fermentation time
   iii. Requires frequent loading and unloading.
   iv. Biogas production is less stable.

b) Continuous flow biodigesters: These are larger biodigesters that process organic waste on a continuous basis. Organic waste is added to the biodigester continuously, and the biogas is collected as it is produced. Continuous-flow biodigesters are typically more efficient than batch biodigesters and are commonly used for industrial-scale biogas production.

   The following are the Advantages of Continuous flow biodigesters:

   i. Can handle large volumes of organic waste.
   ii. More efficient than batch digesters
   iii. More stable biogas production

iv. It can be automated and monitored easily.

The following are the Disadvantages of Continuous flow biodigesters:

i. More complex and expensive than batch digesters
ii. Requires a steady supply of organic waste.
iii. May require more energy to operate.
iv. Requires more maintenance.

c) Plug-flow biodigesters: These are similar to continuous-flow biodigesters, but they are designed to handle high solids content waste such as agricultural residues. The organic waste is fed into the biodigester at one end and moves through the biodigester in a plug-like fashion, with the biogas being collected at the other end.

The following are the Advantages of Plug-flow biodigesters:

i. High biogas yield
ii. Can handle high solids content organic waste.
iii. More efficient compared to batch biodigesters.

The following are the Disadvantages of Plug-flow biodigesters:

i. High construction and operating cost
ii. More complex to operate and maintain.
iii. May require pre-treatment of organic waste.
iv. Requires a steady supply of organic waste.

d) Fixed dome biodigesters: These are small-scale biodigesters that are commonly used in rural areas. The biodigester consists of a sealed, dome-shaped container that is buried underground. Organic waste is added to the biodigester, and the biogas is collected at the top of the dome.

The following are the Advantages of Fixed dome biodigesters:

i. Easy to build and operate.

ii. Low construction cost
iii. High biogas production efficiency
iv. No need for electricity or mechanical parts

The following are the Disadvantages of Fixed dome biodigesters:

i. Limited size and capacity
ii. Cannot handle large amounts of organic waste.
iii. Difficult to repair or maintain.
iv. May emit unpleasant odors.

e) Floating dome biodigesters: These are similar to fixed dome biodigesters, but the biodigester has a flexible, gas-tight membrane that floats on top of the waste. As the biogas is produced, it displaces the membrane and is collected.

The following are the Advantages of Floating dome biodigesters:

i. Higher capacity compared to fixed dome biodigesters.
ii. Can handle a variety of organic wastes.
iii. More flexible and adaptable
iv. Biogas storage is expandable.

The following are the Disadvantages of Floating dome biodigesters:

i. Higher cost compared to fixed dome biodigesters.
ii. May be damaged by storms or strong winds.
iii. Requires more maintenance.
iv. May emit unpleasant odors.

It's important to note that the advantages and disadvantages of biodigesters can vary depending on the specific design and context in which they are used.

### 2.1.6 Comparing Biogas usage with other gases.

According to Karen, Fabio, Shane and Brian, (2022), when it comes to comparing biogas with other gases, it's important to consider the specific properties and characteristics of each gas, as well as their advantages and disadvantages.

Biogas vs Natural Gas:

Natural gas is a fossil fuel that is primarily composed of methane, while biogas is produced from organic waste through the process of anaerobic digestion. Here are some comparisons between the two gases:

Advantages of Biogas over Natural gas:

i. Biogas is a renewable energy source that can be produced from a variety of organic waste materials.
ii. Biogas production reduces the amount of waste that would otherwise end up in landfills.
iii. Biogas production can reduce greenhouse gas emissions by capturing and utilizing methane that would otherwise be released into the atmosphere.

Disadvantages of Biogas over Natural gas:

i. Biogas production can be limited by the availability of organic waste materials.
ii. Biogas production can be affected by temperature and other environmental factors.
iii. Biogas production requires specialized equipment and expertise.

Advantages of Natural Gas:

i. Natural gas is a reliable and abundant source of energy.
ii. Natural gas is relatively inexpensive compared to other fossil fuels.
iii. Natural gas produces fewer emissions compared to other fossil fuels.

Disadvantages of Natural Gas:

i. Natural gas is a finite resource that will eventually be depleted.
ii. Natural gas production can cause environmental damage through the extraction process.

iii. Natural gas can contribute to greenhouse gas emissions through the release of methane during extraction and transportation.

Biogas vs Propane:

From the studies of Buğrahan, (2022) the following are the advantages and disadvantages of propane over biogas and vice-versa.

Propane is a liquefied petroleum gas that is commonly used for heating and cooking. Here are some comparisons between biogas and propane:

Advantages of Biogas over Propane gas:

i. Biogas is a renewable energy source that can be produced locally.
ii. Biogas production reduces waste and greenhouse gas emissions.
iii. Biogas production can be used for decentralized energy production.

Disadvantages of Biogas over Propane gas:

i. Biogas production can be affected by weather and environmental conditions.
ii. Biogas production can require specialized equipment and expertise.
iii. Biogas production may be limited by the availability of organic waste materials.

Advantages of Propane over Biogas:

i. Propane is a reliable source of energy that can be easily transported.
ii. Propane is a clean-burning fuel that produces fewer emissions compared to other fossil fuels.
iii. Propane is widely available and can be used for a variety of applications.

Disadvantages of Propane:

i. Propane is a non-renewable resource that contributes to greenhouse gas emissions.
ii. Propane production can cause environmental damage through extraction and transportation.
iii. Propane prices can fluctuate and may be affected by global market conditions.

iv. Overall, biogas has some unique advantages as a renewable energy source that can be produced from organic waste materials, while natural gas and propane have advantages as reliable and widely available sources of energy. Each gas has its own set of advantages and disadvantages, and the choice of which gas to use will depend on a variety of factors including availability, cost, and environmental impact.

### 2.1.7 Processes to Produce Biogas.

There are several processes that can be used to produce biogas, including:

a) Anaerobic digestion:

According to Bhatia, (2014), Anaerobic digestion is the most common process used to produce biogas. It involves the breakdown of organic matter in the absence of oxygen by microorganisms such as bacteria, fungi, and protozoa. This process can be carried out in a batch or continuous system, and the resulting biogas is composed primarily of methane and carbon dioxide.

Anaerobic digestion is further classified as follows:

i. Wet Anaerobic Digestion:

Wet anaerobic digestion is the most used process for the production of biogas. In this process, organic waste materials such as manure, food waste, and sewage sludge are mixed with water to create slurry. The slurry is then fed into a biogas reactor, where bacteria break down the organic matter in the absence of oxygen to produce biogas. The biogas can then be used for electricity generation or as a fuel source.

ii. Dry Anaerobic Digestion:

Dry anaerobic digestion is similar to wet anaerobic digestion, except that the organic waste materials are not mixed with water. Instead, the waste is shredded and placed in an air-tight container where it is allowed to decompose. The biogas produced is collected and used for energy production.

iii. Two-Stage Anaerobic Digestion:

Two-stage anaerobic digestion is a process that is used for waste materials that are difficult to break down, such as lignocellulosic biomass. In this process, the waste is first treated with enzymes to break down the complex molecules into simpler ones. The resulting mixture is then fed into a biogas reactor where bacteria convert the organic matter into biogas.

Advantages of Anaerobic Digestion:

i. Widely used and well-established process
ii. Produces high-quality biogas with high methane content.
iii. Can handle a variety of organic waste materials, including agricultural residues, food waste, and sewage sludge.
iv. Reduces greenhouse gas emissions and the need for fossil fuels.
v. Produces nutrient-rich fertilizer as a by-product.

Disadvantages of Anaerobic Digestion:

i. Requires a relatively large amount of organic waste material economically viable.
ii. Requires careful management to maintain optimal conditions for the microorganisms responsible for the digestion process.
iii. Can produce odor and other environmental impacts if not managed properly.

b) Bio methanation:

According to Voelklein, Davis, Murphy, (2019), Bio-methanation is a process that involves the biological conversion of organic matter into biogas in the presence of specific microorganisms. Unlike anaerobic digestion, which is a slow process, bio methanation is a faster process that can be carried out at higher temperatures and pressures.

Advantages:

i. Faster process than anaerobic digestion

ii. Can operate at higher temperatures and pressures, which can increase the efficiency of the process.
iii. Can produce biogas with a higher methane content than anaerobic digestion.

Disadvantages:

i. Requires a relatively large amount of organic waste material economically viable.
ii. Requires careful management to maintain optimal conditions for the bio-methanation process.
iii. It can produce pollutants such as hydrogen sulfide and ammonia.

c) Gasification:

According to Mai and Nguyen, (2020), Gasification is a process that involves the partial oxidation of biomass in the presence of a limited amount of oxygen or air. This process produces a gas that is rich in carbon monoxide, hydrogen, and methane, which can be further processed into biogas.

Advantages of Gasification:

i. Can handle a variety of organic waste materials, including wood, agricultural residues, and municipal solid waste.
ii. Produces a gas with a higher energy content than biogas.
iii. Can be used for combined heat and power (CHP) applications.

Disadvantages of Gasification:

i. Requires a relatively large amount of organic waste material economically viable.
ii. Can produce pollutants such as particulate matter, nitrogen oxides, and sulfur dioxide.
iii. Requires careful management to maintain optimal conditions for the gasification process.

d) Pyrolysis:

Pyrolysis is a process that involves the heating of biomass in the absence of oxygen to produce a liquid called bio-oil and a gas called syngas. The syngas can be further processed into biogas (Seonho, Yiu, Kun-Yi, Eilhann & Jechan, 2022).

Advantages:

i. Can handle a variety of organic waste materials, including wood, agricultural residues, and municipal solid waste.
ii. Produces a liquid bio-oil that can be used as a fuel or feedstock for other processes.

Disadvantages:

i. Requires a relatively large amount of organic waste material economically viable.
ii. Can produce pollutants such as particulate matter and volatile organic compounds.
iii. Requires careful management to maintain optimal conditions for the pyrolysis process.

e) Fermentation:

Fermentation is a process that involves the breakdown of organic matter by microorganisms such as yeast or bacteria in the presence of oxygen or air. This process produces a gas that is rich in carbon dioxide and methane, which can be further processed into biogas (Dong, Chen, Li & Zhang, 2018).

Advantages:

i. Can be used to produce biogas from a variety of organic waste materials, including food waste and agricultural residues.
ii. Can be operated at relatively low temperatures and pressures.
iii. Produces a gas with a higher carbon dioxide content than anaerobic digestion.

Disadvantages:

i. Produces a gas with a lower methane content than anaerobic digestion.
ii. Requires careful management to maintain optimal conditions for the fermentation process.

iii. Can produce odor and other environmental impacts if not managed properly.

The specific process used to produce biogas will depend on the type and quantity of organic matter available, as well as the desired output of biogas. Each process has its own advantages and disadvantages in terms of efficiency, cost, and environmental impact.

## 2.2 CHEMICAL COMPOSITION AND EQUATIONS OF BIOGAS

From the research titled Membrane gas separation Technologies for biogas upgrading by Chen, Vinh, Ramirez, Rodrigue and Kaliaguine (2015), the chemical formulae for the main components of biogas are:

Methane ($CH_4$) - Methane is the main component of biogas, typically accounting for 50-75% of its composition. The chemical formula for methane is $CH_4$.

Carbon dioxide ($CO_2$) - Carbon dioxide is another major component of biogas, typically accounting for 25-50% of its composition. The chemical formula for carbon dioxide is $CO_2$.

Trace gases - Biogas may also contain trace amounts of other gases such as hydrogen sulfide ($H_2S$), ammonia ($NH_3$), nitrogen ($N_2$), and water vapor ($H_2O$). The chemical formulae for these gases are:

Hydrogen sulfide: $H_2S$
Ammonia: $NH_3$
Nitrogen: $N_2$
Water vapor: $H_2O$

According to Dong et al., (2018), the exact chemical composition of biogas can vary depending on several factors, including the type of feedstock used and the operating conditions of the biogas system. However, the typical chemical composition of biogas is:

Methane ($CH_4$) - 50-75%

Carbon dioxide ($CO_2$) - 25-50%

Trace gases - 0-5%

The trace gases in biogas can include hydrogen sulfide ($H_2S$), ammonia ($NH_3$), nitrogen ($N_2$), and water vapor ($H_2O$). The amount of these trace gases can vary depending on the type of feedstock used and the operating conditions of the biogas system. For example, if feedstock contains high levels of sulfur, such as in the case of some industrial waste streams, the biogas may contain higher levels of hydrogen sulfide.

The production of biogas through the anaerobic digestion of organic matter can be represented by several chemical equations. Here are some examples:

A simplified equation to produce biogas from organic matter is as follows:

Organic matter → Biogas (mainly methane and carbon dioxide)

The equation for the anaerobic digestion of glucose, a simple sugar commonly found in organic matter:

$C_6H_{12}O_6 \rightarrow 3\ CO_2 + 3CH_4$

This equation shows that one molecule of glucose is converted into three molecules of carbon dioxide and three molecules of methane.

The equation for the anaerobic digestion of complex organic compounds, such as proteins and fats:

Proteins → Amino acids → $NH_3 + CO_2 + H_2S + CH_4$

Fats → Glycerol and fatty acids → $CO_2 + CH_4$

These equations show that complex organic compounds are broken down into simpler molecules such as amino acids, glycerol, and fatty acids, which are then further converted into biogas components such as methane, carbon dioxide, and hydrogen sulfide.

It's important to note that the exact chemical equations for biogas production can vary depending on the specific feedstock being used and the conditions of the biogas system and may involve several intermediate steps. However, these simplified equations provide a general idea of the chemical reactions involved in the production of biogas through anaerobic digestion. The high concentration of methane in biogas makes it an attractive source of renewable energy, as it can be used for heating, electricity generation, or as a transportation fuel. However, the carbon dioxide in biogas can reduce its energy content and make it less attractive for some applications. To increase the energy content of biogas, the carbon dioxide can be removed through a process called biogas upgrading, which involves separating the carbon dioxide from the methane using various technologies such as pressure swing adsorption or membrane separation (Dong et al., 2018).

### 2.2.1 Biogas upgrading

Biogas upgrading is the process of purifying biogas to remove impurities, particularly carbon dioxide ($CO_2$), to increase the concentration of methane ($CH_4$) and other desirable gases, making it suitable for use as a high-quality fuel. The two main methods of biogas upgrading are physical separation and chemical conversion.

i. Physical separation: In physical separation, carbon dioxide and other impurities are removed from biogas through physical processes, such as pressure swing adsorption (PSA) and membrane separation. In PSA, carbon dioxide is separated from biogas by passing the gas through a bed of adsorbent material, such as activated carbon or zeolite, at high pressure. The adsorbent material selectively adsorbs carbon dioxide and other impurities, leaving the purified biogas with a higher concentration of methane. Membrane separation involves the use of semi-permeable membranes to selectively separate the Carbon dioxide and other impurities from biogas based on their molecular size and properties.

ii. Chemical conversion: In chemical conversion, carbon dioxide, and other impurities are converted into other gases or compounds, such as methane or water, through chemical reactions. The most common method of chemical conversion is the use of scrubbing technology, where carbon dioxide is removed from biogas by reacting it with a chemical solvent, such as amine, to form a chemical complex that can be separated from the biogas. Carbon dioxide can then be released from the solvent and either reused or safely disposed of (Adnan, Ong, Nomanbhay, Chew, & Show, 2019).

### 2.2.2 Biogas Upgrading Technologies

One of the challenges in biogas production is the low concentration of methane (typically around 50-70%) in raw biogas, with the remainder made up of carbon dioxide ($CO_2$) and trace gases. For biogas to be used as a clean energy source, particularly for transportation or electricity generation, it must undergo a purification process known as biogas upgrading.

i. **Water Scrubbing**: In water scrubbing, $CO_2$ is removed from biogas by dissolving it in water under pressure. This process is relatively simple and low-cost, making it suitable for small- to medium-scale operations. However, it requires careful management of water quality and temperature to maintain high efficiency (Zhou et al., 2020).

ii. **Pressure Swing Adsorption (PSA)**: PSA is a common technique used in large-scale biogas upgrading, where the biogas is passed through adsorbent materials that selectively capture $CO_2$ and other impurities. The adsorbent is then regenerated by reducing the pressure, releasing the captured gases. PSA is highly efficient and can produce high-purity methane, making it ideal for use in power generation or as vehicle fuel (Khan et al., 2019).

**Membrane Separation**: Membrane technology uses selective membranes that allow methane to pass through while retaining $CO_2$ and other gases. This technology has been growing in popularity due to its ability to achieve high methane purity with relatively low energy consumption. However, it requires continuous maintenance and is more expensive than other methods (Salim, Zainal & Adnan, 2020).

### 2.2.3 Environmental and Economic Benefits of Biogas

Biogas production offers significant environmental and economic benefits, making it an important component of sustainable waste management and renewable energy systems. The environmental advantages of biogas include reduced greenhouse gas (GHG) emissions, decreased waste disposal problems, and improved soil fertility. On the economic front, biogas contributes to local energy production, creates job opportunities, and offers an economically viable solution for managing agricultural and urban waste. These benefits make biogas a promising alternative energy source, particularly for countries like Nigeria, where both waste management and energy access remain pressing challenges.

#### 2.2.3.1 Environmental Benefits

#### a. Reduction in Greenhouse Gas Emissions

One of the most significant environmental benefits of biogas production is its potential to reduce greenhouse gas emissions. Biogas is primarily composed of methane ($CH_4$), a potent GHG. When organic waste is decomposed anaerobically in landfills or open pits, methane is produced and released into the atmosphere, contributing to climate change. However, capturing and utilizing methane in biogas systems prevents its uncontrolled release into the atmosphere, thereby significantly reducing GHG emissions.

Moreover, by replacing fossil fuels with biogas for energy production, the overall carbon footprint is reduced. The combustion of biogas for electricity and heating emits significantly fewer pollutants than traditional fossil fuels such as coal, oil, or natural gas. This contributes to the reduction of $CO_2$ emissions, improving air quality and mitigating climate change (Faaij, 2020).

### b. Waste Management and Resource Recovery

Biogas systems are a form of waste-to-energy technology that helps address the growing problem of waste disposal, especially in urban areas. Organic waste such as agricultural residues, animal manure, and food waste, which would otherwise end up in landfills, is converted into biogas, reducing the pressure on waste management systems and landfills. This diversion of waste from landfills also reduces the risk of leachate formation and the contamination of soil and groundwater (Kinyua et al., 2019).

In addition to producing biogas, anaerobic digestion also results in digestate, a nutrient-rich by-product that can be used as an organic fertilizer for agricultural use. This promotes the recycling of organic materials, reduces the need for chemical fertilizers, and improves soil health (Siddique et al., 2021).

### c. Conservation of Natural Resources

Biogas production contributes to the conservation of natural resources by reducing the dependence on fossil fuels and chemical fertilizers. By utilizing organic waste as a feedstock, biogas production offers an alternative to the extraction and use of non-renewable resources. Moreover, digestate, which is rich in nitrogen, phosphorus, and potassium, can be used to replenish soil nutrients, reducing the need for synthetic fertilizers and promoting sustainable agricultural practices (Akinbomi, et al., 2020).

### d. Improved Air Quality

In rural areas, the use of biogas for cooking and heating can significantly improve indoor air quality. Traditional biomass, such as wood, crop residues, and animal dung, is commonly used for cooking in many parts of Africa, including Nigeria. This practice results in indoor air pollution, leading to respiratory diseases and other health problems. By replacing traditional fuels with biogas, households can reduce the emissions of harmful pollutants such as particulate matter (PM), carbon monoxide (CO), and nitrogen oxides (NOx), improving both health and air quality (Bajpai, 2021).

### 2.2.3.2 Economic Benefits

### a. Energy Access and Local Energy Production

In regions with limited access to electricity, biogas can provide a reliable and renewable energy source. Biogas systems can be used to generate electricity and heat, particularly in rural areas where conventional energy infrastructure is often lacking. Small-scale biogas plants, especially those that utilize agricultural waste or livestock manure, can serve as decentralized power sources, reducing reliance on imported fossil fuels and enhancing energy security.

In addition to providing energy for households, biogas systems can support local industries, including agro-processing, by providing a stable energy source. This decentralized energy generation reduces the costs of energy imports and helps mitigate energy shortages (Kinyua et al., 2019).

### b. Job Creation and Economic Growth

The biogas industry can also stimulate local economic development by creating job opportunities at various stages of the biogas value chain, including feedstock collection, biogas plant construction and operation, and maintenance. In rural areas, where unemployment and underemployment are common, biogas projects can create jobs, support entrepreneurship, and enhance livelihoods. Additionally, biogas production can help local farmers by providing an additional income stream through the sale of digestate as fertilizer (Siddique et al., 2021).

#### c. Cost-Effective Waste Management

Biogas production offers a cost-effective solution to the growing problem of waste management. By converting organic waste into biogas, municipalities and businesses can reduce the costs associated with waste disposal and landfill management. Moreover, the revenue generated from the sale of biogas for energy production or the use of digestate as fertilizer can offset the investment costs and make biogas systems economically viable in the long term. This waste-to-energy model can be particularly beneficial in rapidly urbanizing regions where waste management infrastructure is strained (Faaij, 2020).

### 2.2.3.3 Barriers to Biogas Adoption

While biogas offers considerable environmental and economic benefits, several barriers hinder its widespread adoption, especially in developing countries such as Nigeria.

#### a. High Initial Capital Costs

The initial capital cost of setting up biogas production systems, including the construction of digesters, collection systems, and upgrading facilities, can be a significant barrier to adoption. Many biogas projects require substantial upfront investment, which may be challenging for small-scale farmers, rural communities, or local governments to afford. In Nigeria, where access to financing is often limited, this financial barrier can impede the growth of the biogas industry (Kinyua et al., 2019).

### b. Lack of Infrastructure and Technical Expertise

Biogas production requires specialized infrastructure, including digesters, biogas collection systems, and sometimes upgrading units. In many rural areas, there is insufficient infrastructure to support large-scale biogas projects. Moreover, there is a lack of technical expertise in designing, installing, and maintaining biogas systems, which can result in inefficient operations and system failures. The lack of training and capacity-building programs for local stakeholders further exacerbates this challenge (Akinbomi, Olamide & Adewale, 2020).

### c. Regulatory and Policy Challenges

The absence of clear regulatory frameworks and supportive policies for biogas production is another significant barrier. In many countries, including Nigeria, there is limited government support for biogas projects, including subsidies, incentives, and tax breaks for renewable energy initiatives. Additionally, the lack of standardized policies for waste management and renewable energy can create uncertainty for investors and businesses, hindering the development of the biogas sector (Pereira et al., 2018).

### d. Feedstock Availability and Management

For biogas systems to be effective, a consistent supply of high-quality feedstock is essential. In regions where agricultural waste and animal manure are not adequately managed or collected, it can be challenging to ensure a steady and reliable feedstock supply. Moreover, competition for feedstocks, particularly in urban areas where organic waste may be collected for other purposes, can limit the availability of raw materials for biogas production (Kinyua et al., 2019).

### e. Public Awareness and Acceptance

There is often a lack of awareness about the benefits of biogas and its potential as a renewable energy source. In many communities, traditional cooking fuels such as firewood and charcoal are deeply ingrained in cultural practices. Convincing households and businesses to switch to biogas may require overcoming resistance to change and educating the public about the advantages of biogas, including its environmental and economic benefits (Bajpai, 2021).

### 2.2.4 Future Directions for Biogas in Nigeria

To overcome the barriers to biogas adoption and realize its full potential, several future directions must be pursued:

#### 2.2.4.1 Policy and Regulatory Support

Governments must play a central role in promoting biogas adoption by creating supportive policies and regulatory frameworks. This includes offering financial incentives such as subsidies, tax rebates, and low-interest loans for biogas projects. Additionally, clear guidelines for feedstock collection and waste management should be developed to streamline the process and ensure the sustainability of biogas systems (Pereira et al., 2018).

#### 2.2.4.2 Capacity Building and Training

Building local technical expertise is critical for the successful implementation of biogas systems. Training programs for farmers, technicians, and local governments should be established to build the necessary skills for designing, operating, and maintaining biogas systems. Collaborations with international organizations and universities can also help transfer knowledge and best practices to Nigeria (Akinbomi et al., 2020).

#### 2.2.4.3 Public Awareness Campaigns

Increasing public awareness about the environmental and economic benefits of biogas is essential to foster acceptance and encourage widespread adoption. Public campaigns and education programs can highlight the health, environmental, and economic advantages of biogas, particularly in rural areas where traditional biomass use is prevalent (Bajpai, 2021).

#### 2.2.4.4 Research and Development

Ongoing research is necessary to improve biogas technologies and make them more cost-effective. Research into innovative feedstock management, process optimization, and biogas upgrading technologies will help make biogas production more efficient and economically viable. Additionally, research into the integration of biogas systems with other renewable energy sources, such as solar or wind, could further enhance the sustainability of biogas projects (Faaij, 2020).

#### 2.2.4.5 Integration with Circular Economy Models

Biogas production should be integrated into broader circular economy models that promote waste-to-resource systems. By combining biogas production with composting, recycling, and other waste management practices, biogas projects can become a cornerstone of sustainable urban and rural development. This integrated approach can help address waste management issues while simultaneously providing renewable energy (Kinyua, Akinmoladun & Ogbu, 2019).

## 2.3 MODELS FOR BIOGAS PRODUCTION

There are several mathematical models used to predict the production of biogas from organic waste materials. These models are typically based on the physical and biochemical processes that occur during anaerobic digestion and can be used to optimize the operation of biogas production systems. Some of the commonly used models for biogas production include:

i. Monod model: In their work titled “Review on anaerobic digestion models: Model classification and elaboration of process phenomena”, Samuel, Jiří and Dagmar, (2022) mentioned that the Monod model is based on the microbial growth kinetics of anaerobic bacteria and their ability to convert organic matter into biogas. It predicts the rate of biogas production based on the concentration of substrate and the specific growth rate of the bacteria.

ii. ADM1 model: According to Batstone, Keller, Angelidaki, Kalyuzhnyi, Pavlostathis, Rozzi, Sanders, Siegrist and Vavilin (2002) the Anaerobic Digestion Model No. 1 (ADM1) is a comprehensive model that considers the complex biochemical and physical processes that occur during anaerobic digestion. It includes multiple biochemical reactions that describe the conversion of organic matter to biogas and considers factors such as pH, temperature, and the presence of inhibitors.

iii. Gompertz model: According to the research by Tjørve et al., (2017), this model is commonly used to describe the kinetics of biogas production over time. It assumes that the rate of biogas production is proportional to the amount of substrate available and that the rate of production decreases over time as the substrate is depleted.

iv. Logistic model: According to Bahman and Sina (2018), the logistic model is like the Gompertz model but assumes that the rate of biogas production reaches a maximum level, or carrying capacity, as the substrate is consumed.

v. Modified Stover-Kincannon model: According to Verma, Bhunia, Dash, Francis, Rajesh, & Dash, (2014), this model is based on the concept of mass transfer limitations in anaerobic digestion. It incorporates the rate of transfer of a substrate into the reactor and the specific growth rate of the bacteria to predict biogas production.

### 2.3.1 Monod model

The Monod model is a mathematical model used to predict the rate of biogas production during anaerobic digestion. It is based on the microbial growth kinetics of anaerobic bacteria and their ability to convert organic matter into biogas.

The model assumes that the rate of biogas production is proportional to the concentration of substrate (organic matter) in the reactor and the specific growth rate of the bacteria. The specific growth rate is determined by the availability of nutrients such as carbon, nitrogen, and phosphorus, and by the presence of inhibitors such as ammonia or organic acids.

The Monod model is expressed mathematically as:

$$\mu = \frac{\mu_{max} \text{ x } S}{(K_S + S)} \tag{2.1}$$

whereμ is the specific growth rate of the bacteria, "$\mu_{max}$" is the maximum specific growth rate, S is the concentration of substrate, and Ks is the Monod constant, which represents the substrate concentration at which the specific growth rate is half of its maximum value.

The rate of biogas production (R) can be calculated using the following equation:

$$R = \ Y \mu X \tag{2.2}$$

Where,"Y" is the yield coefficient, which represents the amount of biogas produced per unit of substrate consumed, and "X", is the concentration of biomass in the reactor.

The Monod model can be used to optimize the design and operation of biogas production systems by predicting the rate of biogas production under different operating conditions. It can also be used to determine the substrate concentration and feeding rate that will maximize biogas production.

### 2.3.2 ADM1 model

The Anaerobic Digestion Model No.1 (ADM1) is a comprehensive mathematical model that describes the complex biochemical and physical processes that occur during anaerobic digestion. It includes multiple biochemical reactions that describe the conversion of organic matter to biogas and considers factors such as pH, temperature, and the presence of inhibitors.

The ADM1 model consists of four main components: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These components are linked by intermediate compounds and enzymes that are produced during the different stages of anaerobic digestion.

The hydrolysis component describes the breakdown of complex organic matter into simple molecules such as sugars, amino acids, and fatty acids. The acidogenesis component describes the conversion of these simple molecules into volatile fatty acids such as acetic acid, propionic acid, and butyric acid. The acetogenesis component describes the conversion of these volatile fatty acids into acetate and hydrogen. The methanogenesis component describes the final step in which the acetate and hydrogen are converted into methane and carbon dioxide by methanogenic bacteria.

The ADM1 model considers several factors that affect the rate of biogas production, including the concentration and composition of the substrate, the pH and temperature of the reactor, and the presence of inhibitory compounds. It also includes parameters that describe the activity of the different microbial groups involved in the anaerobic digestion process.

The ADM1 model can be used to simulate the performance of biogas production systems under different operating conditions and to predict the amount of biogas that can be produced from different types of organic waste materials. It can also be used to optimize the design and operation of biogas production systems by predicting the effects of changes in operating conditions or feedstocks on biogas production.

### 2.3.3 Gompertz model

The Gompertz model is a mathematical model used to describe the kinetics of biogas production during anaerobic digestion. It is named after Benjamin Gompertz, who first proposed the model to describe human mortality rates.

The Gompertz model assumes that the rate of biogas production decreases over time due to the depletion of the available substrate and the accumulation of inhibitory compounds. The model is expressed mathematically as:

$$R = A.\exp\left(-\exp\left(\left(\frac{\mu\text{max.exp}(1)}{A}\right).(\lambda - \text{t}) + 1\right)\right) \qquad (2.3)$$

where R is the rate of biogas production at time t, A is the maximum biogas production potential, $\mu_{max}$ is the maximum specific growth rate, and λ is the lag time, which represents the time required for the microorganisms to adapt to the new environment and start growing.

The Gompertz model can be used to estimate the parameters of the anaerobic digestion process, such as the maximum biogas production potential, the maximum specific growth rate, and the lag time. These parameters can be used to optimize the design and operation of biogas production systems by predicting the rate of biogas production under different operating conditions. The Gompertz model can also be used to compare the performance of different feedstocks and to evaluate the effects of inhibitors on biogas production.

### 2.3.4 Logistic model

The logistic model is a mathematical model used to describe the kinetics of biogas production during anaerobic digestion. It is similar to the Gompertz model but assumes that the rate of biogas production reaches a maximum value and then levels off over time due to the depletion of the available substrate and the accumulation of inhibitory compounds.

The logistic model is expressed mathematically as:

$$R = \frac{A}{(1+\mathrm{exp0}\ ((\left(\frac{\mathrm{\mu max}}{A}\right).(\lambda - \mathrm{t})))} \tag{2.4}$$

where R is the rate of biogas production at time t, A is the maximum biogas production potential, $\mu_{max}$ is the maximum specific growth rate, and λ is the lag time, which represents the time required for the microorganisms to adapt to the new environment and start growing.

The logistic model can be used to estimate the parameters of the anaerobic digestion process, such as the maximum biogas production potential, the maximum specific growth rate, and the lag time. These parameters can be used to optimize the design and operation of biogas production systems by predicting the rate of biogas production under different operating conditions. The logistic model can also be used to compare the performance of different feedstocks and to evaluate the effects of inhibitors on biogas production.

### 2.3.5 Modified Stover-Kincannon model

The Modified Stover-Kincannon model (MSK model) is a mathematical model used to describe the kinetics of biogas production during anaerobic digestion. It is a modification of the Stover-Kincannon model, which is a widely used model in wastewater treatment.

The MSK model assumes that the rate of biogas production is proportional to the concentration of the substrate and the concentration of the microorganisms responsible for its degradation. The model is expressed mathematically as:

$$\frac{dS}{dt} = \frac{-k_1.S.X}{Ks+S} \tag{2.5}$$

$$\frac{dS}{dt} = \frac{-k_1.S.X}{Ks+S} - k_2.X \tag{2.6}$$

where S is the concentration of the substrate, X is the concentration of the microorganisms responsible for its degradation, $k_1$ is the maximum specific growth rate, $k_2$ is the specific decay rate, and Ks is the saturation constant, which represents the concentration of the substrate at which the specific growth rate is half of its maximum value.

The MSK model can be used to simulate the performance of anaerobic digestion systems under different operating conditions, such as variations in substrate concentration, temperature, and pH. It can also be used to predict the rate of biogas production and the composition of the biogas, as well as to optimize the design and operation of biogas production systems. The MSK model is particularly useful for modeling the digestion of complex organic substrates, such as agricultural waste, because it takes into account the dynamics of the microbial population and the interactions between the different components of the substrate.

### 2.3.6 Factors for the Determination of the Output of biogas biodigester

The output of a biogas biodigester can be influenced by a variety of factors. According to Sawyerr, Trois, Seyoum, and Okudoh (2019), such factors include:

i. Type of feedstock: The type of organic matter used in the biodigester can affect the amount and quality of biogas produced. Generally, feedstocks that are rich in carbohydrates and proteins, such as manure, food waste, and agricultural residues, produce more biogas than feedstocks with low nutrient content.

ii. Feedstock quantity and quality: The quantity and quality of the feedstock fed into the biodigester can also affect biogas production. The biodigester must receive a consistent amount of feedstock to maintain optimal conditions for biogas production. The feedstock should also be free of contaminants that can inhibit the activity of the microorganisms responsible for biogas production.

iii. Temperature: The optimal temperature for biogas production is typically between 25°C and 40°C. If the temperature is too low or too high, the biogas production rate may decrease or stop entirely.

iv. pH: The pH level in the biodigester should be maintained within a specific range (usually between 6.5 and 8.5) to support the growth of the microorganisms responsible for biogas production.

v. Mixing and agitation: Proper mixing and agitation of the feedstock can help maintain optimal conditions for biogas production by ensuring that the microorganisms are distributed evenly and have access to nutrients.

vi. Retention time: The amount of time that the feedstock remains in the biodigester, known as the retention time, can affect the amount of biogas produced. Generally, longer retention times can lead to higher biogas yields, but too long of a retention time can result in decreased biogas production.

vii. Biodigester design: The design of the biodigester, such as the size, shape, and conFigureuration, can also affect biogas production. A well-designed biodigester will promote efficient biogas production by optimizing the factors mentioned above.

viii. Effect of Loading Rate on Biogas Yield: Loading rate normally expressed as the amount of waste materials fed per unit volume of digester capacity is an important parameter that affects gas yield. Gas output is commonly expressed as m3 of gas produced per kg of volatile solids destroyed.Comparative volumetric loading rates vary from 1.9 to 0.89 $ft^3$ (0.054 to 0.025 $m^3$) per capita per day and were based on a per capita volatile solids contribution of 0.123 lb. per day (0.56 kg per day). A night soil loading rate of 0.1 lb. volatile solids per $ft^3$ (1.6 kg per $m^3$) of digester capacity per day is recommended for temperate climates. The average gas yield was found to vary from 0.8 to 1.2 ft3 (0.023 to 0.034 m3) on per personal basis.

To estimate biogas output from a biodigester, you will need to follow these steps:

Determine the biogas production rate (R): This can be estimated based on the characteristics of the feedstock being used, such as the volatile solids (VS) or chemical oxygen demand (COD) content. The biogas production rate can be obtained from literature or experimentally determined.

Measure the volume of the biodigester (V): This can be done by physically measuring the dimensions of the biodigester and calculating its volume. Alternatively, the volume may be provided by the manufacturer or obtained from technical specifications.

Measure the temperature and pressure of the biogas: This can be done using a thermometer and a pressure gauge, respectively.

Calculate the atmospheric pressure (P): This can be obtained from a weather website or from a local weather station.

Calculate the biogas production using the formula:

The formula for calculating the output of biogas from a biodigester depends on the specific characteristics of the biodigester and the feedstock being used. However, in general, the formula for calculating the biogas production ($B_P$) per day can be expressed as:

$$B_p = \frac{\mathrm{V} \times (\mathrm{R}.10^{-3}).(P/101.3).(\mathrm{T}+273)}{(273 * 1.013 * 10^5)} \tag{2.7}$$

where:

V is the volume of the biodigester ($m^3$)

R is the biogas production rate (L/kg VS added or L/kg COD added)

P is the atmospheric pressure (kPa)

T is the temperature of the biogas (°C)

In this formula, the biogas production rate (R) can be estimated based on the characteristics of the feedstock being used, such as the volatile solids (VS) or chemical oxygen demand (COD) content. The biogas production rate can be obtained from literature or experimentally determined.

It is important to note that this formula provides an estimate of the biogas production and actual production may vary depending on a variety of factors, including the composition and quality of the feedstock, the operating conditions of the biodigester, and the efficiency of the biogas recovery system (Anthony, David, Matthew, Franjo, and Tao, 2016).

## 2.4 RECENT INNOVATIONS IN BIOGAS PRODUCTION

Recent research has introduced various innovations aimed at improving biogas production efficiency and reducing costs. For instance:

i. **Electrochemical Methods**: Electrochemical technologies are being explored for enhancing methane production by supplying electrical energy to anaerobic microbial communities. Electrochemical methane production has shown promise in improving the rate of methane generation, particularly when combined with appropriate feedstock treatments (Wang, Li & Zhang, 2021).

ii. **Microbial Fuel Cells (MFCs)**: MFCs are a type of bio-electrochemical system that can be integrated with anaerobic digestion to increase biogas yields. These systems harness the electrical energy generated by microorganisms during organic matter breakdown, offering a dual benefit of energy generation and enhanced biogas production (Zhang, Liu & Bai, 2020).

### 2.4.1 Feedstock Selection for Biogas Production

The selection of feedstock plays a pivotal role in determining the efficiency and yield of biogas production. Various organic materials, ranging from agricultural residues to municipal solid waste (MSW), are suitable for anaerobic digestion. The choice of feedstock depends on its organic content, biodegradability, availability, and composition. Here is an overview of the most commonly used feedstocks in biogas production and the factors that influence their selection:

#### 2.4.1.1 Agricultural Residues

Agricultural residues, such as crop residues (e.g., maize stalks, rice husks), fruit and vegetable waste, and agricultural by-products like sugarcane bagasse and wheat straw, are abundant in many parts of the world (Svensson, Christensson, and Bjornsson. 2005). In Nigeria, these materials represent a significant portion of the organic waste generated and are crucial feedstocks for biogas production.

i. **Benefits**: Agricultural residues are often rich in carbohydrates, making them suitable for microbial digestion. Additionally, they are readily available, especially in rural areas where agricultural activities are dominant (Akinbomi et al., 2020). They offer a sustainable solution for utilizing waste that would otherwise go to landfills or be burned.
ii. **Challenges**: Many agricultural residues contain lignocellulosic materials that are difficult for microorganisms to break down. As a result, these feedstocks often require

pre-treatment methods, such as mechanical, chemical, or thermal processes, to enhance their digestibility (Nwachukwu, Agboola and Asamoah 2021).

#### 2.4.1.2 Livestock Manure

Livestock manure is one of the most common feedstocks used for biogas production. It is produced in large quantities, especially in rural and agricultural areas, and can be used directly in biogas reactors.

i. **Benefits**: Manure is rich in organic matter, including proteins and carbohydrates, making it an excellent source of methane production. It is also high in nitrogen, which is essential for microbial growth during digestion. Animal manure is often more easily digestible than other agricultural residues, which makes it a preferred feedstock in biogas plants (Onwosi et al., 2019).
ii. **Challenges**: The methane yield from manure depends on the type of livestock and its diet. For example, poultry and pig manure tend to produce more methane compared to cattle or sheep manure. Furthermore, manure from different sources may require mixing to balance nutrients and improve the anaerobic digestion process (Pereira et al., 2018).

#### 2.4.1.3 Municipal Solid Waste (MSW)

Municipal solid waste, consisting of food scraps, paper, plastics, and other biodegradable materials, is a potential feedstock for biogas production, particularly in urban areas where waste generation is high. MSW typically contains a mix of organic materials that are biodegradable and can produce biogas.

i. **Benefits**: MSW is an excellent feedstock for biogas production because it is widely available in urban centers and can contribute significantly to waste-to-energy strategies. The organic fraction of MSW contains large amounts of biodegradable material that can be converted into biogas, reducing the burden on landfills and providing a sustainable source of energy (Kinyua et al., 2019).

ii. **Challenges**: MSW is heterogeneous, containing both organic and inorganic materials. The presence of non-biodegradable materials such as plastics, metals, and glass can complicate the digestion process, requiring pre-sorting and processing. Additionally, the high moisture content of MSW can affect the efficiency of anaerobic digestion (Sprecher et al., 2020).

### 2.4.1.4 Industrial Effluents and Food Waste

Industrial effluents, including organic waste from food processing industries (e.g., brewery waste, dairy effluent, and fruit processing waste), are rich in organic matter and have high potential for biogas production. Food waste, generated in large quantities in urban areas and food processing plants, also contains a high level of biodegradable material.

i. **Benefits**: Food waste and industrial effluents are typically high in sugars, fats, and proteins, which can be easily converted into methane through anaerobic digestion. These feedstocks are rich in nutrients that can support the growth of anaerobic microorganisms, thereby enhancing biogas production (Akinbomi et al., 2020).

ii. **Challenges**: Food waste is often wet, which may increase the operational cost of biogas plants due to the need for additional dewatering or drying. Additionally, the composition of food waste varies, and this variability may result in inconsistent biogas production unless properly managed (Zhou et al., 2020).

### 2.4.1.5 Co-Digestion of Feedstocks

Co-digestion refers to the simultaneous digestion of two or more feedstocks with complementary characteristics. This technique optimizes biogas production by balancing the nutrient composition of the feedstock mix, improving microbial growth conditions, and increasing methane yields.

i. **Benefits**: Co-digestion allows for the use of a wider variety of feedstocks, such as combining livestock manure with agricultural residues or food waste. The presence of high-carbon and nitrogen-rich materials in the feedstock mix enhances microbial activity and results in a more stable digestion process. Furthermore, co-digestion helps reduce the need for external supplementation and increases the overall efficiency of the digestion process (Kinyua et al., 2019).

ii. **Challenges**: Successful co-digestion requires careful management of the feedstock ratios to avoid nutrient imbalances and toxicity. Too much carbon or nitrogen in the mix can inhibit microbial activity, reducing biogas yields (Nwachukwu, Oparinde and Ajayi 2021).

## 2.5 OPTIMIZATION STRATEGIES IN BIOGAS PRODUCTION

The optimization of biogas production involves enhancing the efficiency of anaerobic digestion processes to maximize methane yield while minimizing the operational costs and environmental impact. This is achieved through a variety of strategies that target different stages of the biogas production cycle, including feedstock pre-treatment, process optimization, microbial management, and biogas upgrading. These strategies are critical for increasing biogas production efficiency, improving the sustainability of the process, and making biogas a viable renewable energy source.

