# ASSESSING THE USE OF SCORIA AND STEEL SLAG IN PURIFICATION OF BIOGAS


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## ABSTRACT

This report depicts research done to assess the use of scoria and steel slag in biogas purification. Biogas, a renewable energy source, has been employed globally to meet energy demands as an alternative to fossil fuels. It results from anaerobic digestion of organic matter forming methane and impurities that lower gas quality. Need for purification has risen and current purification techniques, while effective, are expensive, inaccessible and energy intensive for medium scale farmers, particularly in developing areas. Scoria and steel slag exhibit physical and chemical properties suitable for adsorption-based purification.

This project focuses on medium scale farmers in Namulonge, Wakiso District, where affordable, efficient and accessible purification is essential. Specific objectives involve determining biogas composition, optimum material concentration for purification, design and fabricating a purification unit and determining cost effectiveness of these materials. Achieving these contributes to development of sustainable, cost-effective purification, and improving biogas quality for diverse applications.

## DECLARATION

**I AMARA TRACY**, hereby declare that this is my original work, is not plagiarized and has not been submitted to any other institution for any award.

AMARA TRACY

Signature: …………………………….

Date: ………………………………………

## APPROVAL

This research project has been submitted for examination with my approval as the university supervisor.

Signature: ……………………………………

Date: ……………………………………………..

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PROJECT SUPERVISOR

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| | |
|---|---|
| AD | Anaerobic Digestion |
| BC | Benefit Cost Ratio |
| BOF | Basic Oxygen Furnace |
| CAD | Computer Aided Design |
| CBA | Cost Benefit Analysis |
| EAF | Electric Arc Furnace |
| ISO | International Organization for Standardization |
| NPV | Net Present Value |
| PPM | Parts Per Million |
| PSA | Pressure Swing Adsorption |
| UCU | Uganda Christian University |
| VOC | Volatile Organic Compounds |

# CHAPTER ONE: INTRODUCTION

This chapter introduces the study with a background, highlighting the significance of biogas as an energy source and the challenges caused by impurities in raw biogas. The problem statement further identifies difficulties faced by medium scale farmers who rely on biogas, due to costly, inaccessible purification technologies and proposes scoria and steel slag as feasible purification materials. The objectives then outline the key focus areas of the study, and the justification explores the suitable properties of the materials, demonstrating their potential to remove $CO_2$ and $H_2S$. Lastly, this chapter emphasizes the relevance of this project in providing accessible and sustainable biogas purification solutions, which will serve as a basis for future research and practical applications in medium scale biogas systems, where access to simplified purification systems remains limited.

## 1.1 BACKGROUND OF THE STUDY

With the current global shift towards sustainable and renewable energies as alternatives to traditional fossil fuels, biogas offers ways to transform organic wastes into clean cooking fuels, **(Ottakuttiyankel and Ananthu, 2019.** Biogas is a renewable energy source, obtained through anaerobic digestion of organic matter, resulting in a mixture of gases, primarily methane ($CH_4$), **(Shah et al., 2023).** It consists of impurities like carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), ammonia ($NH_3$), nitrogen ($N_2$), moisture ($H_2O$) and other trace gases, **(Jameel et al., 2024; Shah et al., 2023)**. The energy generated can be used for purposes of cooking, lighting, heating, among others, **(National Grid, 2023)**.

With the widespread adoption of biogas for energy production and waste management purposes, there is a growing focus on improving biogas quality to make it more sustainable and efficient for various applications. Presence of impurities in raw biogas, hinder its adoption for more productive applications like clean cooking and heating purposes These gases, particularly carbon dioxide, a recalcitrant gas, increases the density of biogas and when in high amounts, lowers its calorific value, as it is non-combustible, **(Werkneh, 2022; Kiplagat, 2023).** Hydrogen sulfide in biogas is known to be corrosive to numerous metallic components of equipment, which are harmful to the environment, and degrade biogas quality, making it unsuitable for high efficiency applications, **(Andriani et al., 2020; Sotoodeh, 2022)**. Biogas cleaning and purification, which involves removal of impurities, and increase in methane content is therefore necessary to improve biogas quality. According to research, (Andriani et al., 2020; Kalman et al., 2022; Paglini, 2022), purification materials such as like iron oxide, lime, sodium hydroxide, activated carbon among others have been used. However, these are costly, complex and some energy intensive, making their applicability hard in areas where the use of biogas would be beneficial.

This study therefore seeks to assess the use of scoria and steel slag in biogas purification in order to address the limitations of current purification methods. Being inexpensive and abundant in nature, they offer more feasible alternatives for medium scale farmers in Uganda, in the removal of impurities that will in turn increase the methane content, making biogas cleaner and more efficient for various applications.

### 1.2 PROBLEM STATEMENT

For biogas to be optimally utilized to meet domestic energy needs, particularly for cooking, lighting and small-scale heating, it should meet the required standards. In Uganda, biogas used primarily for domestic energy uses should ideally contain (60-75%) methane content, (1-15%) carbon dioxide levels and very minimal or no hydrogen sulfide, **(Cesar et al., 2024)**. In reality, however, biogas production today falls short of these standards. It typically consists of low methane levels (45-55%), significant carbon dioxide levels (35-45%), and notable impurities, such as hydrogen sulfide ($H_2S$), ammonia ($NH_3$), nitrogen ($N_2$), oxygen ($O_2$), moisture ($H_2O$), carbon monoxide and siloxanes, **(Bragança et al., 2020; Thiyagarajan et al., 2023)**.

The impurities present limit their applications, through affecting the biogas quality and efficiency. They not only lower methane content, but also accelerate corrosion and wear out of equipment, increasing the operational costs, and call for frequent need for maintenance, **(Mohammadi and Rasa V, 2023)**. For small scale and medium scale farmers that rely on biogas as a low-cost energy source, these limitations render the biogas systems unsustainable over time.

A case study done on the biogas plants of medium scale farmers in Namulonge, Wakiso District, highlighted these challenges, indicating low methane content of ranges (48-55%), high carbon dioxide, (35-42%) and notable hydrogen sulfide impurities. It was identified that the presence of these impurities, particularly caused corrosion of their equipment due to the corrosive nature of hydrogen sulfide and a reduction in the calorific value of their biogas due to presence of high carbon dioxide levels, **(Namugenyi and Joachim Scholderer, 2024).**

This calls for biogas cleaning and purification to address these challenges. Researchers have employed different materials for purification such as ferric oxide, lime, activated carbon, zeolites, among others, **(Lathifa et al., 2022; Fitrah et al., 2023).** Additionally, various technologies like pressure swing adsorption, cryogenic separation, water scrubbing, and others, have been implemented globally on a large scale **(Andriani et al., 2020)**. However, these techniques remain costly and largely inaccessible for medium scale farmers in Uganda that majorly rely on biogas for energy, making it difficult for them to adequately purify their gas.

This research therefore aims to attain low-cost methods of purifying biogas tailored to the needs of medium scale farmers that are affordable, sustainable and accessible for them, as well as to improve its quality to meet the ideal standards for domestic applications, hence ensuring sustainable energy production for these farmers.

## 1.3 OBJECTIVES OF THE STUDY

### 1.3.1 Main Objective

To assess the use of scoria and steel slag in the purification of biogas.