### 2.5.1 Feedstock Pre-Treatment

Feedstock pre-treatment plays a vital role in improving the biodegradability of organic waste, especially lignocellulosic materials such as agricultural residues and food waste. By enhancing the accessibility of organic matter to microorganisms, pre-treatment methods increase the biogas yield and shorten the retention time in the digester.

i. **Mechanical Pre-Treatment**: Mechanical methods such as shredding and grinding break down large particles and fibers, thereby increasing the surface area available for microbial activity. This is particularly useful for fibrous materials like straw, maize stover, and other agricultural by-products. Mechanical pre-treatment is energy-intensive but relatively simple and effective in enhancing the digestibility of tough feedstocks (Siddique et al., 2021).

ii. **Chemical Pre-Treatment**: Chemical treatments, such as the use of acids or alkalis (e.g., sulfuric acid or sodium hydroxide), are effective in breaking down lignin and cellulose bonds, making the organic material more susceptible to microbial degradation. Chemical pre-treatment can significantly enhance the methane yield from difficult-to-digest feedstocks. However, it requires careful management of the chemicals to avoid toxicity to the microorganisms and maintain the sustainability of the process (Wang et al., 2021).

iii. **Thermal Pre-Treatment**: Thermal treatment involves heating the feedstock to temperatures ranging from 100°C to 180°C to break down lignin and cellulose. This method is particularly effective for agricultural residues and other lignocellulosic materials. Though it enhances methane production, thermal pre-treatment can be costly due to energy consumption and may lead to the formation of inhibitory compounds if not properly controlled (Sprecher et al., 2020).

iv. **Biological Pre-Treatment**: Biological methods, such as the use of specific enzymes or microbial cultures, help in breaking down complex organic polymers before anaerobic digestion. These treatments are environmentally friendly and offer a more sustainable approach to improving biodegradability, but their effectiveness may vary based on the feedstock type (Bajpai, 2021).

### 2.5.2 Process Optimization

To maximize biogas production, process optimization involves fine-tuning operational parameters within anaerobic digesters. Key factors include temperature, pH, retention time, organic loading rate (OLR), and nutrient balance (Demirel, Yenigün & Oz. 2020). Adjusting these parameters can lead to higher methane yields, more stable digestion, and reduced risk of process failure.

i. **Temperature Optimization**: The temperature of the anaerobic digester affects microbial activity and the rate of digestion. There are two main temperature ranges for anaerobic digestion: mesophilic (30–40°C) and thermophilic (50–60°C). Mesophilic conditions are more commonly used because they are less sensitive to temperature fluctuations and require less energy to maintain. However, thermophilic conditions can offer higher methane production rates and faster digestion. The choice between mesophilic and thermophilic digestion depends on the type of feedstock and the desired production rates (Salim et al., 2020).

ii. **pH Control**: Maintaining an optimal pH (typically between 6.8 and 7.4) is crucial for the growth and activity of anaerobic microorganisms, particularly methanogens, which are responsible for methane production. If the pH falls outside this range, microbial activity may be inhibited, leading to reduced biogas production or process failure. pH can be adjusted through the addition of buffers or alkalis like sodium bicarbonate (Kim et al., 2021).

iii. **Organic Loading Rate (OLR)**: The OLR refers to the amount of organic matter added to the digester per unit volume per day. An optimized OLR ensures that the microorganisms have sufficient nutrients to produce methane without overwhelming the system. High OLRs can lead to process imbalances, while too low an OLR may result in underutilization of the digester's capacity. The optimal OLR varies depending on the feedstock and the digester design (Kinyua et al., 2019).

iv. **Retention Time**: The hydraulic retention time (HRT) is the average time that the feedstock remains in the digester. A longer retention time allows for more complete degradation of organic material, leading to higher biogas yields. However, excessive retention times can reduce the efficiency of the system and increase operational costs. The ideal HRT is dependent on the type of feedstock, temperature, and the type of digester used (Nwachukwu et al., 2021).

v. **Nutrient Balance**: Microbial growth requires a balanced supply of nutrients, including nitrogen, phosphorus, and trace minerals. An imbalance in nutrients can reduce microbial activity and biogas production. Nutrient deficiencies or excesses can be addressed through supplementation or by selecting appropriate feedstocks that provide the necessary elements (Zhou et al., 2020).

### 2.5.3 Co-Digestion of Feedstocks

Co-digestion involves mixing two or more feedstocks with complementary characteristics in a single digester. Co-digestion is an optimization strategy that enhances biogas production by improving the nutrient balance, providing a more stable microbial environment, and increasing methane yields. For instance, combining high-carbon feedstocks such as agricultural residues with nitrogen-rich materials like animal manure can lead to more efficient digestion and better gas production.

i. **Benefits of Co-Digestion**: Co-digestion can increase biogas yield by up to 30% compared to the digestion of individual feedstocks (Kinyua et al., 2019). It also reduces the accumulation of potentially toxic intermediates and stabilizes the digestion process. The technique also helps to optimize the use of available feedstocks, reducing the need for external supplementation (Nwachukwu et al., 2021).

ii. **Challenges of Co-Digestion**: While co-digestion offers significant benefits, it requires careful management of feedstock ratios to avoid nutrient imbalances. Excessive amounts of one type of feedstock can lead to overloading the digester or inhibiting microbial activity, which can reduce overall biogas production (Pereira et al., 2018).

### 2.5.4 Biogas Upgrading and Purification

The raw biogas produced from anaerobic digestion contains not only methane but also significant quantities of carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), and trace amounts of other gases. To make biogas suitable for use as a high-quality renewable energy source, it needs to be upgraded and purified to remove impurities, particularly $CO_2$ and $H_2S$.

i. **Upgrading Technologies**: Technologies such as pressure swing adsorption (PSA), water scrubbing, and membrane separation are commonly used to upgrade biogas by removing $CO_2$ and increasing the methane concentration. The choice of upgrading technology depends on factors such as cost, scale, and the desired purity of the methane (Khan et al., 2019).

ii. $H_2S$ **Removal**: Hydrogen sulfide is a corrosive gas that must be removed to prevent damage to equipment and ensure that biogas is suitable for combustion. This can be done using scrubbing methods with alkaline solutions or by using iron-based adsorbents (Zhou et al., 2020).

### 2.5.5 Microbial Management

Microbial communities are central to the anaerobic digestion process. By optimizing the microbial environment, biogas producers can enhance the rate of degradation of organic matter and the yield of methane. This includes managing the growth of specific microbial species such as methanogens, which are responsible for methane production.

i. **Inoculation**: Inoculating digesters with well-established microbial consortia from other operational digesters or synthetic cultures can help to jumpstart the anaerobic digestion process, especially in new biogas plants or when digesting challenging feedstocks (Bajpai, 2021).

ii. **Microbial Additives**: The use of microbial additives such as enzymes, nutrients, and trace elements can improve the digestion process, particularly for lignocellulosic materials that are difficult to digest. These additives can help to speed up the breakdown of complex organic compounds and promote stable biogas production (Salim et al., 2020).

### 2.5.6 Maintenance of Biogas Systems

There are several methods of biogas maintenance that can help to ensure the optimal performance of the system. Some of these methods include:

i. Regular cleaning: Biogas systems should be cleaned regularly to prevent the buildup of solids and sludge, which can reduce the efficiency of the system. Cleaning methods can include the manual removal of debris or the use of mechanical equipment, such as high-pressure water jets.

ii. Gas production monitoring: Regular monitoring of gas production can help identify any issues with the system, such as leaks or blockages. Gas production can be monitored using gas flow meters, pressure gauges, and gas analyzers.

iii. Inspection of pipes and valves: The pipes and valves in the biogas system should be inspected regularly for signs of wear and tear, corrosion, or leaks. Any damaged components should be repaired or replaced as soon as possible.

iv. pH monitoring: The pH level of the digester should be monitored regularly to ensure that it remains in the optimal range for the specific microorganisms involved in the biogas production process. Adjustments to the pH may be necessary if it falls outside of the desired range.

v. Maintenance of the biogas generator: The biogas generator should be maintained regularly to ensure that it is operating at peak efficiency. This includes regular oil changes, filter replacements, and inspections of the electrical components.

vi. Record keeping: It is important to keep accurate records of all maintenance activities performed on the biogas system, including cleaning schedules, gas production measurements, and repairs or replacements of components. This information can help identify patterns or trends in system performance and inform future maintenance decisions.

vii. Use of biogas additives: Biogas additives can be used to improve the performance of the biogas system. These additives can include enzymes, nutrients, or bacteria that can help to break down feedstock more efficiently and increase gas production.

   - Optimization of feedstock: The type and quality of feedstock used in the biogas system can significantly impact system performance. Optimization of feedstock can include selecting feedstock with high nutrient content, mixing different types of feedstocks to improve digestion, and ensuring that the feedstock is properly pre-treated before entering the digester.

## 2.6 DESIGN OF BIOGAS SYSTEMS

According to Abunde (2020), the design of a biogas digester can vary depending on the specific application and the available resources. However, there are some general guidelines that can be followed to ensure that the digester is effective and efficient.

i. Choose the right type of digester: There are several types of biogas digesters, including fixed dome, floating drum, and plug flow digesters. Each type has its own advantages and disadvantages, so it's important to choose the one that is best suited for your specific application.

ii. Determine the size of the digester: The size of the digester will depend on the amount of organic waste you want to process and the amount of biogas you want to produce. A larger digester will produce more biogas, but it will also require more space and resources.

iii. Select the appropriate materials: The materials used to construct the digester should be durable, resistant to corrosion, and able to withstand the pressure of the biogas. Common materials used for biogas digesters include concrete, brick, and plastic.

iv. Determine the feedstock: The feedstock, or organic waste, should be carefully selected to ensure that it is suitable for the digester. Ideally, the feedstock should have high organic content and low moisture content.

v. Provide a mixing system: A mixing system is essential to ensure that the organic waste is evenly distributed throughout the digester and that the biogas production is optimized. Mixing can be achieved using mechanical or hydraulic systems.

vi. Provide temperature control: Biogas production is most efficient at temperatures between 25°C and 35°C. Therefore, it's important to provide a heating system to maintain the temperature within this range.

vii. Install a gas collection system: The biogas produced by the digester can be used for cooking, heating, or electricity generation. Therefore, it's important to install a gas collection system that can efficiently capture and store the biogas.

viii. Provide safety measures: Biogas is a flammable gas and can be dangerous if not handled properly. Therefore, it's important to provide safety measures such as gas detectors, ventilation systems, and pressure relief valves to prevent accidents.

ix. Monitor and maintain the digester: Regular monitoring and maintenance are essential to ensure that the digester is functioning properly and to prevent any problems from arising. This includes monitoring the temperature, pH, and gas production, as well as cleaning the digester and replacing any damaged or worn-out components.

Design Consideration

The requirements for designing a Biodigester are the volume of the digester ($\mathrm{Vol}_{\mathrm{digester}}$), the storage capacity of the gas, the volume of the gas holder ($\mathrm{Vol}_{\mathrm{holder}}$), the retention period, and the amount and type of organic waste contained in the digester. To determine the unit size of a biogas unit, the following equation must be achieved:

$$V_d = D_f * R_t \tag{2.8}$$

Where $V_d$ is the volume of the digester (liters), $D_f$ is the Daily feed-in (liters/day) and $R_t$ is the Retention time (day)

Where the volume of the digester is the volume occupied by the organic raw material (feedstock). The water-to-feedstock ratio is assumed 1:1 (Abunde, 2020).

### 2.6.1 The volume of a biogas digester and the formula for calculating it

According to Obileke, Mamphweli, Meyer, Makaka and Nwokolo (2020), the volume of a biogas digester will depend on several factors, including the amount and type of feedstock being used, the desired production rate of biogas, and the retention time of the digester.

In general, the volume of a biogas digester can be calculated based on the following formula:
Volume = (Amount of Feedstock x Retention Time x Conversion Factor) / Gas Production Rate
Where:
Amount of Feedstock: the amount of organic material being fed into the digester on a daily basis, typically measured in kilograms or pounds.

Retention Time: the amount of time that the feedstock remains in the digester, usually measured in days.

Conversion Factor: a factor that accounts for the efficiency of the anaerobic digestion process and the biogas production potential of the feedstock. This factor can vary depending on the type of feedstock being used.

Gas Production Rate: the amount of biogas produced per unit volume of digester per day, usually measured in cubic meters or cubic feet.

The volume of a biogas digester can also be calculated using the following formula:

$$V = F * HRT * (1 + \lambda) \tag{2.9}$$

Where:

V is the volume of the digester, typically measured in cubic meters ($m^3$).

F is the feedstock flow rate, typically measured in cubic meters per day ($m^3$/day).

HRT is the hydraulic retention time, which is the average amount of time that the feedstock remains in the digester, typically measured in days.

$\lambda$ is the safety factor, which is used to account for any variations in feedstock flow rate or retention time and is usually set to a value between 1.1 and 1.5.

The feedstock flow rate (F) can be calculated as the total amount of feedstock added to the digester per day, divided by the number of days in the retention time (HRT). For example, if 10 tons of feedstock are added to the digester each week and the retention time is 20 days, the feedstock flow rate would be (10 tons / 7 days) * 20 days / 1000 giving 0.286 $m^3$/day

Assuming a retention time of 20 days and a safety factor of 1.2, the volume of the digester would be 0.286 $m^3$/day * 20 days * (1 + 1.2) which gives 8.632 $m^3$

This means that the volume of the biogas digester would be approximately 8.6 cubic meters.

Note that the volume of a biogas digester can vary depending on the specific requirements of a given project and that there are many different types of biogas digesters with varying sizes and configurations.

### 2.6.2 Retention Time of a Biogas Digester and the Formula for calculating it

The retention time of a biogas digester refers to the amount of time that the material being processed in the digester remains inside the digester. This period is important because it determines the rate at which the material is broken down and the quality and quantity of the biogas produced. The retention time can vary depending on several factors, including the type of material being digested, the temperature inside the digester, the mixing and agitation of the material, and the design of the digester itself. Generally, retention times can range from several days to several weeks. For example, a typical retention time for a small-scale batch digester processing animal manure might be around 20-30 days, while a larger continuous-flow digester processing a mixture of organic waste materials might have a retention time of 20-40 days.

It's important to note that the retention time should be optimized to ensure that the biogas produced is of high quality and that the digester operates efficiently. If the retention time is too short, the material may not be fully broken down, resulting in lower biogas yields and the potential for the accumulation of harmful substances. If the retention time is too long, the digester may become overloaded, resulting in reduced biogas production and decreased efficiency. Mathematically, Retention time is given by:

$$R_t = \frac{V_d}{O_{LR}} \tag{2.10}$$

Where $R_t$ is the Retention Time; $V_d$ is the Volume of Digester and $O_{LR}$ is the Organic Loading Rate. Also, the volume of the Digester is the total volume of the digester, including the working volume and any additional space required for mixing gas storage, or other purposes. It is typically measured in cubic meters ($m^3$).

The organic Loading Rate is the amount of organic matter added to the digester per unit of time. It is typically measured in kilograms per day (kg/day).

For example, if the volume of the digester is 100 $m^3$ and the organic loading rate is 50 kg/day, the retention time would be 100 $m^3$ / 50 kg/day which amounts to 2 days

This means that the organic waste should remain in the digester for at least 2 days to ensure that it is properly digested, and that biogas production is optimized.

### 2.6.3 Formula for calculating the amount of gas produced by a biogas digester.

In their work "Design and Fabrication of a Plastic Biogas Digester for the Production of Biogas from Cow Dung" Obileke et al., (2020) mentioned that the amount of gas produced by a biogas digester depends on several factors, including the type and quantity of organic waste, the temperature and pH of the digester and the retention time. However, the general formula for calculating the amount of gas produced is

$$G_V = B_{pr} * R_t * D_{cf} \tag{2.10}$$

Where $G_V$ is the Gas Volume, $B_{pr}$ is the Biogas Production Rate, $R_t$ is the Retention Time and $D_{cf}$ is the Digestate Correction Factor. Also, Gas Volume is the total volume of gas produced by the digester, typically measured in cubic meters ($m^3$).

Biogas Production Rate is the rate at which biogas is produced by the digester, typically measured in cubic meters per day ($m^3$/day).

Retention Time is the amount of time that the organic waste remains in the digester, typically measured in days.

Digestate Correction Factor is a factor that accounts for the volume of digestate, which is the leftover material after digestion, and any gas that may be produced during storage or handling. The biogas production rate can be estimated using the following formula:

$$B_{pr} = D_{fy} * B_y \qquad (2.11)$$

Where:

$D_{fy}$ (Daily Feedstock Volume) is the volume of organic waste added to the digester per day, typically measured in cubic meters ($m^3$/day).

$B_y$ (Biogas Yield) is the amount of biogas produced per unit of organic matter added to the digester, typically measured in cubic meters per kilogram ($m^3$/kg).

$B_{pr}$ (Biogas Production Rate) is the rate of biogas produced daily.

For example, if the daily feedstock volume is 10 $m^3$ and the biogas yield is 0.5$m^3$/kg, the biogas production rate would be 10 $m^3$/day x 0.5 $m^3$/kg which gives 5 $m^3$/day.

Assuming a retention time of 20 days and a digestate correction factor of 1.2, the total gas volume produced would be 5 $m^3$/day x 20 days x 1.2 which gives 120 $m^3$.

This means that the digester would produce 120 cubic meters of biogas over a period of 20 days.

### 2.6.4 Digestate Correction Factor of a biogas digester and the Formula for its Calculation

According to Roman and Julie (2021), the digestate correction factor of a biogas digester is a value used to determine the amount of organic matter that has been converted into biogas within the digester. It is the ratio of the total volatile solids (TVS) in the influent feedstock to the TVS in the effluent digestate. The TVS is the portion of the organic matter that is volatile and can be converted into biogas through the anaerobic digestion process. By comparing the TVS in the influent and effluent, how much of the organic matter has been converted into biogas was determined. It is a factor that accounts for the volume of digestate, which is the leftover material after digestion, and any gas that may be produced during storage or handling. It is used to adjust the amount of gas produced by the digester, based on the actual volume of gas that is available for use.

The digestate correction factor is an important parameter for monitoring and optimizing the performance of a biogas digester. It can be used to adjust the feeding rate and composition of the feedstock, as well as to identify and troubleshoot any problems in the digestion process.

The formula for calculating the digestate correction factor is:

$$D_{cf} = \frac{D_1 + D_2}{D_1} \qquad (2.12)$$

Where $D_{cf}$ is the Digestate Correction Factor, $D_1$ is the Initial Volume of Digestate and $D_2$ is the Volume of New Digestate, also the initial Volume of Digestate is the volume of digestate that was present in the digester at the start of the retention time, typically measured in cubic meters ($m^3$).

The volume of New Digestate is the volume of digestate that is produced during the retention time, typically measured in cubic meters ($m^3$).

For example, if the initial volume of digestate in the digester is 5 $m^3$ and the volume of new digestate produced during the retention time is 1 $m^3$, the digestate correction factor would be (5 $m^3$ + 1 $m^3$) / 5 $m^3$ which gives 1.2

This means that the gas volume produced by the digester would be adjusted by a factor of 1.2, to account for the volume of digestate and any gas that may be produced during storage or handling.

## 2.7 REVIEW OF SOME SELECTED RELATED WORKS IN BIOGAS

### 2.7.1 Comparative Study of Biogas Generation from Chicken Waste, Cow Dung, and Pig Waste Using Constructed Plastic Bio Digesters

In this research work by Atilade et al., (2015), three biodigesters were constructed using locally sourced materials and fed with waste in the ratio 1:2 (i.e. waste: water) for chicken waste and pig waste and 1:3 for cow dung to obtain a homogeneous mixture. The parameters such as temperature within and outside the digesters, and volume of gas generated by each waste were observed and recorded. The graph of the average daily temperature of the biodigesters and ambient were plotted against retention time/day. The gas chromatography of the gas generated from each digester was also carried out to determine the constituent of the gas. The results show that chicken waste generated 71.39% methane gas, 0.48% Ammonia, 1.75% Carbon II Oxide, 0.65% Hydrogen Sulphide and 25.73% Carbon IV Oxide. Cow dung generated 62.68% methane gas, 0.38% Ammonia, 1.39% Carbon II Oxide, 0.13% Hydrogen Sulphide and 35.42% Carbon IV Oxide. Pig waste generated 61.07% methane gas, 0.48% Ammonia, 1.73% Carbon II Oxide, 0.16% Hydrogen Sulphide and 36.56% Carbon IV Oxide. Also, Chicken waste generated the highest volume of gas followed by pig waste and cow dung generated the least volume with the same retention time.

In this research, plastic drums were perforated and drilled on the top and at the bottom using a hot-iron rod of diameter approximately equal to that of the PVC pipe, and a round file was used to shape the hole until the PVC pipe was tightly fitted into the hole. On the top, four holes were drilled as a thermometer opening, gas outlet opening, waste-inlet, and overflow opening. At the inlet and overflow opening, a pipe measuring 30cm in height was inserted into it from the top. This served as the inlet and overflow of slurry. The hole drilled at the bottom served as the outlet for sludge. The pipes were tightly fitted to the holes of the drum with the aid of braces, PVC cement glue, and four-minute glue. This did not only make the pipes tightly fitted but also aided as a sealant to avoid the escape of gases that was generated during the course of fermentation in the digester. The thermometer was inserted into its opening, and a pipe with a gas tap was also inserted into the gas outlet opening, which was further connected to the manifold tester to trap the gas and measure its pressure while transferring the gas into the gas collector. The drums were thoroughly washed with hot water, detergent and left for a week filled with clean tap water before feeding it with slurry. The slurry was prepared by measuring 60 litres (0.06 m3) of pig waste and poured into the mixing drum. Tap water having a volume of 120 litres (0.12m3) was added to the waste inside the drum (i.e. in ratio 1:2; waste to water) which also apply to the poultry waste and cow dung was mixed in the ratio 1:3. The slurry was fully stirred manually with a piece of wood until there were no lumps. The waste was transferred to the plastic digester. It was ensured that foreign materials.

like stone, stick, rubber, sand, gravel, paints, feathers etc. did not enter the digester.

Results: The three digesters produced gas suspected to be biogas with chicken waste generating gases within 24 hours of loading; pig waste generating gases after three days of loading and cow dung generating gas after seven days of loading. It was also observed that Chicken waste generates the highest volume of gas followed by pig waste and cow dung generates the least volume of gas as evidenced by the size of the tubes after opening the gas valves. Pressure is also observed constant throughout the retention days.

Table 2.1: Table showing the Result of biogas analysis for the waste using gas chromatography

| WASTE | Biogas Components % | | | | | |
|---|---|---|---|---|---|---|
| | Methane | Ammonia | Carbon II Oxide | Hydrogen Sulphide | Carbon IV Oxide | Total |
| | **($CH_4$)** | **($NH_3$)** | **(CO)** | **($H_2S$)** | **($CO_2$)** | **%** |
| ChickenWaste | 71.39 | 0.48 | 1.75 | 0.65 | 25.73 | 100 |
| CowDung | 62.68 | 0.38 | 1.39 | 0.13 | 35.42 | 100 |
| PigWaste | 61.07 | 0.48 | 1.73 | 0.16 | 36.56 | 100 |

Source: Atilade et al., (2015)

### 2.7.2 Preparation of Biogas from Plants and Animal Waste

Ubwa, Asemave, Oshido, and Idoko (2013) investigated the biogas potentials of six different plants, Cow rumen liquor, Cowpea, and poultry waste. The Slurry used was prepared by mixing 60 g of the plants' sample with 20 g of chicken dropping in the ratio of 3:1 W/W (weight for weight). These were moistened with varying volumes of pre–warmed water at 37ºC. The results show nonlinear production of gas during the retention period of 16 days, with a corresponding increase in the cumulative volume of biogas. Digesters containing SteculiaSetigera and Grewia mollis produced cumulative volumes of 267 $cm^3$ and 245 $cm^3$ respectively; while Lanneasp, Ficus Capensis, Ficus Trichopoda and Piliostigma Thonnigii produced cumulative volumes of 241, 185, 181 and 95$cm^3$ respectively. The entire samples produced biogas at an early retention time not later than 10 days. The results are such that the higher the lignin contents in the plants, the lower their biogas yield. Low moisture contents (9.1 – 4.6 %) were observed for all the samples. The pH range of 7.53 – 6.80 was found for the samples' slurry. The pH of 7.53 was associated with the sample with highest cumulative volume of biogas. The range 49.02 – 41.18 % was observed as the ash contents for the materials used.

Result from the study of Ubwa, et al., (2013) is presented in Table 2.2 and Table 2.3 below.

Table 2.2: Percentage of pH, moisture content and ash content

| Parameter | S1 | S2 | S3 | S4 | S5 | S6 | P |
|---|---|---|---|---|---|---|---|
| Moisture content (%) | 4.80 | 5.60 | 4.60 | 4.90 | 5.90 | 9.10 | 4.90 |
| Ash content (%) | 43.14 | 44.23 | 41.18 | 48.08 | 49.02 | 47.06 | 45.10 |
| pH | 6.80 | 7.24 | 7.53 | 7.53 | 6.79 | 7.32 | 0.00 |

Source: Ubwa, et al., (2013)

Table 2.3: Daily yield and cumulative volume ($cm^3$) of biogas

| *Day* | *GrewiaMollis* | | *Lanneasp* | | *SteculiaSetigera* | | *FicusCapensis* | | *FicusTrichopoda* | | *PhilostigmaThonnigii* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DY | CY | DY | CY | DY | CY | DY | CY | DY | CY | DY | CY |
| 1. | - | - | - | - | - | - | - | - | - | - | - | - |
| 2. | 56 | 56 | 30 | 30 | 60 | 60 | 20 | 20 | 40 | 40 | 20 | 20 |
| 3. | 24 | 80 | 50 | 80 | 20 | 80 | 21 | 41 | 20 | 60 | 22 | 42 |
| 4. | 14 | 94 | 10 | 90 | 10 | 90 | 49 | 90 | 20 | 80 | 5 | 47 |
| 5. | 10 | 104 | 0 | 90 | 10 | 100 | 20 | 110 | 20 | 100 | 3 | 50 |
| 6. | 5 | 109 | 20 | 110 | 0 | 100 | 5 | 115 | 5 | 105 | 5 | 55 |
| 7. | 11 | 120 | 15 | 125 | 80 | 180 | 5 | 120 | 5 | 110 | 0 | 55 |
| 8. | 10 | 130 | 5 | 130 | 30 | 210 | 5 | 125 | 5 | 115 | 10 | 65 |
| 9. | 7 | 137 | 5 | 135 | 10 | 220 | 0 | 125 | 10 | 125 | 5 | 70 |
| 10. | 20 | 157 | 10 | 145 | 5 | 225 | 5 | 130 | 10 | 135 | 5 | 75 |
| 11. | 15 | 172 | 11 | 156 | 10 | 235 | 10 | 140 | 15 | 150 | 0 | 75 |
| 12. | 15 | 187 | 40 | 196 | 10 | 245 | 20 | 160 | 0 | 150 | 5 | 80 |
| 13. | - | 187 | 15 | 211 | 10 | 255 | 5 | 165 | 7 | 157 | 10 | 90 |
| 14. | 4 | 191 | 20 | 231 | 7 | 262 | - | 165 | 7 | 164 | 5 | 95 |

Table of Daily yield and cumulative volume (cm$^3$) of biogas cont'd

| | *GrewiaMollis* | | *Lanneasp* | | *SteculiaSetigera* | | *FicusCapensis* | | *FicusTrichopoda* | | *PhilostigmaThonnigii* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Day* | DY | CY | DY | CY | DY | CY | DY | CY | DY | CY | DY | CY |
| | | | | | | | | | | | | |
| 15. | 25 | 216 | 5 | 236 | 5 | 267 | 10 | 175 | 7 | 171 | 0 | 95 |
| 16. | 30 | 246 | 5 | 241 | 0 | 267 | 10 | 185 | 10 | 181 | 0 | 95 |
| Total | | 246 | | 241 | | 267 | | 185 | | 181 | | 95 |

Source: Ubwa, et al., (2013)

Where: DY = daily yield; CY = cumulative yield;*Grewia Mollis* (SI);*LanneaSp*(S2); *SteruliaSetigera*(S3);*Ficus Capensis* (S4);*FicusTrichopoda*(S5);*PiliostigmaThonnigii*(S6) andPoultryWaste(P)

The results in Tables 2.2 and 2.3 above, show nonlinear production of gas during the retention period of 16days.On the first day, there was no production of biogas thus suggesting that fermentation has not started. The samples were found to have low moisture contents (9.1-4.6%) and this appeared to increase the cumulative volume of gas produced (Maishanu and Sambo, 1991). The generation of biogas depends on several factors such as pH, temperature, total solid of the slurry, and microbial activities. These samples have ash contents as $S_1$ (43.14), $S_2$ (44.23), $S_3$ (41.18), $S_4$ (48.08), $S_5$ (49.02), $S_6$ (47.06) and P (45.10). The ash content of organic matter is an excellent index for measuring its mineral contents and its nutritional values to both man and animals. The high ash content of these samples suggests they are valuable substrates for bio-fertilizers. The pH range of 7.53 – 6.80 was found for the sample's slurry. The pH of 7.53 was associated with the sample with the highest cumulative volume of biogas. It was reported that at an appropriate pH of 7, there is a balance in the population of the acidogens and methanogens, such that an equal amount of the acid intermediates produced during the digestion process is converted to biogas. If the methanogens are not present in suitable numbers or are inhibited by unfavourable conditions (At low pH), they will not use the acids as rapidly as they are produced. The slurry temperature of 28°C was maintained during the process of fermentation. The ambient temperature fluctuated due to climatic conditions.

From the results in Table 2.3, biogas was produced within fifteen days retention period. Digesters containing *SteculiaSetigera* and *Grewia moll is* produced cumulative total volumes of 267cm$^3$ and 245cm$^3$ respectively. While *nanneasp, Ficus Capensis, Ficus Trichopoda ,*and *Piliostigma Thonnigii* produced cumulative total volumes of 241, 185, 181, and 95cm$^3$ respectively. Digesters of *PiliostigmaThonnigii, Ficus Trichopoda,* and *Ficus Capensis* gave low gas yield owing to high lignin content that characterizes their rigidity.

### 2.7.3 Evaluation of Biogas Yield and Microbial Species from Selected Multi-biomass Feedstocks in Nigeria

This research by Oseji, Ana and Sokan-Adeaga (2017), tries to evaluate the biogas yield and microbial species from mixtures of the following feedstocks Pig dung (PD), Water Hyacinth (WH), Maize cob (MC), Pig dung + Maize cob (PM), Pig dung + Water hyacinth (PW), Pig dung + Maize cob + Water hyacinth (PMW) in which Pig dung (PD), Water Hyacinth (WH), Maize cob (MC) yielded the following biogas 4505.3 ± 35.50ml, 4190.0 ± 21.10, 3338.3 ± 10.60 respectively for Dry Weights of 0.75kg each. Biogas digester was fabricated from 10 liters keg for feedstock biodegradation. Ratio 1:11 (w/v) slurry was prepared from each feedstock sample digested and fed into the corresponding digester, kept for 35 days for anaerobic digestion while samples of the effluent were taken at seven days intervals for five weeks for laboratory analyses of their physicochemical and microbial characteristics. Gas generated was estimated based on Archimedes' Principle. Data were analyzed using descriptive statistics and ANOVA at $p < 0.05$. The temperature was within the mesophilic range and pH (5.80 ± 0.0 to 7.85 ± 0.1) for all the slurries respectively. There was a significant difference in the percentage nitrogen, phosphorus, and potassium of the various slurries. The anaerobic, coliform, and fungal counts ranged from $6.80 \times 10^2$ to $1.0 \times 10^5$cfu/g, $4.3 \times 10^4$ to $6.2 \times 10^6$cfu/g, and $9.1 \times 10^3$ to $6.3 \times 10^6$cfu/g respectively throughout the duration of the study. The highest anaerobic count ($1.0 \times 10^5 \pm 0.03 \times 10^5$cfu/g) and biogas yield (6067.00 ± 38.2ml) was recorded in Pig dung + Water hyacinth (PW) feedstock. There was a significant difference between the mean biogas yields of the various feedstock groups. Co-digestion of pig dung with water hyacinth had the highest number of anaerobes and biogas yield as compared to single feedstocks. Therefore, the use of multi-biomass feedstocks for biogas production as a source of alternative energy production should be fully optimized.

The study was experimental and laboratory-based, involving pre-treatment, anaerobic digestion, biochemical tests, and microbiological examination. Different types of organic wastes such as pig dung, water hyacinth, and maize cob were utilized in the experiment. The experiment was divided into six (6) treatment groups: Treatment A = Pig dung (PD) Treatment B = Water Hyacinth (WH) Treatment C = Maize cob (MC) Treatment D = 1:1 of Pig dung + Maize cob (PM) Treatment E = 1:1 of Pig dung + Water hyacinth (PW) Treatment F = 1:1:1 of Pig dung + Maize cob + Water hyacinth (PMW) The experiment employed a complete randomized design with three replicate of each of the sample biomass. An evaluation of the biogas yielding capacity and microbial load of the different biomass was carried out. The different organic wastes utilized in this study were collected from the following sources in Ibadan: Pig Dung (PD) and Maize Cob (MC) were obtained from the University of Ibadan Teaching and Research Farm (UITRF) located at the north end of the University campus. It covers approximately a land area of hundred and sixty hectares (160 ha) [400acres] which is used for both livestock husbandry (cattle, pig, poultry, and sheep) and crop (maize, cassava, etc.) production. These Agricultural practices led to large generation of biomass wastes which are disposed indiscriminately in the environment. Water Hyacinth (WH) was obtained from Oba-Dam (OD) which is in the outskirt of the University of Ibadan (UI) very close to Ibadan Polytechnic (IP). It is about 130m in length, 12.2m wide at the top, about 27.4m wide at the deepest portion and has a maximum depth of about 5.5m. It has a capacity to hold about 227million litres of water. A feasibility study was carried out on the sample collection area to determine the amount of wastes being generated from the parent food materials. The quantity of biomass by-products generated from the crop production was estimated using the method of which utilizes the residue to crop ratio approach. The weight (kg) and volume ($m^3$) of the waste of the sample population was determined using a weighing balance (Top Load and Silvano Weight Balance), and measuring cylinder (Hirschman Model), with the density calculated in kg/m3. A representative sample of each biomass was obtained from the respective sources. From each heap of biomass wastes, a grab sample was collected into a polythene bag ready for physicochemical characterization.

Single Substrates

i. Treatment 1 - PD: 1.88 kg of wet pig dung was weighed, and 7.12 litres of water was added to form slurry (9 litres).
ii. Treatment 2 - WH: 3.64 kg of wet water hyacinth was weighed out and 5.36 litres of water was added to form slurry (9 litres).
iii. Treatment 3 - MC: 3.30kg of wet maize cob was weighed out and 5.7 litres of water was added to form slurry (9 litres).
iv. Multi-substrates
v. Treatment 4 - PM: 0.94 kg of wet pig dung and 1.65 kg of wet maize cob were weighed out and 6.41litres of water was added to form slurry (9 litres).
vi. Treatment 5 - PW: 0.94kg of wet pig dung and1.82kg of wet water hyacinth was weighed out and 6.24litres of water was added to form slurry (9litres).
vii. Treatment 6 - PMW: 0.63kg of wet pig dung, 1.10kg of wet maize cob and 1.22kg of wet water hyacinth were weighed and 6.05 litres of water was added to form slurry (9 litres). Note: The above weights of each waste used were equivalent to 0.75kg of its dry matter. All mixtures of slurry were poured into their respective digesters and were properly sealed for anaerobic digestion process gin.

According to them, the operational mode was the batch method, using an operational mesophilic temperature. Respective weights were mixed with water at the ratio of 1:3 (w/v) and placed in the digesters. The various variants were charged into the 10L rubber keg digesters as originally weighed out. The wastes were charged up to ¾ of the digester leaving ¼ headspace for collection of gas. The digester contents were stirred adequately and on a daily basis to ensure homogenous dispersion of the constituents of the mixture. The digesters were tightly corked with rubber stopper to create anaerobic condition and connected to a gasometrical chamber. Biogas was monitored and measured daily over a period of 35 days using the gasometrical chamber with the displacement of paraffin wax. The total biogas yields were determined by opening the outlet tap of the anaerobic digester and the inlet tap to the graduated burette. Gas production was measured in $dm^3$ /kg of slurry (35kg) was obtained by downward displacement of water by the gas as shown in Table 2.4 below. The pH and temperature of all slurry mixtures were determined using pH meter and thermometer while 200 ml of each slurry mixture was collected into clean bottled water container and was immediately taken to the laboratory for analysis of the following parameters: Physical characteristics (total solids) and chemical characteristics (TOC, TN, TP, TK, BOD, COD). Samples were also analyzed on days 7, 14, 21, 28 and 35. The AOAC methods (A. O. A. C., 1990) were employed in the determination of the Total Organic Carbon (T.O.C), Total Nitrogen (TN), Total Phosphorus (TP) (%), Total Potassium (TK), Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The T.O.C (%) of the sample was determined quantitatively by using the Walkey-Black Method. The TN (%) of the samples was determined by the routine semi-micro kjeldahl technique. This consists of three techniques namely, Digestion, Distillation and Titration (A. O. A. C., 1990). The TP (%) was determined routinely by the vanado-molybdate colorimetric method (A. O. A. C., 1990). The concentration of the phosphorus was obtained by taking the optical density (OD) or absorbance of the solution on a Spectronic-20 spectrophotometer at a wavelength of 470nm. Anhydrous KH 2PO4 was used as standard phosphate solution to obtain the calibration curve. The TK was determined by flame photometry at a wavelength of 766.5 nm.