### 1.3.2 Specific Objectives

1. To determine the composition of biogas produced by medium scale farms in Namulonge, Wakiso District.
2. To determine the optimum concentration of the scoria and steel slag needed for biogas purification from the selected farms.
3. To design and fabricate a cleaning and purification system for the biogas.
4. To perform a cost benefit analysis for the use of scoria and steel slag, in comparison to other purification materials.

## 1.4 RESEARCH QUESTIONS

1. What is the composition of the biogas produced by medium scale farms in Namulonge, Wakiso District?
2. What optimum concentration of scoria and steel slag is needed for biogas purification from the selected farms?
3. What are the dimensions of the cleaning/purification unit design for placing scoria and steel slag to clean and purify the biogas?
4. What are the costs and benefits of using scoria and steel slag for biogas purification, in comparison to other purification materials?

## 1.5 JUSTIFICATION

The materials being considered for biogas purification are scoria and steel slag, responsible for removal of both the hydrogen sulfide and carbon dioxide respectively from the biogas stream.

Carbon dioxide

Steel slag, rich in Calcium Oxide (CaO), provides an efficient medium for capturing carbon dioxide present in the biogas stream. When in contact with calcium oxide, a chemical reaction occurs to form calcium carbonate that is a stable and harmless solid compound. The reaction can be represented as indicated in the **equation (1)** below according to **(DiGiovanni, et al., 2024)**;

$CaO_{(s)} + CO_{2(g)} = CaCO_{3(s)}$……(equation 1)

This effectively removes carbon dioxide from the biogas stream, thereby enhancing methane concentration in biogas, and leaving it cleaner and more suitable for various applications.

Hydrogen sulfide

Scoria, with its highly porous structure, provides a large surface area-volume ratio for interaction with hydrogen sulfide molecules making it effective in adsorption of the hydrogen sulfide gas. Iron oxides are present in scoria and these can react directly with hydrogen sulfide gas, forming iron sulfide and water, as indicated in **equation (2)** below, which effectively reduces hydrogen sulfide from the biogas stream, according to **(Alraddadi and Assaedi, 2021)**.

$Fe_2O_{3(S)} + 3H_2S_{(g)} = Fe_2S_{3(s)} + 3H_2O_{(l)}$…… **(equation** 2)

**1.6 SIGNIFICANCE OF STUDY**

The purpose of this research is to provide a sustainable, affordable and accessible solution for the cleaning and purification of biogas, particularly for medium scale farmers within Namulonge, Wakiso District, Uganda. By utilizing locally available materials, the study seeks to capture and remove impurities from the biogas stream and in turn improve its quality, so as to further promote its adoption as a clean and reliable source for various applications.

**1.7 SCOPE OF STUDY**

This project is intended for medium scale farmers in Namulonge, Wakiso district, Uganda producing and using biogas.

# CHAPTER TWO: LITERATURE REVIEW

This chapter provides the literature that guided this research. It gives insights on the biogas production process, biogas composition and impurities, purification techniques, materials considered for purification among others. Through establishing a theoretical foundation, this review supports the research objectives to enhance biogas quality and design a cost-effective cleaning and purification system.

## 2.1 Biogas

Biogas is a colorless combustible gas, generated through the biological breakdown of organic matter, in the absence oxygen, **(Jameel et al., 2024)**. The organic sources include agricultural waste (animal dung, human excreta, crop residues, energy crops), municipal waste (food scrap, sewage sludge, landfill sites), **(Ramírez et al., 2015; McCabe and Schmidt, 2018).** This fuel can be used for heating, cooking, lighting and when upgraded to bio-methane, can be used as a vehicle fuel, **(Mertins and Wawer, 2022).** Biogas is considered a sustainable energy source because it contributes to reduction of greenhouse gas emissions, waste management, production of organic fertilizers, which offer effective means to reduce environmental impact.

## 2.2 Biogas Production

Biogas is produced through anaerobic digestion, a biological process in which microorganisms break down organic material in an oxygen free-environment. It occurs in four stages; hydrolysis, acidogenesis, acetogenesis and methanogenesis as discussed in detail below.

Under hydrolysis, biomass consists of complex organic polymers such as proteins, fats and carbohydrates, that are broken down or hydrolyzed into simpler soluble molecules as shown in **figure one** on page 9, like fatty acids, amino acids, and simple sugars, by fermentative bacteria, **(Velmurugan, et al., 2014).** Products such as acetate and hydrogen that can later be applied in the process are formed, **(Raja and Wazir, 2017)**.

The next stage, acidogenesis involves further breakdown of biomass and organic products by acidogenic microorganisms. According to **(Clifford, 2010),** fermentative bacteria create an acidic environment in the digester and soluble monomers are converted to short-chain acids (propionic, formic, butyric acids), ketones (glycerol, acetone) and alcohols. Additionally, carbon dioxide, hydrogen sulfide, ammonia, water, and other by-products are formed, **(Detman et al., 2021)**.

Acetogenesis involves creation of an acetate, from carbon and energy sources by acetogens. These catabolize most of the products formed during acidogenesis into material that can be utilized by methanogens such as acetic acid, carbon dioxide and water, **(Detman et al., 2021)**.

Lastly, methanogenesis occurs which involves production of methane from the final products by methanogens as indicated in **figure one** on the next page**.** Methane creation mainly involves two pathways, one involving the use of carbon dioxide and the other the use of acetic acid as expressed in the chemical reactions (a) and (b) below according to **(Uddin and Wright, 2022).**

(a)$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

(b)$CH_3COOH \rightarrow CH_4 + CO_2$

The main mechanism of methane creation involves the path with acetic acid, forming methane and carbon dioxide as the main products, **(Raja and Wazir, 2017).**

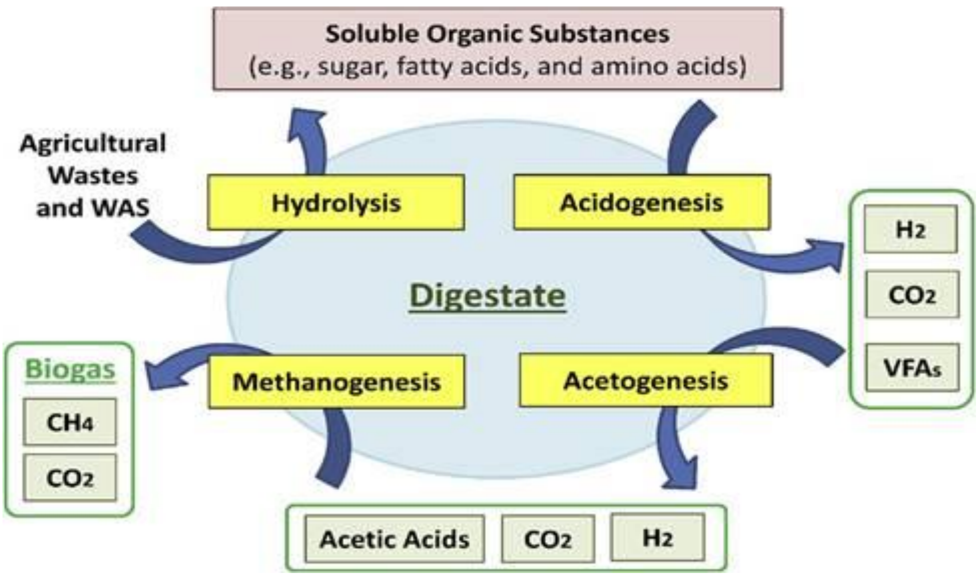



*Figure 1: Biogas production process. Adapted from (Pan et al., 2021)*

## 2.3 Factors affecting biogas production

Temperature choice and control greatly affect biogas yield and quality. Methanogenic microorganisms operate under various conditions: cryophilic(0-15°C), mesophilic (15-40°C) and thermophilic (40-60°C), **(Taddese et al., 2018)**. Mesophilic digestion is majorly used as it offers a more stable environment, conducive for microbial activity, easier to manage and less energy intensive.