***Table2.4:*** **Estimation of the quantity of agro-based wastes from parent source**

| Mean Weight(Kg) Mean ± Mean Volume ($m^3$) Density Sample S.D Mean ± S.D(Kg/$m^3$) | | | | | |
|---|---|---|---|---|---|
| | Min. Limit | Max. Limit | Min. Limit | Max. Limit | Mean ± S.D |
| Pig dung | 99.0±9.6 | 123.8±12.1 | 0.14±0.02 | 0.18±0.23 | 702.67±34.30 |
| Water hyacinth | 3895.2±681.4 | 5842.82±1022.1 | 38.7±6.7 | 58.05±10.0 | 100.6±1.4 |
| Maize cob | 1163.6±36.8 | 1933.3±61.1 | 0.71±0.02 | 1.02±0.3 | 1641.5±36.2 |

Source: Oseji, et al., (2017)

Table 2.5: Pattern of Physicochemical Properties of the slurry mixtures at weekly interval (days 0 - 14)

| Day | Slurry mixtures | Temperature of slurry | pH | TOC (%) | TN % | C/N ratio | TP(mg/l) | Potassium(mg/l) | BOD5 (mg/l) | COD(mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | PD | 25.8±0.4 | 6.6±0.0 | 41.7±4.9 | 2.1±.1 | 20.1±2.1 | 208.3±2.9 | 29.7±.58 | 2533.3±15.3 | 4675.0±15.0 |
| | WH | 25.9±.3 | 7.9±.06 | 45.9±1.3 | 2.0±.1 | 23.3±.1 | 191.7±2.9 | 28.7±.6 | 2223.3±12.6 | 3925.0±21.8 |
| | MC | 26.2±.3 | 5.8±.0 | 63.4±1.1 | 0.7±.0 | 97.5±3.3 | 153.3±2.9 | 23.0±1.0 | 1456.7±16.1 | 2630.0±10.0 |
| | PD/MC | 25.9±.4 | 6.0±.0 | 58.0±.6 | 1.0±.0 | 57.3±.2 | 198.3±5.8 | 29.7±.6 | 2336.7±15.3 | 4248.3±20.8 |
| | PD/WH | 26.1±.2 | 7.3±.1 | 56.5±8.1 | 2.0±.0 | 28.5±4.2 | 198.3±2.9 | 30.7±1.2 | 2250.0±8.7 | 4130.0±13.2 |
| | PMW | 26.1±.2 | 6.2±.0 | 56.9±3.8 | 1.1±.0 | 49.9±2.9 | 203.3±2.9 | 30.3±.6 | 2448.3±25.7 | 4653.3±22.6 |
| 7 | PD | 28.0±.5 | 6.4±0.1 | 41.7±4.0 | 2.1±.0 | 20.0±1.8 | 225.0±5.0 | 31.0±1.0 | 2263.3±15.3 | 4323.33±12.6 |
| | WH | 28.2±.4 | 7.3±.1 | 44.1±.1 | 2.0±.0 | 21.7±.2 | 205.0±.0 | 29.0±1.0 | 2040.0±20.0 | 3783.3±07.6 |
| | MC | 28.3±.2 | 4.0±3.5 | 60.4±1.4 | 0.7±.0 | 90.2±1.4 | 166.7±2.9 | 26.0±1.0 | 1226.7±15.3 | 2185.0±13.2 |
| | PD/MC | 28.4±.1 | 6.1±.0 | 55.1±1.5 | 1.1±.0 | 52.5±2.4 | 211.7±2.9 | 31.3±.6 | 2166.7±41.6 | 4051.7±2.9 |
| | PD/WH | 27.9±.1 | 7.2±.0 | 56.1±2.3 | 2.0±.0 | 27.9±1.1 | 213.3±2.9 | 32.3±.6 | 2098.3±47.5 | 4005.0±31.2 |
| | PMW | 28.2±.3 | 6.2±.0 | 55.9±1.0 | 1.2±.0 | 48.2±1.0 | 218.3±2.9 | 32.0±.0 | 2168.3±38.2 | 4228.3±17.6 |

| Pattern of Physicochemical Properties of the slurry mixtures at weekly interval (days 0 - 14) Cont'd | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Day | Slurry mixtures | Temperature of slurry | pH | TOC (%) | TN % | C/N ratio | TP(mg/l) | Potassium(mg/l) | BOD5 (mg/l) | COD(mg/l) |
| | | | | | | | | | | |
| 14 | PD | 28.5±.0 | 6.5±.1 | 41.3±3.3 | 2.1±.0 | 19.6±1.8 | 235.0±.0 | 32.0±.0 | 2140.0±10.0 | 4013.3±22.6 |
| | WH | 28.3±.6 | 7.3±.1 | 39.0±2.8 | 2.1±.0 | 18.8±1.3 | 210.0±5.0 | 29.3±.6 | 1988.3±18.9 | 3570.0±00.0 |
| | MC | 28.0±.0 | 6.2±.0 | 55.6±.8 | 0.7±.0 | 78.3±.1 | 176.7±5.8 | 27.7±.6 | 1041.7±17.6 | 1813.3±2.9 |
| | PD/MC | 28.7±.3 | 6.2±.0 | 50.9±.0 | 1.1±.0 | 47.6±.0 | 218.3±2.9 | 32.3±1.2 | 2073.3±20.8 | 3981.7±10.4 |
| | PD/WH | 28.6±.1 | 7.3±.0 | 55.4±3.2 | 2.1±.0 | 26.8±1.9 | 225.0±.0 | 33.7±.6 | 1980.0±5.0 | 3506.7±25.2 |
| | PMW | 28.0±.5 | 6.4±.0 | 54.8±1.3 | 1.2±.0 | 46.4±.1 | 230.0±.0 | 33.3±.6 | 2088.3±33.3 | 3766.7±15.3 |

Source: Oseji, et al., (2017)

Table 2.6: Pattern of Physicochemical Properties of the slurry mixtures at weekly interval (days 21 - 35)

| **Day** | **Slurry mixtures** | **Temperature of slurry** | **pH** | **TOC(%)** | **TN %** | **C/N ratio** | **TP(mg/l)** | **Potassium(mg/l)** | **BOD5 (mg/l)** | **COD(mg/l)** |
|---|---|---|---|---|---|---|---|---|---|---|
| 21 | PD | 28.2±.3 | **6.4±.1** | 43.8±3.6 | 2.2±.0 | 19.8±1.7 | 273.3±2.9 | 33.7±.6 | 2051.7±12.6 | 3888.3±67.9 |
| | WH | 28.5±.3 | **7.3±.0** | 33.9±.3 | 2.1±.0 | 15.9±.1 | 231.7±2.9 | 29.7±.6 | 1893.3±15.3 | 3456.7±16.1 |
| | MC | 28.5±.1 | **6.1±.1** | 47.0±1.5 | 0.8±.0 | 62.7±1.9 | 196.7±5.8 | 28.0±1.0 | 996.7±12.6 | 1733.3±36.9 |
| | PD/MC | 28.4±.2 | **6.1±.1** | 44.2±1.2 | 1.2±.0 | 38.5±1.4 | 250.0±5.0 | 35.0±.0 | 1996.7±20.8 | 3875.0±96.6 |
| | PD/WH | 28.3±.3 | **7.2±.0** | 54.5±.0 | 2.1±.0 | 26.0±.0 | 260.0±5.0 | 36.0±1.0 | 1913.3±7.6 | 3485.0±21.8 |
| | PMW | 28.4±.2 | **6.3±.** | 52.3±2.3 | 1.2±.0 | 42.2±1.5 | 270.0±.0 | 34.7±1.5 | 1995.0±25.0 | 3723.3±12.6 |
| 28 | PD | 28.1±.5 | **6.6±.1** | 38.4±2.6 | 2.3±.0 | 16.9±1.3 | 285.0±5.0 | 34.3±.6 | 2010.0±10.0 | 3790.0±10.0 |
| | WH | 28.6±.2 | **7.2±.1** | 31.5±.1 | 2.2±.0 | 14.1±.1 | 238.3±2.9 | 30.7±.6 | 1853.3±11.6 | 3371.7±7.6 |
| | MC | 28.8±.4 | **6.2±.0** | 39.2±.3 | .8±.0 | 51.0±.8 | 208.3±2.9 | 29.3±.6 | 976.7±7.6 | 1631.7±16.1 |

Pattern of Physicochemical Properties of the slurry mixtures at weekly interval (days 21 - 35) Cont'd

| Day | Slurry mixtures | Temperature of slurry | pH | TOC(%) | TN % | C/N ratio | TP(mg/l) | Potassium(mg/l) | BOD5 (mg/l) | COD(mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|
| | PD/MC | 27.6±1.8 | **6.3±.1** | 35.7±.8 | 1.2±.0 | 29.7±.3 | 258.3±7.6 | 35.7±.6 | 1963.3±05.8 | 3681.7±30.1 |
| | PD/WH | 28.3±.3 | **7.0±.0** | 52.5±4.8 | 2.1±.0 | 24.6±2.3 | 268.3±2.9 | 36.7±.6 | 1888.3±2.9 | 3393.3±30.6 |
| | PMW | 28.6±.2 | **6.2±.0** | 50.9±3.6 | 1.3±.0 | 38.8±1.9 | 276.7±2.9 | 35.0±1.0 | 1976.7±10.4 | 3668.3±16.1 |
| 35 | PD | 28.0±.5 | **6.5±.0** | 37.8±2.7 | 2.3±.0 | 16.3±1.1 | 301.7±2.9 | 35.0±1.0 | 1995.0±10.0 | 3698.3±25.7 |
| | WH | 28.0±.0 | **7.2±.0** | 29.1±2.4 | 2.3±.0 | 13.0±1.2 | 251.7±2.9 | 31.0±1.0 | 1846.7±2.9 | 3360.0±13.2 |
| | MC | 28.2±.3 | **6.1±.0** | 37.2±.7 | 0.8±.0 | 47.7±1.3 | 221.7±2.9 | 29.5±.6 | 968.3±10.4 | 1576.7±25.2 |
| | PD/MC | 28.3±.1 | **6.1±.1** | 34.9±2.9 | 1.2±.0 | 28.3±2.1 | 273.3±2.9 | 36.0±.0 | 1956.7±7.6 | 3588.3±28.4 |
| | PD/WH | 27.9±.2 | **7.0±.1** | 52.0±4.2 | 2.2±.0 | 24.2±2.0 | 281.7±2.9 | 36.7±.6 | 1870.0±5.0 | 3355.0±5.0 |
| | PMW | 28.3±.3 | **6.2±.0** | 49.5±3.0 | 1.3±.0 | 37.2±2.4 | 290.0±5.0 | 35.7±1.0 | 1961.7±7.6 | 3526.7±12.6 |

Source: Oseji, et al., (2017)

Table 2.7: Projected mean value of biogas yield of pig dung ,water hyacinth and maize cob that was generated from the parent sources.

| Experimental quantity of Waste used and its corresponding total biogas yield | | | | Total wastes generated from parent source and its projected total biogas yield | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample | Waste(kg) Wet Weight(WW) | | Biogas yield | Mean weight of waste (tons) Mean±SD | | Dry weight (DW) | | Mean Biogas yield (L) (ml) Mean ±SD | |
| | WW | DW | | Min. limit | Max limit | Min limit | Max limit | Min. limit | Max. limit |
| PD | 1.88 | 0.75 | 4505.3±35.50 | 0.10±0.01 | 0.12±0.01 | 0.04±0.01 | 0.05±001. | 237.30±31.30 | 296.69±37.90 |
| WH | 3.64 | 0.75 | 4190.0±21.10 | 3.90±0.68 | 5.84±1.02 | 0.80±0.14 | 1.20±0.21 | 4482.29±769.52 | 6723.43±1154.27 |
| MC | 3.30 | 0.75 | 3338.3±10.60 | 1.16±0.04 | 1.93±0.06 | 0.27±0.008 | 0.44±0.01 | 1177.04±33.42 | 1955.66±55.56 |

Source: Oseji, et al., (2017)

The findings from this study revealed that huge quantities of waste are generated from University of Ibadan (U.I.) Anaerobic bacteria, especially the methanogens, are sensitive to the acid concentration within the digester and their growth can be inhibited by acidic conditions. It has been reported that an optimum pH value for AD lies between 5.5 and 8.5.In this study, also from Table 2.5, pH range of about 5.80 ± 0.0 to 7.85 ± 0.1 was observed which conforms with the reported range.

The temperature of the digester in this study remained constant at mesophilic range (25.8 ± 0.4°C to 28.8 ± 0.4°C) throughout the digestion period as seen in Table 2.5 and Table 2.6. Temperature has been observed by most researchers quite critical for anaerobic digestions, since methane – producing bacteria operate most efficiently at temperatures 30.0 – 40.0°C or 50.0 – 60.0°C. Temperature does not seem to have any significant effect on the amount of gas produced daily as revealed in this study. Daily gas generations tend not to follow specific temperature pattern, and this is indicative by the fact that other parameters apart from temperature could be responsible for the quantity of biogas generated per day.

From this study of Oseji, et al., (2017), the mean T.O.C decreased as the duration of anaerobic digestion increased, meaning that the organic bonded carbon in the slurries were oxidized to carbon dioxide ($CO_2$) and other inorganic Carbon (IC) such as carbonate, bicarbonate, etc. (Lal and Reddy, 2005). Among the various substrates, the mean T.O.C was greatest for the MC throughout the duration of the anaerobic digestion while the least mean T.O.C was found in PD, the implication being that MC had a high quantity of organic bonded carbon in its composition than other wastes. Environmentally, this implies that the natural degradation of these wastes contributes a substantial amount of greenhouse gases such as $CO_2$, $CH_4$, etc. to the environment. This was in agreement with Lal et al., 2005 who also reported that the natural degradation of lignocellulosic wastes by anaerobic digestion of methanogenic bacteria generates about 25 million tons of methane gas annually worldwide.

In this study by Oseji, et al., (2017), it was observed that the total nitrogen content of the slurries increased steadily as the anaerobic digestion progressed daily and this was in agreement with other studies which have found an increased yield and nitrogen availability with the application of anaerobically digested material as compared to non-digested material, possibly due to increased nitrogen content and reduced carbon content, which can result in nitrogen mineralization by microbes. In this study, it was found that the Total Phosphate of all the slurries increased throughout the experiment. Nutrient speciation data collected from previous AD studies suggest that a high percentage of the P can be found in the inorganic form in the AD effluent and colleagues demonstrated a 26% increase of inorganic P in digested swine slurry compared to the raw swine slurry 1591 mg/L and 1256.2 of PO 3- respectively as seen in Table 2.5. It was observed that potassium increased steadily in all slurries throughout the duration of the anaerobic digestion. PD had the highest potassium while MC had the least. Tchobanoglous, Burton and Stensel, (2003) reported that for the proper functioning and continuous reproduction of methanogens in the anaerobic digestion process, there is a need for synthesis of new cellular materials, of which inorganic elements such as potassium play a key role.

The relationship between the amount of carbon and nitrogen present in organic materials is expressed in terms of the Carbon/Nitrogen, C-N ratio. A C-N ratio ranging from 20 to 30 is considered optimum for anaerobic digestion. Mean C-N ratio of the various slurries decreased from day 0 to day 35 as follows: 20.05 ± 2.1 to 16.27 ± 1.1, 23.28 ± 0.1 to 12.95 ± 1.2,97.54 ± 3.3 to 47.70 ± 1.3, 57.27 ± 0.2 to 28.34 ± 2.1, 28.52 ± 4.2 to 24.19 ± 2.0 and 49.86 ± 2.9 to37.24 ± 2.4 for PD, WH, MC, PM, PW, and PWM respectively. In this study, it was observed that the values obtained for the C:N of PM and PW lies within the optimum range while those of the other substrates (PD, WH, MC and PWM) lies outside the optimum value of C:N for biogas generation from biomass. This high biogas production observed in PM and PW may be attributed to their C:N which lies within the optimum range (20: 1-30:1), please refer to Tables 2.5 and 2.6.

The result of the analysis of the feedstocks during the anaerobic digestion revealed that there is a reduction in BOD and COD indicating that anaerobic digestion is a potent way of reducing these parameters from sludge or wastewater. From the environmental point of view, anaerobic digestion treatment helps to avert the serious public health risk posed by these wastes, which if discharged directly into water bodies can contribute to algal blooms and cyano-bacterial growth thus destroying the aquatic ecosystem. Also, the reduction in BOD and COD is in agreement with Wei et al., 2011 who reported a high BOD and COD removal from the supernatant of hydrothermally treated municipal sludge by an up-flow anaerobic sludge blanket reactor.

The groups of bacteria isolated from the digester feedstock include Bacillus, Escherichia, Clostridium, Klebsiella, Proteus, and Bacteroides some of which are acid-formers and a methane former Methanococcus species, the correct balance between these two groups of microorganisms determines the successful operation of anaerobic digesters for biogas production. The methane formers however multiply at a slower rate than acid formers and are very sensitive to environmental changes as seen in this research. Fungal isolates include spergillius spp and Candida spp whose source could be the feedstock. The decreasing trend seen in the aerobic count could be attributed to the increasing anaerobiosis. The acidic nature of the feedstock over the first four weeks of digestion could have supported the growth of acid-producing organisms despite the anaerobic condition. A decrease in fungal isolates over the first three weeks even as the digestion becomes more anaerobic is in support of fungal general physiology and metabolism which is known purely aerobic. In support of this, Triolo, Sommer, Moller, Weisbjerg and Jiang (2011), in their research, reported that the acidic condition of the digester could be a support for fungi which are known acid-loving.

Gas generation commenced on the twentieth (20th) [PD, PD/MC and PD/WH] and twenty-second (22nd) [WH, MC, and PMW] days, it increased steadily and reached the peak on the 23rd (PD); 24th (PW and PM); 25th (MC), and 26th (WH and PMW) days before dropping as reflected in Table 2.7. This result agrees with the findings of Wei et al., 2011, who reported an increasing trend of biogas production from commencement and a drop after 30 days from supernatants of hydrothermally treated municipal sludge by up-flow anaerobic sludge blanket reactor. Alkan-Ozkaynak et al., (2011), also reported a high rate of biogas production from treated thin sillage with a drop towards the end of the experiment. According to the research, the seeding of co-digested pig waste and cassava with wood ash was reported to result in a significant increase in biogas production compared with an unseeded mixture of pig waste and cassava peels (Adeyanju, 2008). He identified four other substrates, namely Eupatorium odoratum, water lettuce, water hyacinth, and cow dung as potential substrates for biogas production. Eupatorium odoratum gave the highest yield of biogas and cow dung was the poorest substrate. These laboratory studies demonstrated the potential of biogas production from agricultural, industrial, urban, and animal wastes in Nigeria.

### 2.7.4 Evaluation of Biogas Production from Food Waste

According to this research by Ojikutu and Osokoya (2014), the anaerobic digestion of some common food wastes (yam peels, plantain peels, orange rind, and fish waste) and mixtures of these wastes were carried out in batch-type digesters for 70 days digestion period. During the experiment, the digestion temperature and volume of biogas produced were monitored daily while the pH of the slurry was monitored weekly. The digestion was carried out in a mesophilic temperature range of 30 ˚C to 37 ˚C with a total solid concentration of 8%. The results of the study showed that the food waste type had a significant (P≤0.05) effect on substrate temperature and pH but had no significant (P>0.05) effect on biogas production. The mean values showed that biogas production was in the range of 1090 ml/day and 8016.67 ml/day as shown in Table 2.9. The study concluded that anaerobic digestion of the mixture of the food wastes enhanced biogas production although not significantly (P>0.05).

The Dry weight of each food waste used in this research work is as follows: Yam Peels 2.2kg, Orange Rind 1.8kg, Plantain Peel 3.3kg, and Fish waste 2.7kg producing biogas of 149.8ml, 217.6ml, 130.9ml, and 137.8ml respectively. The amount of fermentable material of feed in a unity volume of slurry is defined as solid concentration, 7 – 9% solids concentration. The yam peels, plantain peels, and orange rind were chopped into smaller sizes (< 4 mm sieve size) to facilitate digestion. Each of the food waste was measured and poured into the mixing tank which contained cow dung (about 60% of the digester volume) and then stirred to ensure homogeneity. The homogenous mixture of food waste and cow dung slurry was then introduced into the digesters and hermetically sealed. Manual agitation was performed on the digester daily to ensure intimate contact between the microorganisms and the substrate for effective biogas production.

The water tank was filled with water to its brim. The gas produced by the substrates inside the anaerobic digester was channeled to the water tank on which two separate holes were drilled at the top, two rubber hoses were inserted in the holes, the first one (1000 mm in length and 7 mm in diameter) was used to connect the digester while the second (800 mm in length and 7 mm in diameter) was used to connect the water collector. The weight of gas produced was equivalent to the amount of water displaced in the water chamber (Archimedes' principle of floatation). The displaced water was collected in the water collector. The volume of water displaced in the water collector was measured daily (between 2 pm and 3 pm) using a measuring cylinder. A hole was bored at the bottom of the digester where the thermometer probe was fitted tightly with a rubber cork. The temperature reading was taken between 2 pm and 4 pm daily throughout the period of the experiment. The pH was measured weekly using a digital pH meter. The sample analyzed was collected in a dry bottle from the digester. The probe of the pH meter was immersed into the sample analyzed and the meter was allowed to stabilize before the reading was taken. Each treatment was repeated three times. The result of the C:N ratio is shown in Table 2.8 below. From the result, it can be seen that the C/N ratio for Cow dung was the highest (46:23)

Table 2.8: Properties of food waste and cow dung used.

| **Sample** | **MC(%)** | **Ash(%)** | **Carbon(%)** | **Nitrogen(%)** | **C:N ratio** |
|---|---|---|---|---|---|
| YamPeel | 77.27 | 1.14 | 54.92 | 1.26 | 43.59 |
| OrangeRind | 52.35 | 1.74 | 54.59 | 1.26 | 43.33 |
| PlantainPeel | 84.65 | 1.84 | 54.53 | 1.47 | 37.10 |
| Fish | 81.43 | 2.14 | 54.37 | 10.85 | 5.01 |
| CowDung | 57.21 | 4.312 | 53.16 | 1.15 | 46.23 |

Source: Ojikutu, et al., (2014)

Table 2.9: Duncan's Multiple Range Tests on the Effect of Food Waste Type on Temperature, pH and Biogas Production

| Treatment | Temperature(˚C) | pH | Biogas(ml) |
|---|---|---|---|
| Fish | 29.6000$^{a}$ | 7.0367$^{a}$ | 137.8$^{a}$ |
| Yampeel | 29.4000$^{a}$ | 4.6300$^{c,d}$ | 149.8$^{a}$ |
| Orangerind | 28.6667$^{b}$ | 4.4500$^{d}$ | 217.6$^{a}$ |
| Plantainpeel | 28.5333$^{b}$ | 4.8700$^{b,c}$ | 130.9$^{a}$ |
| Mixture | 29.2667$^{a}$ | 4.9767$^{b}$ | 345.7$^{a}$ |

Source: Ojikutu, et al., (2014)

### 2.7.5 Co-digestion of Sewage Sludge and Organic Fraction of Municipal Solid Waste

This research work carried out by Di Maria et al., (2012) tries to analyze the anaerobic co-digestion of the Organic Fraction of Municipal Solid Waste (OFMSW) with the Sewage Sludge (SS) in the Anaerobic Digestion (AD) section of an existing Wastewater Treatment Plant. The result of the preliminary batch runs shows that the introduction of the OFMSW can have positive effects on process efficiency and on biogas yield. As the OFMSW concentration added in the SS rises some instability phenomena can occur on the batch runs. Furthermore, a higher OFMSW concentration can lead to a significant increase in the Organic Load Rate of the existing AD section of the WWTP from about 0.6 kg COD/$m^3$ day to about 2.5 kg COD/$m^3$ day.

In the research, the OFMSW arising from the source-segregated collection was withdrawn from the inlet stream of an existing composting plant. The OFMSW sample was manually sorted for eliminating both inert and other not rapidly biodegradable materials. The sample was diluted with de-ionized water and then fluidized by a blender for achieving a mixture with TS concentration of about 3% w/w comparable with the one of the sludges entering the AD reactors at design conditions. Sludge samples have been withdrawn from the thickener outlet before the AD reactor inlet. All the samples have been stored between the temperatures of 24°C to 35°C for at least 3 days. The COD, total Nitrogen ($N_{tot}$), and phosphorous (P-PO4) concentrations (mg/l) have been determined both for the samples and for the Inoculums (I) by spectrophotometer analyzer and the results for these are as shown in Table 2.11 below. Electrical Conductivity (EC) (mS/cm), Total Dissolved Solids (TDS) (g/l), TS, and pH have also been evaluated. Further, for evaluating both COD reduction and Volatile Fatty Acids evolution also during batch runs, about 4 ml of the mixture has been sampled at given periods. Preliminary experimental batch analysis of the anaerobic batch runs has been performed in triplicate by 500ml bottles, maintained at mesophilic conditions (35°C±2°) by a thermal bath.

A water gasometric apparatus connected with bottles was utilized for Biogas Production measurement. Each test was activated by exploiting a 1:1 volumetric ratio with I obtained from mesophilic AD laboratory tests of cow manure. The BP of SS, OFMSW, and three different OFMSW:SS concentration ratios mixtures have been analyzed in triplicate. The OFMSW and SS concentration ratio is expressed by means of TS content (i.e. gTS/gTS) (Table 2.12). Also, a blank test was activated for evaluating the I contribution to the total BP.

The results of the research showed that the SS withdrawn from the WWTP shows an average Humidity value higher than 96% assumed at design conditions (Table 2.11). The COD concentration corresponds to typical values of about 4,000 mg/l along with N and P ones. The OFMSW diluted sample has a COD of about 70,000 mg/l and a high N and P concentration (Table 2.12). OFMSW and SS show acid values of pH whereas I have a quite alkaline value. The three mixtures show quite similar pH, TDS, and EC values mainly as a consequence of the buffer effect of the amount of I exploited for starting the process (Table 2.12). The BP runs show that the SS biogas yield has currently achieved (i.e. after 100 days) about 300ml/gTS. The OFMSW BP run has currently achieved about 600 ml/gTS resulting in coherence compared to the other data proposed in the literature. Even if tests are not finished yet, the runs with only OFMSW and with 6 g TS of OFMSW per g TS of SS, have a particular shape demonstrating the possibility of some inhibition phenomena mainly due to a high Volatile Fatty Acids (VFA) concentration. This aspect is currently under investigation and final results are not available yet.

Table 2.10: WWTP main features

| Parameter | Values | U.M. |
|---|---|---|
| Inhabitants eq. | 35,000 | - |
| SS rate | 140 | $m^3$/day |
| AD Volume 1st | 2,000 | $m^3$ |
| AD Volume 2nd | 659.4 | $m^3$ |
| AD TSS | 4 | % w/w |
| AD VSS | 64 | %ofTSS |
| AD temperature | 35 | °C |

Source: Di Maria et al., (2012)

Table 2.11: OFMSW, SS and I main characteristic.

| Parameter | OFMSW | SS | I |
|---|---|---|---|
| Humidity (%) | 97.1 | 98.5 | 98.9 |
| pH | 4.93 | 6.60 | 8.47 |
| TDS (g/l) | 4.890 | 0.795 | 2.010 |
| EC (mS) | 0.997 | 1.590 | 4.010 |
| COD(mg/l) | 68,327 | 4,085 | 24,644 |
| $N_{tot}$(mg/l) | 570 | 279 | 378 |
| P-$PO_4$(mg/l) | 105 | 93 | 240 |

Source : Di Maria et al., (2012)

Table 2.12: Mixture average characteristics for SSTS in (gTS)

| **Parameter** | **SSTS (1)** | **SSTS (2)** | **SSTS (3)** |
|---|---|---|---|
| pH | 7.60 | 7.54 | 7.50 |
| TDS (g/l) | 1.380 | 1.334 | 1.306 |
| EC (mS/cm) | 2.770 | 2.670 | 2.613 |

Source : Di Maria et al., (2012)

### 2.7.6 Harvesting Biogas from wastewater sludge and food waste

According to this study by Chua et al., (2013) on investigates the potential biogas generation from wastewater sludge and food wastes as well as the effects of temperature on biogas generation. A lab-scale reactor was used to simulate biogas generation. The results show that wastewater sludge produced up to 44.82 ml biogas/kg of sludge. When the wastewater sludge was mixed with food waste at a ratio of 30:70, the biogas generated was 219.07 ml/kg of waste. Anaerobic digestion of food waste alone produced a biogas amount of 59.75 ml/kg of food waste. The effect of temperature shows that higher temperature produces more biogas than lower temperature.

To carry out the research, sewage sludge, and food waste samples were collected from the site and delivered to an experimental laboratory analyzed. Some of the samples' chemical characteristics were given in Table 2.13. A series of laboratory-scale reactors consisting of circular PVC containers with a volume of about 20 liters were prepared. Each reactor had a gas outlet and tube for gas collection. The chemical analysis followed Standard Method for the examination of water and wastewater by APHA. COD was measured using Hach Spectrophotometer 2100. BOD measurement was measured by YSI BOD meter. All the samples were subjected to dilution as the concentration of BOD5 and COD are extremely high.

Table 2.13: Sample Characteristic

| Parameters | Sewage sludge | Food waste |
|---|---|---|
| Biochemical oxygen demand, $BOD_5$ ,(mg/l) | 29,524 | 162,086 |
| Chemical oxygen demand, COD (mg/l) | 135,711 | 682,847 |
| Ratio of BOD: COD | 1:4.60 | 1:4.21 |
| Moisture content, (%) | 68.9 | 94.3 |
| Biochemical oxygen demand, $BOD_5$,mg/l | 29,524 | 162,086 |
| Chemical oxygen demand, COD (mg/l) | 135,711 | 682,847 |
| Ratio of BOD: COD | 1:4.60 | 1:4.21 |

Source: Chua et al., (2013)

The proportion of co-digestion of food waste and sludge (w/w) and initial mass are given in Table 2.14. All the reactors were placed in a shaded area except Sample 3 which was placed under direct sunlight. The average temperature for shaded areas and direct sunlight were 28.5°C and 30.5°C respectively. The reactors were monitored over 65 days.

Table 2.14: Proportions of food waste and sewage sludge

| | Food waste | Sewage sludge | Total initial mass,(kg) |
|---|---|---|---|
| *Sample1* | 100 | 0 | 7.13 |
| *Sample2* | 70 | 30 | 8.16 |
| *Sample3* | 70 | 30 | 7.97 |
| *Sample4* | 30 | 70 | 9.77 |
| *Sample5* | 0 | 100 | 9.75 |

Source: Chua et al., (2013)

The effects of anaerobic digestion on BOD5 and COD removal after 65 days are given in Table 2.15 below. It shows that the percentage removal of BOD5 ranges from 93.24 to 97.63%. In term of COD, the percentage removal ranges from 35.4 to 59.42%. It shows that the percentage removal for food waste in terms of BOD5 and COD from anaerobic digestion is higher than sewage sludge.

Table 2.15: $BOD_5$and COD Concentration and percentage removal

| | Initial $BOD_5$ con. (mg/l) | $BOD_5$ con .after 65days (,mg/l) | (%) removal | Initial COD con, (mg/l) | COD con. After 65days, (mg/l) | (%) removal |
|---|---|---|---|---|---|---|
| *Sample1* | 162086 | 5510 | 96.60 | 682847 | 277129 | 59.42 |
| *Sample2* | 122298 | 5890 | 95.18 | 518706 | 335067 | 35.40 |
| *Sample3* | 122560 | 2906 | 97.63 | 519340 | 310000 | 40.31 |
| *Sample4* | 69287 | 4650 | 93.29 | 299851 | 147500 | 50.81 |
| *Sample5* | 29524 | 1997 | 93.24 | 135711 | 62500 | 53.94 |

Source: Chua et al., (2013)

According to the authors, this is expected as the sewage sludge is the residue from the biological treatment of wastewater which contains 0.8 to 1.2% dried solids of which 59% to 88% volatile solids and 32 to 41 % protein. Food waste however has higher biodegradable organic matter that allows microbes to digest. Comparison between Sample 2 and Sample 3 indicates that BOD5 and COD removal correlate with ambient temperature. Higher removal for higher temperatures indicates higher biological activities. The biogas generation is presented in Table 2.16 below. The accumulated biogas per mass of waste ranges from 13.41 ml/kg of waste to 219.07 ml/kg of waste. These are empirical values based on experimental set-up. On-site, the generation of biogas ranges from 0.75 to 1.2 m3/kg volatile solid. The laboratory scale result shows that sewage sludge is able to generate more biogas per mass of total solids than food waste. A comparison between Sample 2 and Sample 4 indicated a similar trend. Sample 5 has a much higher moisture content than Sample 1 hence in terms of dried solids; it yields much higher gas generation.

**Table 2.16:** Biogas Generation

| | Initial Moisture content (%) | Volume of biogas accumulated (ml) | Gas generation, (ml/kg) mass of waste | Gas generation (ml/kg) mass of total solids |
|---|---|---|---|---|
| *Sample1* | 68.87 | 426 | 59.75 | 191.92 |
| *Sample2* | 75.48 | 138 | 16.91 | 68.97 |
| *Sample3* | 76.12 | 1746 | 219.07 | 917.38 |
| *Sample4* | 85.76 | 131 | 13.41 | 94.17 |
| *Sample5* | 92.8 | 437 | 44.82 | 622.5 |

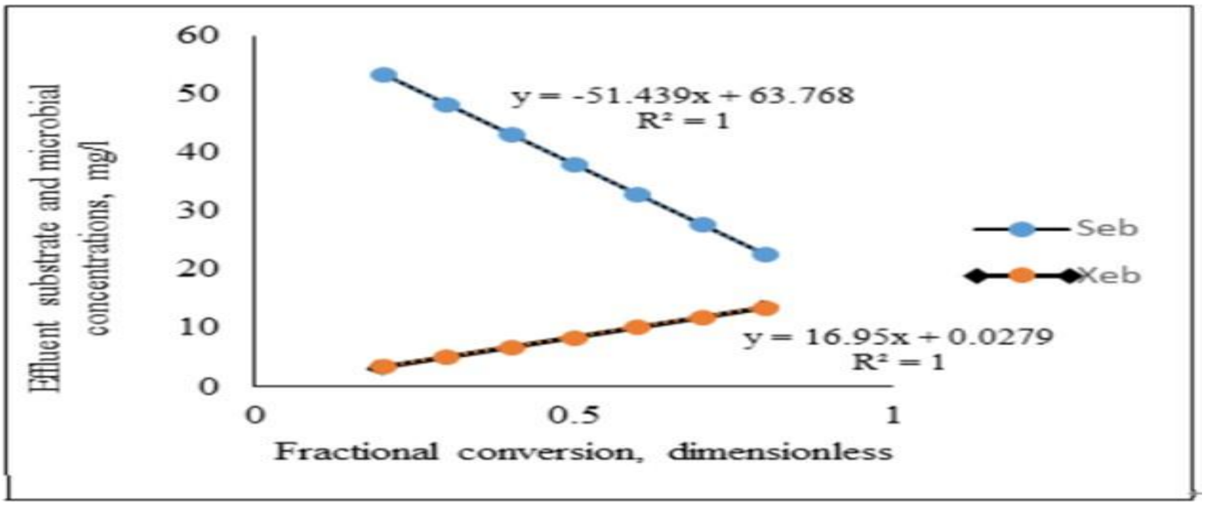
Source: Chua et al., (2013)

The highest biogas generation is in Sample 3 where the reactor was under direct sunlight as compared with Sample 2. It can increase biogas generation by 13-folds. The proportion of sewage sludge to food waste was 30:70. Higher temperature enhances the microbial growth dynamic and allows more waste converted to biogas.

### 2.7.7 Analyses of Anaerobic Batch Digestion of Municipal Solid Waste in the Production of Biogas Using Mathematical Models

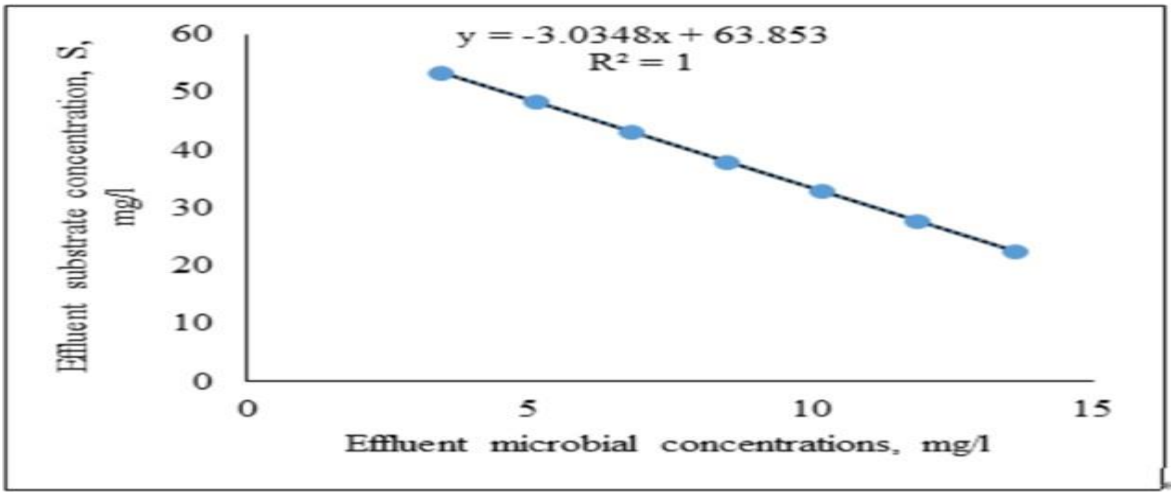
The research work by Asinyetogha (2016) presents the process dynamics of anaerobic digestion of municipal solid waste (MSW) in a batch bioreactor to produce biogas has been analyzed. An anaerobic batch digester was designed for the treatment of MSW in the Port-Harcourt metropolis, Nigeria, while at the same time generating biogas as a useful by-product. In the course of the design, the biochemical behaviour of the MSW in batch processing was investigated and analyzed. Mathematical models were developed to describe the behaviour of the waste using material balance analysis. The models were validated by the formulation of a Microsoft Visual Basic Version 6.0 program to simulate the digestion process for a fractional conversion of 0.2 - 0.8 and Total solids (TS) concentration of 4-30%. The results were analyzed using Microsoft Chart Editor and showed that the fractional conversion has various levels of effect on other process parameters like the mean cell residence time, substrate and microbial concentrations, and the volume of biogas/methane produced.

The models were validated by simulating the anaerobic batch processing with a computer program using the Microsoft Visual Basic Version 6.0 programming language. The simulation was done through a range of fractional conversion factors of 0.2 - 0.8 and percentage total solids concentrations of 4 – 30. As a result of the simulation results were obtained, which served as data for analysis. The simulation considered the effect of the fractional conversion on the time required for digestion; volumes of methane and biogas; effluent substrate and microbial concentrations; and effluent substrate stabilization. The resulting curves from the above relationships were further analyzed mathematically using the Microsoft Chart Editor. The resulting curves are shown in Figureures 2.1 to 2.5.



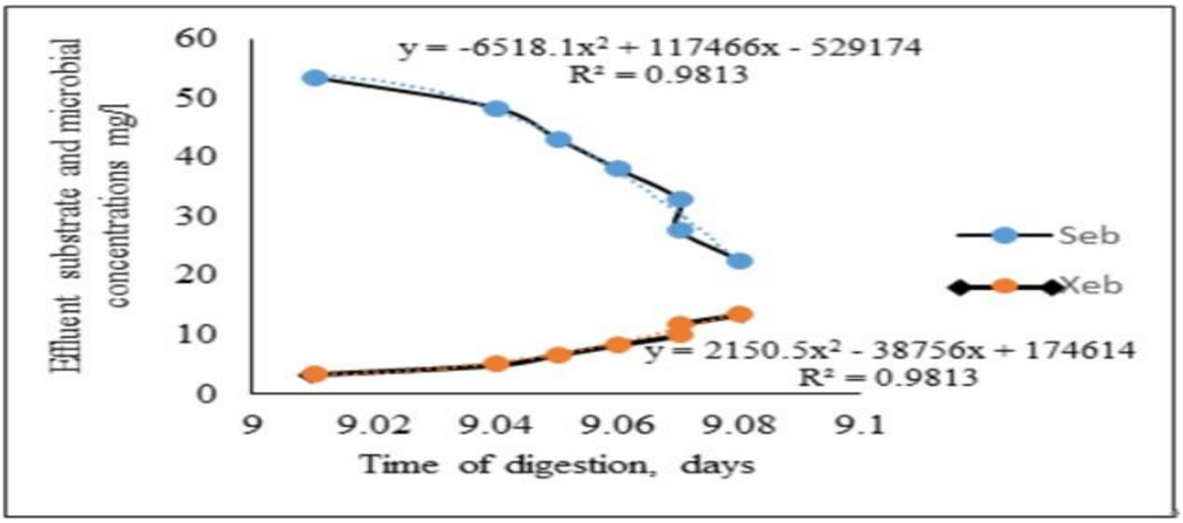
Figureure 2.1: Effect of fractional conversion on effluent substrate and microbial concentration

*Source: Asinyetogha (2016)*

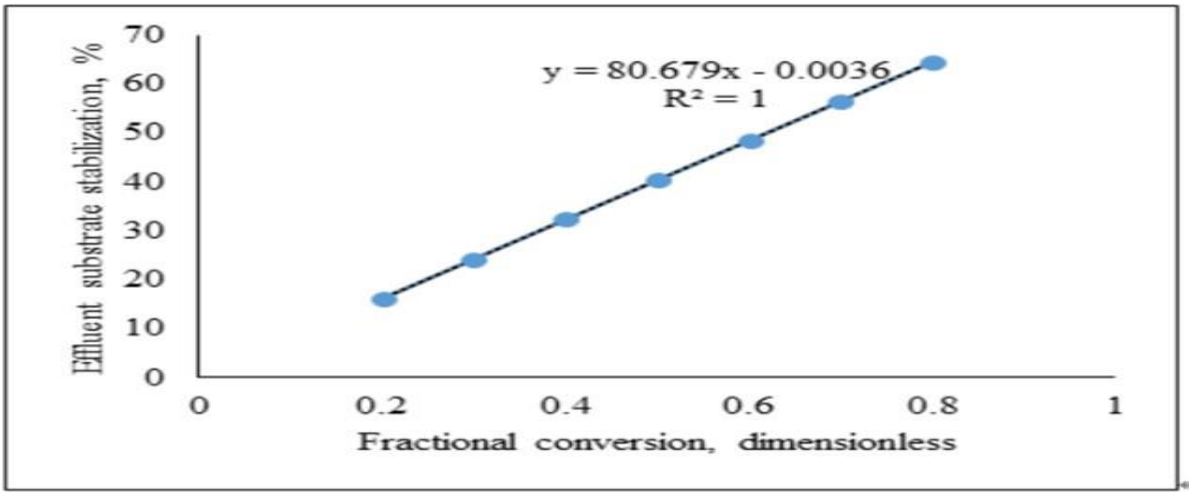


Figureure 2.2: Effect of fractional conversion on effluent substrate and microbial concentration

*Source: Asinyetogha (2016)*



Figureure 2.3: Effect of time of digestion on effluent substrate and microbial concentrations
*Source: Asinyetogha (2016)*



Figureure 2.4: Effect of fractional conversion on effluent substrate stabilization

*Source: Asinyetogha (2016)*

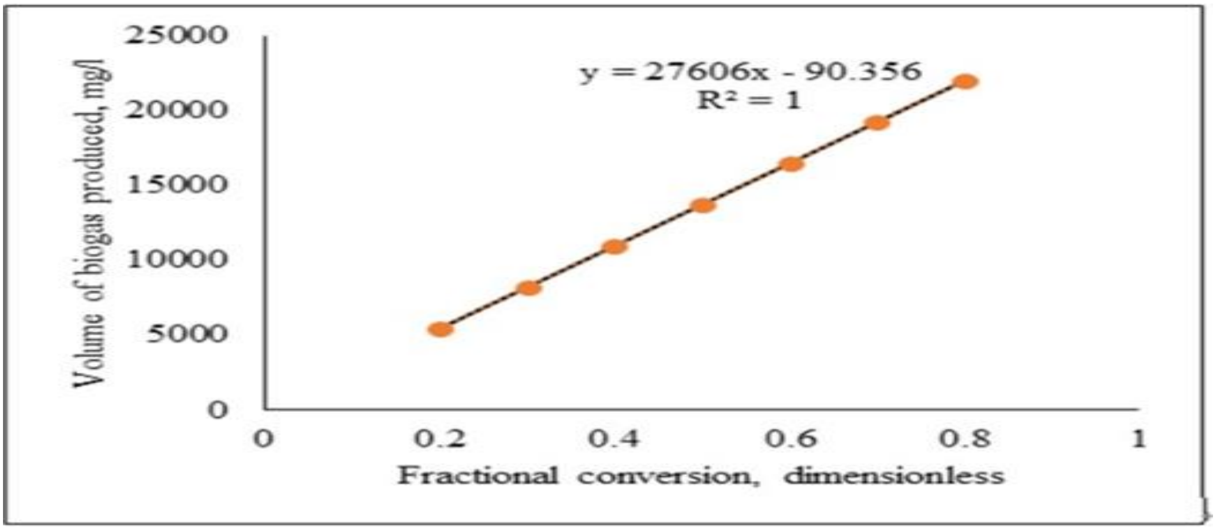


Figure 2.5: Effect of fractional conversion on the volume of gas produced.
*Source: Asinyetogha (2016)*

Figure 2.1 shows that the best approximation for the dependence of the time of digestion on fractional conversion is a logarithmic function, with the following mathematical relationship:

$$t_b = 0.0475\ln(\alpha) + 9.0917 \tag{2.13}$$

From this relationship, after an initial conversion requiring considerable time, successive conversions would require less and less time. This is easily understandable because from Figureure 2.2, while the effluent substrate concentration has a decreasing linear relationship with fractional conversion, that of the effluent microbial concentration is an increasing linear function. The following relationships are respectively established.

$$S_e = 51.439\alpha + 63.768 \tag{2.14}$$

$$X_e = 16.95\alpha + 0.0279 \tag{2.15}$$

The linear relationship between effluent substrate concentration and effluent microbial concentration is shown in Figureure 2.3. From Equations (2.16) - (2.17), an increase in fractional conversion results in increased microbial growth, a decreased substrate concentration, and a marginal increase in the time of digestion. This is also depicted in Figureure 2.4, relating the time of digestion with effluent substrate and microbial concentrations, respectively resulting in the following second-order polynomial functions.

$$S_e = 6518.1t_b^2 + 117466t_b - 529174 \quad (2.16)$$

$$X_e = 2150.5t_b^2 - 38756t_b + 174614 \quad (2.17)$$

These findings corroborate the position of Reynolds and Richards (1996) when they said that, in substrate kinetics, the rate of decrease in substrate concentration is proportional to the rate of increase of microbial growth.

Figureure 2.5 shows that the relationship between the effluent substrate stabilization and fractional conversion is a linear function of the fractional conversion, such that the progression of the conversion process results in a more effective stabilization of the ensuing substrate. The mathematical relationship is as in equation (2.20).

$$E_e = 80.679\alpha - 0.0036 \quad (2.18)$$

The effect of fractional conversion on the volume of biogas produced is shown in Figureure 2.6. The more substrate converted, the more gas produced, represented by the linear function in equation (2.21)

$$V_b = 27606\alpha - 90.356 \quad (2.19)$$

### **2.7.8 Anaerobic digestion model No 1 (ADM1)**:

According to Batstone et al., (2002), the International Water Association's (IWA) Anaerobic Digestion Modelling Task Group was established in 1997 at the 8th World Congress on Anaerobic Digestion (Sendai, Japan) with the goal of developing a generalized anaerobic digestion model. The structured model includes multiple steps describing biochemical as well as physico-chemical processes. The biochemical steps include disintegration from homogeneous particulates to carbohydrates, proteins, and lipids; extracellular hydrolysis of these particulate substrates to sugars, amino acids, and long chain fatty acids (LCFA), respectively; acidogenesis from sugars and amino acids to volatile fatty acids (VFAs) and hydrogen; acetogenesis of LCFA and VFAs to acetate; and separate methanogenesis steps from acetate and hydrogen/ $CO_2$. The physico-chemical equations describe ion association and dissociation, and gas-liquid transfer. Implemented as a differential and algebraic equation (DAE) set, there are 26 dynamic state concentration variables and 8 implicit algebraic variables per reactor vessel or element. Implemented as differential equations (DE) only, 32 dynamic concentration state variables exist.