Hydraulic Retention Time is the average time in which a substrate is retained in the digester. According to **(Dobre, et. al, 2014),** it is determined by digester volume and organic loading rate. Complex organic pollutants require a longer HRT which requires greater reactor volume and costs.

The ideal Carbon/Nitrogen ratio for optimal biogas production ranges from 20:1 and 30:1. For a higher ratio, nitrogen is depleted rapidly by methanogens that utilize it to fulfill their protein requirements, leaving excess carbon that reduces biogas yield. In cases of lower ratios, excess nitrogen results into ammonia, ultimately lowering gas production rates, **(Yadav et al., 2018; Taddese et al., 2018)**.

Microorganisms require moisture for their metabolic activity. Therefore, according to **(Uddin et al., 2022),** feedstock requires an optimum moisture content of about 90% of its total volume. Excess moisture lowers production rate while inadequate water leads to accumulation of acetic acids and scum that inhibit mixing and digestion.

The optimal pH range is 6.5-8, enabling microorganism populations to co-exist effectively in digesters. pH below 6, strongly inhibit methanogens, while pH above 8, reduce microbial activity. Variations in pH values may be due to presence of ammonia, charging flux, or volatile fatty acids that accumulate in the reaction medium, **(Yadav and Kumar, 2018)**.

### 2.4 Biogas Composition and impurities

Biogas mainly consists of methane, carbon dioxide and significant quantities of hydrogen sulfide, ammonia, nitrogen, water vapor, siloxanes, volatile organic compounds, among others, **(Awe et al., 2017)**. **Table one** on the next page shows the typical composition of raw biogas components.

*Table 1: Typical composition of raw biogas*

| CONSTITUENTS | COMPOSITION (%) |
|---|---|
| Methane ($CH_4$) | 55-65 |
| Carbon dioxide ($CO_2$) | 35-45 |
| Hydrogen sulfide ($H_2S$) | 0-1 |
| Nitrogen ($N_2$) | 0-1 |
| Hydrogen ($H_2$) | 0-1 |
| Carbon monoxide (CO) | 0-3 |
| Oxygen ($O_2$) | 0-2 |

Source: (Awe et al., 2017)

The concentration of impurities in biogas is influenced by the type of feedstock, digester conditions and biochemical processes as previously discussed. The study majorly focuses on animal feedstock which is a critical resource for medium-scale farmers relying on biogas and therefore, understanding these variations is essential for optimizing biogas production and quality.

Animal dung as feedstock typically contains high lignocellulosic content that slows hydrolysis, and favors methanogens that efficiently produce methane, **(Paranhos et al., 2020; Sittijunda et.al, 2017)**. Meanwhile, proteins from the feed are broken down and sulphate reducing bacteria convert the released sulphates into hydrogen sulfide. The differences among animal manures are notable.

Cow dung is derived from a fiber-rich, low sulfur, herbivorous diet and ruminant digestion, which ensures a balanced carbon-nitrogen ratio that limits excess ammonia, **(Paranhos et al., 2020)**. According to **(Nahm, 2003),** poultry dung, due to its monogastric digestive system tends to yield higher levels of ammonia and hydrogen sulfide, owing to incomplete protein digestion. Furthermore, pig dung that reflects an omnivorous diet, typically exhibits moderate ammonia and high hydrogen sulfide levels, **(Karnachuk et al., 2021).**

The presence of impurities in the biogas poses various challenges.

Carbon dioxide, a natural byproduct of microbial metabolism, can occur in high amounts due to poor feedstock quality or digester conditions. According to **(Bragança et al., 2020)**, this reduces the overall calorific value of biogas, diluting methane. Hydrogen sulfide, a highly corrosive and toxic gas, leads to corrosion and damage of pipes, engines and storage facilities of biogas, **(Ephodia et al., 2024).**

Water vapor can also cause equipment corrosion by reacting with other impurities, while siloxanes cause formation of hard deposits on engine components during combustion which reduces their efficiency and calls for frequent maintenance, **(Mendiara et al., 2021)**. Other impurities like carbon monoxide, ammonia and volatile organic compounds (VOCs), contribute to air pollution, **(Bragança et al., 2020**; **Werkneh, 2022)**.

### 2.5 Biogas Purification

Purification of biogas is essential to improve its energy efficiency by increasing the methane concentration. Removal of impurities such as carbon dioxide and hydrogen sulfide, not only enhances the biogas quality, but also protects equipment from corrosion, reducing need for frequent maintenance. This makes it a more environmentally friendly fuel and effective for various applications. Various purification technologies have been employed worldwide to purify biogas and these include; Membrane separation, Pressure swing adsorption, water scrubbing, cryogenic separation, physical and chemical adsorption among others, **(Rufford et al., 2012; Songolzadeh et al., 2014).**

## 2.6 Adsorption Techniques

Adsorption refers to a process that involves selective binding or adhesion of one or more components of a mixture on the surface of a micro- porous solid, preferably with a large surface area per unit mass, **(Sahota et al., 2018).** It requires an adsorbate and adsorbent to occur. An adsorbate is the substance to be adsorbed onto the surface of another material, **(Mwaniki, 2022)**. In this case, the adsorbate is carbon dioxide, hydrogen sulfide and other impurities in biogas that require removal. An adsorbent is a material onto which an adsorbate adheres, and provides an adequate surface for interaction with the adsorbate molecules, **(Chiang and Gao, 2022).** There are mainly two types: physical adsorption (physisorption) and chemical adsorption (chemisorption) as discussed in detail below.

### 2.6.1 Physical Adsorption

Physical adsorption refers to a process that involves the adherence of gas or liquid molecules to the surface of an adsorbent as indicated in **figure two on the next page**, through weak Van der Waal forces without altering the electronic structure between the adsorbate and adsorbent, **(Sahota et al., 2018; Vlab, 2011)**. It largely depends on surface area of a material, porosity, adsorption kinetics and many others. This process is easily reversed by decreasing or increasing the pressures since the forces existing between them are weak, **(Heney, 2021)**. Materials commonly used in physical adsorption include activated carbon, molecular sieves, zeolites, natural minerals among others, **(Fatma et al., 2022)**.