According to them, High organic loading rates and low sludge production are among the many advantages anaerobic processes exhibit over other biological unit operations. But, the one feature emerging as a major driver for the increased application of anaerobic processes is energy production. Not only does this technology have a positive net energy production but the biogas produced can also replace fossil fuel sources and therefore has a direct positive effect on greenhouse gas reduction. This according to them will most certainly ensure the ongoing, and likely drastically increase the popularity of anaerobic digestion processes for waste treatment in the future.

### 2.7.9 Modeling of biogas production by anaerobic digestion for the generation of electricity.

In this study by Onosakponome, Ademiluyi and Odenigbo (2023), the biogas yield from an experimental reactor was modeled and the results obtained suggested a good correlation between the Model and the experimental production rates with an average value of 0.95 correlation value.

Furthermore, the other part of this study focuses on modeling the energy output from the treatment process. In this, the model gave a well fitted prediction with an average correlation of 0.96. energy recovery from the treatment of wastewater has become a potent tool in proffering solution to the energy crises facing many developing countries and in turn reduce the over dependency on petroleum as the major source of energy.

### 2.7.10 Optimization of biogas production from multiple feedstocks through co-digestion

This paper by Lopes, Oliveira, and Rodrigues(2015) investigates the optimization of biogas production by co-digesting multiple feedstocks. The study aims to maximize biogas production and assess the economic viability of the process. The researchers conducted experiments using different mixtures of organic waste as feedstocks and evaluated biogas production under varying conditions. They optimized the process by adjusting the feedstock ratio, temperature, and hydraulic retention time (HRT).

The results showed that co-digestion of multiple feedstocks significantly increased biogas production compared to digesting individual feedstocks. The optimal conditions for biogas production were found a feedstock ratio of 1:1:1, a temperature of 37°C, and an HRT of 30 days.

The study also found that co-digestion improved the economic viability of biogas production, as it allowed for the utilization of diverse waste streams and increased biogas yield. The findings demonstrate the potential of co-digestion as a sustainable method for biogas production from organic waste.

### 2.7.11 Biogas production from co-digestion of multiple organic wastes: A review

This paper by Chanakya, Maheswarappa, and Goud(2018) reviewed literatures on biogas production through co-digestion of multiple organic wastes. The study aims to assess the feasibility and benefits of co-digestion compared to mono-digestion processes. The review highlights those various organic wastes such as municipal solid waste, sewage sludge, food waste, animal manure, and agricultural residues have been successfully used as feedstocks for co-digestion. These feedstocks offer a wide range of benefits, including improved biogas production, enhanced process stability, and better utilization of nutrient content.

The review also discusses the key factors influencing biogas production in co-digestion processes, such as feedstock composition, ratio, and substrate characteristics. The results indicate that co-digestion can significantly increase biogas production compared to mono-digestion, with some studies reporting up to 30% higher biogas yield.

### 2.7.12 Synergistic effect of co-digestion on biogas production from mixed organic substrates

This study by Patil, Stöckl, and Vogel (2016) investigated the synergistic effects of co-digestion on biogas production from mixed organic substrates. The study aims to optimize biogas production and assess the benefits of co-digestion compared to mono-digestion processes.

The researchers conducted experiments using a mixture of organic substrates, including cattle manure, maize silage, and grass clippings, as feedstocks. They evaluated biogas production under different conditions, such as substrate composition, mixing ratio, and hydraulic retention time (HRT).

The results showed that co-digestion significantly increased biogas production compared to mono-digestion of individual substrates. The optimal mixing ratio for biogas production was found 50% cattle manure, 30% maize silage, and 20% grass clippings, with an HRT of 30 days. The study also found that co-digestion improved the degradation efficiency of organic matter and enhanced the stability of the digestion process.

### 2.7.13 Biogas production from co-digestion of multiple organic wastes: An integrated approach

This study by Rao, Sarada, and Babu (2017) explored the potential of co-digestion of multiple organic wastes for biogas production using an integrated approach. The study aims to optimize biogas production and assess the feasibility of utilizing various organic wastes as feedstock.

The researchers conducted experiments using a combination of organic wastes, including cow dung, poultry litter, vegetable waste, and food waste, as feedstocks. They evaluated biogas production under different conditions, such as feedstock ratio, temperature, and retention time.

The results showed that co-digestion significantly increased biogas production compared to mono-digestion processes. The optimal feedstock ratio for biogas production was found 1:1:1:1 for cow dung, poultry litter, vegetable waste, and food waste, with a temperature of 35-40°C and a retention time of 20-30 days. The study also highlighted the economic and environmental benefits of co-digestion, including waste reduction, energy generation, and nutrient recycling. Summary of the findings in this research work is as follows: Cattle manure alone generally produces a lower methane yield due to its low C/N ratio and the presence of complex lignin. It showed one of the lowest methane yields among the substrates tested; Fruit and Vegetable Wastes (FVW) typically have a higher C/N ratio, which enhanced the methane production when co-digested with cattle manure or other nitrogen-rich substrates. The methane yield from

FVW was found to be significantly higher compared to cattle manure alone; as for Food Waste, the research highlighted that food waste had a high methane yield. For instance, the maximum methane yield for food waste was found to be 573 mL $CH_4$/g volatile solids (VS) under optimal conditions (MDPI); and finally, when Sewage Sludge was used, the maximum methane yield observed was 334 mL $CH_4$/g VS (MDPI).

### 2.7.14 Enhanced biogas production through co-digestion of multiple feedstocks: A review

This paper by Kumar, Smitha, and Khanal (2021) provides a comprehensive review of studies on enhancing biogas production through co-digestion of multiple feedstocks. The review aims to summarize the key findings and trends in this field.

Various organic feedstocks, including agricultural residues, food waste, animal manure, sewage sludge, and industrial waste, have been used in co-digestion processes to enhance biogas production. The review highlights that co-digestion offers several advantages over mono-digestion, including increased biogas yield, improved process stability, and enhanced nutrient recycling.

The review also discusses the factors influencing biogas production in co-digestion, such as feedstock characteristics, mixing ratios, and process parameters. The results from the reviewed studies indicate that co-digestion can significantly increase biogas production compared to mono-digestion, with some studies reporting up to 40% higher biogas yield.

### 2.7.15 Biogas production from co-digestion of sewage sludge with various organic wastes

This study by Yuan, Chang, and Chang (2019) investigated the biogas production potential of co-digestion of sewage sludge with various organic wastes. The study aims to assess the feasibility and benefits of co-digestion in enhancing biogas production.

The researchers conducted experiments using sewage sludge mixed with different organic wastes, including food waste, agricultural residues, and animal manure, as feedstocks. They evaluated biogas production under different mixing ratios and process conditions.

The results showed that co-digestion significantly increased biogas production compared to mono-digestion of sewage sludge. The optimal mixing ratio for biogas production varied depending on the type of organic waste, with some mixtures showing higher biogas yields than others. The summary of the findings is that co-digestion with food waste and agricultural residues resulted in the highest biogas production.

The study also found that co-digestion improved the stability of the digestion process and reduced the need for additional nutrients, such as nitrogen and phosphorus. The findings suggest that co-digestion of sewage sludge with various organic wastes can be an effective strategy for enhancing biogas production and managing organic waste streams in an environmentally sustainable manner.

### 2.7.16 Co-digestion of multiple organic wastes for enhanced biogas production: A techno-economic analysis

This research work by Prakash, et al., (2020) presents a techno-economic analysis of co-digestion of multiple organic wastes for enhanced biogas production. The study aims to assess the feasibility and economic viability of co-digestion compared to mono-digestion processes.

The researchers conducted a detailed analysis using various organic wastes, including cow dung, poultry waste, food waste, and agricultural residues, as feedstocks. They evaluated biogas production, substrate degradation efficiency, and economic parameters such as capital cost, operational cost, and revenue generation.

The results showed that co-digestion significantly increased biogas production compared to mono-digestion of individual substrates. The optimal mixing ratio of feedstocks varied depending on the composition of organic wastes, with some mixtures showing higher biogas yields than others. The study also found that co-digestion improved substrate degradation efficiency and reduced the overall cost of biogas production.

The techno-economic analysis revealed that co-digestion can be a cost-effective and sustainable approach for biogas production, especially when utilizing diverse organic waste streams. The findings suggest that co-digestion of multiple organic wastes has the potential to not only enhance biogas production but also provide economic benefits and contribute to waste management and environmental sustainability.

### 2.7.17 Biogas production from co-digestion of multiple feedstocks: A comparative study

This study by Singh, Jha, and Sharma (2018) presents a comparative study on biogas production from the co-digestion of multiple feedstocks. The study aims to evaluate the performance of different feedstock combinations and assess their potential for biogas production.

The researchers conducted experiments using various combinations of feedstocks, including cow dung, poultry waste, food waste, and agricultural residues. They compared biogas production, methane content, and process stability among different feedstock combinations.

The results showed that co-digestion of multiple feedstocks significantly increased biogas production compared to mono-digestion of individual feedstocks. The optimal combination of feedstocks varied depending on the composition and characteristics of the organic waste, with some combinations showing higher biogas yields and methane content than others.

The study also found that co-digestion improved the stability of the digestion process and reduced the accumulation of volatile fatty acids (VFAs), indicating better process efficiency. Finally, the findings suggest that co-digestion of multiple feedstocks can be an effective strategy for enhancing biogas production and optimizing the anaerobic digestion process.

### 2.7.18 Integration of multiple feedstocks for biogas production: A feasibility study

This study by Prasad, Patel, and Tyagi (2017) investigated the feasibility of integrating multiple feedstocks for biogas production. The study aims to assess the potential benefits and challenges of co-digestion compared to mono-digestion processes.

The researchers conducted experiments using a combination of organic feedstocks, including cow dung, food waste, and agricultural residues, as well as varying proportions of these feedstocks. They evaluated biogas production, methane content, and process stability under different conditions.

The results showed that integrating multiple feedstocks significantly increased biogas production compared to mono-digestion of individual feedstocks. The optimal combination of feedstocks and proportions varied depending on the characteristics of the organic wastes, with some combinations showing higher biogas yields and methane content than others.

The study also found that integrating multiple feedstocks improved the overall efficiency of the anaerobic digestion process and reduced the risk of process inhibition. However, the feasibility of integration depended on factors such as feedstock availability, transportation costs, and processing infrastructure.

### 2.7.19 Biogas production from co-digestion of multiple substrates: A review on process challenges and strategies.

This study by Shukla, Singh, and Tyagi (2019) provided a comprehensive review of the challenges and strategies associated with biogas production from co-digestion of multiple substrates. The study aims to summarize key findings and suggest strategies for optimizing biogas production through co-digestion.

Various organic substrates, including agricultural residues, food waste, municipal solid waste, animal manure, and sewage sludge, have been used as feedstocks for co-digestion. The review highlights that while co-digestion can significantly increase biogas production compared to mono-digestion, several challenges need to be addressed, such as substrate variability, process instability, and inhibition.

The review discusses various strategies to overcome these challenges, including feedstock pre-treatment, process optimization, microbial community management, and co-substrate selection. The results from the reviewed studies indicate that these strategies can improve biogas production efficiency, process stability, and substrate degradation rates.

Mostly, the review emphasizes the importance of understanding the complexities of co-digestion processes and implementing appropriate strategies to maximize biogas production from multiple substrates. The findings suggest that co-digestion can be a sustainable approach for biogas production, provided that process challenges are effectively manage.

### 2.7.20 Methane Production from Anaerobic Co-digestion of Cow Dung, Chicken Manure, Pig Manure and Sewage Waste.

According to this research work by Sebola, Tesfagiorgis, and Muzenda (2015), Anaerobic co-digestion of CD, CM, PM and SW was carried out in three identical plastic batch reactors, each having a working volume of 1 litre. The top of each digester had two outlets which were used for introducing feedstock and collecting biogas, respectively. The biological methane production potentials (BMPs) of the CD, CM, PM and SW mixtures were examined at the ratios of 1:1:1:1 (Treatment A), 2:1:1:1(Treatment B) and 3:1:1:1(Treatment C) in 1-litre digesters made from plastic bottles. The mass of VS of CD, CM, PM and SW added to the 1-litre digester for ratio of 1:1:1:1 was 25g each. Tap water was added to each digester to give a working volume of 800 ml. The initial pH of the mixed solution in each digester was adjusted to 7.26. The digesters were placed in shaker incubators set to 35 °C, 40 °C, 50 °C and 55 °C. The biogas produced was measured daily as described above. The methane content and the biogas volume produced from each digester were measured once daily. The percentage of methane in the biogas was calculated by dividing overall methane measured daily by the total volume of biogas produced daily. No supplemental nutrients were added to the substrate. The digesters were agitated daily to avoid clogging of the feed. There were two replicates for each experiment.

The result showed that In Treatments A, B and C, the initial biogas and methane produced was low. During Day 1, no biogas production was observed. In Day 2, 3.13 %, 2.35 % and 2.05 % percentages of methane were observed for treatments A, B and C, respectively (Table 2.17). The pattern of daily biogas production was also similar as shown in Figure. 2.6. This was probably due to the low initial concentrations of methanogens in the reactors. After Day 2, methane production increased sharply for all three treatments. The increase in methane yields from Day 3 indicates the enrichment of methanogens in the reactors. At the end of the experiment (Day 8 and Day 9), methane percentages declined due to the high consumption of soluble biodegradable organic substances by the process which resulted in low microbial activities. In Treatment A, B and C, methane production started to decrease on Day 8 and Day 9 due to lower final pH values which led to the accumulation of VFAs in the reactor.

Table 2.17: Table showing initial and Final PH in the reactor.

| **Feedstock** | **Initial** | **Final** |
|---|---|---|
| Treatment A | 7.26 | 6.94 |
| Treatment B | 7.26 | 7.01 |
| Treatment C | 7.26 | 6.90 |

Source: Sebola et al., (2015)

Co-digestion of animal manure made up of low C/N ratio with any biodegradable material with higher C/N ratio allow more stable digestion and high methane yield as compared to digestion of manure alone. In this study, animal manure with higher C/N ratios was co-digested with other manure with low C/N ratio. Although no significant difference was obtained from the ANOVA at $P<0.05$, the overall trend showed that, from the beginning of the experiment, Treatment A had higher methane yield as compared to Treatments B and C. This is probably due to the high fraction of CD manure in Treatment B and C which made it difficult to reach system performance in terms of methane production potential. In Treatment A, the highest daily methane yield occurred on Day 6 and Day 8 with 53 % and 55 %, respectively. In Treatments B and C, peaks of the highest daily methane yield occurred on Day 7 with 47 % and 49 %, respectively (Figure. ). However, for treatment C, the methane yield for Day 6 and Day 7 remained constant at 49 %. The methane content in biogas at different ratios, the methane contents rose from Day 3 to reach a higher peak of 55%, 47% and 49% in Treatments A, B and C, respectively. During Days 3 – 9, the methane contents at

Treatment A ranged between 6-8% higher as compared to Treatments B and C. In Day 8, the methane contents for Treatments A, B and C decreased steadily to 46%, 47% and 44%, respectively. A further gradual decline in methane contents occurred in Day 9 due to low organic contents available in the digester to enhance further methane production. Therefore, the optimal ratio of CD to PM, CM and SW was of Treatment A because of its high methane production potential at a shorter biogas production period. The findings of this study are comparable to those of Lehtomaki et al., (2004) who reported an increased in methane production by 30% using anaerobic co-digestion of animal manure with grass silage, sugar beet tops and oat straw within the range of 1:1 to 1:3.

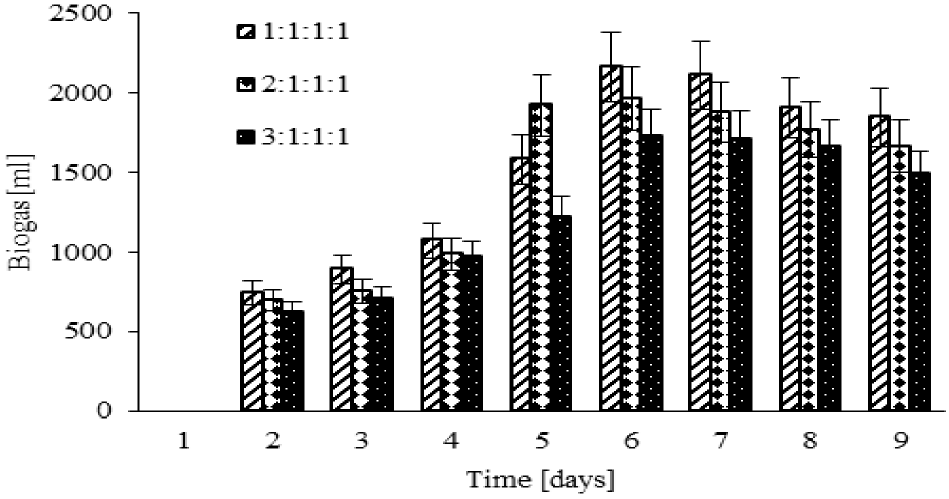


Figure. 2.7 Daily biogas produced for Treatments A, B and C
Source: Sebola et al., (2015)

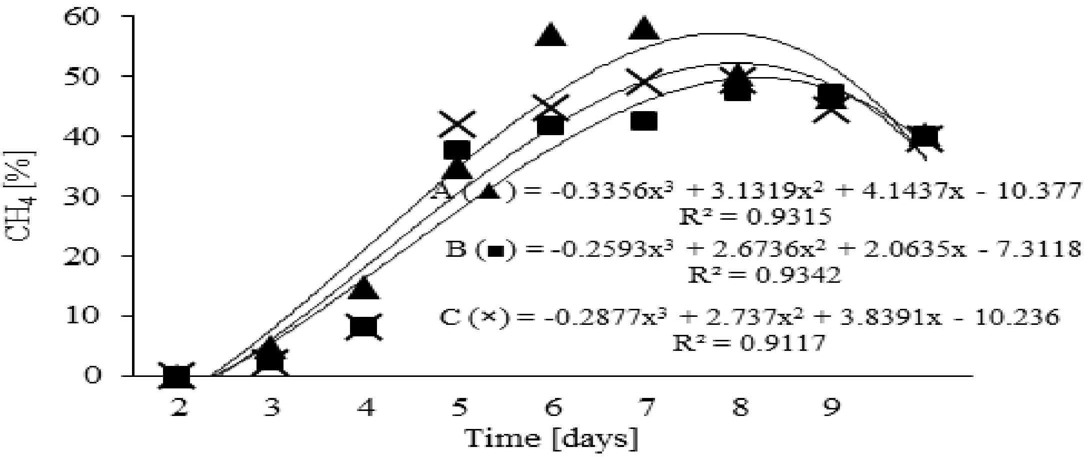


**Figure. 2.8** Daily methane produced for Treatment A, B and C.
Source: Sebola et al., (2015)

Below is the Table showing the summary of Past-related works done in Biogas as described above.

Table 2.18: Summary Review of Past works in Biogas

| S/N | PROJECT TITLE | NAME OF AUTHORS | NO. OF FEEDSTOCK | NAMES OF FEEDSTOCKS | TYPE OF BIO-DIGESTER | MODELING | BIOGAS COMPONENTS PRODUCED | AREA NOT COVERED |
|---|---|---|---|---|---|---|---|---|
| 1 | Comparative study of biogas generation from chicken waste, cow dung and pig waste using constructed plastic bio digesters | Atilade, A.O., Onanuga O. K. and Coker J. O. (2015) | 3 | chicken waste, cow dung and pig waste | constructed plastic bio digesters | No | chicken waste generated 71.39% methane gas, Cow dung generated 62.68% methane gas, Pig waste generated 61.07% methane gas | Sewage and Home-made wastes |
| 2 | Preparation of Biogas from Plants and Animal Waste | Ubwa, S. T., Asemave, K., Oshido B., and Idoko A. (2013) | 9 | Cow rumen liquor, Cowpea, poultry waste, Lanneasp, Ficus Capensis, Ficus Trichopoda, PiliostigmaThonnigii, SteculiaSetigera and Grewia mollis | A set six of improvised I litre cylindrical container | No | Lanneasp, Ficus Capensis, Ficus Trichopoda, PiliostigmaThonnigii, SteculiaSetigera and Grewia mollis produced cumulative volumes of 241cm3, 185cm3, 181cm3, 95cm3, 267 cm3 and 245 cm3respectively | Sewage and Home-made wastes |
|  | Evaluation of Biogas Yield and Microbial Species from Selected Multi-biomass | Oseji, M. E., |  | Pig dung (PD), Water Hyacinth (WH), Maize cob (MC), Pig dung + Maize cob (PM), Pig dung + Water |  |  | Pig dung (PD) 4505.3±35.50ml, Water Hyacinth (WH) | Sewage |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Summary Review of Past works in Biogas Cont'd | | | | | | | | |
| 3 | Feedstocks in Nigeria | Ana G.R., andSokan-Adeaga A.A. (2017) | 6 | hyacinth (PW), Pig dung + Maize cob + Water hyacinth (PMW). | fabricated 10 litres keg for feedstock biodegradation | Yes, Statistical Analysis | 4190.0±21.10ml, Maize cob (MC) 3338.3±10.60ml for Dry Weights of 0.75kg each | and Home-made wastes |
| 4 | Evaluation of Biogas Production from Food Waste | Ojikutu, A. O. and Osokoya, O. O. (2014) | 4 | yam peels, plantain peels, orange rind and fish waste | batch type digesters | Yes, Statistical Analysis | Yam Peels 2.2kg, Orange Rind 1.8kg, Plantain Peel 3.3kg, and Fish waste 2.7kg producing biogas of 149.8ml, 217.6ml, 130.9ml, and 137.8ml respectively | Sewage and Agricultural wastes |
| 5 | Co-digestion of sewage sludge and organic fraction of municipal solid waste | Di Maria, F., Micale, C. Sordi, A. and Cirulli, G. (2012) | 2 | Municipal Solid Waste (OFMSW) and the Sewage Sludge (SS) | Waste Water Treatment Plant | No | Sewage sludge 300ml/gTS and Organic Fraction of Municipal Solid Waste (OFMSW) 600 ml/gTS | Home made and Agricultural wastes |
| 6 | **Harvesting biogas from wastewater sludge and food waste** | Chua, K. H., Cheah, W.L., Tan, C.F., and Leong, Y.P. (2013) | 2 | Sewage and food wastes | circular PVC containers with volume of about 20 litres were used | No | wastewater sludge produced 44.82 ml biogas/kg of sludge; food waste produced a biogas of 59.75 ml/kg of food waste; and wastewater sludge mixed with food waste at a ratio of 30:70 generated biogas of 219.07 ml/kg of waste | Agricultural Waste |
| | Analyses of Anaerobic | | | | | | | Home |

Summary Review of Past works in Biogas Cont’d

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 7 | Batch Digestion of Municipal Solid Waste in the Production of Biogas Using Mathematical Models | Asinyetogha, H.I. (2016) | 1 | Municipal Solid Waste | bioreactor | Yes, Mathematical Model | | made and Agricultural wastes |
| 8 | Anaerobic digestion models No 1 (ADM1) | Batstone, Damien & Keller, J &Angelidaki, Irini &Kalyuzhnyi, Sergey &Pavlostathis, S & Rozzi, A & Sanders, W & Siegrist, H &Vavilin, Vasily. (2002) | 0 | Unclassified | N/A | Yes, Mathematical Model | N/A | Home made, Sewage, and Agricultural wastes |
| 9 | Modeling of biogas production by anaerobic digestion for the generation of electricity. | Onosakponome O. R, Ademiluyi J. O and Odenigbo C. (2023) | 0 | Unclassified | N/A | Yes,Mathematical Model | N/A | Homemade, Sewage, and Agricultural wastes |
| 10 | Optimization of biogas production from multiple feedstocks through co-digestion. | M. E. Lopes, R. C. Oliveira, and M. A. S. Rodrigues | 0 | Unclassified | N/A | Yes, Mathematical Model | N/A | Homemade, Sewage, |

Summary Review of Past works in Biogas Cont’d

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | and Agricultural wastes |
| 11 | Biogas production from co-digestion of multiple organic wastes: A review | H. N. Chanakya, G. M. Maheswarappa, and R. N. K. Goud. | Multiple | Unclassified | N/A | No | N/A | Sewage |
| 12 | Synergistic effect of co-digestion on biogas production from mixed organic substrates | S. Patil, M. Stöckl, and H. J. Vogel | 5 | municipal solid waste, sewage sludge, food waste, animal manure, and agricultural residues | bioreactor | No | N/A | Sewage |
| 13 | Biogas production from co-digestion of multiple organic wastes: An integrated approach | K. S. Rao, A. K. Sarada, and P. R. Babu | 3 | cattle manure, maize silage, and grass clippings | bioreactor | No | N/A | Home made, and Sewage |
| 14 | Enhanced biogas production through co-digestion of multiple feedstocks: A review | P. S. Kumar, S. S. Smitha, and S. K. Khanal | 4 | cow dung, poultry litter, vegetable waste, and food waste | batch type digesters | No | N/A | Sewage |
| 15 | Biogas production from co-digestion of sewage sludge with various organic wastes | R. S. Yuan, Y. H. Chang, and C. Y. Chang | 0 | Unclassified | bioreactor | No | N/A | Sewage |
| 16 | Co-digestion of multiple organic wastes for enhanced biogas production: A techno-economic analysis | A. T. Prakash, S. K. Sharma, and R. R. Soni. | 4 | cow dung, poultry waste, food waste, and agricultural residues | bioreactor | No | N/A | Sewage |
| 17 | Biogas production from co-digestion of multiple | J. P. Singh, A. K. Jha, and S. | 4 | cow dung, poultry waste, food | N/A | No | N/A | Sewage |

| Summary Review of Past works in Biogas Cont'd | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | feedstocks: A comparative study | K. Sharma | | waste, and agricultural residues | | | | |
| 18 | integration of multiple feedstocks for biogas production: A feasibility study | Prasad S. R., Patel R. K., and Tyagi S. K(2017) | 3 | cow dung, food waste, and agricultural residues | bioreactor | No | N/A | Sewage |
| 19 | Biogas production from co-digestion of multiple substrates: A review on process challenges and strategies | S. K. Shukla, P. N. Singh, and S. K. Tyagi. | 5 | agricultural residues, food waste, municipal solid waste, animal manure, and sewage sludge | bioreactor | No | N/A | - |
| 20 | Methane Production from Anaerobic Co-digestion of Cow Dung, Chicken Manure, Pig Manure and Sewage Waste | M. R. Sebola, H. B. Tesfagiorgis, E. Muzenda | 4 | Cow Dung, Chicken Manure, Pig Manure and Sewage Waste | plastic batch reactors | No | N/A | Homemade waste |
| | modeling of biogas production efficiency from different sources of waste by anaerobic digestion. | Udechukwu John Abaraogu, J.C. Osuagwu, R.O. Onosakponome and N. L. Nwakwasi | 4 individual feedstocks and 16 combinations of feedstocks | Pig waste, Poultry waste, Sewage, and Home-made food wastes (Pineapple and watermelon peels) | biodigester | Yes Optimization Model | Optimization model | - |

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 MATERIALS

### 3.1.1 Materials and Equipment for determining the biogas production capacity of the Biodigester

**Materials**

i. Feedstocks (organic materials):

   a. Animal manure (Pig and Poultry waste).

   b. Food waste from kitchen scraps or municipal solid waste (Watermelon and Pinneapple).

   c. Sludge from wastewater treatment plants.

ii. Water:

   For adjusting the feedstock-to-water ratio (typically 1:2 or 1:3).

iii. pH Adjusting Agents (if necessary):

   Lime to maintain a neutral pH.

iv. Lubricants or Sealants: To ensure airtight seals in the biodigester system.

**Equipment**

1. Laboratory-Scale Biodigester Setup:

Gas-tight anaerobic digestion chambers (Mini-Biodigester of 120L and 40L respectively) with Mechanically operated mixing system attached for homogeneous distribution of feedstock.

2. Biogas Collection System: Gas-tight tubes for temporary biogas storage
3. Biogas Measurement Equipment:
   - i. Gas Flow Meters: To measure biogas volume accurately.
   - ii. Pressure Gauge: To monitor system pressure.
   - iii. Thermometer: to measure temperature.
   - iv. pH Meter: To monitor and maintain optimal pH (6.0–7.5).
   - v. Weighing Balance: To measure feedstock accurately.
4. Gas Composition Analysis Tools:

   Gas Chromatograph (GC): To determine methane ($CH_4$), carbon dioxide ($CO_2$), and other trace gas compositions.

5. Safety Equipment:
   - i. Gas leak detectors to ensure system safety.
   - ii. Fire extinguishers (biogas are flammable).
6. Data Logging/Analyzing Devices:
   - a. Sensors and data loggers for real-time monitoring of temperature, pressure, and gas production.
   - b. Gas Analyzer to determine the methane content and $CO_2$ concentrations:

Menthane Analyzer, Gas Analyzer ($CO_2$, $O_2$)

7. Sealing and Connective Accessories:

Rubber stoppers, clamps, tubing, and connectors for assembling the biodigester system:

### 3.1.2 Materials and equipment for determining the compositions and qualities of the biogas produced.

**Materials**

1. Biogas Sample: Collected from the biodigester using gas-tight bags, syringes, or a gas sampling valve.
2. Standard Gas Mixtures (for calibration): Certified gas mixtures of methane ($CH_4$), carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), oxygen ($O_2$), and nitrogen ($N_2$) for calibration of analytical equipment.

**Equipment**

1. Gas Composition Analysis using Gas Chromatograph (GC) which is equipped with appropriate detectors for Thermal Conductivity Detector (TCD): For measuring $CH_4$, $CO_2$, and $N_2$.
2. Infrared (IR) Gas Analyzer: For real-time monitoring of methane ($CH_4$) and carbon dioxide ($CO_2$) levels.
3. Gas Sampling Tubes: Thermoplastic polyurethane (TPU) Tube for temporary collection of biogas samples.

Safety and Miscellaneous

i. Gas Leak Detector:

To ensure there are no leaks during handling and analysis.

ii. Fire Extinguisher:

For safety when working with flammable biogas.

iii. Data Logging Devices:

To record gas composition and quality parameters during analysis.

### 3.1.3 Materials and equipment for deriving an optimization model that determines the optimum combinations of the selected feedstocks.

In deriving the optimization model for this work, mathematical expressions and data that represent the problem were used, including decision variables, objective function, and constraints, all expressed through algebraic equations and inequalities, allowing for the calculation of the optimal solution based on the given parameters and conditions.

### 3.1.4 Materials and equipment for Calibrating and Verifying the derived model

#### a. Calibration

Calibration is the process of determining and documenting the difference in readings given by a tool compared with a reading given by a measuring standard, therefore, a model is perfectly calibrated if the predicted probabilities of outcomes align closely with the actual outcomes. Calibration methods are related to quantitative analysis. In this research, the external standard method known also as the calibration curve method was adopted.

The calibration curve method for optimizing a model involves creating a plot that compares the model's predicted probabilities to the actual observed outcomes across different ranges of predictions, allowing you to visually assess and adjust the model to ensure its predicted probabilities accurately reflect the true likelihood of events occurring, essentially "calibrating" the model to produce more reliable predictions; this is typically achieved by dividing predictions into bins, calculating the average predicted probability within each bin, and comparing it to the observed frequency of positive outcomes in that bin, then plotting the results to identify areas where adjustments are needed.

Key steps in the calibration curve method:

a. **Generate predictions:**

b. Run your model on a test dataset and obtain predicted probabilities for each data point.

c. **Binning:**

d. Group the predictions into a set of bins based on their predicted probabilities.

e. **Calculate observed frequencies:**

f. For each bin, calculate the proportion of actual positive outcomes (the "observed frequency") among the data points within that bin.

g. **Plot the calibration curve:**

h. On a graph, plot the average predicted probability within each bin on the x-axis and the corresponding observed frequency on the y-axis.

i. **Interpret the curve:**

i. **Ideal calibration:** A perfectly calibrated model will result in a straight line with a slope of 1, indicating that the predicted probabilities closely match the actual occurrence of events.

ii. **Overconfident model:** If the curve curves upwards, the model is overconfident, predicting probabilities higher than the actual occurrence rate.

iii. **Underconfident model:** If the curve curves downwards, the model is underconfident, predicting probabilities lower than the actual occurrence rate.

### b. Validation

Validation on the other hand is a process of comparing the model and its behavior to the real system and its behavior. The Bayesian Validation Metric (BVM) method for optimization model verification was adopted for this model.

The Bayesian Validation Metric (BVM) method for optimization model verification uses Bayesian statistical principles to quantify the probability of agreement between a model's predictions and observed data, essentially allowing you to assess how well your model fits the real-world scenario by considering uncertainty in both model parameters and data itself; this is achieved by defining a "validation function" that specifies the conditions under which the model is considered to be in agreement with the data, then calculating the probability of that condition being met based on the posterior distribution of the model parameters.

Key steps in implementing BVM:

i. **Define your model:**

Specify the mathematical structure of your optimization model, including the decision variables, objective function, and constraints.

ii. **Set up the prior distribution:**

Before observing any data, define a prior probability distribution for the model parameters based on prior knowledge or expert opinions. This represents your initial belief about the parameter values.

iii. **Calculate the likelihood function:**

Given observed data, calculate the likelihood function which represents the probability of observing the data given specific parameter values in the model.

iv. **Update the posterior distribution:**

Using Bayes Theorem, combine the prior distribution with the likelihood function to obtain the posterior distribution which represents the updated belief about the model parameters after considering the observed data.

v. **Specify the validation function:**

Define a Boolean function that specifies the conditions under which your model is considered to be in agreement with the observed data. This function should clearly state the acceptable range of discrepancies between model predictions and observed values.

vi. **Calculate the BVM:**

a. Sample parameter values from the posterior distribution.

b. For each parameter sample, run the model and compare its predictions to the observed data using the validation function.

c. Calculate the proportion of samples where the validation function returns "true" - this represents the Bayesian Validation Metric, which is the probability that the model is considered "valid" based on the observed data.

## 3.2 METHODS

### 3.2.1 Determining the biogas production capacity of the feedstocks

The research method for this work was experimental design. Experimental design for this research work involved the design and construction of a mini biodigester of 1Nr 60 liters and 2Nr 120 litres Biodigesters which was used in the laboratory to access the production of biogas production from three major types of feedstocks which are Homemade waste, Sewage waste and Agricultural waste. This involved setting up controlled experiments in a laboratory, measuring and analyzing data, and drawing conclusions about the capacity of different biogas production feedstocks and the best combination of feedstock that will give the maximum production of biogas. The biodigester used for this experiment had an inlet device that could be opened to feed the plant, a gas collection vent, and a slurry (digestate) evacuation outlet at the bottom of the biodigester. The anaerobic digesters were fed with different types of feedstocks on different occasions with the Agricultural waste, Sewage waste, and Home-made waste feedstocks individually and in different combinations of the feedstocks respectively and the rate of production of biogas was compared. Biogas yields for each feedstock or combination of feedstocks were monitored over a period of 30 days for each trial. Below is a schematic representation of the biogas production process:

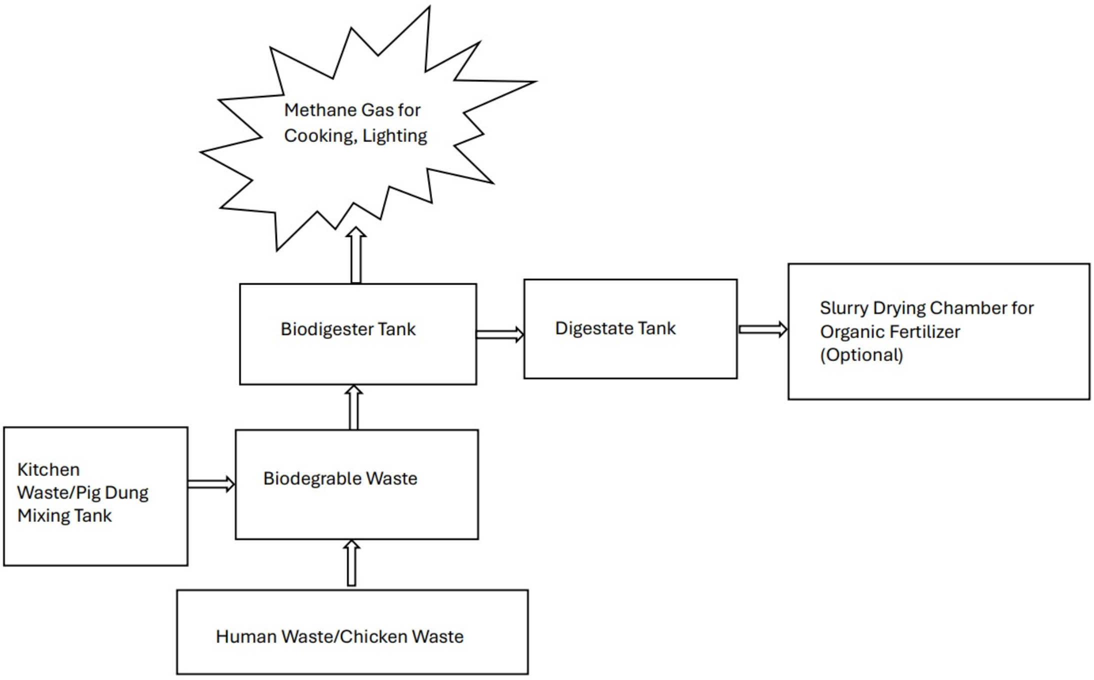


Figure 3. 1: Schematic drawing of a biogas production process

The following are the methods employed in achieving the objectives of this research:

1. **Feedstock Characterization**

Before starting the bio digestion process, it was essential to understand the properties of the feedstock:

- **Moisture Content:** the water content using a drying oven was determined.
- **Volatile Solids (VS):** the organic portion of the feedstock was measure after removing moisture (essential for biogas potential).
- **Carbon-to-Nitrogen (C: N) Ratio:** the balance between carbon and nitrogen was analyzed to ensure optimal microbial activity (ideal ratio is ~15-30:1).
- **pH:** the feedstock's pH was tested to ensure it's in the range of 6.0–7.5.

2. **Design of 120- and 40-Liters biogas bio-digester**

A. **Design of 40-Liters biogas bio-digester:**

**Basic Parameters**

i. Volume (Capacity): 40 liters
ii. Shape: Cylinder
iii. Material: High Density Poly Ethylene (HDPE)

**Dimensions**

The formula for the volume of a cylinder is:

$$V = h\pi r^2 \tag{3.1}$$

Where: V is the volume and it is 40 liters which means 40,000 cm$^3$, R is the radius and h is the height

Assume the height-to-diameter ratio is approximately 2:1 for better space utilization and mixing efficiency.

**Solving for Dimensions**

1. Let r=d/2 (where d is diameter).
2. Rearrange for height h: $h = V/\pi r^2$

Assuming a diameter of 30 cm (r=15cm)

$$h = 40{,}000/\pi(15)^2 \tag{3.2}$$

$$h\ is\ approximately\ 56.7\ which\ is\ 57\ cm\ to\ the\ nearest\ whole\ number$$

Thus, approximate dimensions:

Height (h): 57 cm

Diameter (d): 30 cm

Radius (r): 15 cm

Components and Placement

Top Components

i. Safety Valve
   a. Located at the center of the top cover.
   b. Releases excess pressure when it exceeds a safe threshold (2-3 bar).
ii. Gas Outlet
   a. Positioned near the safety valve, slightly off-center.
   b. Connects to a pipe or fitting for collecting biogas.
iii. Pressure Gauge
   a. Located on the opposite side of the gas outlet, near the top edge.
   b. Measures internal pressure for monitoring.

Side Probes

iv. Temperature Probe (Thermometer)
   a. Installed on the side of the biodigester at a height of 20 cm from the base.
   b. Provides real-time temperature readings for monitoring microbial activity.
v. pH Probe

    a. Also installed on the side, slightly below the temperature probe (15 cm from the base).
    b. Measures the pH level of the digestate to ensure optimal conditions for biogas production.

Lower Components

vi. Stirrer Mechanism
    a. A mechanical stirrer was placed inside the tank for mixing the contents.
    b. The stirrer shaft exits through a sealed port 10 cm above the base.
    c. A manual or motorized handle was located outside for operation.

vii. Digestate Outlet
    a. Positioned at the bottom center of the cylinder or slightly offset for drainage.
    b. Equipped with a 1-inch valve for the controlled discharge of digestate.

Table 3.1 Summary Table for the designed 40 Liter Biodigester

| **Component** | **Location** | **Specifications** |
|---|---|---|
| **Cylinder** | Height: 57 cm; Diameter: 30 cm | Stainless steel, HDPE, or fiberglass |
| **Safety Valve** | Top center | Pressure release at max 2-3 bar |
| **Gas Outlet** | Top (near safety valve) | 12 mm or 15 mm outlet |
| **Pressure Gauge** | Top | Analog or digital gauge |
| **Temperature Probe** | Side, 20 cm from base | Digital/analog thermometer |
| **pH Meter Probe** | Side, 15-20 cm from base | Digital pH sensor |
| **Stirrer** | Lower side, 10 cm from base | Manual or motorized with sealed bearing exit |
| **Digestate Outlet** | Bottom | PVC/stainless steel valve (1-inch diameter) |

B. **Design of 120-Liters biogas bio-digester:**

Basic Parameters

iv. Volume (Capacity): 120 liters

v. Shape: Cylinder

vi. Material: High Density Polyethylene (HDPE)

*Dimensions:*

The formula for the volume of a cylinder is the same as (3.1) above

Where:

V=40 liters=120,000 $cm^3$

r = radius

h = height

Assume the height-to-diameter ratio is approximately 2:1 for better space utilization and mixing efficiency.

Solving for Dimensions

3. Let r = d/2 (where d is diameter).
4. Rearrange for height h: $h = V/\pi r^2$

Assuming a diameter of 40 cm (r=15cm)

$h = 120{,}000/\pi(20)^2$

$$h \text{ is approximately } 95.5 \text{ cm which is equal to } 96 \text{ cm to the nearest whole number}$$

Thus, approximate dimensions:

- Height (h): 96 cm; Diameter (d): 40 cm; Radius (r): 20 cm

Components and Placement

The component and Placement is the same as that of 40 Liters above

Table 3.2: Component Specifications

| **Component** | **Specifications** |
|---|---|
| Safety Valve | Pressure release at 2-3 bar |
| Gas Outlet | Diameter: 12 mm or 15 mm |
| Pressure Gauge | Analog or digital; range: 0-5 bar |
| Temperature Probe | Digital thermometer with a probe depth of 5-10 cm |
| pH Probe | Digital sensor capable of measuring pH range 6.5–8.5 |
| Stirrer Mechanism | Internal blades with a sealed external shaft exit; manual or motorized operation |
| Digestate Outlet | Bottom-mounted 1-inch valve (PVC or stainless steel) for easy discharge |

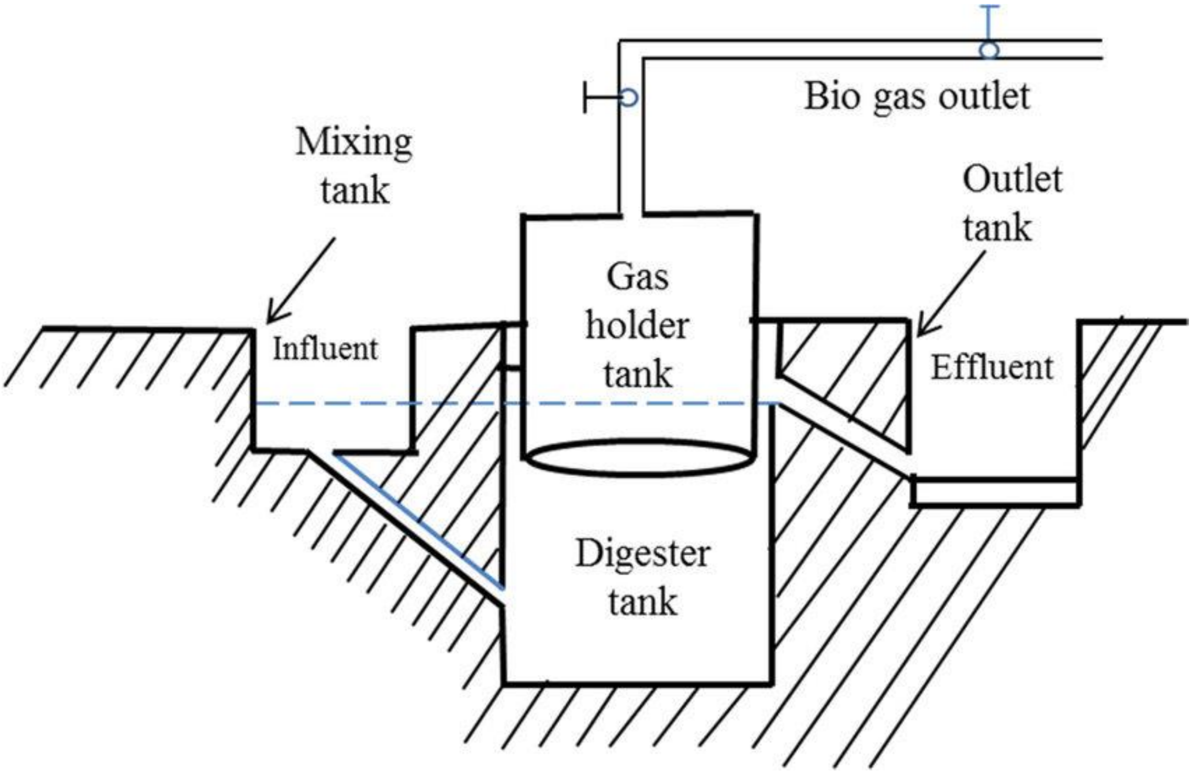


Figure 3.2 Typical biogas set-up in the Laboratory

Plate 3.1: Plate showing the constructed mini- digester used for the Biogas production

## 3. Loading the Biodigester

### a. Prepare the Feedstock:

i. The materials were homogenized to ensure uniformity.

ii. Water was used to dilute the raw feedstocks as necessary to achieve a slurry consistency (Total Solids ~8-12% is ideal), sewage already had enough water so there was no need of diluting it with water.

b. **Load the Biodigester:**

i. In loading the biodigester, the biodigester was filled up to 60-70% of its volume, leaving headspace of between 30 to 40% for gas collection.

ii. It was ensured that the feedstock is well-mixed using the mechanical internal stirrer installed in the biodigester, this stirring was done at different time intervals up to the retention time.

### 4. Monitoring the Bio-digestion Process

Once the biodigester is operational, various parameters must be monitored to determine the biogas production capacity.

**a. Biogas Measurement using Gas Flow Measurement:** a gas flow meter was installed at the gas outlet to measure the volume of gas produced over time.

**b. Temperature Monitoring:** Temperature was monitored using the thermometer probe. Mesophilic conditions between (~35–40°C) was adopted for this work for biogas production.

**c. pH Monitoring:** The PH was measured using the pH meter probe. The PH was adjusted whenever the pH drops below 6.0 or rises above 7.5, as extreme pH levels can inhibit microbial activity.

### 5. Calculate Biogas Production Capacity

The biogas production capacity was calculated based on the results obtained from the measurements. The biogas production capacity is usually expressed as **Biogas Yield** in terms of:

**Volume of biogas per unit of feedstock (e.g., $m^3$/kg of volatile solids):**

Biogas Yield=Volume of Biogas Produced/Volatile Solids Added

### 6. Methods for Enhancing Accuracy

To improve the determination of biogas production capacity:

i. **Batch Tests:** batch anaerobic digestion tests were conducted using the Biochemical Methane Potential (BMP) method by feeding the biodigester once and monitoring gas production over several days.

ii. **Continuous Operation:** The biodigester was operated continuously with regular feeding and monitoring to maintain steady-state gas production.

iii. **Replicates:** multiple biodigesters were used with the same feedstock under identical conditions to ensure reproducibility of results.

**iv. Interpretation of Results**

v. **High Biogas Yield:** Indicates a good feedstock with high biodegradable organic content.

vi. **Low Biogas Yield:** Suggests the presence of inhibitors, suboptimal operating conditions, or low-quality feedstock.

### 3.2.2 Determining Biogas Composition and Quality

#### 1. Determining Biogas Composition

The composition of biogas typically includes **methane ($CH_4$)**, **carbon dioxide ($CO_2$)**, **hydrogen sulfide ($H_2S$)**, **water vapor ($H_2O$)**, and trace gases. These components, especially methane and Carbon dioxide was be determined using the following methods:

#### a. Gas Chromatography (GC)

i. **Principle:** Separates the gas mixture into individual components for precise quantification.

ii. **What It Measures:** $CH_4$, $CO_2$, $H_2S$, $O_2$, and other trace gases, but our focus was on $CH_4$ and $CO_2$

iii. **Procedure:**

   a. biogas samples were collect in a gas-tight syringe.

   b. They were then Inject into a gas chromatograph equipped with detectors.

iv. **Advantages:** Highly accurate, suitable for research-grade analysis.

#### b. Infrared Gas Analyzers

i. **Principle:** Measures the absorption of infrared light by specific gas molecules (e.g., $CH_4$ and $CO_2$).

ii. **What It Measures:** Methane, carbon dioxide, and sometimes $H_2S$.

iii. **Advantages:** Fast, reliable, portable, and suitable for field applications.

Also, in order to ensure the quality of the gas produced, the following methods were used in obtaining the results for the PH, the temperature, the Carbon-Nitrogen ratio, and methane content of the experiment

### 3.2.2.1 Determination of the change in PH of the biodigester as the day goes by

The change in pH was determined by measuring the difference in pH values before and after a particular event or process. The 3 methods to determine the change in pH are as follows: pH Indicator, pH Meter, and pH Calculation, but the use of the PH meter was adopted for this work.

pH Meter: A pH meter is a more accurate and precise instrument for measuring pH. It consists of a probe that is dipped into the solution. The pH meter measures the voltage difference between the probe and a reference electrode and converts it into a pH value. By comparing the pH readings before and after the event, you can determine the change in pH.

### 3.2.2.2 Determination of the Carbon-Nitrogen Ratio of the Raw Materials

The Carbon-Nitrogen (C/N) ratio of organic materials was determined through laboratory analysis. There are several methods you can use, depending on the type of organic material you are dealing with and the equipment available to you. Here are two common methods: Elemental Analysis and Near-Infrared Spectroscopy (NIRS). In this research, the use of the Elemental Analysis method was adopted.

Elemental Analysis: This is the most accurate and widely used method for determining the C/N ratio. It involves measuring the carbon and nitrogen content of the organic material and calculating the ratio. Specifically, the CHN analyzer was used as the Elemental analyzers for the purpose of our wok. The organic material was dried, ground, and weighed before analysis. The analyzer combusts the samples, converting all the carbon to carbon-dioxide ($CO_2$) and all the nitrogen-to-nitrogen gas ($N_2$), which are then measured. From these measurements, the C/N ratio can be calculated by dividing the carbon content by the nitrogen content.

#### 3.2.2.3 The Biochemical Methane Potential (BMP) test:

The BMP determines the methane quality produced was achieved through the following steps:

i. Substrate Preparation: In the BMP test, a substrate (such as wastewater or waste biomass) is mixed with an anaerobic bacteria culture. This culture is typically retrieved from an active digester.

ii. Incubation Period: The mixture is placed in sealed bottles and stored at a stable temperature (usually either 35 °C or 55 °C). The bottles are constantly mixed during a period of 30–60 days. 40 days was used in this research.

iii. Anaerobic Degradation: Over time, the anaerobic degradation of organic contents in the substrate occurs. As a result, methane ($CH_4$) and carbon dioxide ($CO_2$) are produced.

iv. Measurement: The amount of methane produced during the testing period is measured. This provides valuable information about the substrate's methane potential and biodegradability.

### 3.2.2.4 Daily Determination of the change in temperature of the biodigester

To determine the change in temperature of a biodigester, the initial temperature and the final temperature were measured and then the difference between them calculated. Here's a step-by-step guide:

i. Measure the initial temperature: Before starting the biodigester, a thermometer was used to measure the temperature inside the biodigester. It was ensured that the instrument used is suitable for the environment and can accurately measure the temperature.

ii. The initial temperature reading was noted down. It's good practice to record the temperature at the same time the biodigester is started or when you begin monitoring the temperature.

iii. Monitor the biodigester: Allow the biodigester to operate for a specific period while generating biogas or undergoing the desired anaerobic digestion process. Keep track of the time elapsed during the monitoring.

iv. The final temperature Measured after the desired time has passed. It was ensured that the temperature measurement was at the same location or location as the initial measurement.

v. The final temperature reading was also Note down the.

vi. The change in temperature was calculated by subtracting the initial temperature from the final temperature from all the different feedstocks. The results from these calculations gave the change in temperatures shown in the Chapter for Results and Discussion.

### 3.2.3 Model Derivation

#### 3.2.3.1 Assumptions in the Model

i. That the Biogas production was done at natural temperature and pressure of the laboratory environment (no external temperature or pressure was introduced).

ii. Specific digester characteristics of the wastes e.g. food waste must be well decayed in the anaerobic system before gas production can commence,

iii. It is assumed that the different solid to water mix ratios by weight are as follows: Pig waste (1:1.2); Poultry waste (1:2); and Homemade waste (1:1.3). As for sewage waste the water content was reduced by 20% in order to achieve at least a Target solids content of 8–12% total solids (TS)sensitivity

iv. The sewage and animal dung must be freshly derived; and

v. The anaerobic digestion process employed must be airtight e.g. able to produce biogas the biodigester must be airtight; and

vi. It is assumed that the whole biogas production system which is a non-linear problem will be solved using a linear optimization model.

#### 3.2.3.2 Constraints Assumptions

Under natural temperature and pressure, the earliest gas production time (in days) and the latest production time (in days) for each of the feedstock will serve as the limits of the constraints used for the model:

i. The retention time inversely varies with the organic content. The more the organic content the faster the anaerobic digestion, therefore the shorter the retention time.

ii. Temperature ranges: 20 – 40C (68F – 104F) the biogas production increases with increase in temperature and vice versa.

iii. PH Ranges: 6.0 – 8.0 increasing the substrate PH level leads to reduction of biogas volume production.

iv. C/N Ratio: 10 – 30:1 - If the C/N ratio is very high (i.e. excess carbon), decomposition is slow in the biodigester, but if the C/N ratio is too low (i.e. excess Nitrogen), it will produce a stinky pile or ammonia gas which causes inhibition. Anaerobic microbes tend to utilize carbon 25 – 30 times faster than Nitrogen. Lime addition to the system can increase the Nitrogen level thereby decreasing the C/N ratio.

v. Organic Loading Rate (OLR): The OLR of a biodigester is expected between 0.5 – 5kg/$m^3$/day.

1$m^3$ =1000L: 120L=120/1000 =0.12$m^3$

1$m^3$ = 4kg: 0.12$m^3$ = 0.12 x 4kg = 0.48kg

4kg/$m^3$ of fresh cow dung is required for optimum gas production (from Organic loading rates – an overview (obileke et al., 2020 and sugumaretal 2016).

Hydraulic Retention Time: 25 – 40days

### 3.2.3.3 Model Formulation for Biogas Production

Following the successful production of biogas from the different sources: sewage, agricultural wastes, and home-made food wastes, the next steps is to formulating an optimization model for maximizing biogas production. The following are the Modelling process and procedure applied to achieve this:

**Step 1: Definition of the variables:**

Let X*i* represent the decision variable, proportion of feedstock ‘i’ in the mix (e.g. $X_1$, $X_2$, …., $X_4$)

**Step 2: Setting of the objective function:**

The objective is to maximize gas production, whereby the Objective function can be represented by ‘Z’ which is the total methane yield (to maximize).

So, the objective function can be written as: Maximize Z.

**Step 3: Defining the constraints:**

The following are the different constraints used in the model:

1. **Non-Negativity of Decision variables**:

$$x_i \geq 0 \quad \forall_i \in \{1, 2, \ldots, n\} \tag{3.4}$$

2. **Total production Limit:**

$$\sum_{i-1}^{n} x_i \leq 1 \tag{3.5}$$

This ensures the sum of proportions does not exceed 100%.

3. **Retention Period Constraint:**

$$25 \leq R_i \leq 40 \quad \forall_i \in \{1, 2, \ldots, n) \tag{3.6}$$

Where $\boldsymbol{R_i}$ is the retention period for feedstock ***i***.

4. **Temperature constraint:**

$$20 \leq T_i \leq 40 \quad \forall_i \in \{1, 2, \ldots, n) \tag{3.7}$$

Where $T_i$ is the temperature for feedstock *i*.

5. **PH Constraint**:

$6.0 \leq PH_i \leq 8.0 \quad \forall_i \in \{1, 2, \ldots, n)$ (3.8)

6. **Carbon/Nitrogen Ratio Constraint**:

$10 \leq \frac{C}{N_i} \leq 30 \quad \forall_i \in \{1, 2, \ldots, n\}$ (3.9)

7. **Organic Loading Rate (OLR) Constraint**:

$0.5 \leq OLR_i \leq 5 \quad \forall_i \in \{1, 2, \ldots, n)$ (3.10)

**Step 4: Combine the objective function and constraints:**

The mathematical expression of the optimization equation can be written as:

Maximize Z = $\sum_{i=1}^{n}(C_i . P_i . x_i .)$ (3.11)

Subject to

**$x_i \geq 0 \quad \forall_i \in \{1, 2, \ldots, n\}$** (3.11a)

$\sum_{i-1}^{n} x_i \leq 1$ (3.11b)

$25 \leq R_i \leq 40 \quad \forall_i \in \{1, 2, \ldots, n)$ (3.11c)

$20 \leq T_i \leq 40 \quad \forall_i \in \{1, 2, \ldots, n)$ (3.11d)

$6.0 \leq PH_i \leq 7.5 \quad \forall_i \in \{1, 2, \ldots, n)$ (3.11e)

$10 \leq \frac{C}{N_i} \leq 30 \quad \forall_i \in \{1, 2, \ldots, n\}$ (3.11f)

$0.5 \leq OLR_i \leq 5 \quad \forall_i \in \{1, 2, \ldots, n)$ (3.11g)

**Step 5: Solving the optimization model:** the optimization model was solved using the linear programming model technique (Simplex Method in excel solver), and the optimal values of the variables that maximize gas production (Z) were obtained.

**Step 6: Interpret the Results:**

- As the solver completes the analysis, the solution obtained was reviewed to understand the optimal values of the decision variables and the corresponding gas production at these optimal values of the decision variables.

- The optimal values of the decision variables indicated the amounts and best combinations of waste sources necessary to maximize gas production.

- The optimal gas production value (Z) represents the maximum possible gas production based on the given constraints and waste source availability.

**Step 7: Implement the Solution:**

- the optimal values of the decision variables are to be applied to the gas production process.

- the recommended amounts of sewage, agricultural waste sources, and home-food waste sources are to be used to achieve the maximum gas production as prescribed by the model.

### 3.2.4 Method for Model Calibration and Verification

#### Calibration

The following are the step-by-step methods applied in the Calibration and Verification of this model

#### 2. Collect and Analyze Data

To calibrate the model, data was gathered that can validate or refine its components:

- **Experimental Results:** Data from the results of the Laboratory works carried out under controlled conditions were used as test-data to calibrate and verify the accuracy of the objective function coefficients.

### 3. Sensitivity Analysis

A **sensitivity analysis** was conducted to determine the impact of variations in parameters or constraints:

- The coefficients and observed changes in the optimal solution were varied.
- The constraint bounds were adjusted to test their impact on feasibility and the optimal value of Z.

### 5. Validate with Observed Results

The model predictions were tested against actual results:

- **Comparison with Real Data:** the model was applied using real-world values for the variables and Z was compared to observed performance metrics.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 RESULTS

### 4.1.1 Production of Biogas from different Feedstocks

#### 4.1.1.1 Biogas Production Rates

The biogas production rate refers to the amount of biogas generated per unit of time from an anaerobic digestion process. The biogas production rates for feedstocks were measured in cubic meters per day as seen in Table 6.1 in the appendix.

Table 4.6 summarizing the daily biogas production rates for all feedstocks used is presented below. The data of the daily biogas production rates for all the feedstocks were recorded over a 9-Month Period, also the focus was only on the 14days of maximum production period. Biogas production rates are a fundamental indicator of the efficiency and performance of anaerobic digestion processes. Here are the descriptive statistics for biogas production from both sewage and homemade food waste:

From Sewage:

i. Mean Production Rate:

Mean is calculated by adding the entire biogas production rate for sewage and dividing it by the total number of days.

Mean = $\frac{0.46}{14}$ = 0.0329m$^3$/day

ii. Standard Deviation: 0.0002445

iii. Minimum Production Rate: 0.025m$^3$/day

iv. Maximum Production Rate: 0.0333m$^3$/day

From Pig waste:

v. Mean Production Rate:

Mean is calculated by adding the entire biogas production rate for pig and dividing it by the total number of days.

Mean = $\frac{0.52}{14}$ = 0.0372m³/day

vi. Standard Deviation: 0.000352386

vii. Minimum Production Rate: 0.0366m³/day

viii. Maximum Production Rate: 0.0377m³/day

From Poultry waste:

**i.** Mean Production Rate:

Mean is calculated by adding all the biogas production rate for sewage and dividing it by the total number of days.

Mean = $\frac{0.495}{14}$ = 0.0354m³/day

ii. Standard Deviation: 0.000352386

iii. Minimum Production Rate: 0.0348m³/day

iv. Maximum Production Rate: 0.0359m³/day

From Homemade Food Waste:

**v.** Mean Production Rate:

Mean is calculated by adding the entire biogas production rate for sewage and dividing it by the total number of days.

Mean = $\frac{0.4139}{14}$ = 0.02964m³/day

vi. Standard Deviation: 0.000347756

vii. Minimum Production Rate: 0.029m³/day

viii. Maximum Production Rate: 0.0301m³/day

### 4.1.1.2 Graphical Representations of the Daily biogas production rates

Below are the graphical representations of the above data with respect to the 14 days duration taken: From the Graphs in Figureures 4.8 to 4.14, it can be seen that the volume of biogas produced as the days go by continues to increase until it get to maximum and then begins to decrease after reaching the maximum until the volume produced becomes negligible. The time from the beginning of gas production and the end of production is known as the retention time. Immediately the Retention time is reached the Biodigester's digestate needs emptied and new feedstock put in for the process to repeat. Also note that the volume of gas produced tends to increase as the days gets closer to the maximum volume of gas production. Also after getting to the maximum, the rate of gas production decreases in very slowly as compared to the rate increase before the maximum volumetric rate.

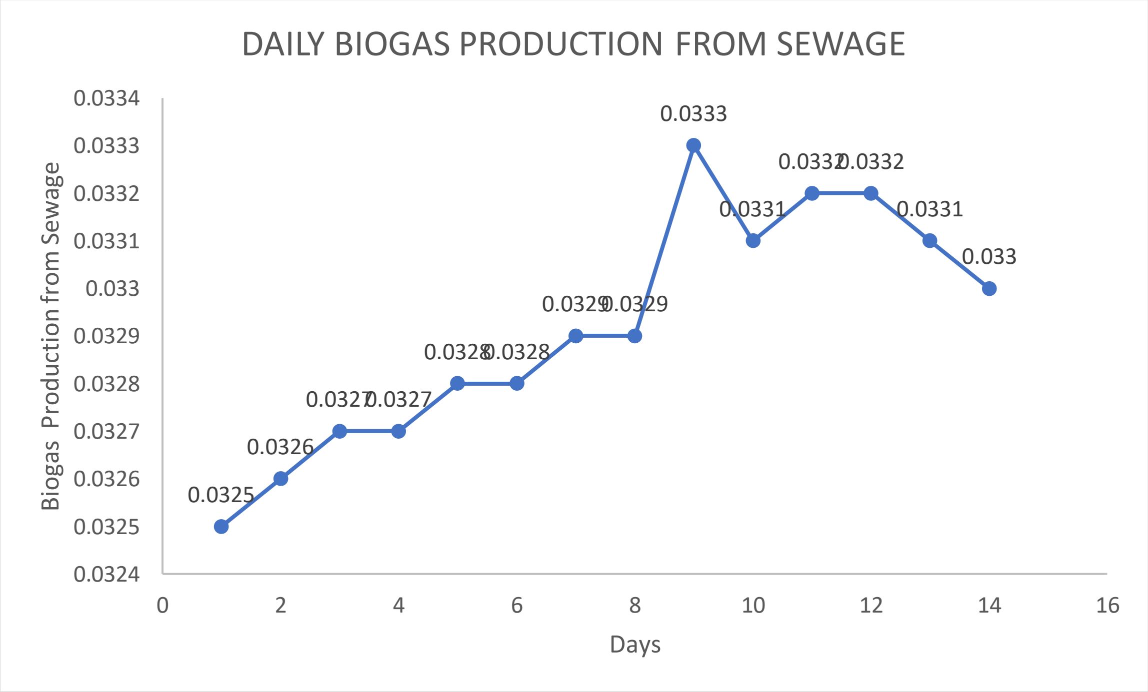


Figure 4.1: Daily Biogas Production Rates from Sewage( m³/day)

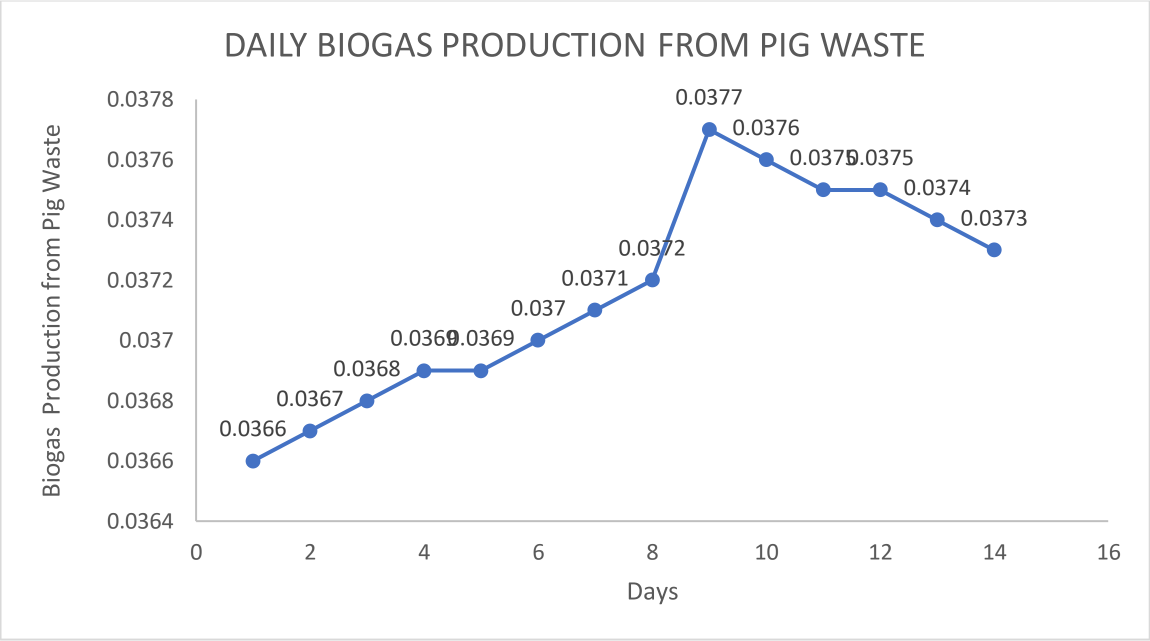


Figure 4.2: Daily Biogas Production Rates from Pig Waste ( m³/day)

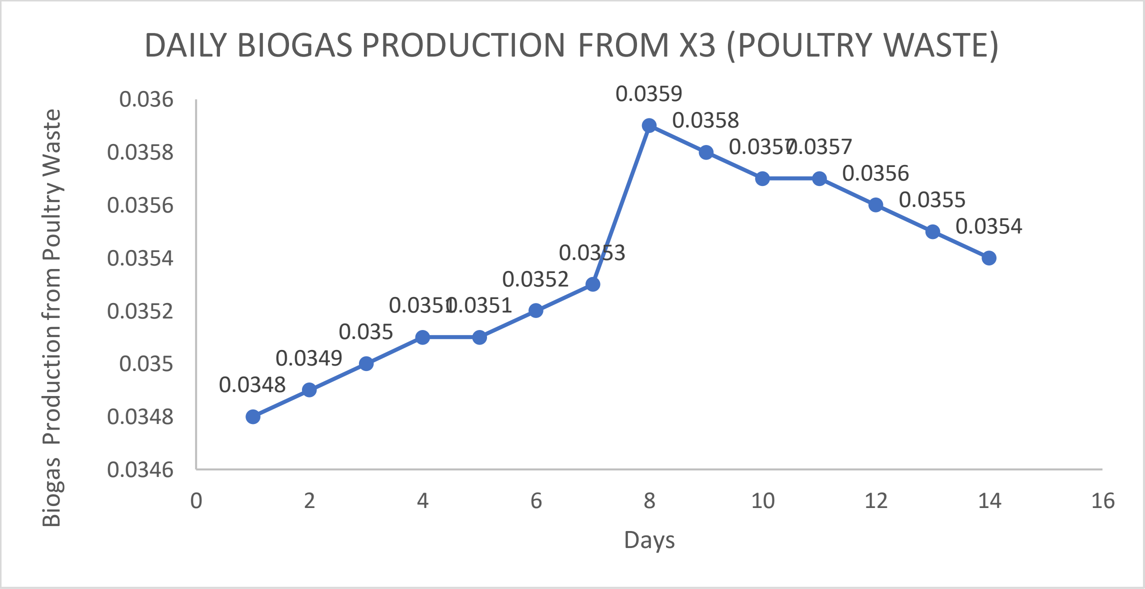


Figure 4.3: Daily Biogas Production Rates from Poultry Waste ( m³/day)

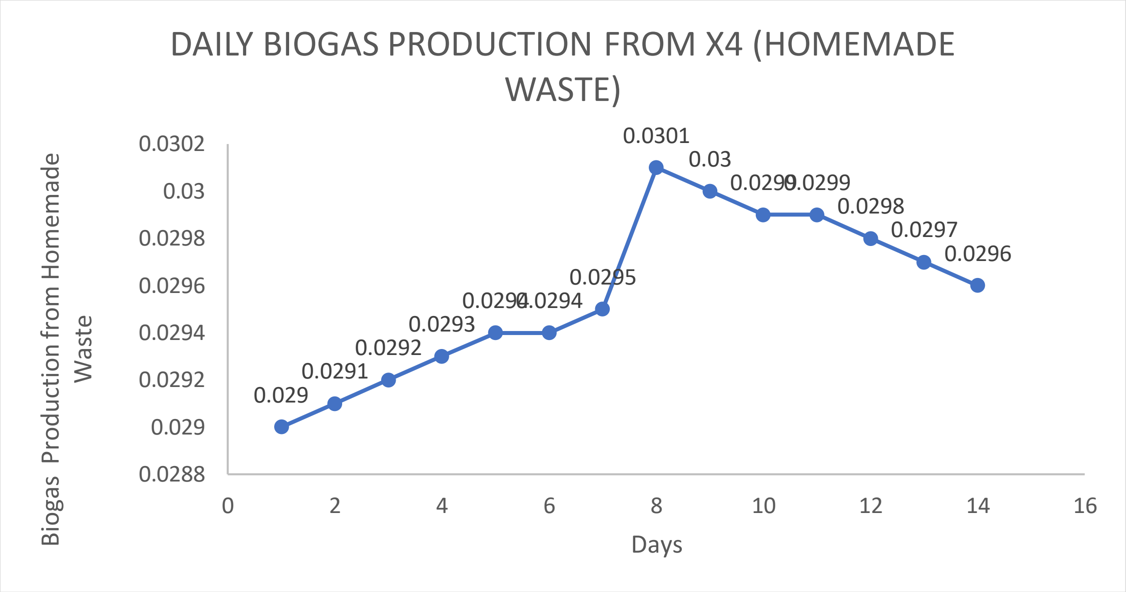


Figure 4.4: Daily Biogas Production Rates from Homemade Waste ( m³/day)

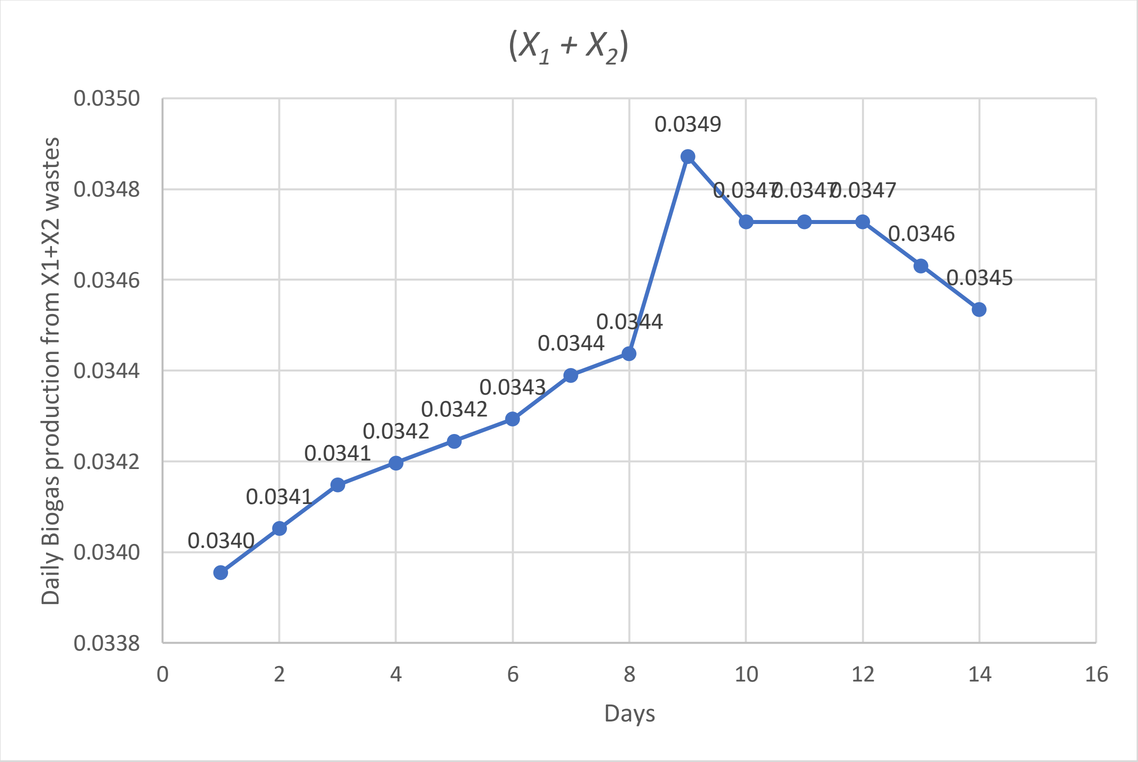


Figure 4.5: Daily Biogas Production Rates from Sewage and Pig Wastes ( m³/day)

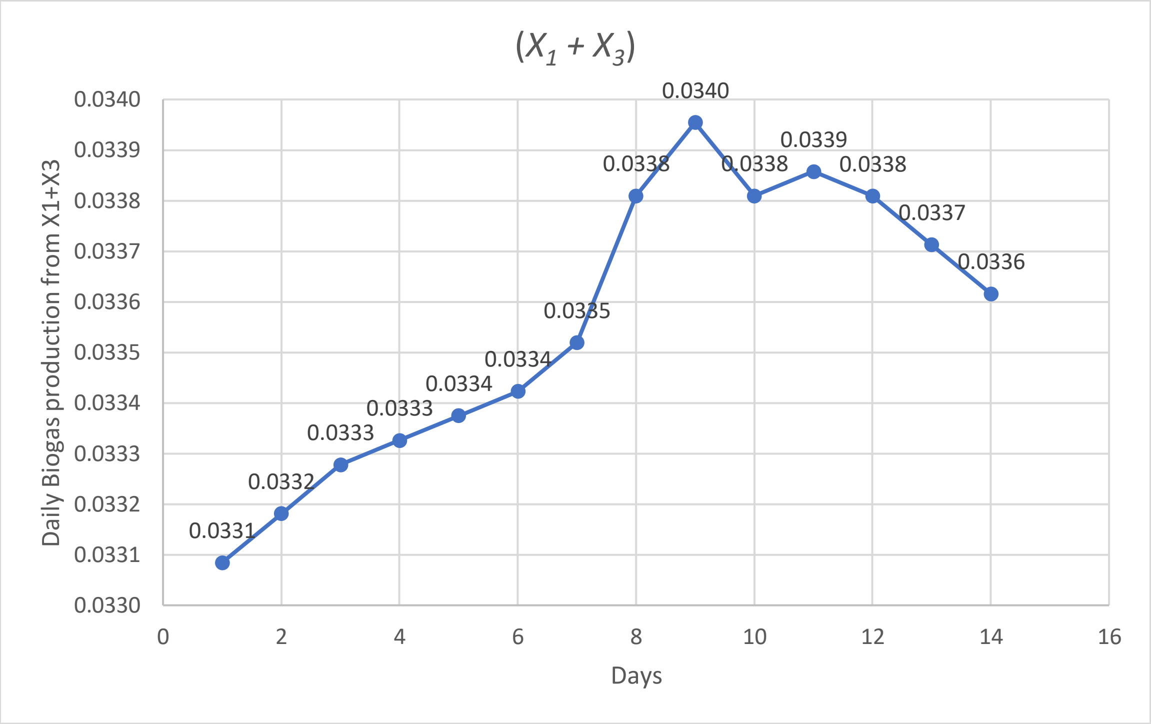


Figure 4.6: Daily Biogas Production Rates from Sewage and Poultry Wastes ( m³/day)

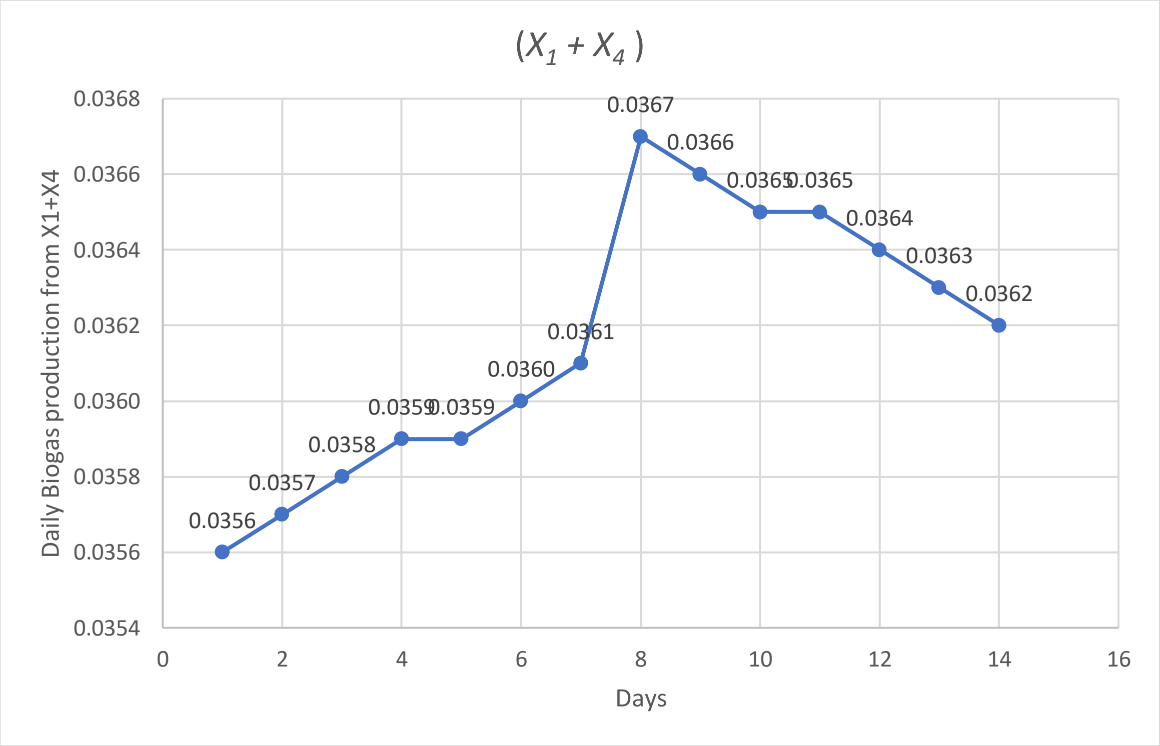


Figure 4.7: Daily Biogas Production Rates from Sewage and Homemade food Wastes ( m³/day)

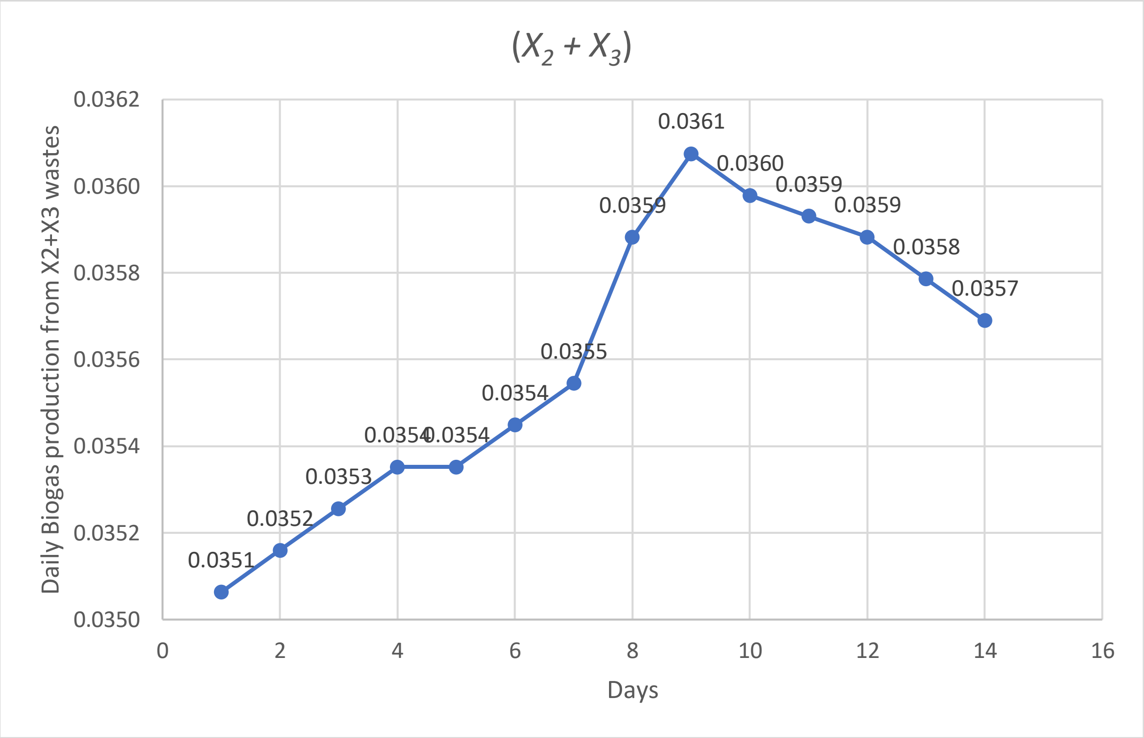


Figure 4.8: Daily Biogas Production Rates from Pig and Poultry Wastes ( m³/day

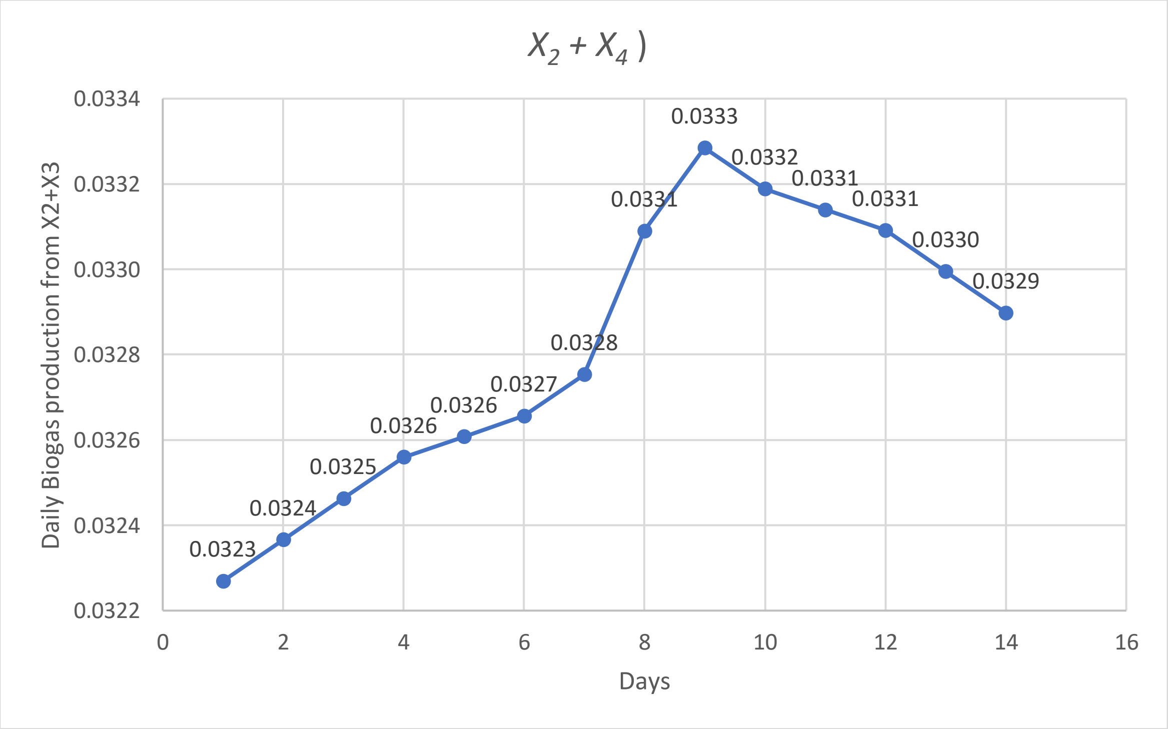


Figure 4.9: Daily Biogas Production Rates from Pig and Homemade food Wastes ( m³/day)