### 2.6.2 Chemical Adsorption

Chemical adsorption, involves the formation of a chemical reaction between an adsorbate and adsorbent material as indicated in **figure two**, forming strong chemical bonds that cannot easily be reversed, **(Klet et al., 2018**; **Chiang and Gao, 2022)**. This method is effective in removing reactive gases like hydrogen sulfide, ammonia, carbon dioxide and others, as the adsorbents react with these impurities and immobilize them on the surface of the material. Materials commonly used for this process include materials with metal oxides like iron oxides, zinc oxides, particularly used in the removal of hydrogen sulfide and alkali metals such as calcium oxides, sodium hydroxide, potassium hydroxides, used in the removal of carbon dioxide, **(BYJU's, 2024; Koo-amornpattana et al., 2023; Wang et al., 2020)**.

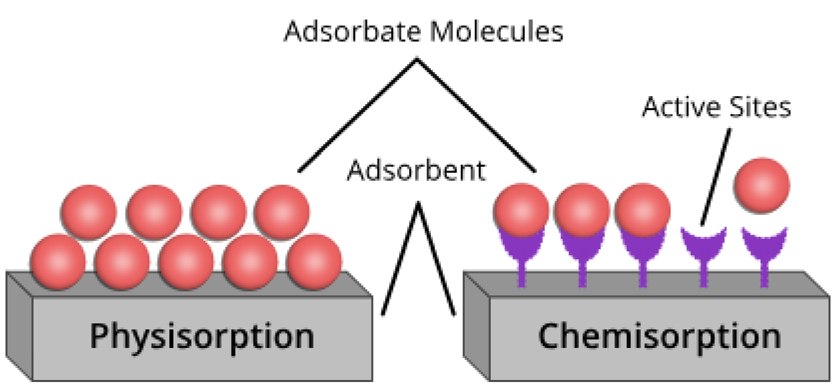



*Figure 2: Physical and Chemical adsorption mechanism. Adapted from (PSIBERG, 2022)*

### 2.6.3 Characteristics of a good adsorbent

A good adsorbent for biogas purification should possess specific physical, chemical and biological characteristics that enhance its ability to capture and remove impurities effectively.

According to **(Pavolová et al., 2016)**, a large surface area which provides more active sites for gas molecules to adhere, increases its adsorption capacity.

Pore structure and pore size distribution. Pore structures particularly micropores (<2 nm) and mesopores (2–50 nm) are more effective in removing small gas molecules like carbon dioxide. Some adsorbents with tailored pore sizes enhance selectivity and adsorption kinetics, for example, chemically activated carbons optimized for specific gas molecules, **(Gaj, 2020).**

Selectivity for specific gases. The material preferably adsorbs one gas over the other which is influenced by chemical affinity. According to **(Nurul et al., 2023)**, iron oxides are selective in the removal of hydrogen sulfide due to the strong chemical interactions between metal and sulfur atoms.

Thermal and chemical stability. It should be able to withstand operating conditions that involve fluctuations in temperature and exposure to acidic or base gases without degrading. This ensures that the material remains effective over multiple adsorption cycles without easily degrading, **(Pavolová et al., 2016)**.

Ability to regenerate. The ability of adsorbents to regenerate through heat or chemical treatment extends their lifespan and reduces operational costs, **(Nurul et al., 2023)**.

## 2.7 Materials under study for biogas cleaning and purification

The materials considered for biogas purification were scoria and steel slag and this section provides an overview of their adsorption mechanisms, physiochemical properties, operational performance among other things.

### 2.7.1 Scoria

Scoria is an extrusive vesicular igneous rock that forms as a result of volcanic activity and solidification of molten lava. Its unique structure and properties make it a valuable material in various contexts.

Formation and structure

Scoria originates from gas-rich lava flows which erupt on the earth's surface. As the magma ascends, dissolved gases like water vapor and carbon dioxide expand under reduced pressure, and come out of solution, forming bubbles within the lava. Rapid cooling of lava on the surface traps bubbles within the solidifying rock, forming vesicles (small cavities), that vary in size and distribution on the scoria rock, **(Kiyosugi et al., 2013; Science, 2019)**.

Physical properties of scoria

Scoria has a rough sponge like texture with colors ranging from black to reddish-brown influenced by the minerals present, that is iron and magnesium, **(King, 2018)**. Due its porosity, it has a density (1.5-2.5 g/cm$^3$), which is typically lower than most rocks and therefore, useful in light weight applications, **(Deer et al., 2013).**

Chemical properties of scoria

It is typically rich in iron oxides, silicon dioxide, aluminum oxides and contains other chemical compounds such as calcium oxide, sodium oxide and other trace minerals. Iron oxides present are highly reactive since they have a redox-active nature, and therefore easily engage in exchange of electrons during chemical reactions, making them highly effective in capturing sulfur compounds in gas, **(Sander and Gorski, 2015)**.

Adsorption mechanism of scoria

Physical Adsorption. Scoria's porous structure offers a large surface area for adsorption that enables gas molecules to adhere to its surface and within its pores by weak van der Waals forces, The adsorption is influenced by pore size distribution and surface area of the adsorbent, **(Geleta et.al, 2022**; **Yang et al., 2019)**. The porous network facilitates the diffusion of biogas through the material, where impurities like hydrogen sulfide are trapped within the pores.

Chemical adsorption. The surface of scoria also contains functional groups such as iron oxides, which chemically interact with adsorbates. For instance, hydrogen sulfide reacts with iron oxides on scoria to form iron sulfides thereby reducing hydrogen sulfide impurities. It is a more specific interaction as compared to physical adsorption and often involves stronger chemical bonds, **(Osouleddini et al., 2018)**.

Applications of scoria

Scoria's low density and thermal insulation properties make it ideal for lightweight concrete and insulation materials. It is used in filtration of water and wastewater due its ability to trap sediments. Scoria's porosity and permeability make it ideal for drainage purposes like walkways, garden beds among others, which prevents water logging and improves soil aeration, **(Science, 2019)**.

### 2.7.2 Steel slag

With the growing demand for steel in the world, there is a continuous increase in production of steel. According to **(Muwanguzi et al., 2020)**, an average of 1.1 million tons of steel are being produced in Uganda annually, and for every ton produced, about 160 to 180 kilograms of steel slag are being produced. This makes it a sustainable material suitable for use in the adsorption of carbon dioxide in biogas.

Formation of steel slag

Steel slag, a by-product of the steel manufacturing process, is formed during the separation of molten steel from impurities in steel making furnaces, **(Aziz et al., 2020; (Lim et al., 2016)**. It is a complex mixture of oxides and silicates that solidifies upon cooling. Basing on the production process or raw materials used in steel making, slag is classified depending on the furnace type used as discussed below;

Basic Oxygen Furnace (BOF). Molten metal from blast furnaces, iron ore and fluxes are sent to the furnace and subjected to high-pressure steam of pure oxygen through a lance, **(Naidu et.al., 2020). C**onstituents like silicon, phosphorus, manganese, aluminum, sulfur react with oxygen to form various oxides. These react with lime and dolomite fluxes to form steel slag, which due to its lower density, is easily separated from the purified liquid metal, **(Ren et al., 2023**; **Kombathula, 2020)**.

Electric Arc Furnace (EAF). EAF primarily involves the recycling of scrap metal to form steel. It uses a high voltage current to melt the scrap, and fluxes are added to reduce excess silicon and carbon hence refining molten iron. The slag produced is referred to as Electric Arc Furnace slag, **(Ren et al., 2023); (Zanelli et al., 2021)**.