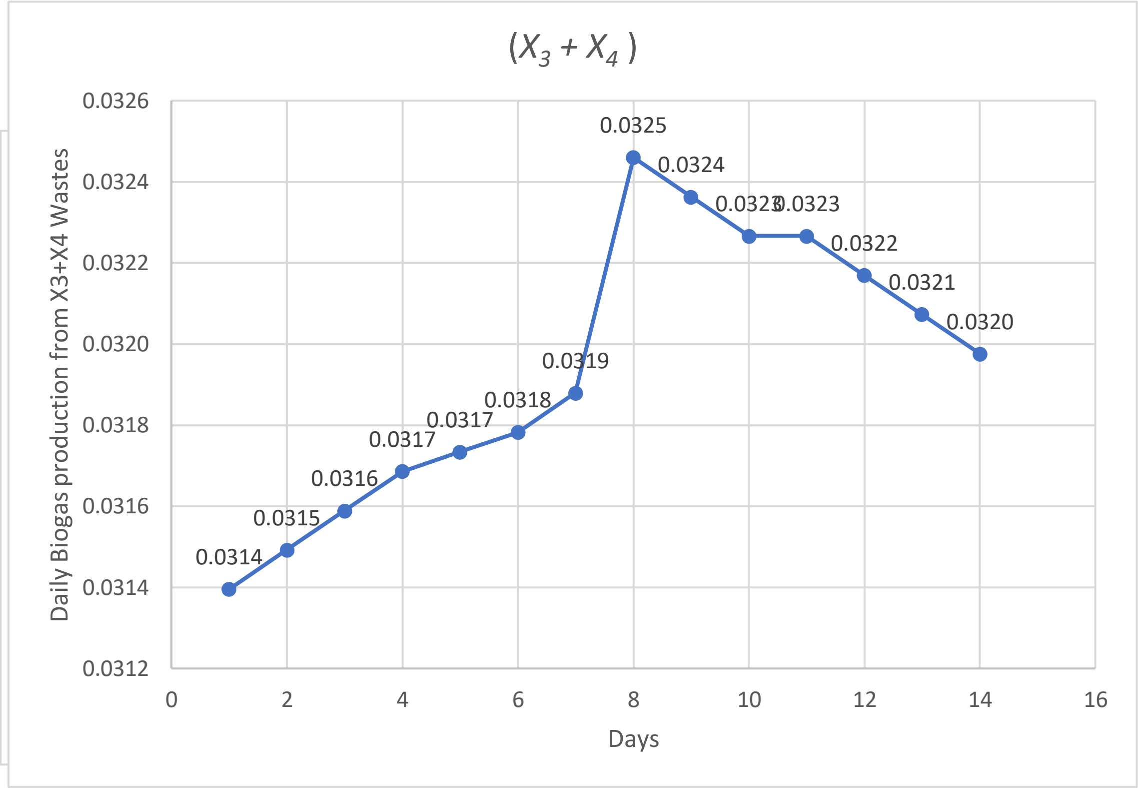


Figure 4.10: Daily Biogas Production Rates from Poultry and Homemade food Wastes (m³/day)

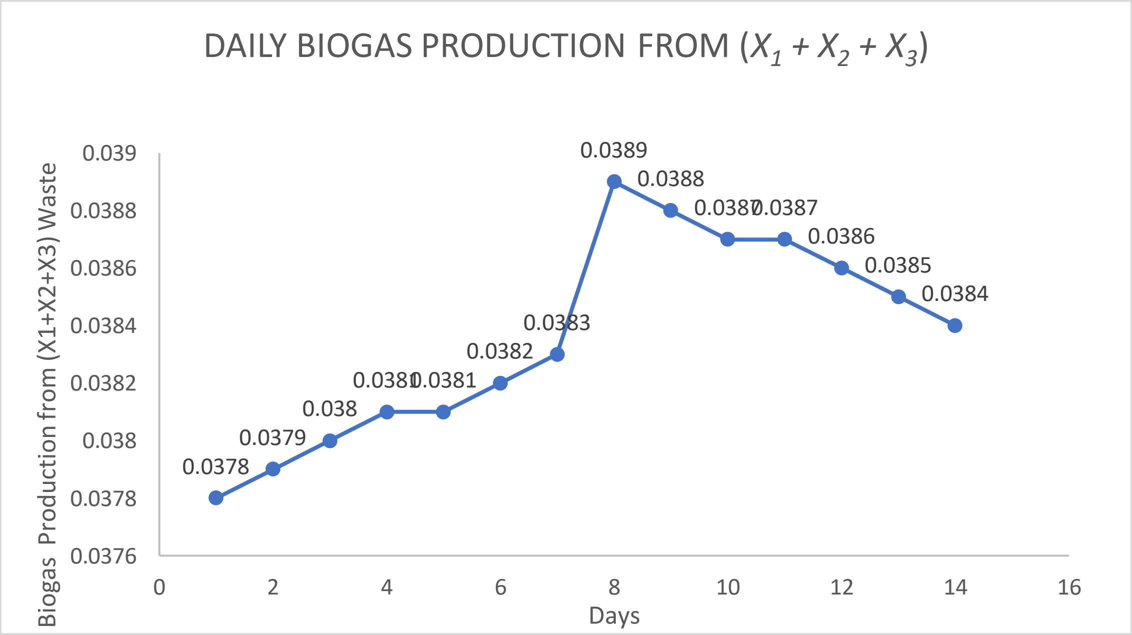


Figure 4.11: Daily Biogas Production Rates from Sewage, Pig and Poultry Wastes ( m³/day)

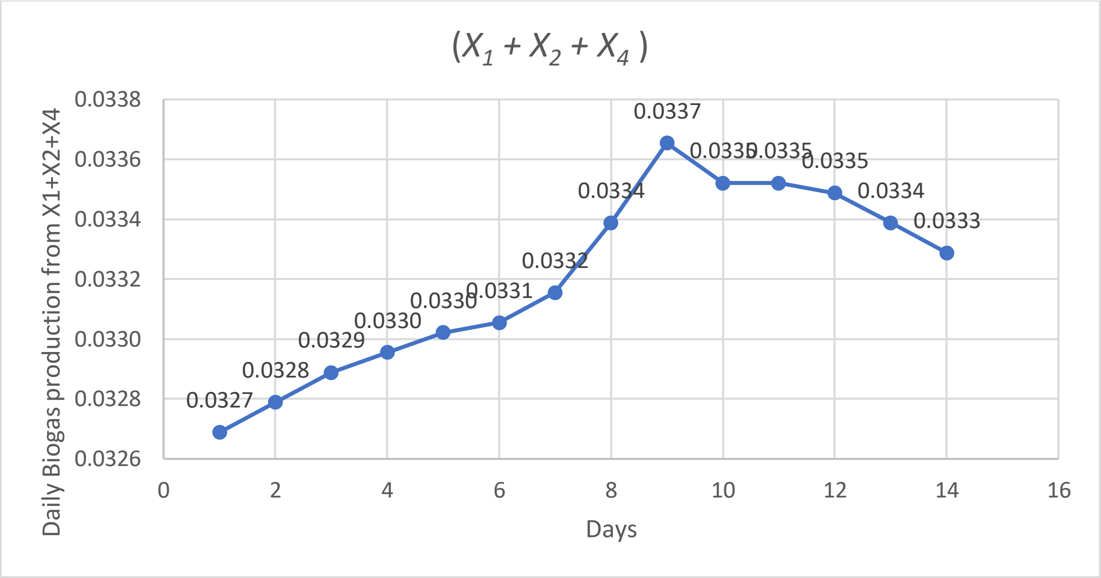


Figure 4.12: Daily Biogas Production Rates from Sewage, Pig and Homemade Wastes ( m³/day)

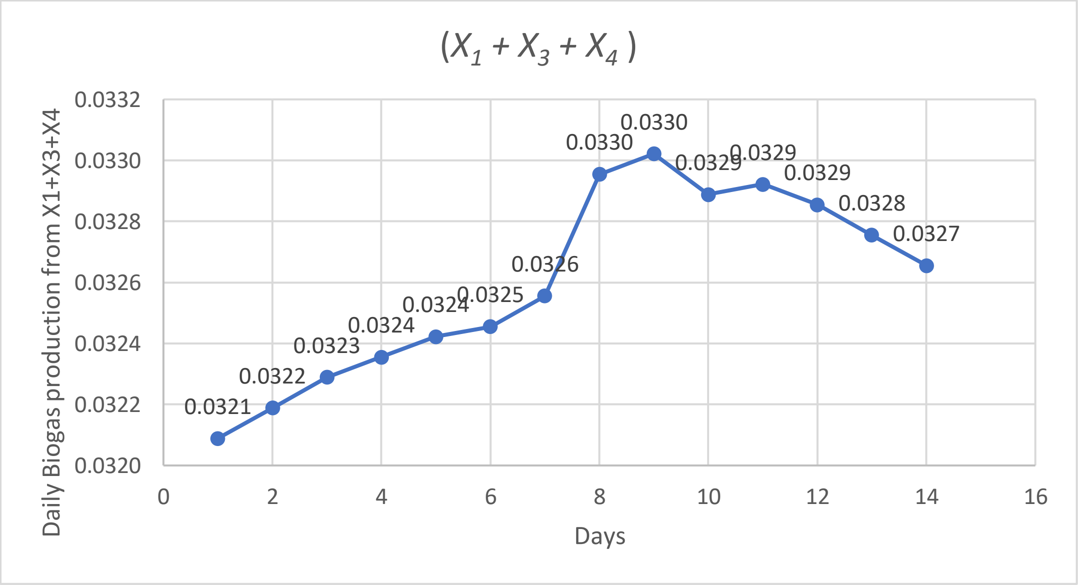


Figure 4.13: Daily Biogas Production Rates from Sewage, Poultry and Homemade Wastes (m³/day)

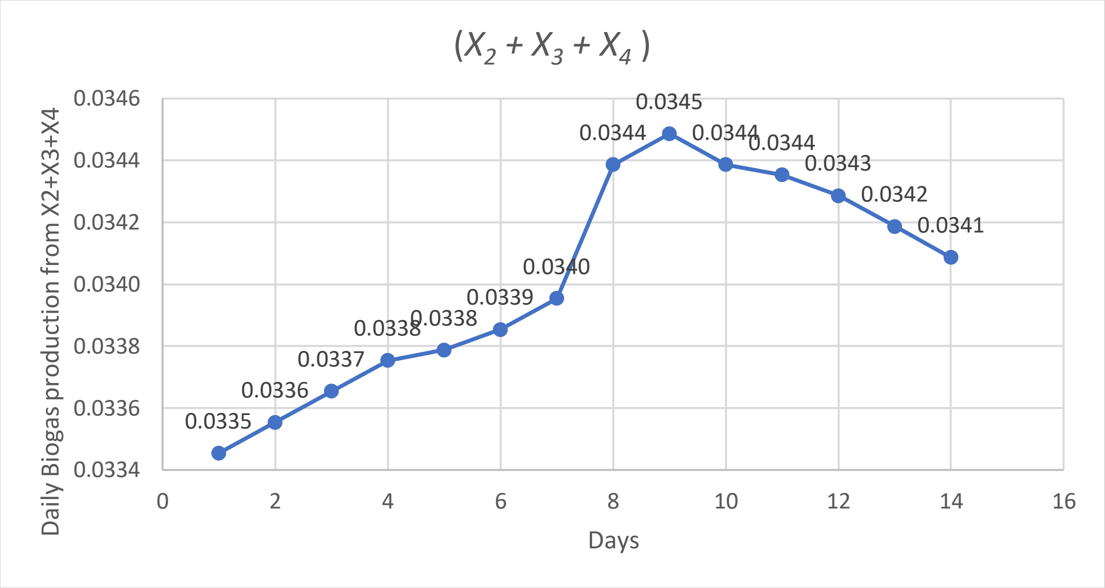


Figure 4.14: Daily Biogas Production Rates from Pig, Poultry and Homemade Wastes ( m³/day)

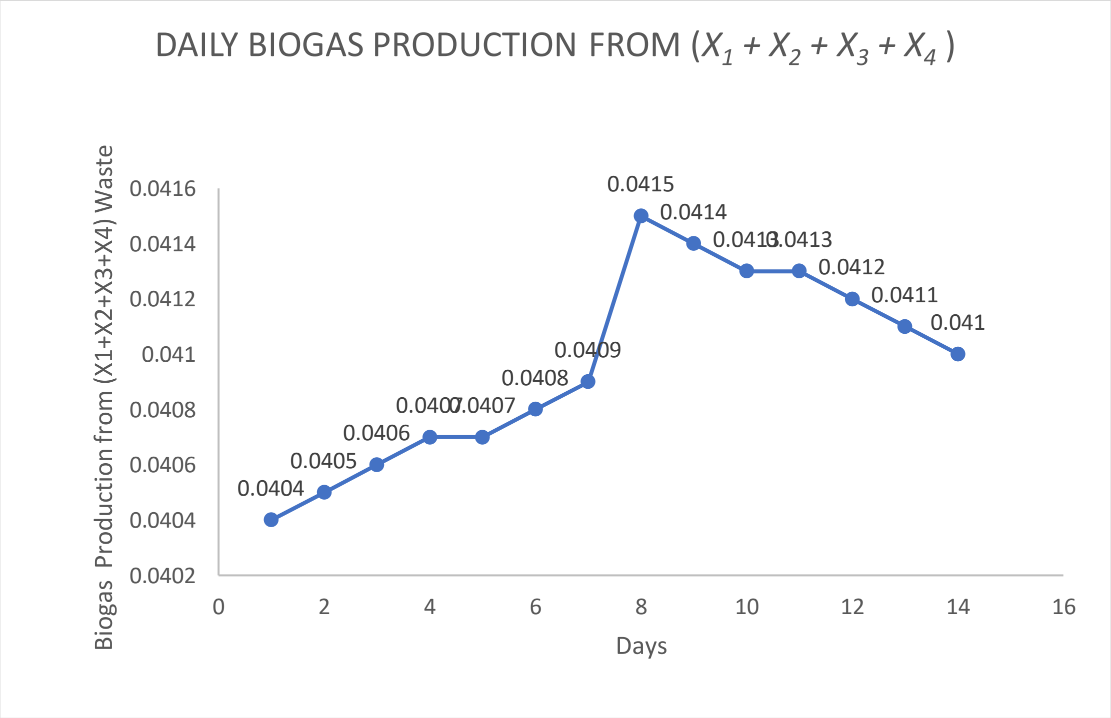


Figure 4.15: Daily Biogas Production Rates from Sewage, Pig, Poultry and Homemade Wastes ( m³/day)

Figureures 4.1 to 4.15 show that the daily production rate of the biogas increased gradually from the start of production and climaxed between the 8th and the 9th days of peak production for the different production processes and then afterwards the production rates began to reduce. This is further shown in Figure 4.16: Chart Showing the Biogas production for all feedstock Samples below:

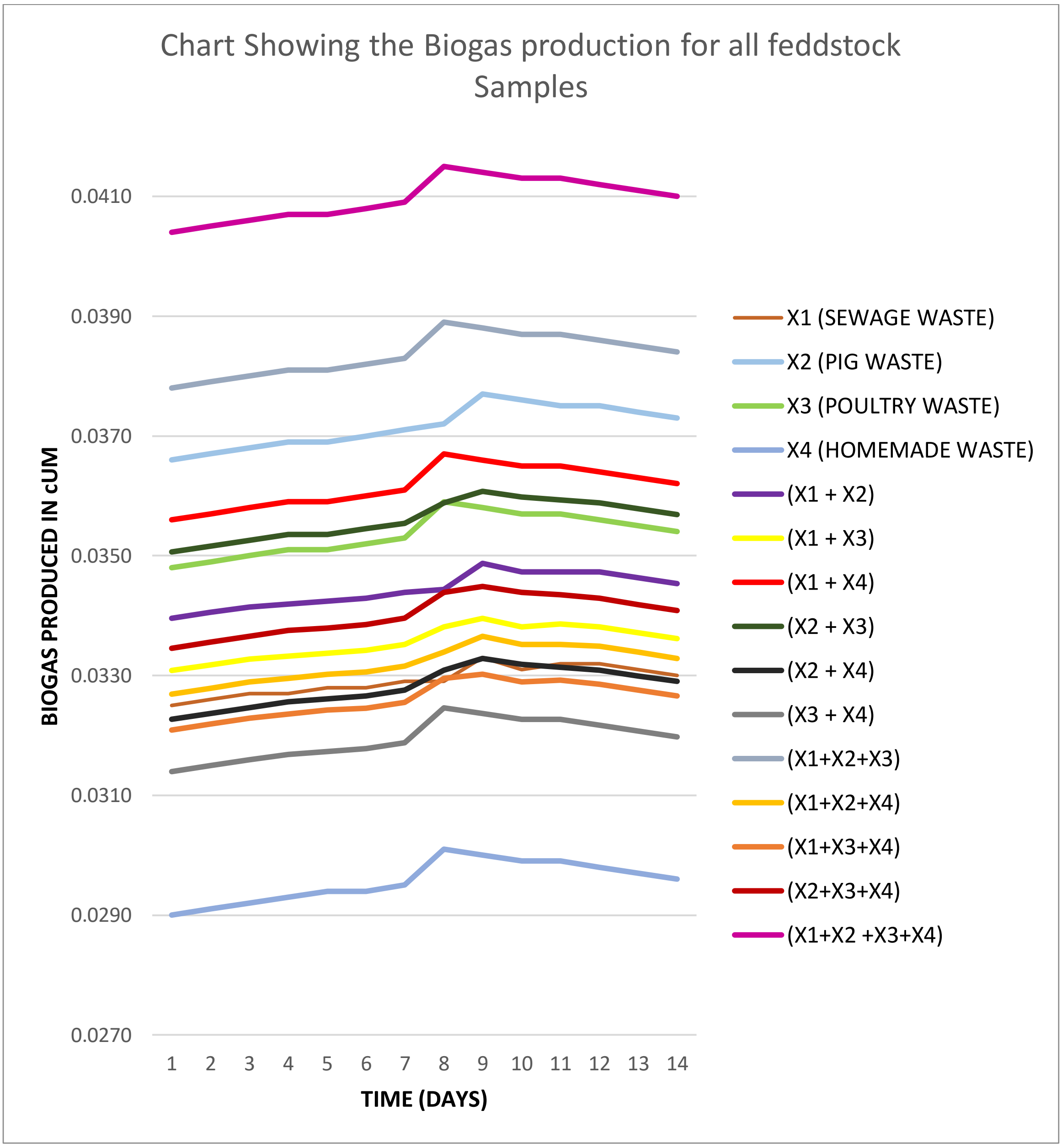


Figure 4.16: Chart Showing the Biogas production for all feedstock Samples:

The reason for this rate of increase and decrease movement was because, at the onset (when the feedstocks were added), the bacteria inside the anaerobic system was at minimum and so there was need for the bacteria to multiply. As the time goes by, the few bacteria continue to feed on the organic matters from the feedstocks, grows and replicates. This replication process continues until the available bacteria becomes more that the food (organic contents of the feedstock) available and as such, some of the bacteria begins to die due to inadequate food for all of them. As the bacteria community continues to increase, gas production also increases simultaneously until at the point where the organic matter in the feedstock is no longer adequate to feed the available bacteria community. As soon as the bacteria community begins to deplete, the rate of gas production also began to reduce. This process continues until the organic content of the feedstock is completely depleted and at this point the production of gas reaches a minimum. There is a need to ensure that the production rate is not allowed to reach this minimum before the introduction of more feedstocks to ensure continuity of the system. Locating the best time for the introduction of additional feedstock, removal of the digestate as well as the amounts of feedstocks to be introduced and amount of digestate to be removed to keep the system sustainably productive with continues high rates of daily biogas production will require another research work to determine these parameters.

### 4.1.2 Composition of the Biogas

#### 4.1.2.1 Statistical Comparison of Data for Home-made food waste, Agricultural Wastes and Sewage Wastes

Below is a Statistical Comparison of Data for Sewage Waste, Agricultural wastes (Pig and Poultry wastes), Home-made food waste (Pineapple and watermelon peels) obtained in the Laboratory before feeding them into the Biodigester.

Table 4.1: Summary of findings from the laboratory work for Sewage Waste, Pig Waste, Poultry Waste and Homemade Waste

| **Parameter** | **Percentage (%)** | | | |
|---|---|---|---|---|
| | **SEWAGE WASTE** | **PIG WASTE** | **POULTRY WASTE** | **HOMEMADE WASTE** |
| Organic Matter | 7.8% | 20.5% | 46.42% | 91% |
| Moisture Content | 99.00% | 70.00% | 30.09% | 13.50% |
| Carbon Content | 8.64% | 58.00% | 36.12% | 35.10% |
| Nitrogen Content | 0.32% | 5.80% | 2.40% | 1.30% |
| Carbon-to-Nitrogen (C/N) Ratio | 26:1 | 10:1 | 15:1 | 27:1 |
| Ph | 6.70 | 6.50 | 6.94 | 6.30 |
| Temperature | 22°C | 20°C | 20°C | 36.4°C |

From the laboratory table above, the laboratory result analysis of sewage waste, pig waste, poultry waste, and homemade waste revealed significant differences in their composition and suitability for composting or resource recovery. Homemade waste recorded the highest organic matter content at 91%, indicating a rich source of biodegradable material, while sewage waste had the lowest at 7.8%, likely due to dilution or prior treatment. Moisture content was extremely high in sewage waste (99%), making it unsuitable for composting unless dried, whereas homemade waste had the lowest moisture (13.5%), making it more manageable. In terms of nutrient content, pig waste stood out with the highest carbon (58%) and nitrogen (5.8%) concentrations, followed by poultry and homemade waste, while sewage waste had the least nutrient value. The carbon-to-nitrogen (C/N) ratio, which affects the rate of decomposition, was optimal in pig waste (10:1) and poultry waste (15:1), suggesting these are well-balanced for composting. In contrast, sewage and homemade waste had higher C/N ratios

(26:1 and 27:1 respectively), which could slow decomposition unless supplemented with nitrogen. The pH levels of all the wastes were slightly acidic to near neutral, ranging between 6.3 and 6.94, favorable for microbial activity. Temperature readings showed that homemade waste was the most biologically active, recording a temperature of 36.4°C, while the others were close to ambient levels. Overall, pig and poultry wastes are most suitable for direct composting due to their favorable moisture, nutrient, and C/N ratios, whereas homemade waste, though highly organic, would require nitrogen addition, and sewage waste needs both drying and nutrient enhancement before use.

#### 4.1.2.2 Biogas Composition

Biogas is primarily composed of methane, which is the main energy-carrying component, and carbon dioxide, a major byproduct. It also contains hydrogen sulfide, a toxic gas that requires careful management, along with small amounts of nitrogen, which is mostly inert. Additionally, water vapor is present, and trace amounts of other gases like ammonia and volatile organic compounds may also be found. The specific composition of biogas can vary depending on factors such as the type of organic material used and the conditions under which it is produced. The composition of biogas, particularly the percentages of methane ($CH_4$) and carbon dioxide ($CO_2$), play a crucial role in assessing the quality of the biogas generated. Our major focus in biogas composition is therefore on the Methane and Carbon dioxide. Here are the descriptive statistics result for biogas composition for the four main feedstocks:

**From Sewage:**

i. Methane ($CH_4$) Percentage: 54.8%

ii. Carbon-dioxide ($CO_2$) Percentage: 39.4%

iii. Other Impurities: 5.8%

**From Pig waste:**

i. Methane ($CH_4$) Percentage: 58.7%

ii. Carbon-dioxide ($CO_2$) Percentage: 35.0%

iii. Other Impurities: 6.3%

**From Poultry waste:**

iv. Methane ($CH_4$) Percentage: 56.6%

v. Carbon-dioxide ($CO_2$) Percentage: 36.5%

vi. Other Impurities: 6.9%

**From Homemade Food Waste:**

vii. Methane ($CH_4$) Percentage: 51.7%

viii. Carbon-dioxide ($CO_2$) Percentage: 41.1%

ix. Other Impurities: 7.2%

#### 4.1.2.3 Pie Chart Representation of Data

Figures 4.17 to 4.31 illustrates the composition of biogas produced by the different feedstocks by displaying the percentage of methane, carbon-dioxide and other gases in each feedstock. This graphical representation underscores the differences in biogas quality.

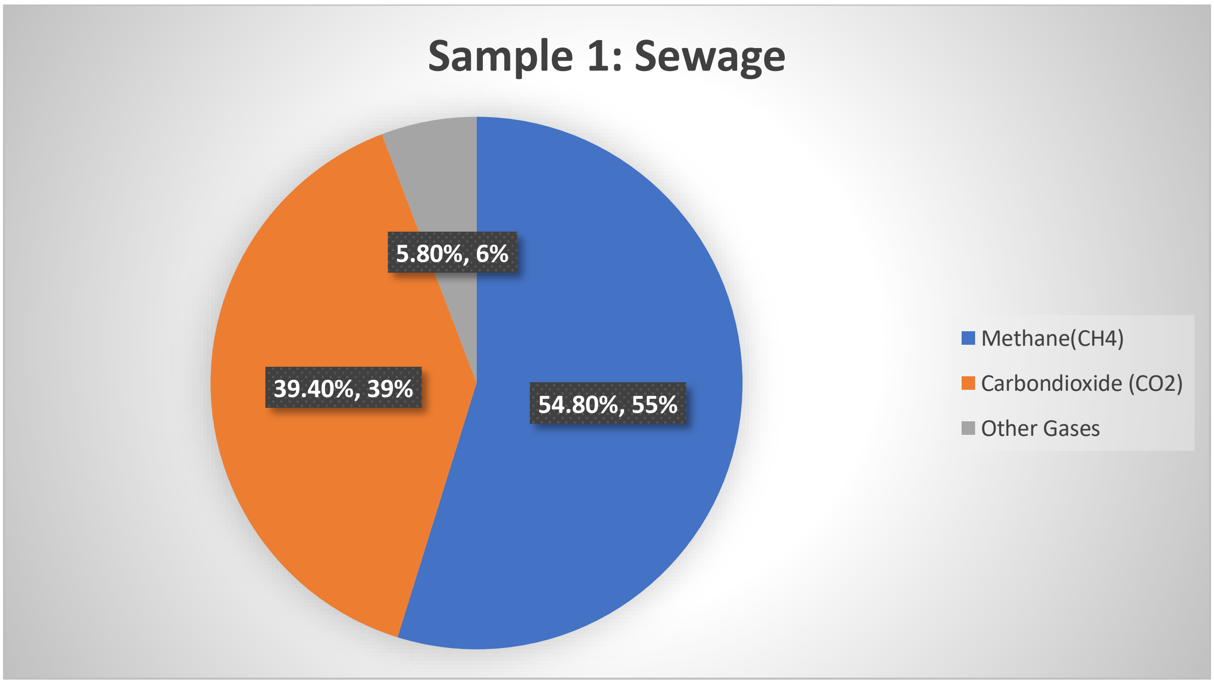


Figure. 4.17: Percentage composition of gas in sewage produced biogas.

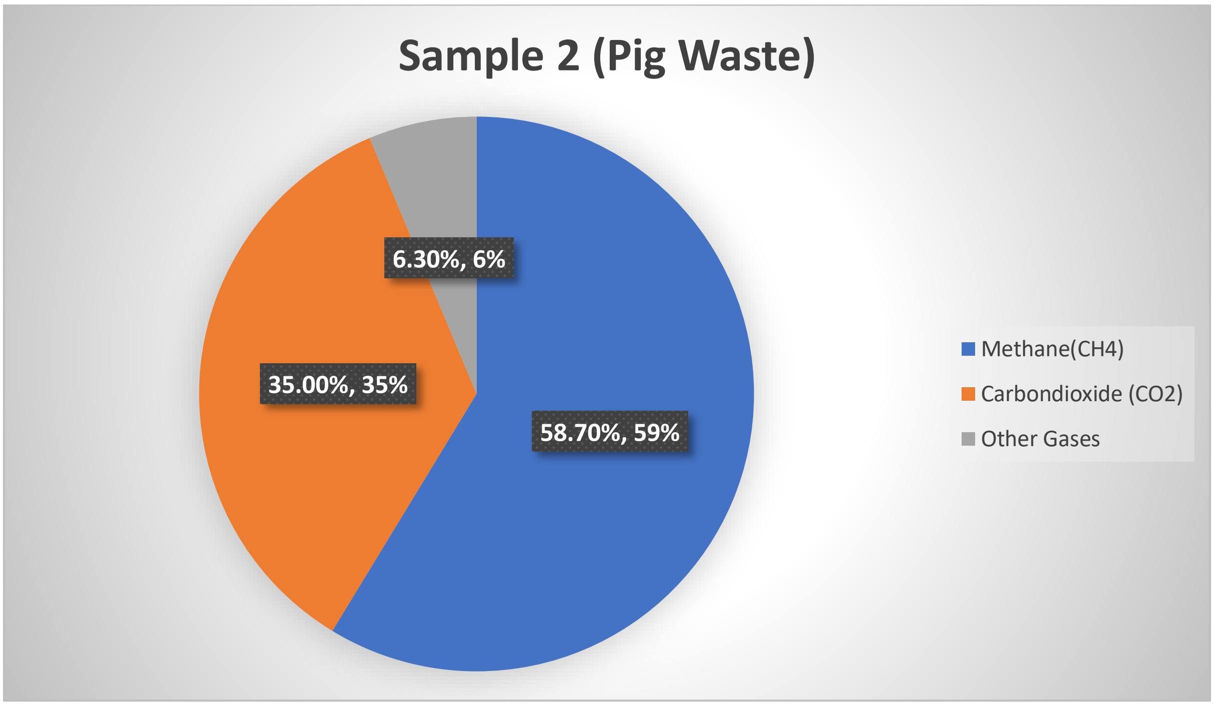


Figure. 4.18: Percentage composition of gas in pig waste produced biogas.

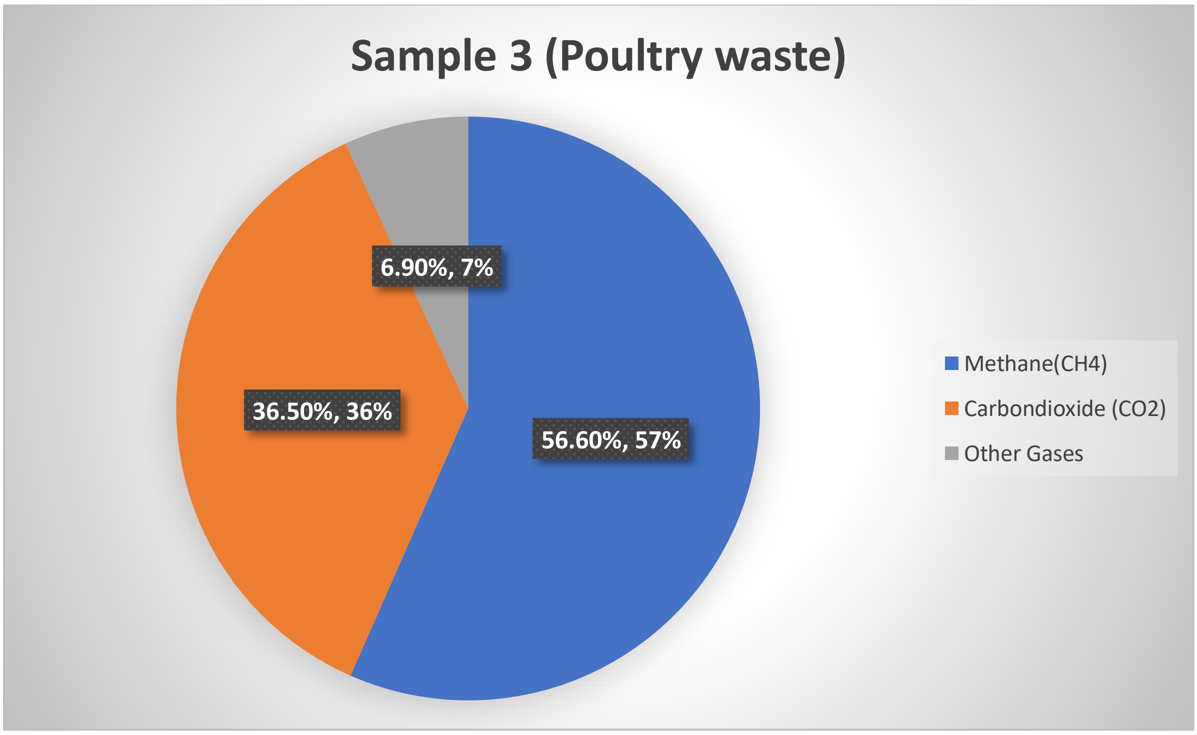


Figure. 4.19: Percentage composition of gas in poultry waste produced biogas

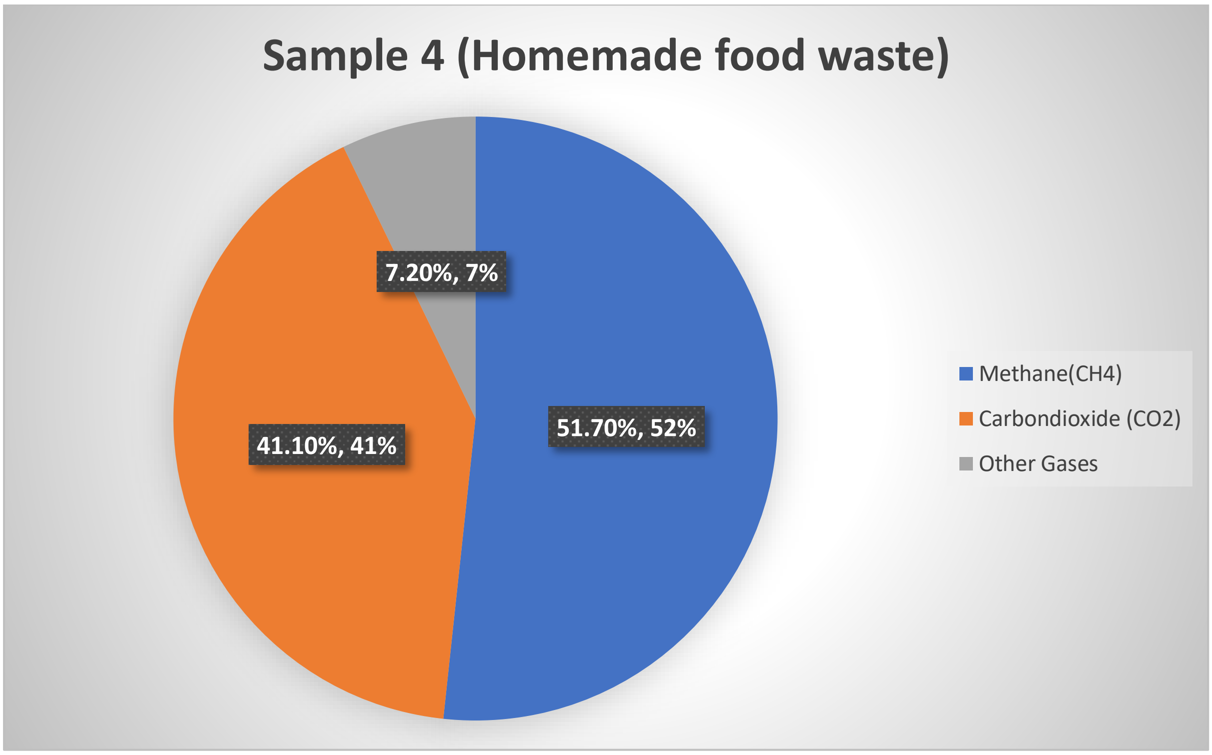


Figure. 4.20: Percentage composition of gas in homemade food waste produced biogas

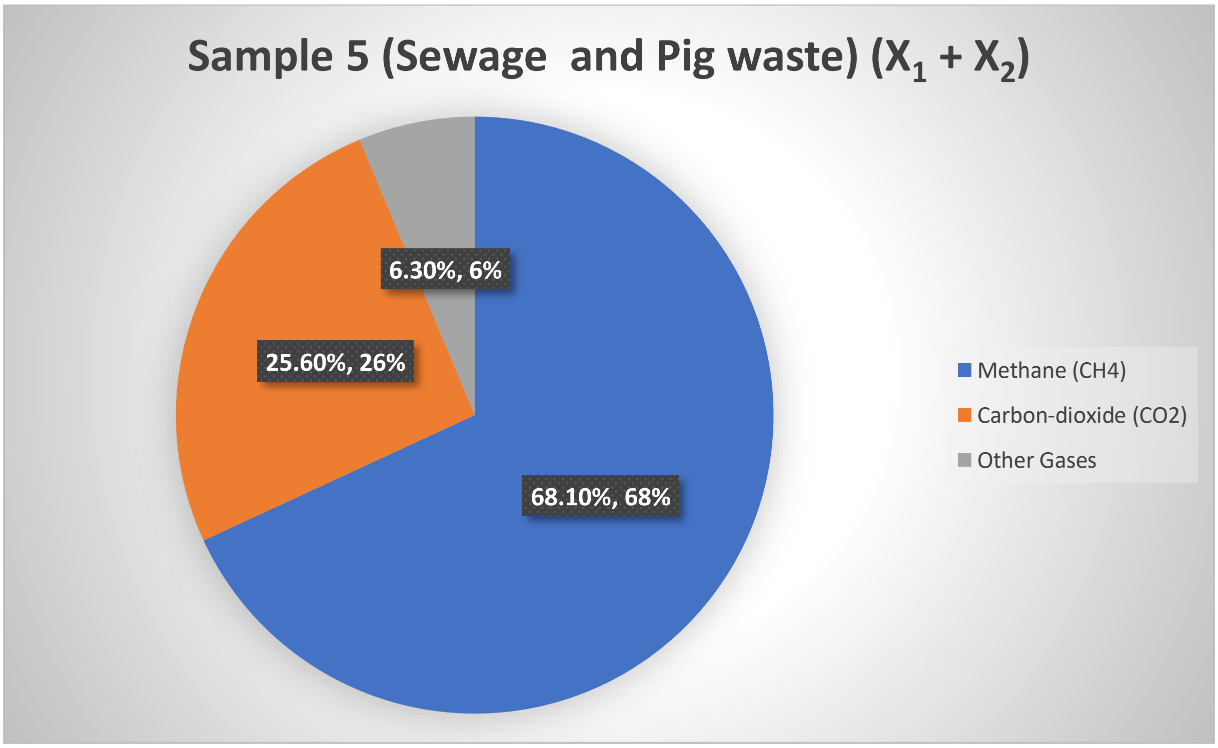


Figure. 4.21: Percentage composition of gas in Sewage and Pig waste produced biogas

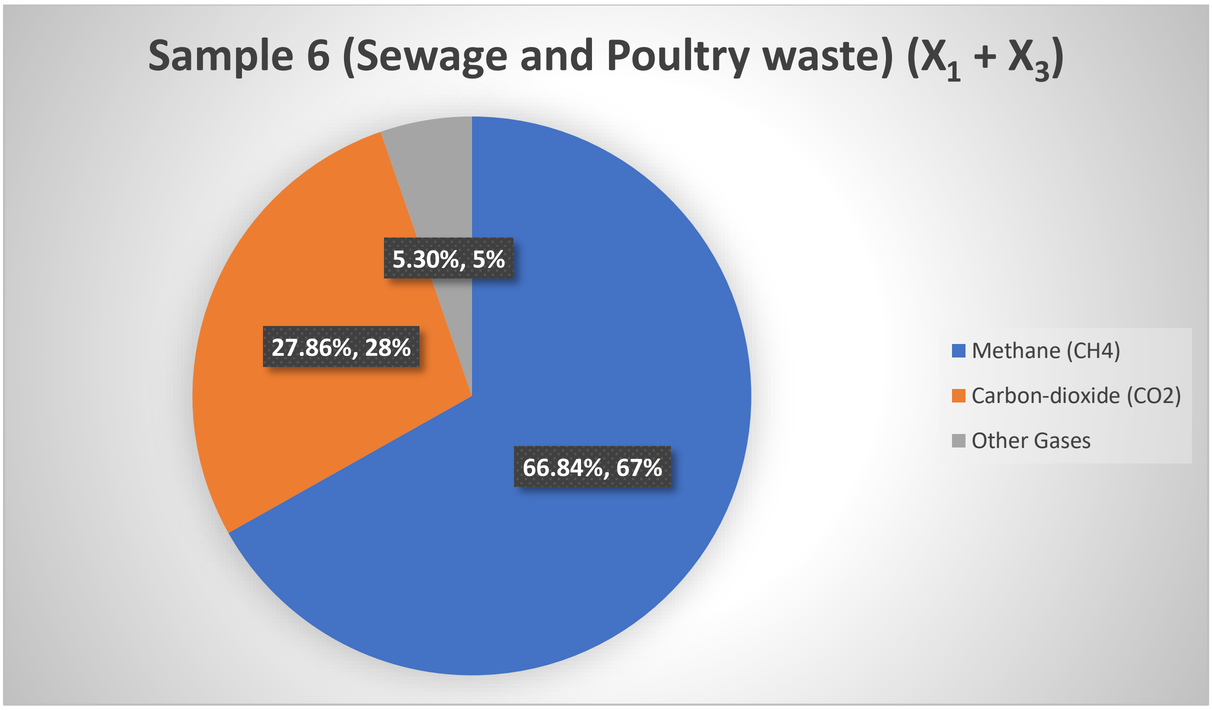


Figure. 4.22: Percentage composition of gas in Sewage and Poultry waste produced biogas

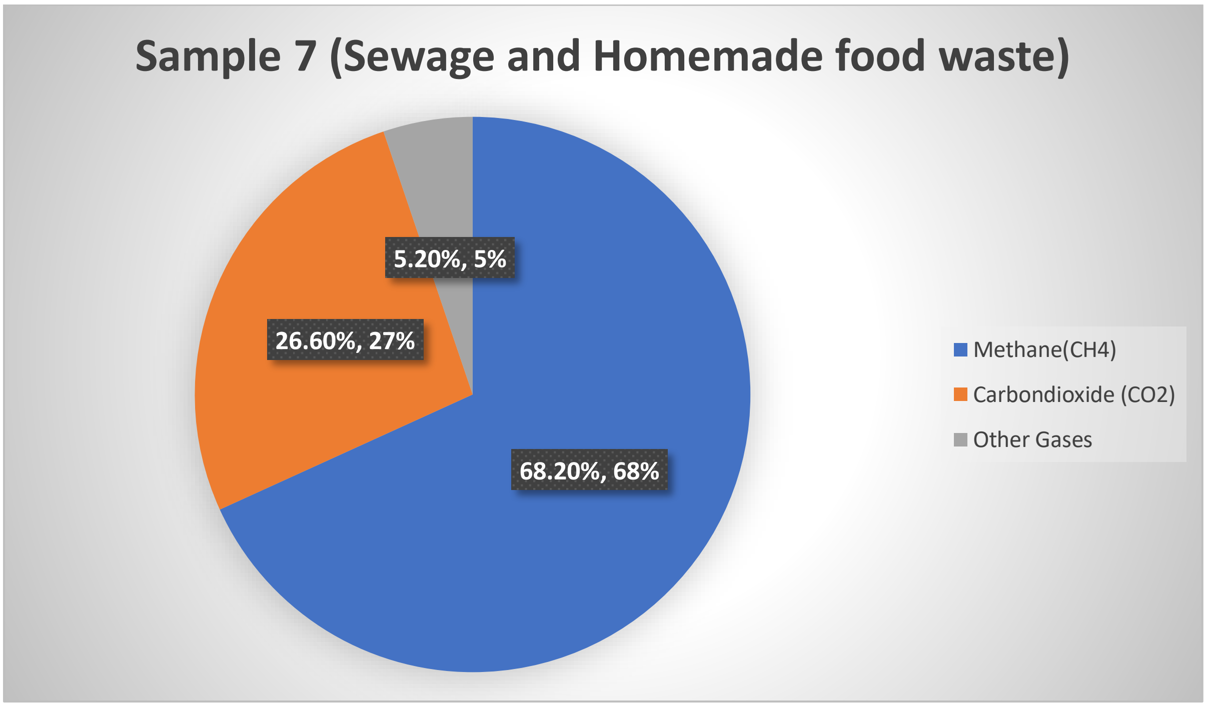


Figure. 4.23: Percentage composition of gas in sewage and homemade food waste produced biogas.

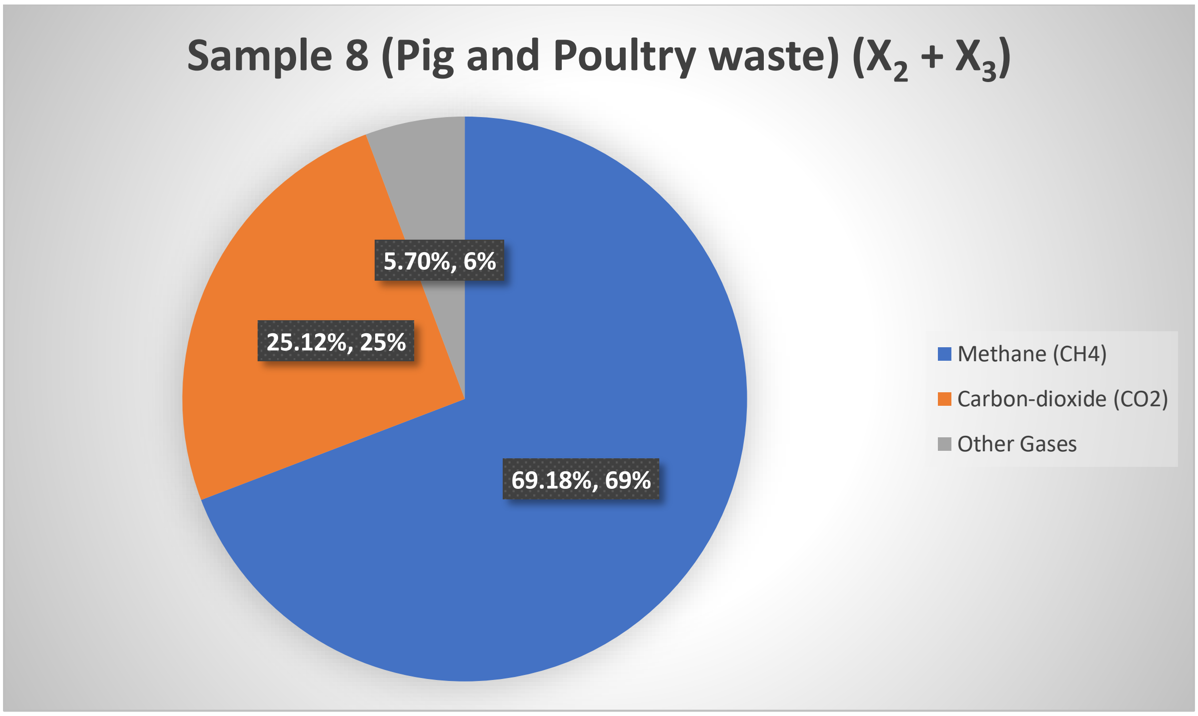


Figure. 4.24: Percentage composition of gas in Pig and Poultry waste produced biogas.

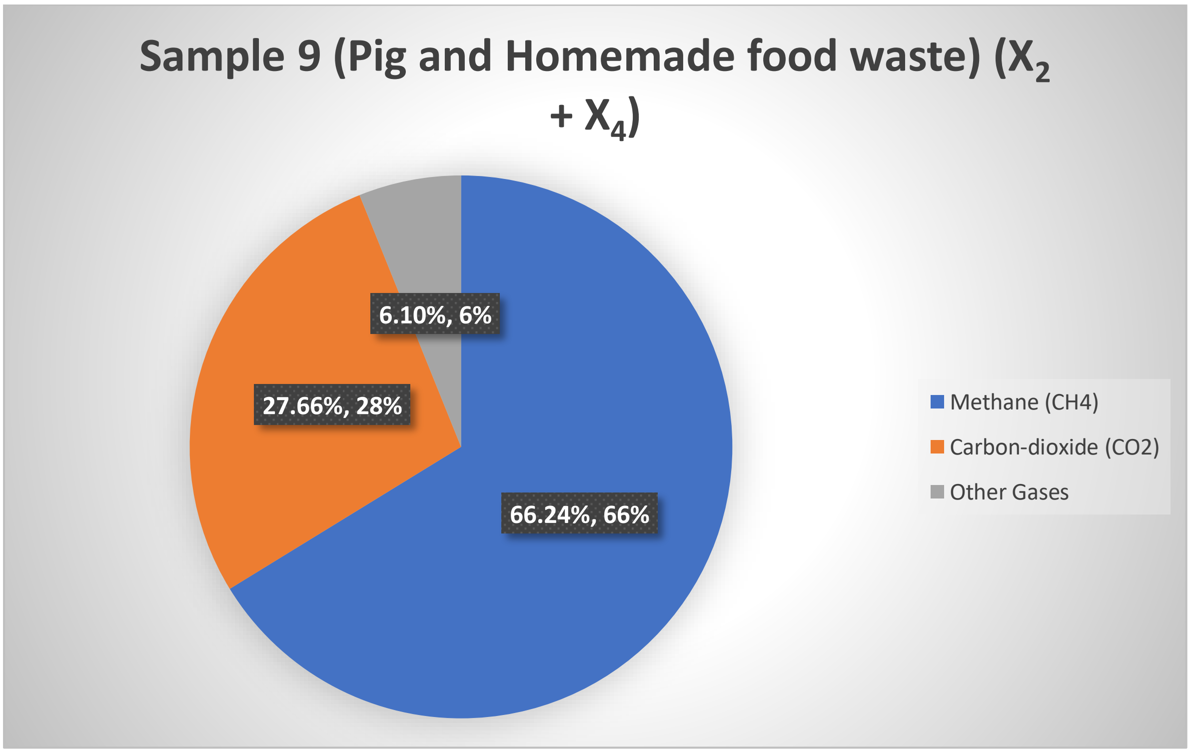


Figure. 4.25: Percentage composition of gas in Pig and Homemade food waste produced biogas.

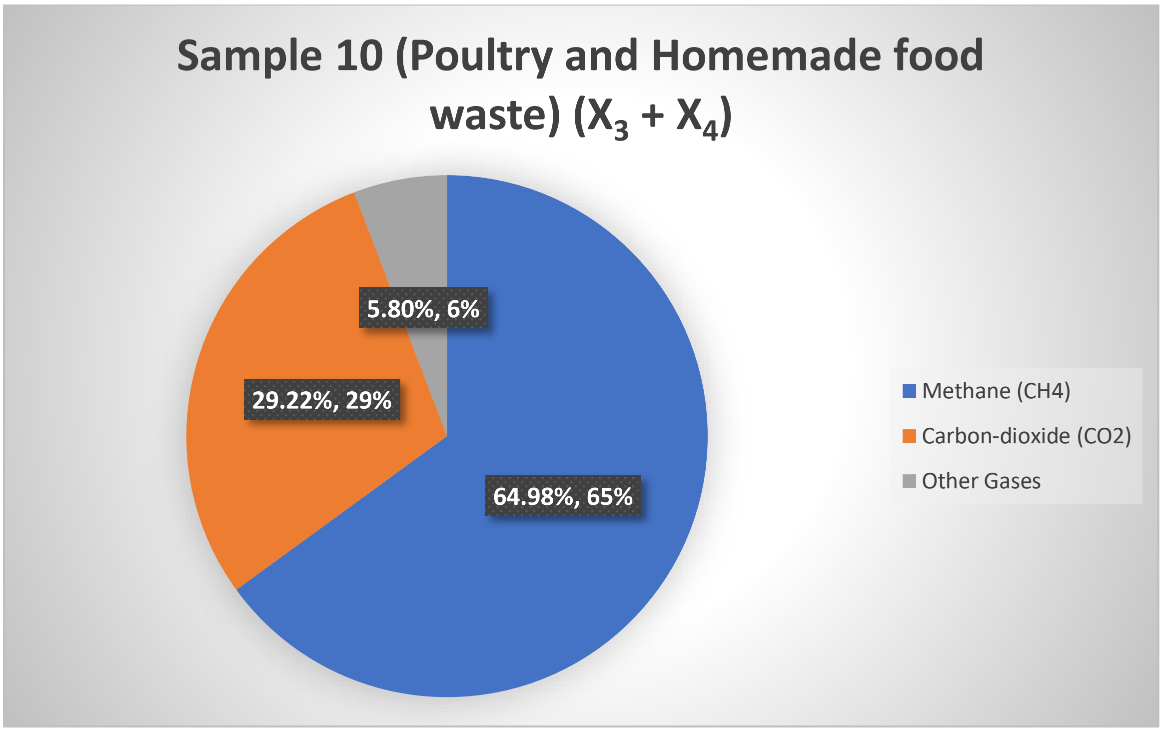


Figure. 4.26: Percentage composition of gas in Poultry and Homemade food waste produced biogas.

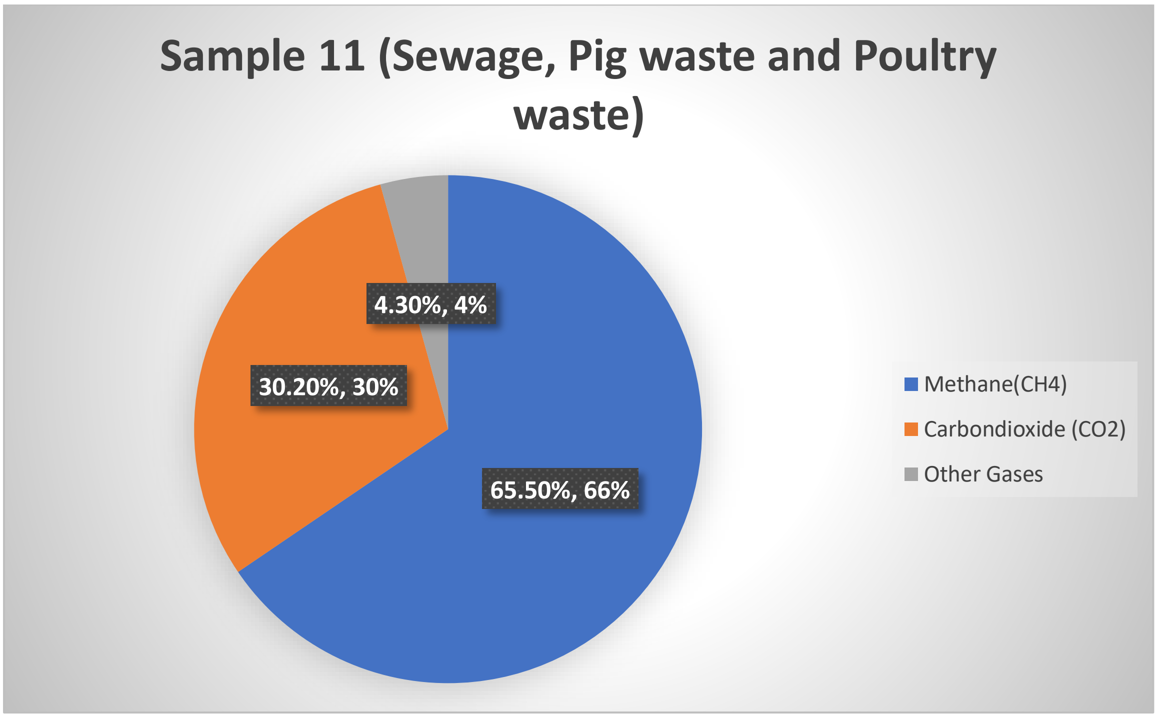


Figure. 4.27 Percentage composition of gas in sewage, pig and poultry waste produced biogas.

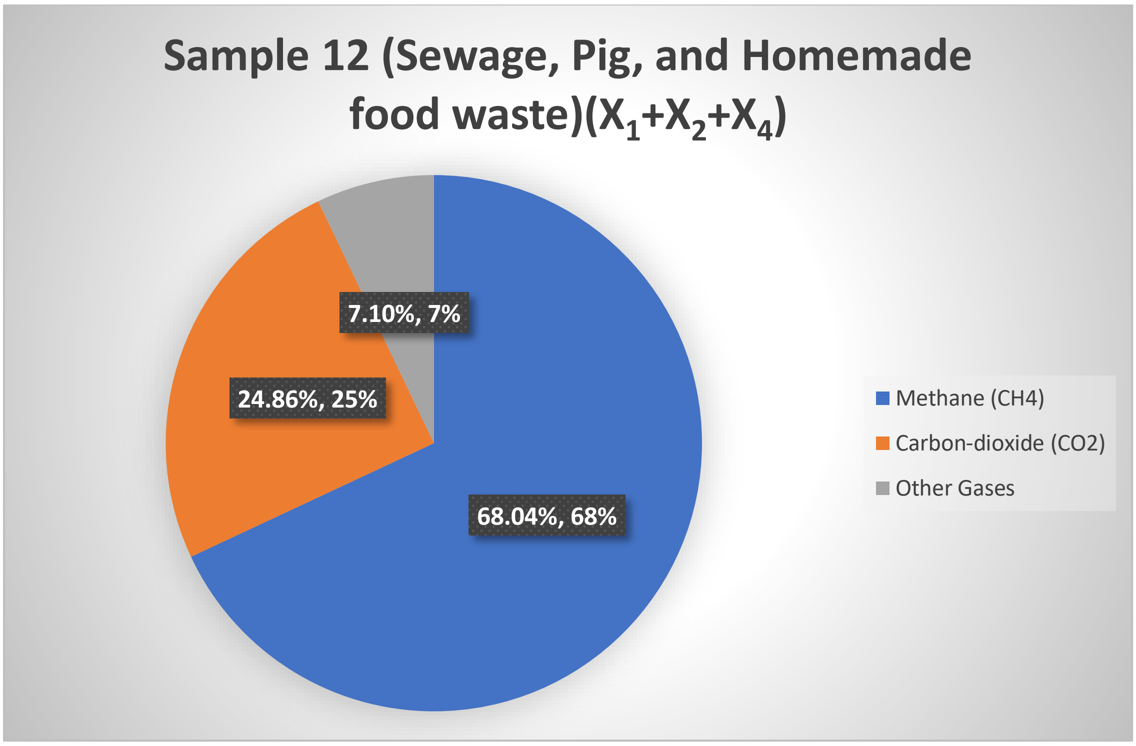


Figure. 4.28: Percentage composition of gas in Sewage. Pig and Homemade food waste produced biogas.

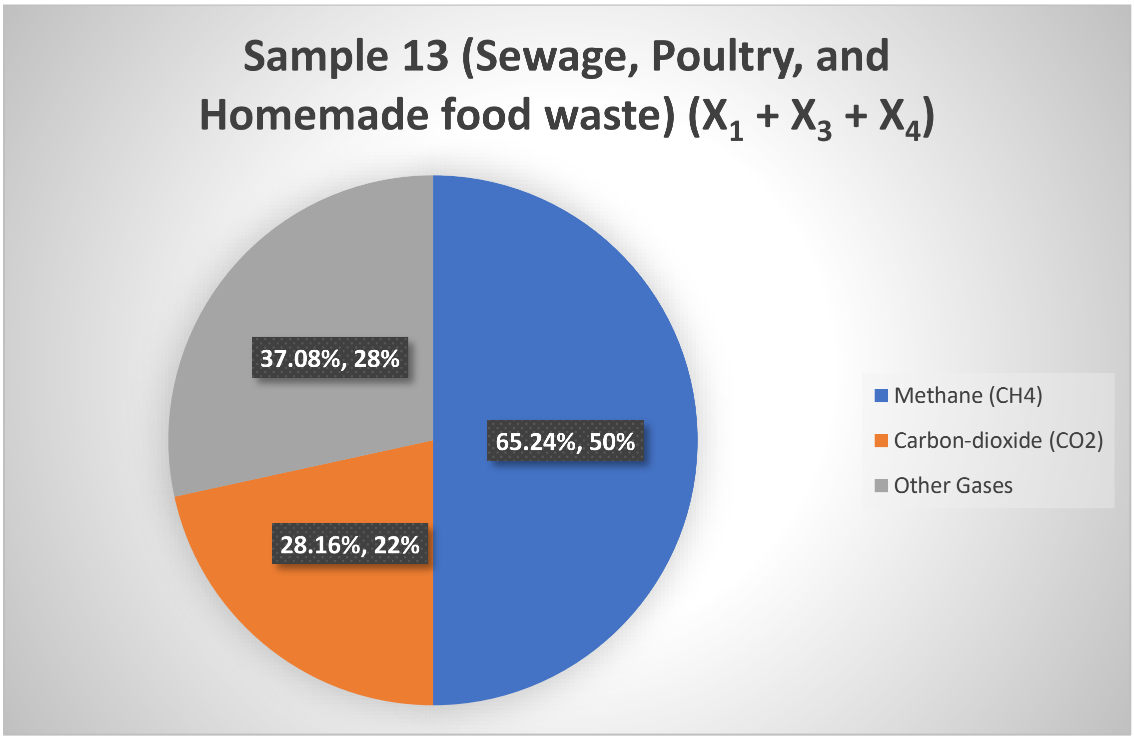


Figure. 4.29: Percentage composition of gas in Sewage. Poultry and Homemade food waste produced biogas.

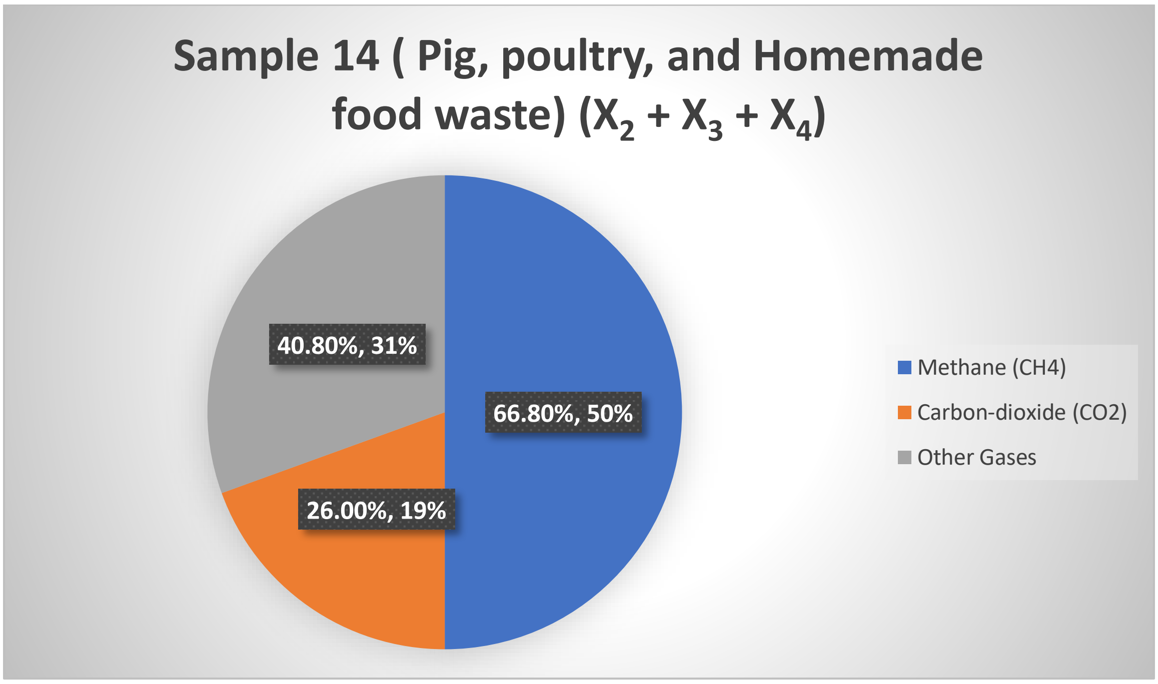


Figure. 4.30: Percentage composition of gas in Sewage. Poultry and Homemade food waste produced biogas.

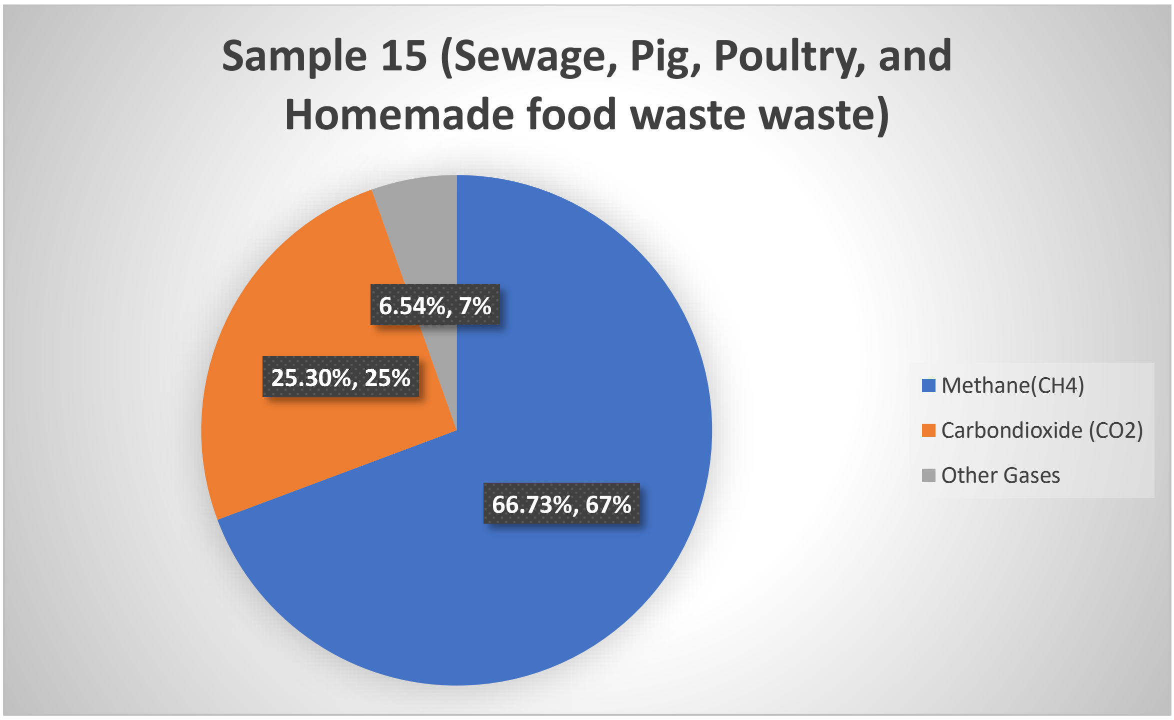


Figure. 4.31: Percentage composition of gas in sewage, pig, poultry, and Homemade food waste produced biogas.

### 4.1.2.4 Analysis of Results:

**1. Correlation Analysis:**

i. **Methane (**$CH_4$**) vs.** $CO_2$**:** Strong negative correlation (-0.989), meaning an increase in methane results in a decrease in $CO_2$, which indicates efficient biogas production.

ii. **Methane (**$CH_4$**) vs. Other Gases:** Weak negative correlation (-0.359), suggesting other gases contribute minimally to overall output.

iii. $CO_2$ **vs. Other Gases:** Weak positive correlation (0.220), implying $CO_2$ and other gases are not strongly related.

**2. Contribution Analysis:**

Comparing individual samples ($X_1, X_2, X_3, X_4$) to their combinations:

i. **Highest** $CH_4$ **Production:** Combination $X_1 + X_2 + X_3 + X_4$ (66.73%), which improved methane content by **18.06%** compared to the highest single feedstock ($X_2$ at 58.70%).

ii. **Best Combination for** $CH_4$ **Improvement:** $X_2 + X_3$ (69.18%), yielding a **17.85%** improvement over $X_2$ alone.

iii. **Lowest** $CO_2$ **Levels:** The combination $X_1 + X_2 + X_4$ resulted in the lowest $CO_2$ content (24.86%).

**3. Efficiency Analysis (**$CH_4$/ $CO_2$ **Ratio):**

i. The most efficient combination is $X_1 + X_2 + X_3 + X_4$ with a ratio of **2.66697**, meaning a high methane yield with minimal $CO_2$ output.

ii. The least efficient feedstock is $X_4$ (1.258), which shows poor performance when used individually.

iii. **Percentage Improvement:** Compared to the highest single feedstock, combinations improved methane yield by up to **18.06%.**

In conclusion, the **Best Overall Combination is** $X_1 + X_2 + X_3 + X_4$ which achieved the highest methane yield of 66.73% and an efficiency ratio of 2.739. the m**ost Significant Contributor is the** Pig waste ($X_2$) which individually provides the highest methane of 58.70% but further improves when combined with others. The l**east Effective Individually:** Homemade food waste ($X_4$), yielding the lowest methane (51.70%) and highest $CO_2$ (41.10%).

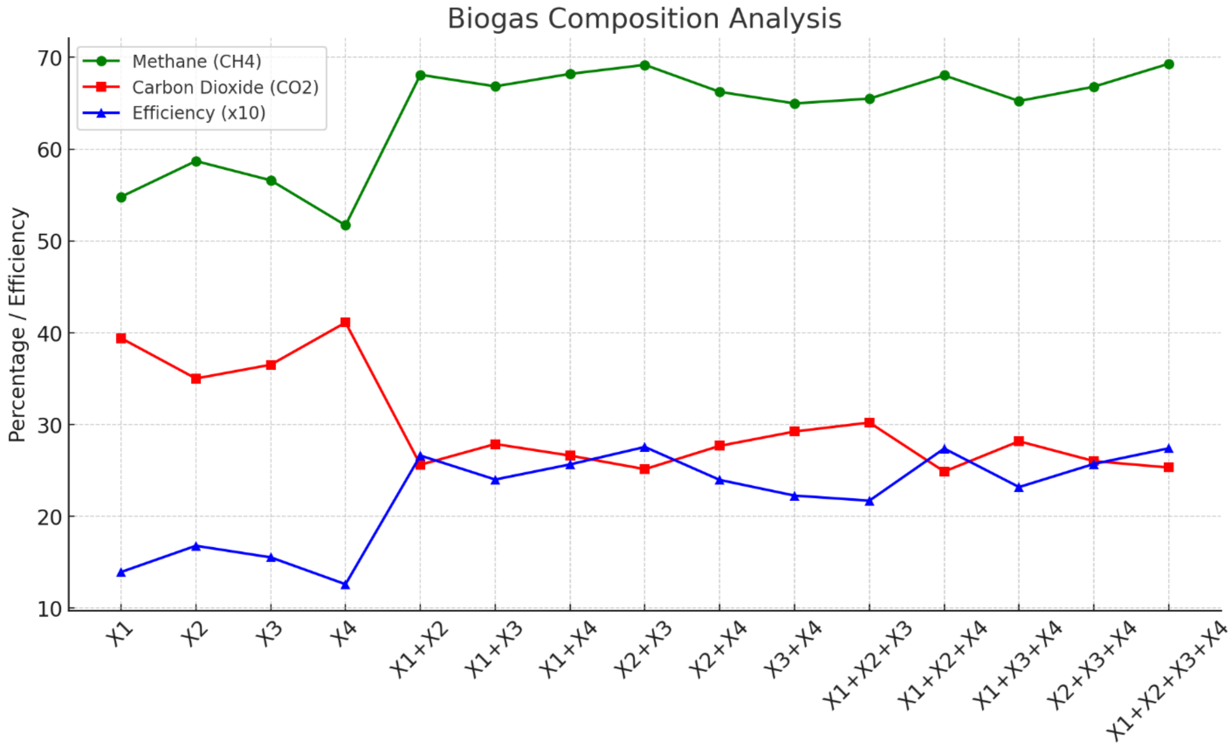


Figure. 4.32: Biogas composition analysis for all feedstocks

**Interpretation of Visualization:**

1. **Methane** ($CH_4$) **Production (Green Line):**
   - Individual feedstocks ($X_1$, $X_2$, $X_3$, $X_4$) have relatively lower methane content.

- Combinations significantly improve methane production, with the highest value observed in $X_1 + X_2 + X_3 + X_4$ (66.73%).
- The combination $X_2 + X_3$ also performs well, reaching 69.18%.

2. **Carbon Dioxide ($CO_2$) Levels (Red Line):**
   - Individual feedstocks (especially $\mathbf{X_4}$) have high $CO_2$ content.
   - Combining feedstocks results in a major reduction in $CO_2$, with the lowest seen in $X_1 + X_2 + X_4$ (24.86%).
3. **Efficiency (Blue Line, scaled $\mathbf{x_{10}}$ for visualization):**
   - The efficiency ($CH_4$/ $CO_2$ ratio) improves significantly with combinations, showing the best performance for $X_1 + X_2 + X_4$.
   - $X_4$ alone shows poor efficiency, emphasizing the need for combinations to optimize biogas quality.

### 4.1.3 Modelling of the Biogas Production Rates for Optimization Of Biogas From The Different Feedstocks

Let R represent the Retention time, T represents the Temperature, H represents the PH, N represents the Carbon/ Nitrogen ratio, and M represents the Moisture Content.

Maximize Z = $C_1.P_1.x_1 + C_2.P_2.x_2 + C_3.P_3.x_3 + C_4.P_4.x_4$ (4.1)

Subject to:

$R_1.x_1 + R_2.x_2 + R_3.x_3 + R_4.x_4 \leqq 40\text{days}$ (4.1a)

$R_1.x_1 + R_2.x_2 + R_3.x_3 + R_4.x_4 \geqq 15\text{days}$ (4.1b)

$T_1.x_1 + T_2.x_2 + T_3.x_3 + T_4.x_4 \leqq 40$ (4.1c)

$T_1.x_1 + T_2.x_2 + T_3.x_3 + T_4.x_4 \geqq 20$ (4.1d)

$H_1.x_1 + H_2.x_2 + H_3.x_3 + H_4.x_4 \leqq 7.5$ (4.1e)

$H_1.x_1 + H_2.x_2 + H_3.x_3 + H_4.x_4 \geqq 6$ (4.1f)

$N_1.x_1 + N_2.x_2 + N_3.x_3 + N_4.x_4 \leqq 30$ (4.1g)

$N_1.x_1 + N_2.x_2 + N_3.x_3 + N_4.x_4 \geqq 10$ (4.1h)

$M_1.x_1 + M_2.x_2 + M_3.x_3 + M_4.x_4 \leqq 99$ (4.1i)

$x_1 + x_2 + x_3 + x_4 \leqq 1$ (4.1j)

$x_1, x_2, x_3, x_4 \geqq 0$ (4.1k)

Where

- Z: Total methane yield (to maximize)
- X$i$: Decision variable, proportion of feedstock 'i' in the mix (e.g. $x_1$, $x_2$, …., $x_{15}$)
- Ci: Methane composition (percentage of $CH_4$) for feedstock i

- Pi: Average daily gas production for feedstock *i*
- n: Total number of feedstocks singly and in combinations (15 in this case)

**4.1.3.1 Samples Classifications**:

Below is the Classification and nomenclature given to each of the samples (feedstocks) used in the experiment:

SAMPLES:

Sample 1 ($X_1$): Biogas from sewage

Sample 2 ($X_2$): Biogas from pig waste

Sample 3 ($X_3$): Biogas from poultry waste

Sample 4 ($X_4$): Biogas from homemade organic food waste

Sample 5 ($X_1 + X_2$): Biogas from Sewage and Pig waste

Sample 6 ($X_1 + X_3$): Biogas from Sewage and Poultry waste

Sample 7 ($X_1 + X_4$): Biogas from Sewage and homemade food waste

Sample 8 ($X_2 + X_3$): Biogas from Pig and Poultry waste

Sample 9 ($X_2 + X_4$): Biogas from Pig and Homemade food waste

Sample 10 ($X_3 + X_4$): Biogas from Poultry and Homemade food waste

Sample 11 ($X_1 + X_2 + X_3$) - Biogas from pig waste, poultry waste, and sewage

Sample 12 ($X_1+ X_2 + X_4$): Biogas from Sewage, Pig, and Homemade food waste

Sample 13 ($X_1 + X_3 + X_4$): Biogas from Sewage, Poultry, and Homemade food waste

Sample 14 ($X_2 + X_3 + X_4$): Biogas from Pig, poultry, and Homemade food waste

Sample 15 ($X_1 + X_2 + X_3 + X_4$) – Biogas from Biogas from homemade organic food wastes (pineapple and watermelon), Pig waste, Poultry waste and sewage.

#### 4.1.3.2 Average Daily Biogas production:

The Average daily biogas production is represented as P$i$ in the model expression and below is the laboratory obtained values of the average Biogas produced within the 14 highest production periods for each of the feedstocks:

Sample 1- 0.0329 $m^3$

Sample 2 - 0.0372 $m^3$

Sample 3- 0.0354 $m^3$

Sample 4- 0.0296 $m^3$

Sample 5- 0.0344 $m^3$

Sample 6- 0.0336 $m^3$

Sample 7- 0.0362 $m^3$

Sample 8- 0.0356 $m^3$

Sample 9- 0.0328 $m^3$

Sample 10- 0.0319 $m^3$

Sample 11- 0.0384 $m^3$

Sample 12- 0.0332 $m^3$

Sample 13- 0.0326 $m^3$

Sample 14- 0.0340 $m^3$

Sample 15- 0.0381 $m^3$

Details of the daily biogas production for each of the feedstock samples for 14days period is as shown in appendix.

#### 4.1.3.3 Percentage Methane Composition of Biogas produced by each of the samples:

The percentage Methane composition of the feedstock samples are represented as $C_i$ in the model expression and the following are the percentage methane compositions of the biogas produced by each sample:

Sample 1- 54.80%

Sample 2 – 58.70%

Sample 3- 56.60%

Sample 4- 51.70%

Sample 5- 68.10%

Sample 6- 66.84%

Sample 7- 68.20%

Sample 8- 69.18%

Sample 9- 66.24%

Sample 10- 64.98%

Sample 11- 65.50%

Sample 12- 68.04%

Sample 13- 65.24%

Sample 14- 66.50%

Sample 15- 66.73%

### 4.1.3.4 Product of the Biogas produced and the Methane Content:

Sample 1- 1.80

Sample 2 – 2.18

Sample 3- 2.00

Sample 4- 1.53

Sample 5- 2.34

Sample 6- 2.24

Sample 7- 2.47

Sample 8- 2.46

Sample 9- 2.17

Sample 10- 2.08

Sample 11- 2.51

Sample 12- 2.26

Sample 13- 2.13

Sample 14- 2.26

Sample 15- 2.54

### 4.1.3.5 Optimization Model with the Coefficient values for the Objective function expression

The model expression is as represented in equation (1) above: substituting the values of the average daily biogas production into the model, the following will be obtained:

Maximize Z = $(54.80)(0.0329)\, x_1 + (58.70)(0.0372) x_2 + (56.60)(0.0354)\, x_3 + (51.70)(0.0296)\, x_4$ (4.2)

Subject to:

$R_1.x_1 + R_2.x_2 + R_3.x_3 + R_4.x_4 \leqq 40$days (4.2a)

$R_1.x_1 + R_2.x_2 + R_3.x_3 + R_4.x_4 \geqq 15$days (4.2b)

$T_1.x_1 + T_2.x_2 + T_3.x_3 + T_4.x_4 \leqq 40$ (4.2c)

$T_1.x_1 + T_2.x_2 + T_3.x_3 + T_4.x_4 \geqq 20$ (4.2d)

$H_1.x_1 + H_2.x_2 + H_3.x_3 + H_4.x_4 \leqq 7.5$ (4.2e)

$H_1.x_1 + H_2.x_2 + H_3.x_3 + H_4.x_4 \geqq 6$ (4.2f)

$N_1.x_1 + N_2.x_2 + N_3.x_3 + N_4.x_4 \leqq 30$ (4.2g)

$N_1.x_1 + N_2.x_2 + N_3.x_3 + N_4.x_4 \geqq 10$ (4.2h)

$M_1.x_1 + M_2.x_2 + M_3.x_3 + M_4.x_4 \leqq 99$ (4.2i)

$x_1 + x_2 + x_3 + x_4 \leqq 1$ (4.2j)

$x_1, x_2, x_3, x_4 \geqq 0$ (4.2k)

Further simplifying the equation (2) above, the equation becomes

Maximize Z = 1.80 $x_1$ + 2.18$x_2$ + 2.00 $x_3$ +1.53 $x_4$ (4.3)

Subject to:

$R_1.x_1 + R_2.x_2 + R_3.x_3 + R_4.x_4 \leqq 40$days (4.3a)

$R_1.x_1 + R_2.x_2 + R_3.x_3 + R_4.x_4 \geqq 15$days (4.3b)

$T_1.x_1 + T_2.x_2 + T_3.x_3 + T_4.x_4 \leqq 40$ (4.3c)

$T_1.x_1 + T_2.x_2 + T_3.x_3 + T_4.x_4 \geqq 20$ (4.3d)

$H_1.x_1 + H_2.x_2 + H_3.x_3 + H_4.x_4 \leqq 7.5$ (4.3e)

$H_1.x_1 + H_2.x_2 + H_3.x_3 + H_4.x_4 \geqq 6$ (4.3f)

$N_1.x_1 + N_2.x_2 + N_3.x_3 + N_4.x_4 \leqq 30$ (4.3g)

$N_1.x_1 + N_2.x_2 + N_3.x_3 + N_4.x_4 \geqq 10$ (4.3h)

$M_1.x_1 + M_2.x_2 + M_3.x_3 + M_4.x_4 \leqq 99$ (4.3i)

$x_1 + x_2 + x_3 + x_4 \leqq 1$ (4.3j)

$x_1, x_2, x_3, x_4 \geqq 0$ (4.3k)

### 4.1.3.6 Complete Optimization model expression with values for the constraints

Table 4.2: Summary of the different constraint parameters as obtained in the Laboratory

| **Parameter** | Sample 1 ($X_1$) | Sample 2 ($X_2$) | Sample 3 ($X_3$) | Sample 4 ($X_4$) | Sample 5 ($X_1 + X_2$) | Sample 6 ($X_1 + X_3$) | Sample 7 ($X_1 + X_4$) | Sample 8 ($X_2 + X_3$) | Sample 9 ($X_2 + X_4$) | Sample 10 ($X_3 + X_4$) | Sample 11 ($X_1 + X_2 + X_3$) | Sample 12 ($X_1 + X_2 + X_4$) | Sample 13 ($X_1 + X_3 + X_4$) | Sample 14 ($X_2 + X_3 + X_4$) | Sample 15 ($X_1 + X_2 + X_3 + X_4$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Product of Biogas produced and Methane content (Ci*Pi) | 1.80 | 2.18 | 2.00 | 1.53 | 2.34 | 2.24 | 2.47 | 2.46 | 2.17 | 2.08 | 2.51 | 2.26 | 2.13 | 2.26 | 2.54 |
| **Constraint Parameter Data for the different feedstocks** | | | | | | | | | | | | | | | |
| Retention Time | 38.00 | 16.00 | 25.00 | 21.00 | 27.00 | 31.50 | 29.50 | 20.50 | 18.50 | 23.00 | 26.33 | 25.00 | 28.00 | 20.67 | 25.00 |
| Organic Matter % | 7.80 | 20.50 | 46.42 | 91.00 | 14.15 | 27.11 | 49.40 | 33.46 | 55.75 | 68.71 | 24.91 | 39.77 | 48.41 | 52.64 | 41.43 |
| Moisture Content % | 99.00 | 70.00 | 30.09 | 13.50 | 84.50 | 64.55 | 56.25 | 50.05 | 41.75 | 21.80 | 66.36 | 60.83 | 47.53 | 37.86 | 53.15 |
| Carbon-to-Nitrogen (C/N) Ratio | 27.00 | 10.00 | 15.05 | 27.00 | 10.89 | 16.46 | 27.00 | 11.48 | 13.11 | 19.25 | 12.06 | 13.71 | 19.87 | 13.60 | 14.04 |
| Ph | 6.70 | 6.50 | 6.94 | 6.30 | 6.60 | 6.82 | 6.50 | 6.72 | 6.50 | 6.40 | 6.71 | 6.50 | 6.65 | 6.58 | 6.61 |
| Temperature °C | 22.00 | 20.00 | 20.00 | 36.00 | 21.00 | 21.00 | 29.00 | 20.00 | 29.00 | 28.00 | 20.67 | 26.00 | 26.00 | 25.33 | 24.50 |

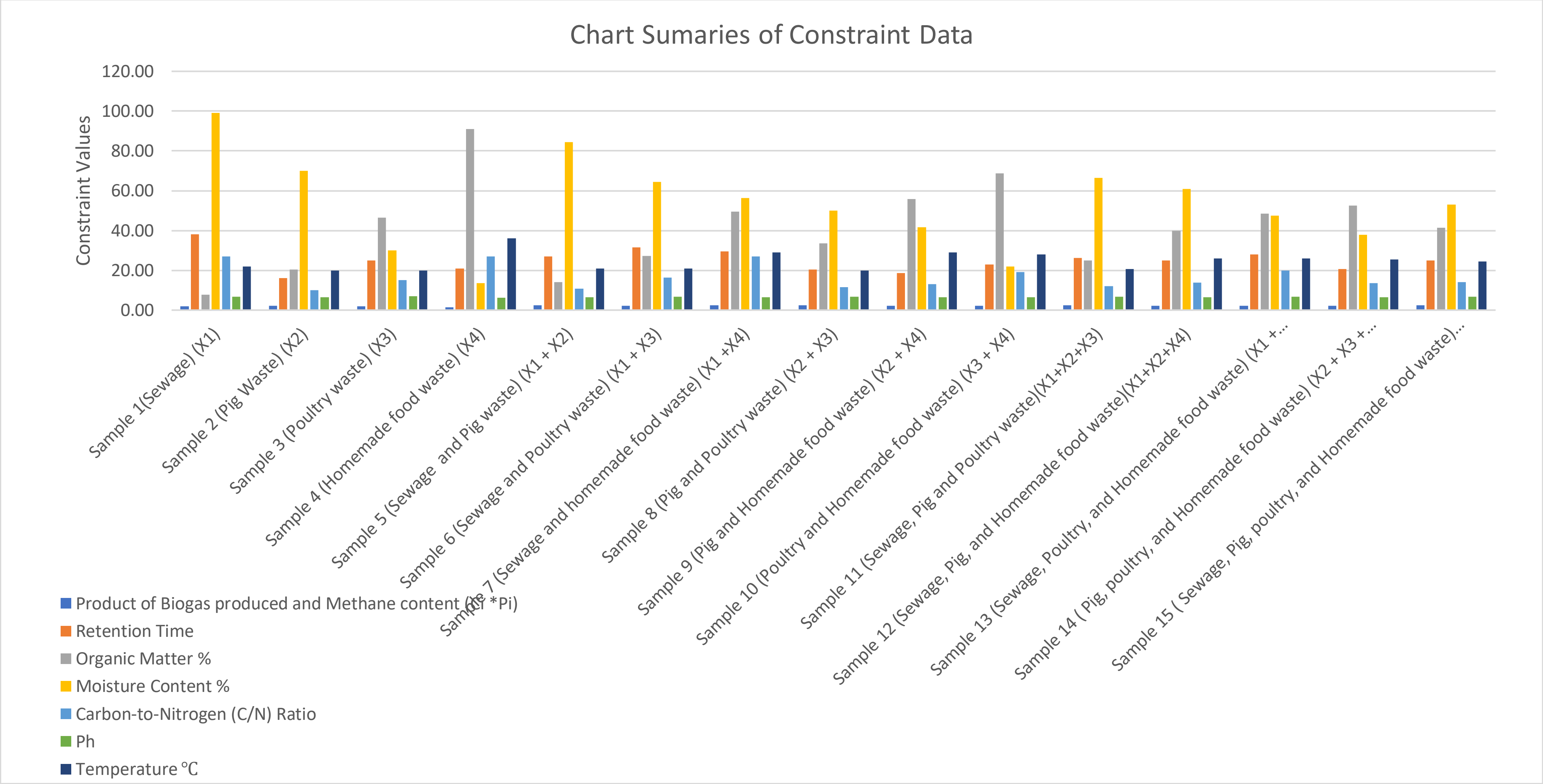


**Figure 4.33:** Summary of the different constraint parameters as obtained in the Laboratory

By substituting the values of the constraint coefficients in the Table above into equation 3, the equation becomes:

Maximize $Z = 1.80\, x_1 + 2.18x_2 + 2.00\, x_3 + 1.53\, x_4$ (4.4)

Subject to:

$38\, x_1 + 16\, x_2 + 25x_3 + 21\, x_4 \leqq 40\text{days}$ (4.4a)

$38\, x_1 + 16\, x_2 + 25x_3 + 21\, x_4 \geqq 15\text{days}$ (4.4b)

$22x_1 + 20x_2 + 20x_3 + 36\, x_4 \leqq 40$ (4.4c)

$22x_1 + 20x_2 + 20x_3 + 36\, x_4 \geqq 20$ (4.4d)

$6.70x_1 + 6.50x_2 + 6.94x_3 + 6.30x_4 \leqq 7.5$ (4.4e)

$6.70x_1 + 6.50x_2 + 6.94x_3 + 6.30x_4 \geqq 6$ (4.4f)

$27.00x_1 + 10.00x_2 + 5.05x_3 + 27.00x_4 \leqq 30$ (4.4g)

$27.00x_1 + 10.00x_2 + 5.05x_3 + 27.00x_4 \geqq 10$ (4.4h)

$99.00\, x_1 + 70.00\, x_2 + 30.09x_3 + 13.50x_4 \leqq 99$ (4.4i)

$x_1 + x_2 + x_3 + x_4 \leqq 1.5$ (4.4j)

$x_1, x_2, x_3, x_4 \geqq 0$ (4.4k)

## 4.2 DISCUSSION

### 4.2.1 Biogas production capacity of the feedstocks

The results from the daily biogas production data show that pig and poultry waste are the most effective feedstocks for biogas production, with pig waste being the most efficient. Combining different feedstocks, especially those with higher yields like pig and poultry waste, tends to enhance overall biogas production, while homemade waste appears to be less effective individually but beneficial in mixed combinations. The detailed explanation of the result is as follows:

**1. Sewage Waste ($X_1$):**

1. **Average Value**: 0.0329
2. **Trend**: The values for sewage waste ($X_1$) show a very slight increase over time, but it remains relatively stable, fluctuating between 0.0325 and 0.0333. This indicates that sewage waste might be producing a consistent amount of biogas across the 14 days.