Ladle Furnace. Under this, molten steel is transferred to a ladle for further refining and removal of the impurities in the steel, resulting in formation of ladle slag as a by-product, **(Levy, 2023).**

Physical properties of steel slag

Surface Area and Porosity. Its porous structure, due to rapid cooling from extreme temperatures in a blast furnace, can enhance adsorption capacity, **(Manchisi et al., 2020)**. This is because the surface area of the structure is increased, available for interaction with gases to trap impurities such as carbon dioxide. Thermal stability. Steel slag is capable of withstanding very high temperatures without significant structural degradation, **(Kana et al., 2021)**.

Steel slag comprises of various constituents as clearly shown in **table two** below;

*Table 2:Chemical Composition of steel slag*

| Chemical Composition | Content (%) |
|---|---|
| Calcium oxide (CaO) | 45–60 |
| Silicon oxides ($SiO_2$) | 10-15 |
| Aluminum oxide ($Al_2O_3$) | 1-5 |
| Iron Oxides | 7-20 |
| Magnesium oxide (MgO) | 3-13 |

Source: (Sun et al., 2023)

Applications of steel slag

Environmental remediation through carbon capture and storage through mineral carbonation, **(Kamal et al., 2024)**. It is also used in construction as aggregate in concrete and road bases and as a soil amendment to improve stability, among others, **(Lim et al., 2016)**.

In a nutshell, steel slag and scoria are placed within the same cleaning unit and do not chemically react with each other, as the process occurs at ambient temperatures and dry conditions. Any reaction between the two would require very high temperatures that are not present in the purification process. Therefore, the combination of the materials is solely intended to leverage their individual properties for effective biogas cleaning and purification as discussed in the essays above.

## 2.8 Biogas Cleaning and Purification Units

In biogas improvement, two distinct processes, cleaning and purification address different impurities to optimize its quality. Cleaning involves the removal of carbon dioxide, a major impurity that dilutes the methane content of biogas. Purification then focuses on removal of impurities like hydrogen sulfide, a corrosive and toxic gas that corrodes equipment and causes harm to human health when in high concentrations. Together, these processes performed in a cleaning and purification system facilitate a comprehensive purification strategy that improves the quality of biogas.

### 2.8.1 Factors Influencing the design of biogas cleaning and purification units

Composition of biogas. The composition of impurities in biogas such as hydrogen sulfide, siloxanes, carbon dioxide, moisture content, and others inform the number of stages and types of purification, suitable materials, **(None Djomdi et al., 2021)**.

The biogas flow rate from digester helps to determine the design capacity and size of the cleaning unit. They also inform the material dimensions that should be considered in design, contact time in the unit as well as allowances for pressure drop, **(Koonaphapdeelert et.al, 2019**).

Desired levels of purity. The purity levels are dictated by the intended use of the purified biogas. Applications such as cooking may require lower purity requirements such as methane levels above 60, while applications in engines require very high methane levels above 95% with no impurities, **(Atelge et al., 2021)**. These targets influence the selection of purification material, and complexity of the purification unit and process.

Method of purification employed influences the design configuration for example adsorption-based units that involve materials like activated carbon, steel slag, may require bed columns for material packing. Chemical scrubbing units that use sodium or calcium hydroxides, require recirculation mechanisms. Membrane separation methods may require units with membranes to separate gases from impurities among others, **(Atelge et al., 2021)**.

Contact time and flow configuration ensure sufficient interaction of the biogas and purification media within the cleaning unit depending on material types. Configuration of flow within the system (up-flow or downflow) are selected based on the properties of materials to be used and system pressure.

Flexibility and scalability. Purification units should be designed in a way that can enable them to be scaled-up or down and accommodate changes in adsorbent amounts, **(Koonaphapdeelert et.al, 2019).**

Cost considerations. Initial construction and installation costs of the unit, operational costs such as replacement of material, maintenance, should be in line with its performance and cost effectiveness, **(Yuan, Kang., 2014).**

## 2.9 Cost effectiveness of materials

A cost benefit analysis refers to a systematic approach of comparing projected costs and benefits of a decision or project to evaluate its economic feasibility, **(Hayes, 2024).** It is used to determine whether an investment or decision is economically viable as it involves identifying, quantifying, and assigning monetary values to all costs and benefits. A positive net benefit indicates that a decision is justifiable while a negative suggests reconsiderations or modifications. Common financial metrics used in a CBA include Benefit Cost Ratio, Net Present Value (NPV), Payback Period, among others.

A well-designed unit can ensure optimal impurity removal while maintaining economic and operational efficiency. Given the purification materials considered for biogas purification scoria and steel slag, it is crucial to conduct a Cost Benefit Analysis (CBA) to assess their economic viability. Evaluating various factors such as material acquisition, operational and replacement costs in relation to their depletion rate and purification efficiency helps to determine their cost effectiveness in comparison to the materials currently being used for purification. Use of such low-cost adsorbents like scoria and steel slag can enhance both sustainability and affordability of biogas purification systems.

## Chapter Conclusion

In conclusion, the literature review establishes a comprehensive framework for enhancing the quality of biogas by detailing its production, composition, challenges posed by impurities, purification methods, key design factors and cost considerations. This emphasizes the need for purification of biogas using low-cost adsorbents scoria and steel slag, hence leading to the next chapter, which details the methodology undertaken to achieve this.

# CHAPTER THREE: METHODOLOGY

The following chapter highlights the research design employed to determine and achieve the different specific objectives of the project. This methodology discusses the materials, equipment used, testing methods and detailed procedures, followed to achieve the project objectives. Primary and secondary data collection approaches were used, where primary data collection entailed different series of tests performed in accordance with the specified standards and testing methods. Secondary data collection mainly focused on the use of available literature to ascertain some objectives such as the cost benefit analysis.

## RESEARCH DESIGN

The research design used for this project lays out the systematic approach followed to assess the use of scoria and steel slag in biogas purification. This design was divided on four phases as illustrated in **figure three** below;