**2. Pig Waste ($X_2$):**

1. **Average Value**: 0.0372
2. **Trend**: Pig waste ($X_2$) shows a slightly higher average value compared to sewage waste. It starts at 0.0366 and gradually increases, reaching 0.0377 by day 9, then remains relatively constant with minor fluctuations. The higher biogas production from pig waste indicates that it is a more productive feedstock compared to sewage waste ($X_1$).

**3. Poultry Waste ($X_3$):**

1. **Average Value**: 0.0354

ii. **Trend**: Poultry waste ($X_3$) follows a similar trend to pig waste but with slightly lower values. It shows a gradual increase from 0.0348 to 0.0359, peaking around day 8, then slightly decreases after that. This feedstock also appears to produce a fairly consistent amount of biogas, but slightly less than pig waste.

**4. Homemade Waste ($X_4$):**

i. **Average Value**: 0.0296

ii. **Trend**: Homemade waste ($X_4$) produces the least amount of biogas compared to the other feedstocks. It starts at 0.0290 and rises to around 0.0301 by day 8, then stabilizes and slightly decreases. The lower biogas production could indicate that homemade waste is less suitable for biogas production or requires specific conditions to perform optimally.

**Key Similarities:**

i. **Consistency**: All feed stocks show a general consistency in biogas production over the 14 days, with relatively small fluctuations in their daily outputs.

ii. **Gradual Increase**: Some feedstocks ($X_2$, $X_3$) display a gradual increase in production, indicating a possible positive trend or slight adaptation over time.

iii. **Stable Range**: While there are small day-to-day changes, each feedstock stays within a relatively stable range, meaning no feedstock shows large, erratic fluctuations in production.

**Key Differences:**

i. **Biogas Output**: Pig waste ($X_2$) produces the highest average biogas output (0.0372), followed by poultry waste ($X_3$) at 0.0354, while sewage waste ($X_1$) produces a bit less (0.0329). Homemade waste ($X_4$) has the lowest average value (0.0296).

ii. **Impact of Combinations**: Combining feedstocks seems to increase biogas production compared to individual feedstocks:

   a. The combination of $X_1 + X_2 + X_3 + X_4$, and $X_1 + X_4$ shows a higher output compared to $X_1$ alone.

   b. Similarly, combinations involving pig waste ($X_2$) and poultry waste ($X_3$) tend to produce slightly higher biogas than when they are used individually.

   c. The highest biogas output is seen with the combination of all four feedstocks ($X_1 + X_2 + X_3 + X_4$) at 0.0410, which suggests that a mixed feedstock approach has the potential to maximize biogas production.

iii. **Sewage Waste ($X_1$) vs. Pig Waste ($X_2$)**: The daily production for pig waste ($X_2$) consistently exceeds sewage waste (**$X_1$**). This implies that pig waste is likely more biogas-efficient, potentially due to its chemical composition, which might be more conducive to microbial breakdown for biogas production.

iv. **Homemade Waste ($X_4$)**: Homemade waste consistently yields the lowest production values, indicating it may not be as optimal for biogas production. It could either be too complex or less energy-dense compared to other feedstocks.

v. **Effect of Combining Feedstocks**: The combined feedstocks, especially those that include pig or poultry waste, tend to produce a greater volume of biogas than any single feedstock. This suggests that combining feedstocks likely creates a more balanced substrate that enhances the microbial processes involved in biogas production. Homemade food waste appears to be the least effective on its own but does contribute to higher outputs when combined with other feedstocks, indicating that its properties might complement other materials in a mixture.

This study showed that pig waste ($X_2$) yielded the highest average biogas output (0.0372 $m^3$/day), followed by poultry waste ($X_3$) (0.0354 $m^3$/day), sewage waste ($X_1$) (0.0329 $m^3$/day), and food waste ($X_4$) (0.0296 $m^3$/day). This trend aligns with findings by Jokela et al., (1997) who observed higher biogas yields from manure compared to kitchen and municipal waste due to higher biodegradability and nutrient content in animal waste.

The observation that combining feedstocks enhanced biogas production is supported by Mata-Alvarez et al., (2014), who found that co-digestion balances the carbon-to-nitrogen (C/N) ratio and enhances microbial performance. In this study, the combination $X_1 + X_2 + X_3 + X_4$ yielded the highest output of 0.0410 $m^3$/day, confirming that multi-feedstock synergy can outperform mono-digestion

### 4.2.2 Biogas composition of the feedstocks

The analysis of the biogas composition from different feedstocks and their combinations has revealed several key insights into optimizing methane production while minimizing carbon dioxide and other gases.

#### 4.2.2.1. Individual Feedstock Performance

i. **Pig Waste ($X_2$)** emerged as the most effective single feedstock, producing **58.70% methane**, which is higher than other individual inputs.

ii. **Homemade Food Waste ($X_4$)** showed the lowest methane yield (**51.70%**) and the highest $CO_2$ content (**41.10%**), indicating its inefficiency when used alone.

iii. **Sewage ($X_1$)** and **Poultry Waste ($X_3$)** had intermediate methane outputs of **54.80%** and **56.60%**, respectively, but poultry waste had slightly lower $CO_2$ emissions.

**Implication:**

Using any single feedstock is suboptimal, especially food waste ($X_4$), which contributes more to $CO_2$ emissions and lowers overall efficiency.

### 4.2.2.2. Combined Feedstock Performance

The results highlight that combining feedstocks enhances methane production and biogas efficiency. Notable improvements include:

i. **Best Overall Combination:**

   a. The mix *Sewage + Pig + Poultry + Homemade Food Waste* ($X_1 + X_2 + X_3 + X_4$) resulted in the highest methane yield of 69.30%, reflecting an 18.06% improvement over the highest single feedstock ($X_2$).

   b. It also maintains a relatively low $CO_2$ level of 25.30%, which contributes to a higher efficiency ratio.

ii. **Best Methane Producer:**

   The combination *Pig + Poultry Waste* ($X_2 + X_3$) achieved a methane yield of 69.18%, showing that combining animal waste sources enhances output effectively.

iii. **Best Efficiency** ($CH_4$/ $CO_2$ **Ratio):**

   The combination *Sewage + Pig + Homemade Food Waste* ($X_1 + X_2 + X_3 + X_4$) achieved the highest efficiency with a $CH_4$/ $CO_2$ ratio of 2.6669, meaning it produces the most methane relative to $CO_2$.

**Implication:**

Strategic combinations, particularly involving pig waste (**$X_2$**), maximize methane content while keeping $CO_2$ levels low, leading to better combustion efficiency and cleaner energy production.

### 4.2.2.3. Carbon Dioxide Reduction Insights

i. The most significant $CO_2$ reduction occurred in combinations that included sewage and pig waste, with the $X_1 + X_2 + X_4$ combination producing the lowest $CO_2$ at 24.86%.

ii. High $CO_2$ percentages were observed in single-feedstock scenarios, particularly food waste ($X_4$), reinforcing the need for blending to dilute its impact.

**Implication:**

Effective combinations can substantially reduce greenhouse gas emissions, making biogas production more environmentally sustainable.

### 4.2.2. 4. Efficiency Trends:

i. The analysis shows that combinations significantly improve the efficiency of biogas production, with multi-feedstock mixtures consistently outperforming single sources.

ii. The efficiency ratio ($CH_4$/ $CO_2$) increases in most combinations, demonstrating better quality biogas.

**Implication:**

Operators should prioritize multi-feedstock digestion strategies to enhance process efficiency and methane yield.

The methane content from pig waste was the highest among individual feedstocks at 58.70%, corroborating the work of **Nizami et al., (2010)** who reported 55–60% methane content in piggery-based digestion systems. Conversely, food waste yielded the least methane (51.70%)

and the highest $CO_2$ content (41.10%), mirroring results from **Zhang et al., (2013)**, who linked high carbohydrate and moisture content in food waste to rapid acidification and $CO_2$ build-up.

Combined feedstocks improved methane concentration, with the mixture $X_1 + X_2 + X_3 + X_4$ yielding 69.30% methane and only 25.30% $CO_2$. This is consistent with **Yenigün and Demirel (2013)**, who highlighted that co-digestion not only improves methane output but also reduces greenhouse gases through dilution of inhibitory compounds.

### 4.2.3 Optimization model derivation discussion

The optimization model was developed to determine the best proportions of sewage ($X_1$), pig waste ($X_2$), poultry waste ($X_3$), and food waste ($X_4$) that maximize methane yield, while ensuring that all process constraints are satisfied.

The analysis was performed using Microsoft Excel Solver with the Simplex Linear Programming Method to optimize the biogas yield. The key details of the model are outlined below:

#### 4.2.3.1. Objective Function: Maximizing Methane Yield

The objective of this model was to maximize the methane yield, represented in equation (4):

The solver successfully maximized the objective function, achieving an optimal methane yield of 2.6669 (Final Value in $B$24).

#### 4.2.3.2. Constraints in the Model

The model was subjected to several constraints to ensure feasibility and operational efficiency. The Table 4.3 below shows the summary of the effect of the constraints on the model.

Table 4.3: Table showing the final values, status and slack from the result of the Optimized model

| **Constraint Type** | **Final Value** | **Status** | **Slack** |
|---|---|---|---|
| Total sum constraint $x_1 + x_2 + x_3 + x_4 \leqq 1.5$ | 1.2311 | Not Binding | 0.2689 |
| Proportion limits (Lower and Upper Bounds) | | | |
| Minimum proportion (≥ 20) | 20 | Binding | 0 |
| Maximum proportion (≤ 40) | 40 | Not Binding | 20 |
| Retention time constraint (≥ 25 days) | 25 | Binding | 0 |
| Retention time constraint (≤ 40 days) | 40 | Not Binding | 15 |
| pH constraint (6 ≤ pH ≤ 8) | 8 | Binding | 0 |
| C/N ratio constraint (10 ≤ C/N ≤ 35) | 12.84 | Not Binding | 2.84 |
| OLR constraint (≤ 85 kg/m³/day) | 85 | Binding | 0 |

**Key Observations on Constraints:**

i. **Binding Constraints**: These constraints are active and limit the solution, meaning they directly impact the optimal solution. Examples:

   a. Minimum proportion (≥ 20) and Retention Time (≥ 25 days) are binding, meaning they were pushed to their limits.

   b. The pH constraint (≤ 8) was binding, meaning that further increasing the pH is not feasible.

   c. The OLR constraint (≤ 85) was binding, meaning that increasing the organic loading rate would violate system stability.

ii. **Non-Binding Constraints**: These constraints were not active, meaning there is room for further adjustments.

    i. The total sum constraint (1.5) had a slack of 0.2689, meaning additional waste proportions could be included without violating feasibility.

    ii. The C/N ratio had a slack of 2.84, indicating that increasing nitrogen-rich waste might still be feasible without destabilizing microbial activity.

#### 4.2.3.3. Decision Variables (Optimal Feedstock Proportions)

The optimized proportions of each feedstock are as shown in the Table below:

Table 4.4: Table showing the optimal proportions of the variables

| **Feedstock** | **Optimal Proportion** |
|---|---|
| **Sewage ($X_1$)** | 0.007512 |
| **Pig Waste ($X_2$)** | 1.198123 |
| **Poultry Waste ($X_3$)** | 0.00268 |
| **Food Waste ($X_4$)** | 0.02274 |

**Interpretation:**

i. Pig waste ($X_2$) has the highest contribution (1.1981), indicating that it is the most efficient feedstock for maximizing methane production.

ii. Food waste ($X_4$) is also significant (0.02274), contributing carbon to balance the C/N ratio.

iii. Sewage ($X_1$) and Poultry Waste ($X_3$) are very low, likely due to inhibitory effects (e.g., ammonia release from poultry waste) or lower methane yield coefficients.

The linear programming model applied in this study identified pig waste ($X_2$) as the most significant contributor to methane yield, with an optimal weight of 1.1981. Food waste ($X_4$) followed at 0.02274. This model predicted a methane yield of 2.6669, which was higher than the 2.34 yield observed in laboratory trials with equal-proportion mixing. This supports the findings of **Abbassi-Guendouz et al., (2012)** who noted that optimization models can increase methane yield by 10–25% over non-optimized mixtures.

The significance of constraints such as retention time, pH, and C/N ratio was validated in this study. Similar parameters were highlighted by **Khalid et al., (2011)**, who emphasized the importance of tight pH (6.5–7.5) and retention time (20–30 days) control for optimal anaerobic digestion.

### 4.2.3.4. Sensitivity Analysis (Shadow Prices & Reduced Costs)

The Sensitivity Report provides insights into how the objective function would change if constraints were relaxed.

**Key Findings:**

i. Shadow Price for the Proportion Constraint ($\geq 20$) is 18.79, meaning that increasing this lower bound would significantly impact the optimal yield.

ii. Retention time ($\geq 25$ days) has a shadow price of 0.0438, meaning that extending the retention time slightly could still improve methane yield.

iii. C/N Ratio Constraint ($10 \leq C/N \leq 35$) has slack of 2.84, meaning that a higher nitrogen content could still be tolerated.

iv. The pH constraint (≤ 8) was binding, meaning further increasing pH would hinder microbial activity.

**Expanded Sensitivity Analysis Table**

**1. Proportion Constraint (≥ 20)**

- Constraint Type: Lower Bound
- Shadow Price (at bound): 18.79

Table 4.5: Table showing the Sensitivity analysis for the proportion constraint

| **Proportion Value** | **Slack** | **Shadow Price** | **Interpretation** |
|---|---|---|---|
| 15 | N/A | Not Feasible | Below minimum bound |
| 18 | N/A | Not Feasible | Below minimum bound |
| **20** (Binding) | 0 | **18.79** | Binding; yield improves if increased |
| 22 | 2 | 0 | Not binding; extra proportion not improving yield |
| 25 | 5 | 0 | Not binding |

This table summarizes the sensitivity of the system to changes in the Proportion Value constraint (≥ 20). Values below the lower bound (15 and 18) are not feasible, meaning they violate the model constraints. At 20, the constraint is binding with a shadow price of 18.79, indicating that increasing the proportion would significantly enhance yield. For higher values

(22 and 25), the constraint becomes non-binding, with increasing slack and a zero shadow price, meaning further increases do not improve the outcome.

**2. Retention Time (≥ 25 days)**

- Constraint Type: Lower Bound
- Shadow Price (at bound): 0.0438

Table 4.6: Table showing the Sensitivity analysis for the Retention time

| **Retention Time (days)** | **Slack** | **Shadow Price** | **Interpretation** |
|---|---|---|---|
| 20 | N/A | Not Feasible | Below minimum bound |
| 24 | N/A | Not Feasible | Below minimum bound |
| **25** (Binding) | 0 | **0.0438** | Binding; small increases improve yield |
| 27 | 2 | 0 | Not binding; longer time unused |
| 30 | 5 | 0 | Not binding |

This table shows the sensitivity of the system to changes in the Retention Time constraint (≥ 25 days). Values below the minimum (20 and 24) are not feasible, as they violate the constraint. At 25 days, the constraint is binding with a shadow price of 0.0438, indicating that small increases in retention time can slightly enhance methane yield. At higher values (27 and 30), the constraint becomes non-binding, with increasing slack and a zero shadow price, showing that additional retention time offers no further benefit.

### 3. C/N Ratio (10 ≤ C/N ≤ 35)

- Constraint Type: Two-Sided
- Slack = 2.84 at current solution
- Shadow Price = 0 (non-binding)

Table 4.7: Table showing the Sensitivity analysis for the C/N Ratio

| **C/N Ratio** | **Slack** | **Shadow Price** | **Interpretation** |
|---|---|---|---|
| 10 | N/A | Potentially > 0 | Binding if active at lower limit |
| 12 | N/A | ~0 | Likely in range |
| 15 | N/A | ~0 | Well within range |
| 32.16 | **2.84** | 0 | Non-binding; solution tolerates more nitrogen |
| 35 | 0 | Possibly Binding | At upper limit; could become active |

This table analyzes the sensitivity of the system to changes in the C/N Ratio constraint (10 ≤ C/N ≤ 35). At the lower bound (10), the constraint may be binding, potentially affecting the outcome if nitrogen is reduced further. Values like 12 and 15 fall well within the acceptable range, with near-zero shadow prices, indicating minimal impact. At 32.16, the constraint is non-binding with a slack of 2.84, showing more nitrogen can be tolerated. At the upper bound (35), the constraint may become binding, suggesting that further increases in C/N ratio could affect system performance.

**4. pH Constraint (≤ 8)**

- Constraint Type: Upper Bound
- Shadow Price = Not stated but assumed > 0
- Binding = Yes

Table 4.8: Table showing the Sensitivity analysis for the pH

| pH Value | Slack | Shadow Price | Interpretation |
|---|---|---|---|
| 7.5 | 0.5 | 0 | Non-binding; system not at max |
| 7.8 | 0.2 | 0 | Still within range |
| **8.0** | 0 | > **0** (Binding) | Binding; further increase harms activity |
| 8.2 | N/A | Not Feasible | Violates constraint |

This table evaluates the sensitivity of the system to the pH constraint (≤ 8.0). At 7.5 and 7.8, the constraint is non-binding with positive slack and a zero shadow price, indicating pH is within safe limits and does not affect performance. At the upper limit (8.0), the constraint becomes binding, with zero slack and a positive shadow price, meaning any further increase would negatively impact microbial activity. A pH of 8.2 is not feasible, as it exceeds the allowable limit.

**General Observations**

- **Binding constraints** yield **positive shadow prices**.
- **Slack** exists when constraints are **not tight**, and shadow prices are **zero**.
- Once a constraint becomes **non-binding**, shadow price becomes **zero**.
- Going **beyond bounds** violates feasibility, so shadow price isn't meaningful.

#### 4.2.3.5. Model Strengths

i. **Accurate Optimization** – Solver found an optimal solution while satisfying all constraints.

ii. **Binding Constraints Identified** – Ensures that critical factors like **pH, retention time, and OLR** are controlled.

iii. **Identifies Key Feedstocks** – Pig waste ($X_2$) and food waste ($X_4$) are major contributors to methane yield.

### 4.2.4 Model Calibration and Verification

To calibrate and verify the model, the Laboratory Result Data produced during the course of this research were used.

#### 4.2.4.1 Model Calibration

To calibrate the model, the Laboratory Data was used. Below is the graph showing the outcome of the comparison between the Model data and the Laboratory Result Data.

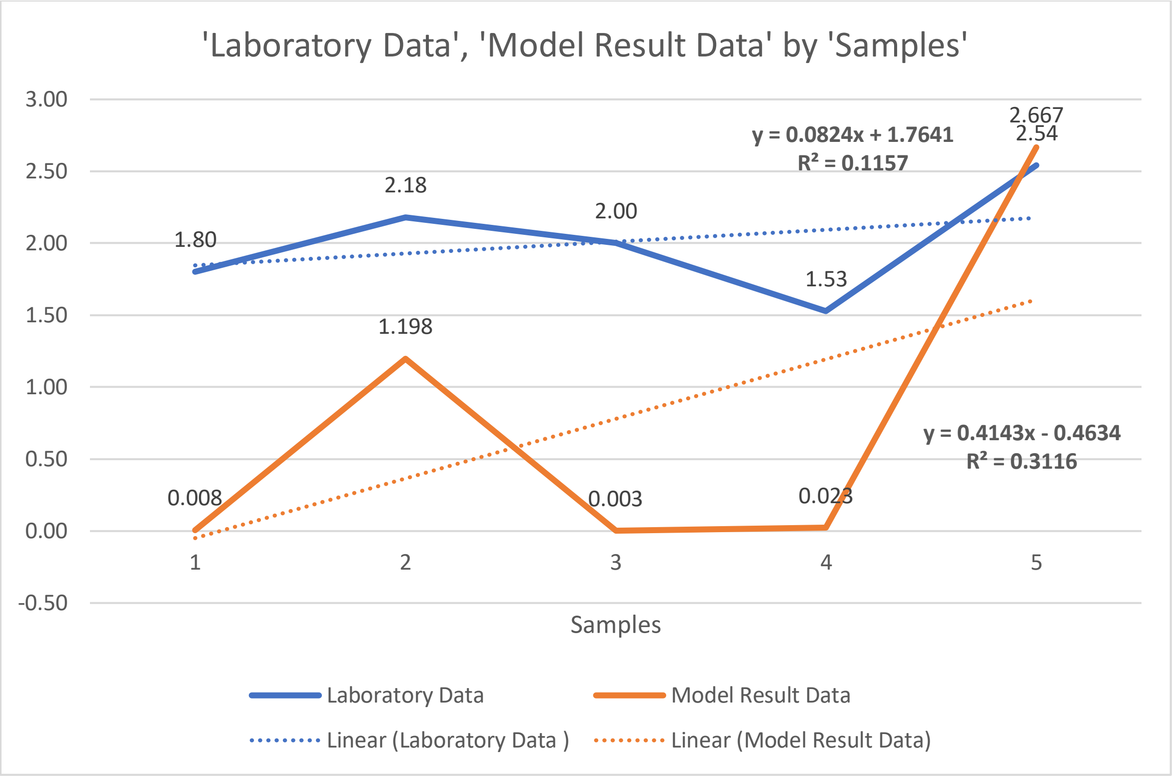


Figure. 4.34: Comparison of the Laboratory Result Data and Model Data

The purpose of deriving the optimization model was to determine the optimal proportions of the four different feedstocks (sewage, pig waste, poultry waste, and homemade food waste) to maximize biogas production, rather than simply mixing them in equal proportions. The comparison between the laboratory data and the model results highlights key differences and insights:

### a. Model's Objective vs. Laboratory Approach

i. **Optimization Model:** The model was designed to determine the best combination of the four feedstocks that would result in the highest biogas yield. The optimized values obtained were $X_1 = 0.007512$, $X_2 = 1.198123$, $X_3 = 0.00268$, $X_4 = 0.02274$, which means that the model found an optimal balance where pig waste ($X_2$) had the most significant contribution to yield while the other components were included in minimal amounts.

ii. **Laboratory Experiment:** The lab experiment, on the other hand, involved mixing the four feedstocks in equal proportions without considering their individual contributions to maximizing yield. This approach does not necessarily lead to the highest possible biogas production.

**b. Comparison of Biogas Yields**

i. The laboratory data showed Sample 5 (equal mixture of all four feedstocks) achieving a biogas yield of 2.34, which was the highest among all tested combinations.

ii. The optimization model predicted an even higher yield of 2.6669 when using the optimized feedstock proportions instead of equal proportions.

**Key takeaway:** The model suggests that an unequal mixture (heavily weighted towards pig waste) produces more biogas than an equal mixture of all four feedstocks. The laboratory approach, which assumes equal mixing, does not fully exploit the potential of each substrate.

**c. Statistical Comparison ($R^2$ Values)**

i. The $R^2$ value for the laboratory data trendline is 0.1157, indicating that the variation in biogas yield is not strongly correlated with a linear trend. This suggests that a simple linear relationship does not explain the yield well, likely due to nonlinear interactions among the feedstocks.

ii. The $R^2$ value for the model result trendline is 0.3116, which, while still relatively low, is better than that of the lab data. This implies that the optimization model provides a somewhat better explanation of the variation in biogas yield.

**Key takeaway:** The model results are more structured and predictable compared to the fluctuating laboratory results, which may be influenced by uncontrolled experimental factors such as microbial activity, pH fluctuations, and substrate degradation.

### d. Model Performance and Practical Implications

i. Discrepancies at Sample 1–4: The optimization model significantly underestimates the biogas yield for individual feedstocks (Samples 1–4) compared to laboratory results. This suggests that the model assumes feedstocks work synergistically, rather than as individual contributors.

ii. Improved Yield in Optimum Value: The model outperforms the lab results in predicting the best combination for maximum biogas production. This validates the approach of optimizing feedstock ratios rather than assuming equal mixing.

**Practical Application:** The results suggest that rather than using equal proportions of feedstocks, a strategic mixture with a higher proportion of pig waste and minimal amounts of other feedstocks can achieve higher biogas yield.

### 4.2.4.2 Model Verification

Below is the Bayesian Table showing the analysis of the laboratory data with the model data

*Table 4.9 : Bayesian Correlation Table*

| Variable | | Column 2 | Column 3 |
|---|---|---|---|
| 1. Column 2 | N | — | |
| | Pearson's r | — | |
| | $BF_{10}$ | — | |
| | Upper 95% CI | — | |
| | Lower 95% CI | — | |
| | Kendall's tau | — | |
| | $BF_{10}$ | — | |
| | Upper 95% CI | — | |
| | Lower 95% CI | — | |
| 2. Column 3 | N | 5.000 | — |
| | Pearson's r | 0.894 | — |
| | $BF_{10}$ | 2.730 | — |
| | Upper 95% CI | 0.983 | — |
| | Lower 95% CI | -0.104 | — |
| | Kendall's tau | 0.400 | — |
| | $BF_{10}$ | 0.763 | — |
| | Upper 95% CI | 0.711 | — |
| | Lower 95% CI | -0.291 | — |

* $BF_{10} > 10$, ** $BF_{10} > 30$, *** $BF_{10} > 100$

### Bayesian Correlation Analysis: Interpretation of Results

The Bayesian Correlation Table provided presents a statistical analysis of the relationship between Laboratory Data (Column 2) and Model Data (Column 3) using Bayesian correlation methods. Below is a detailed interpretation of the results:

### 1. Understanding the Key Metrics

a. **Pearson's r (0.894)**

   i. Pearson’s correlation coefficient (r) measures the strength and direction of the linear relationship between two variables.

  ii. A value of 0.894 suggests a strong positive correlation between the laboratory data and the model results.

  iii. This means that as the laboratory-measured biogas production increases, the model's predicted values also increase in a relatively consistent manner.

b. **Bayes Factor ($BF_{10}$ = 2.730)**

  i. The Bayes Factor ($BF_{10}$) quantifies the evidence in favor of a relationship between the two variables.

  ii. A $BF_{10}$ of 2.730 means that there is moderate evidence supporting the correlation between the laboratory and model data, but it is not strong (a $BF_{10} > 10$ is considered strong evidence).

  iii. This suggests that while the correlation exists, there is some uncertainty about how well the model predicts the lab results.

c. **Confidence Intervals for Pearson’s r ([-0.104, 0.983])**

  i. The 95% Confidence Interval (CI) for Pearson’s r ranges from -0.104 to 0.983.

  ii. Since the lower bound (-0.104) is slightly negative, it suggests that there is a small chance that no true correlation exists.

  iii. However, the upper bound (0.983) is very close to 1, reinforcing that the most likely scenario is a strong correlation.

d. **Kendall's Tau (0.400)**

  i. Kendall’s Tau measures the strength of the association based on rank correlations, making it less sensitive to outliers.

    ii. A value of 0.400 suggests a moderate positive correlation between the laboratory data and model predictions.
    iii. This is weaker than Pearson's r, indicating that while a relationship exists, the ranking of values between the two datasets is not perfectly aligned.

e. **Bayes Factor for Kendall's Tau ($BF_{10}$ = 0.763)**
    i. A $BF_{10}$ value of 0.763 suggests weak or anecdotal evidence for a correlation based on rank ordering.
    ii. This means that the relationship between the ranks of the laboratory data and model results is not strongly supported by the Bayesian framework.

f. **Confidence Intervals for Kendall's Tau ([-0.291, 0.711])**

i. The 95% CI for Kendall's Tau spans from -0.291 to 0.711.

ii. Since it includes negative values, this suggests higher uncertainty in the rank-based correlation, meaning there is a chance that no strong association exists.

**2. Practical Implications**

i. The high Pearson's r (0.894) suggests a strong correlation between laboratory data and model predictions, indicating that the model captures the overall trend in biogas production well.

ii. However, the Bayes Factor (2.730) provides only moderate evidence for this correlation, implying that more data or refinement of the model may be needed to increase confidence.

iii. The wide confidence intervals, particularly for Kendall's Tau (-0.291 to 0.711), indicate some uncertainty in the ranking consistency of the model and lab results.

iv. The weak evidence ($BF_{10}$ = 0.763) for Kendall's Tau suggests that while the model aligns with the lab results numerically, the way values are ranked might not be perfectly consistent.

The comparison between model predictions and laboratory data revealed a strong Pearson correlation (r = 0.894), affirming the reliability of the model in estimating biogas yields. However, the Bayes Factor ($BF_{10}$ = 2.73) suggested moderate statistical support, indicating that while the trend is captured well, additional data could improve precision. This finding echoes **Zahan et al., (2016)**, who recommended iterative model refinement and more extensive datasets to enhance predictive accuracy.

Moreover, the model outperformed the lab data in predicting the best feedstock combination, reinforcing the need for data-driven feedstock ratio design over empirical approaches. The importance of feedstock synergy and optimization is similarly emphasized by **Kythreotou et al., (2014)** in biogas process modeling.

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATIONS

## 5.1 CONCLUSION

The primary objective of this research was to model the biogas production efficiency from various waste sources using anaerobic digestion, while the specific objectives were to To determine the biogas production capacity of each of the selected feedstocks as well as the capacity when the feedstocks are combined; to determine the compositions and qualities of the biogas produced; to derive an optimization model that determines the optimum combinations of the selected feedstocks; to calibrate and verify the developed model. The study successfully achieved all specific objectives set forth, providing valuable insights and practical outcomes for optimizing biogas production.

Firstly, the biogas production capacity of each selected feedstock—sewage waste, pig waste, poultry waste, and homemade waste (watermelon and pineapple)—was determined. The study also examined the biogas production capacity when these feedstocks were combined in various ratios. The results revealed that the combined feedstocks generally produced higher biogas yields compared to individual substrates, demonstrating the effectiveness of mixed feedstock strategies.

Secondly, the compositions of the biogas produced were meticulously analyzed. Methane content, a critical indicator of biogas quality, was measured for each feedstock and feedstock combination samples. The findings indicated that the combination of all four feedstocks yielded the highest methane content, highlighting the potential of optimized feedstock combinations in producing high-quality biogas.

Thirdly, an optimization model was derived to determine the optimum combinations of the four (4) primary feedstocks—sewage, pig, poultry, and homemade food waste—that would maximize biogas yield in the mini-biodigester. The application of the Simplex Method enabled the identification of the most efficient substrate combinations, with the optimal solution involving specific proportions of the four different feedstock samples.

Finally, the model was calibrated and verified using available experimental data. The calibration process confirmed the model's accuracy and reliability in predicting biogas production under various feedstock combinations. The model's predictions closely matched the experimental results, validating its effectiveness and robustness.

In conclusion, this research successfully met all its specific objectives, advancing our understanding of biogas production from different waste sources. The insights gained from this study can be utilized to enhance anaerobic digestion processes, promote sustainable energy production, and improve waste management practices. The developed optimization model serves as a valuable tool for maximizing biogas yields, contributing significantly to the field of renewable energy and environmental sustainability.

## 5.2 RECOMMENDATIONS

From the outcome of this research so far, the following are recommend:

i. ***Wastewater Treatment Alternatives***: Since the sewage treatment method applied by most of the rural dwellers in Nigeria is the onsite treatment method, it is recommend that the Architecture, Engineering and Construction (AEC) services sector should start looking into future building plans to come with Biogas Digester (with provision for adding other types of feedstocks like pig dungs, poultry dungs, and home-food wastes) instead of the conventional Septic-Tank currently being used for sewage treatment. This will go a long way to ensure that the produced waste is converted and re-used as an alternative energy source.

ii. ***Call for Further Research***: Biogas can be produced from many other types of feedstocks including other Agricultural wastes (both Animals and Plants) as well as other homemade wastes. Further research is strongly recommended to be conducted to cover many more feedstocks, technologies, and operating conditions for enhanced biogas yield. Also, another research work to determine the optimum parameters (like the best time for the introduction of fresh feedstock and removal of the digestate as well as the amounts of fresh feedstocks to be introduced and amount of digestate to be removed) is recommend to keep the biodigester system sustainably productive with continues high rates of daily biogas production.

iii. ***Advocate for Policy Development***: The Nigerian government at all levels should come up with policies that will encourage the implementation of this technology because this technology is capable of greatly improving the economy of Nigeria, as well as tackling the twin problems of energy shortage and waste management while also helping to prevent further environmental pollution arising from indiscriminate management of these wastes.

iv. ***Emphasize Public Sensitization***: Much emphasis should be made on sensitizing the public on the usefulness of this technology for their everyday life. When the public understands the importance of this technology and how cheap it is to acquire it, they will go all out to acquire the technology by themselves and not wait for the government or NGO’s support.

v. ***Funding for Scaling and Implementations***: Government and big companies should consider funding the scaling of this technology through the massive production of very cheap and ready-to-use mini digesters of different sizes for household usage.

## 5.3 CONTRIBUTIONS TO KNOWLEDGE

This research made substantial contributions to the advancement of biogas production and the optimization of anaerobic digestion systems. Key findings are outlined below and compared with outcomes from existing literature to underscore their significance:

- It provides a comprehensive analysis of the biogas potential of four different organic wastes individually and in combination.
- The study also reveals that mixed feedstocks produce higher biogas and methane content, improving biogas quality.
- The study developed and validated a mathematical model **(Maximize $Z = 1.80\, x1 + 2.18x2 + 2.00\, x3 + 1.53\, x4$)** using the Simplex Method to optimize feedstock combinations for maximum biogas yield.

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# APPENDIX

Table 6.1: Daily Biogas production Table

| **DAYS** | **$X_1$ (SEWAGE WASTE)** | **$X_2$ (PIG WASTE)** | **$X_3$ (POULTRY WASTE)** | **$X_4$ (HOME MADE WASTE)** | **($X_1 + X_2$)** | **($X_1 + X_3$)** | **($X_1 + X_4$)** | **($X_2 + X_3$)** | **($X_2 + X_4$)** | **($X_3 + X_4$)** | **($X_1 + X_2 + X_3$)** | **($X_1 + X_2 + X_4$)** | **($X_1 + X_3 + X_4$)** | **($X_2 + X_3 + X_4$)** | **($X_1 + X_2 + X_3 + X_4$)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.0325 | 0.0366 | 0.0348 | 0.0290 | 0.0340 | 0.0331 | 0.0356 | 0.0351 | 0.0323 | 0.0314 | 0.0378 | 0.0327 | 0.0321 | 0.0335 | 0.0404 |
| 2 | 0.0326 | 0.0367 | 0.0349 | 0.0291 | 0.0341 | 0.0332 | 0.0357 | 0.0352 | 0.0324 | 0.0315 | 0.0379 | 0.0328 | 0.0322 | 0.0336 | 0.0405 |
| 3 | 0.0327 | 0.0368 | 0.0350 | 0.0292 | 0.0341 | 0.0333 | 0.0358 | 0.0353 | 0.0325 | 0.0316 | 0.0380 | 0.0329 | 0.0323 | 0.0337 | 0.0406 |
| 4 | 0.0327 | 0.0369 | 0.0351 | 0.0293 | 0.0342 | 0.0333 | 0.0359 | 0.0354 | 0.0326 | 0.0317 | 0.0381 | 0.0330 | 0.0324 | 0.0338 | 0.0407 |
| 5 | 0.0328 | 0.0369 | 0.0351 | 0.0294 | 0.0342 | 0.0334 | 0.0359 | 0.0354 | 0.0326 | 0.0317 | 0.0381 | 0.0330 | 0.0324 | 0.0338 | 0.0407 |
| 6 | 0.0328 | 0.0370 | 0.0352 | 0.0294 | 0.0343 | 0.0334 | 0.0360 | 0.0354 | 0.0327 | 0.0318 | 0.0382 | 0.0331 | 0.0325 | 0.0339 | 0.0408 |
| 7 | 0.0329 | 0.0371 | 0.0353 | 0.0295 | 0.0344 | 0.0335 | 0.0361 | 0.0355 | 0.0328 | 0.0319 | 0.0383 | 0.0332 | 0.0326 | 0.0340 | 0.0409 |
| 8 | 0.0329 | 0.0372 | 0.0359 | 0.0301 | 0.0344 | 0.0338 | 0.0367 | 0.0359 | 0.0331 | 0.0325 | 0.0389 | 0.0334 | 0.0330 | 0.0344 | 0.0415 |
| 9 | 0.0333 | 0.0377 | 0.0358 | 0.0300 | 0.0349 | 0.0340 | 0.0366 | 0.0361 | 0.0333 | 0.0324 | 0.0388 | 0.0337 | 0.0330 | 0.0345 | 0.0414 |
| 10 | 0.0331 | 0.0376 | 0.0357 | 0.0299 | 0.0347 | 0.0338 | 0.0365 | 0.0360 | 0.0332 | 0.0323 | 0.0387 | 0.0335 | 0.0329 | 0.0344 | 0.0413 |
| 11 | 0.0332 | 0.0375 | 0.0357 | 0.0299 | 0.0347 | 0.0339 | 0.0365 | 0.0359 | 0.0331 | 0.0323 | 0.0387 | 0.0335 | 0.0329 | 0.0344 | 0.0413 |
| 12 | 0.0332 | 0.0375 | 0.0356 | 0.0298 | 0.0347 | 0.0338 | 0.0364 | 0.0359 | 0.0331 | 0.0322 | 0.0386 | 0.0335 | 0.0329 | 0.0343 | 0.0412 |
| 13 | 0.0331 | 0.0374 | 0.0355 | 0.0297 | 0.0346 | 0.0337 | 0.0363 | 0.0358 | 0.0330 | 0.0321 | 0.0385 | 0.0334 | 0.0328 | 0.0342 | 0.0411 |
| 14 | 0.0330 | 0.0373 | 0.0354 | 0.0296 | 0.0345 | 0.0336 | 0.0362 | 0.0357 | 0.0329 | 0.0320 | 0.0384 | 0.0333 | 0.0327 | 0.0341 | 0.0410 |
| **TOTAL** | **0.4608** | **0.5202** | **0.4950** | **0.4139** | **0.4819** | **0.4698** | **0.5062** | **0.4984** | **0.4594** | **0.4471** | **0.5370** | **0.4648** | **0.4564** | **0.4762** | **0.5734** |
| **AVERAGE** | **0.0329** | **0.0372** | **0.0354** | **0.0296** | **0.0344** | **0.0336** | **0.0362** | **0.0356** | **0.0328** | **0.0319** | **0.0384** | **0.0332** | **0.0326** | **0.0340** | **0.0381** |

Table 6.2: Summary of the percentage composition of gas in biogas

| COMPOSITION | Sample 1(Sewage) ($X_1$) | Sample 2 (Pig Waste) ($X_2$) | Sample 3 (Poultry waste) ($X_3$) | Sample 4 (Homemade food waste) ($X_4$) | Sample 5 (Sewage and Pig waste) ($X_1 + X_2$) | Sample 6 (Sewage and Poultry waste) ($X_1 + X_3$) | Sample 7 (Sewage and homemade food waste) ($X_1 + X_4$) | Sample 8 (Pig and Poultry waste) ($X_2 + X_3$) | Sample 9 (Pig and Homemade food waste) ($X_2 + X_4$) | Sample 10 (Poultry and Homemade food waste) ($X_3 + X_4$) | Sample 11 (Sewage, Pig and Poultry waste) ($X_1 + X_2 + X_3$) | Sample 12 (Sewage, Pig, and Home made food waste) ($X_1 + X_2 + X_4$) | Sample 13 (Sewage, Poultry, and Home made food waste) ($X_1 + X_3 + X_4$) | Sample 14 ( Pig, poultry, and Home made food waste) ($X_2 + X_3 + X_4$) | Sample 15 ( Sewage, Pig, poultry, and Home made food waste) ($X_1 + X_2 + X_3 + X_4$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Methane ($CH_4$) | 54.80% | 58.70% | 56.60% | 51.70% | 68.10% | 66.84% | 68.20% | 69.18% | 66.24% | 64.98% | 65.50% | 68.04 % | 65.24 % | 66.50 % | 66.73% |
| Carbon-dioxide ($CO_2$) | 39.40% | 35.00% | 36.50% | 41.10% | 25.60% | 27.86% | 26.60% | 25.12% | 27.66% | 29.22% | 30.20% | 24.86 % | 28.16 % | 26.00 % | 25.30% |
| Other Gases | 5.80% | 6.30% | 6.90% | 7.20% | 6.30% | 5.30% | 5.20% | 5.70% | 6.10% | 5.80% | 4.30% | 7.10% | 6.60% | 7.20% | 5.40% |