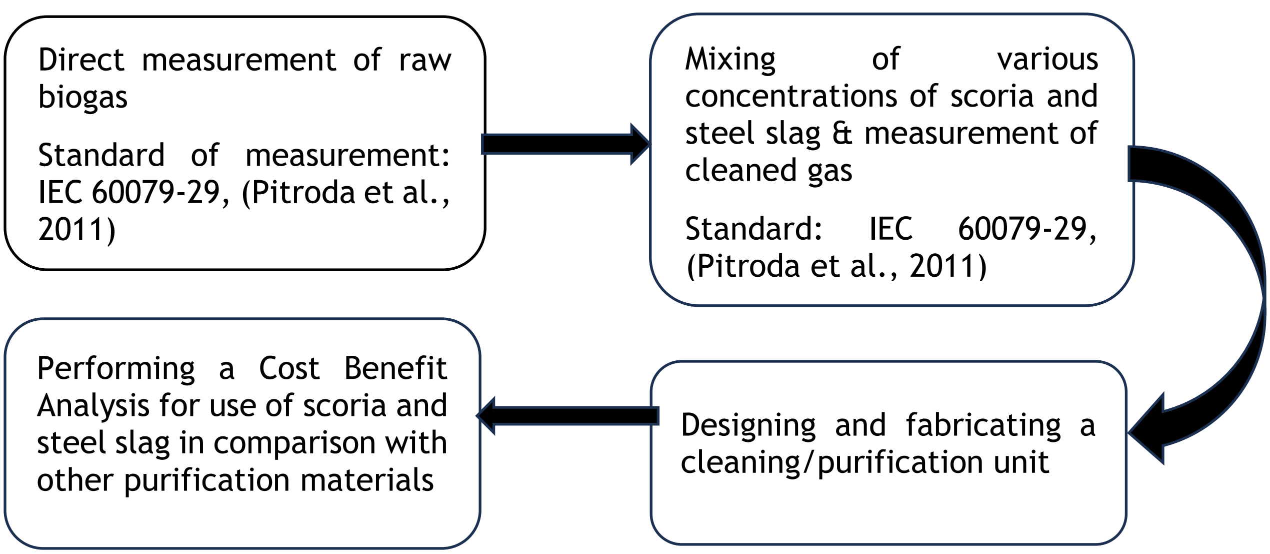



*Figure 3: Research design for methodology*

**3.1 Determining the composition of biogas produced by medium scale farms in Namulonge, Wakiso District.**

**Purpose of methodology**: Biogas quality tests were performed to determine the composition of biogas being produced by medium scale farmers in Wakiso. Gas analyzers measure and analyze concentrations of various gases in an environment, offering real-time monitoring and data logging, that allows for continuous monitoring of gas components.

**Standards:** Tests done with reference to **IEC 60079-29** testing methods, **(Pitroda et al., 2011).**

Sample preparation and collection

Biogas samples were collected from three medium-scale biogas plants within Namulonge, Wakiso District. Sampling was done using floater bags inspected to ensure they were free of holes, airtight and devoid of ambient air that could compromise sample integrity. Each bag was attached to the digester's gas outlet pipe via a rubber tube to let biogas flow into it. Once filled, the pipe's valve was closed and tightly clamped to prevent leakages. Gas bags were tightly sealed and transported to UCU research laboratory for testing.

To capture a true representative of the biogas composition, samples were collected over different days under varying temperature variations. This provided a realistic assessment of fluctuations in microbial activity, and how they influence methane production and gas quality giving a more accurate reflection of the biogas composition.

Equipment used.

Floaters, Gas analyzers (Multi Tec 540, Bosean Gas Detector), Connecting tube

Procedure

Suitable gas analyzer devices were used to detect and measure composition of biogas components (methane, carbon dioxide, hydrogen sulfide, carbon monoxide, oxygen). The devices were turned on, calibrated to ensure accurate results and bags were connected to each analyzer through a tube, with an air tight connection. Multi Tec 540 analyzer was used to measure methane and carbon dioxide whereas a Bosean Gas Detector measured oxygen, carbon monoxide and hydrogen sulfide. Different concentrations were displayed in real time and recorded manually. Each sample was measured in triplicates to enhance the reliability and accuracy of results, as it accounts for potential sampling inconsistencies, instrument variability and any slight fluctuations. The tube was then disconnected from the analyzer, excess gas was released safely into a well-ventilated area, and the analyzers cleaned and turned off. Average values for each constituent were computed in percentages and parts per million, and data obtained was analyzed through comparison of readings with the ideal standards of composition.

## 3.2 Determining the optimum concentration of the scoria and steel slag needed for biogas purification from the selected farms.

Trial mixes are experimental formulations of materials done, in different ratios to obtain optimal proportions of various components within a mixture for a desired outcome. These mixes are essential in ascertaining the performance characteristics of materials in given ratios before their full-scale applications.

**Purpose:** To obtain the optimum proportions of the proposed cleaning materials, scoria and steel slag needed for biogas purification. It will also be done to determine the effectiveness of each mix in adsorbing carbon dioxide and hydrogen sulfide.

Standards of measurement: Reference to IEC 60079-29 testing methods, (Pitroda et al., 2011).

Material collection and preparation

Steel slag was acquired from Roofings Rolling Mills Limited in Namanve, where an induction or electric furnace, is used in which heat is applied by induction heating of metal. Scoria was obtained from Kisoro district. Both materials were crushed separately with a hammer and sieved to obtain the required particle sizes of 2mm each, that was chosen to increase the surface area for maximum adsorption of gas impurities. Studies have demonstrated that this particle size enhances the reactive surface, and optimizes the pore accessibility without compromising structural integrity, **(Slamet, Ahmat, et al., 2020).** They were then thoroughly washed with distilled water to remove impurities like dust, debris that blocks pores and others and thereafter dried in an oven at controlled temperatures of 105°C for 24 hours to ensure thorough removal of moisture, without altering its mineral structure, **(Kaihua et al., 2013).**

Equipment used

Scoria, steel slag, hammers, floaters, gas analyzers

Procedure

Various iterations of trial mixes were prepared using various weight ratios of the scoria and steel slag in controlled proportions. Each mix was then placed in a simple unit and raw biogas passed through individual mixes at a constant gas flow rate to ensure consistency across all trials. The cleaned and purified gas was collected in floaters and transported to the laboratory where gas analyzers were used to measure the quality of the cleaned gas. These tests were done with reference to **IEC 60079-29** testing methods, **(Pitroda et al., 2011).** From these gas analysis tests, the trial mix that resulted in the highest methane content, lowest carbon dioxide and least trace elements of hydrogen sulfide, carbon monoxide and others was considered the optimum concentration required for effective biogas purification. This optimal mix was then used to design a suitable purification unit.

### 3.3 Designing and fabricating a purification system for the biogas.

**Purpose:** This methodology explains the processes that were involved in the design of a biogas purification unit. This was done basing on factors like biogas flow rate, its composition and the optimum concentration of the materials.

Methodology

Determination of factors for design. For design of this cleaning unit, factors like biogas flow rate, composition, optimum concentration and desired purification levels were mainly considered.

Sizing of key components of the purification system. This involved sizing the adsorption chamber for the materials (scoria and steel slag). This was done through calculating required volume, diameter and height of the chamber, as well as required bed thickness of adsorbents, using the optimum obtained, to ensure sufficient contact with biogas. Factors like allowances for pressure drop were considered during design and sizing of inlet and outlet pipes was done to facilitate smooth gas entry and exit without causing excess pressure losses.

Drawing a prototype in CAD software. A detailed drawing layout was created using ArchiCAD. This consisted of two meshes for scoria and steel slag, inlet and outlet pipes, with valves at necessary control points. Material selection for components, such as pipes, valves, tank was considered and the unit was designed for easy maintenance, by incorporating removable mesh units for easy replacement of adsorbent materials and repair. Fabrication of the unit was then done according to suitable design specifications, according to **(FACT Foundation, 2012).**

### 3.4 Performing a Cost Benefit analysis for the use of scoria and steel slag in comparison to other purification materials.

A Cost-Benefit Analysis involves data collection of the associated initial and operational costs of the use of both materials. An economic analysis was done to determine different parameters like Net Present Value and Benefit-Cost Ratio over an analysis period. The two materials were compared to the different conventional materials currently being used in the market for purification such as activated carbon, ferric oxide, clay pellets, lime, among others.

**Purpose of Methodology:** This aims to determine the economic feasibility of using scoria and steel slag for biogas purification, through comparison of the costs incurred and benefits derived from using them versus the conventional purification materials.

Methodology

Data collection which involved determining costs like material costs, i.e., purchase price for materials under comparison, costs of preparation such as crushing, washing, sieving and thermal treatment where necessary was done. Operational costs, energy requirements in crushing and treatments, labor costs, transportation costs and maintenance costs of the cleaning unit, were considered.

Determination of monetary benefits. This involved determining the savings in costs associated with using each of the materials in impurity reduction and methane improvement. This includes reduction in maintenance costs for biogas equipment related to corrosion, among others. Furthermore, computations such as Net Present Value (NPV) and Cost Benefit Ratio (C/B) were done using discount tables to provide a clearer picture of the short-term economic benefits of adopting these materials, **(Atlassian, 2024).**

Chapter conclusion

This chapter details a systematic methodology following the research design that involved determining biogas composition, optimizing scoria and steel slag ratios effective for purification, designing and fabricating a purification unit and performing a cost benefit analysis. Each of these phases generated critical data and insights that establish a strong foundation for both the technical performance and economic viability of the purification system. The findings obtained from following the protocols and methods discussed in this chapter directly inform the next chapter where the results and discussions will evaluate the process's effectiveness and practical feasibility.

# CHAPTER FOUR: RESULTS AND DISCUSSIONS

This chapter is mainly a discussion of the results and findings obtained from the laboratory tests carried out under each objective, and their significance towards the overall purpose of the research being done. Tests were conducted following the specified testing methods in the preceding chapter, and results were obtained and recorded as depicted in the appendix. The process of analyzing, interpreting and discussing the results was done in respect to the different research questions.

## 4.1 RESULTS: OBJECTIVE ONE

To determine the composition of biogas produced by medium scale farmers in Namulonge, Wakiso District.

As discussed in chapter three, the main purpose of this objective was to determine the amounts of methane and impurities contained in biogas from different farms. This would assist in obtaining the suitable cleaning quantities for the varying proportions of impurities.

### 4.1.1 Farm selection

According to **(Guest Columnists, 2023),** it is revealed that by 2023, there were about 7000 operational biogas digesters in Uganda and about 19.4% of these account for the biogas plants within Wakiso district. Within the national context, Wakiso stands out as a significant hub for biogas technology largely due to its high density of animals like cows, poultry, pigs, among others, that create an abundant supply of primary feedstock for biogas. Namulonge, within Wakiso contains a localized density of biogas plants with organized zero grazing systems, **(Kabirizi et al, 2024)** and therefore, not only mirrors the district's overall potential but also provides a focused and representative setting for the detailed biogas study.

Surveys according to **(Mukisa, Ketuama et al, 2022)**, indicate that about 85% of biogas plants rely entirely on cow dung, reflecting its dominance as a primary feedstock. The remaining percentage consist of systems that incorporate other animal wastes, with about 10% co-digesting cow and poultry dung and 5% co-digesting cow and pig dung, **(Mukisa et al, 2022**). This distribution suggests that while most farmers depend solely on cow dung, those rearing other animals tend to integrate their waste into the digestion process, particularly poultry and pigs. Given that Namulonge hosts 5% of Wakiso's biogas plants, three representative farms of different feedstock compositions commonly used in medium scale plants that is: one farm, using cow dung alone serving as the baseline, one co digesting cow and poultry dung and farm three using cow and pig dung were selected. This effectively captures the major variations in feedstock use, and assessing how they impact biogas quality and impurity levels, **(Wasajja et al., 2021)**, which will further aid in optimizing the purification strategies.

#### 4.1.2 Gas analyzing Results

Samples from the three farms were collected in gas bags and transported to the UCU laboratory. Tests were conducted using gas analyzers, (Multi tech 540 and a Bosean gas detector) and gas quality was ascertained in triplicates to ensure accuracy of the results. Samples were collected over various days to capture the variations in biogas composition under different external temperature conditions, as these influence the internal digester conditions, microbial activity and enzymatic reactions that drive anaerobic digestion and therefore production of biogas, **(Pham et al., 2014).** Refer to

**table nine** in the appendix which represents averages of the various results of composition from each farm carried out over different days in percentages and parts per million.

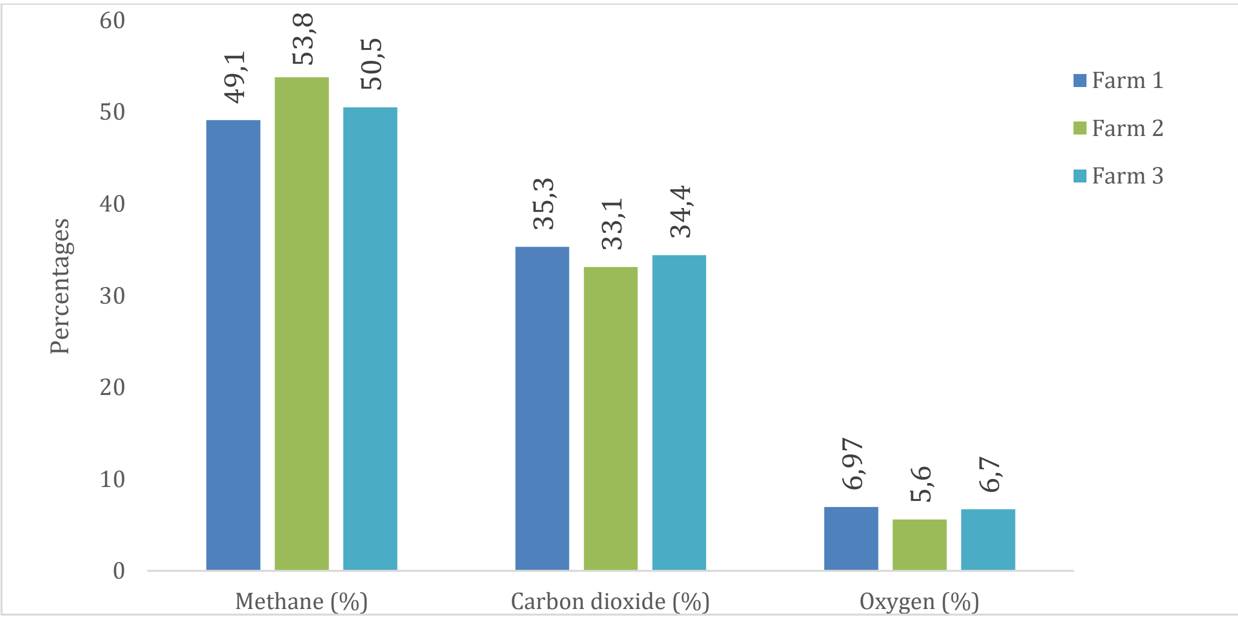



*Figure 4: Average composition of raw biogas in percentages before purification*

From each farm, the analyzed results of impurities, that is methane, carbon dioxide and oxygen in **figure four** above were measured in percentages.

Farm 1, which uses cow dung feedstock only, has methane of 49.1%, the lowest among the three. This is likely attributed to the cow dung having a higher carbon to nitrogen ratio, that limits microbial activity and therefore yields lower methane. In contrast, farm 2 which combines cow and poultry dung records the highest methane at 53.8%. This is due to higher nitrogen content in chicken waste that balances the C:N ratio, leading to enhanced degradability and a higher methane yield.

Additionally, farm 1 exhibits the highest carbon dioxide (35.3%) which suggests that cow dung alone is not as effective in promoting an optimal conversion of organic material to methane. Farm 2, with the lowest $CO_2$ at 33.1% indicates a more efficient digestion process.

The oxygen content ranged from 6.97% in farm 1 to 5.6% in farm 2. This lower oxygen concentration suggests a more favorable anaerobic environment for the bacteria, explaining the higher methane yield at farm 2. The slightly higher levels could be due to air leaks in the system or incomplete anaerobic conditions that potentially hinder growth of microorganisms.

The graph below in **figure five**, depicts the composition of the impurities measured in parts per million.

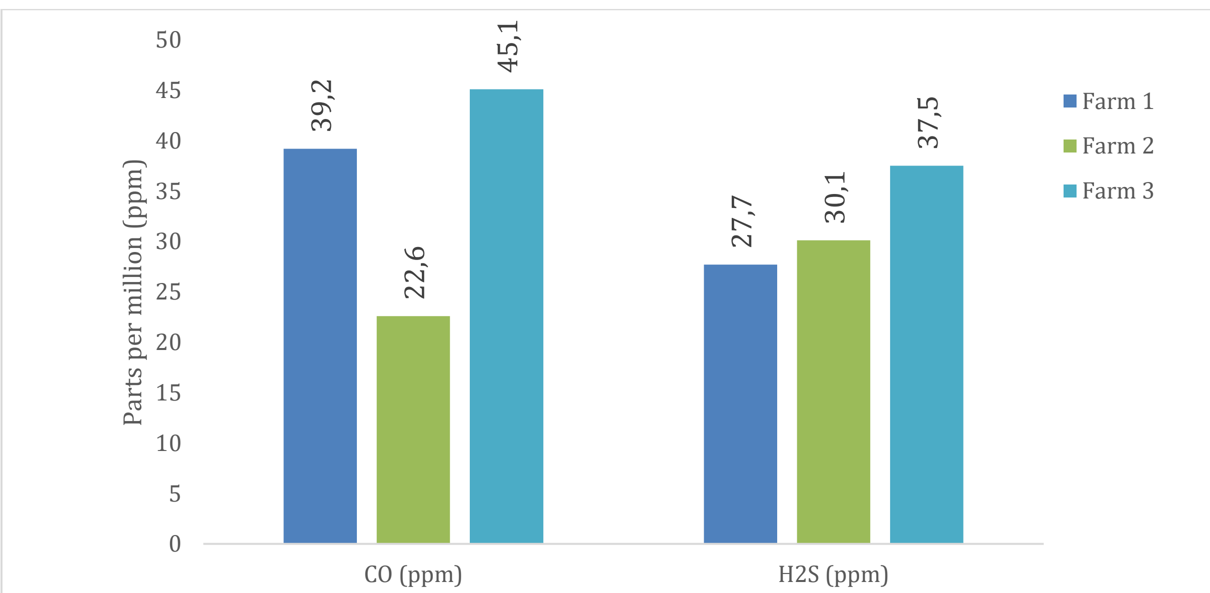



*Figure 5: Average composition of biogas impurities in ppm before purification*

Farm 3 records a carbon monoxide of 45.1ppm, attributed to incomplete anaerobic digestion in the digester, combined with a higher microbial activity leading to CO formation. Farm 2's lower CO concentration indicates that the better digester conditions support methanogenic bacteria, reducing carbon monoxide formation.

Similarly, hydrogen sulfide levels vary with 37.5 ppm from farm 3 to 27.7 ppm from farm 1, reflecting differences in feedstock composition particularly, pig dung containing sulfur compounds could lead to higher hydrogen sulfide impurities.

### 4.1.3 Comparative analysis from literature

The biogas composition obtained from these farms was compared against the typical composition of the varying biogas feedstocks according to research, **(Artanti, Saputro et al, 2012; Atilade, Onanuga and Coker, 2015; Rahim et al., 2023)** as shown in table three below.

*Table 3: Comparison of results with typical biogas composition*

| Component | Cow dung only | Farm one | Co-digestion (Cow+poultry) | Farm two | Co-digestion (cow+pig) | Farm three |
|---|---|---|---|---|---|---|
| Methane(%) | 50-70 | 49.1 | 55-70 | 53.8 | 55-65 | 50.5 |
| $CO_2$ (%) | 25-45 | 35.3 | 25-35 | 33.1 | 25-35 | 34.4 |
| Oxygen (%) | 0-2 | 6.97 | 0-2 | 5.6 | 0-2 | 6.7 |
| CO (ppm) | 10-30 | 39.2 | 5-20 | 22.6 | 5-20 | 45.1 |
| $H_2S$ (ppm) | 0-30 | 27.7 | 0-30 | 30.1 | 0-30 | 37.5 |

From **table three** above, the results obtained fall within the typical range of biogas compositions for the respective feedstocks although, they are seen to lie on the lower end in methane content and on the higher end for the impurities which emphasizes the need for effective purification to enhance its quality.

**Conclusion**

The analyzed and discussed results above, highlight the critical role feedstock composition and digester conditions play in determining biogas quality. They also depict the potential benefits of co-digestion, as combining feedstocks with high degradability can create a more efficient digestion process, leading to higher methane yields as compared to mono digestion. While farm 2 exhibited the highest methane yield due to its optimized nutrient balance from co digesting cow and poultry dung, methane content across all farms is still low, with significant impurities. By understanding the specific impurities present and their concentrations, the results obtained above guide the next phase of research, that involves determining the optimal amount of cleaning materials needed for purification and subsequently designing a purification unit.

## 4.2 RESULTS: OBJECTIVE TWO

To determine the optimum concentration of steel slag and scoria in the purification of biogas from the selected farms.

Different trial mixes of varying ratios were prepared, (150:300, 300:300, 500:500. 600:600, 600:700, 700:800) of steel slag and scoria respectively. Considerations made for the choice of trial mixes used, were the amounts of impurities expected to be cleaned out, the amount of material needed for use for a reasonable time period before requiring renewal, as well as the amount of material needed to be sized in a portable unit suitable for the medium scale farmers, **(Fitrah et al., 2023)**.

From the first farm, raw biogas was passed through the six different trial mixes as shown in **table ten** in the appendix, to identify the proportions offering the best impurity removal. Gas was collected in floater bags and transported to UCU laboratory and biogas quality tests were conducted to assess how the different mixtures cleaned out the impurities. Following the various trial mixes, compositions of the gas were obtained as indicated in table eleven in the appendix.

The graph shown in **figure six** below shows a clear trend for the components measured in percentages, where methane content gradually increases with higher concentration of adsorbents, obtaining its highest at 66.4% in trial mix 4 (600:600). Similarly, carbon dioxide gradually decreases, reaching its lowest level of 11% at the same mix, and oxygen significantly dropped to 3.2%. this indicates that mix 4 provided the optimal concentration of materials for effective purification.

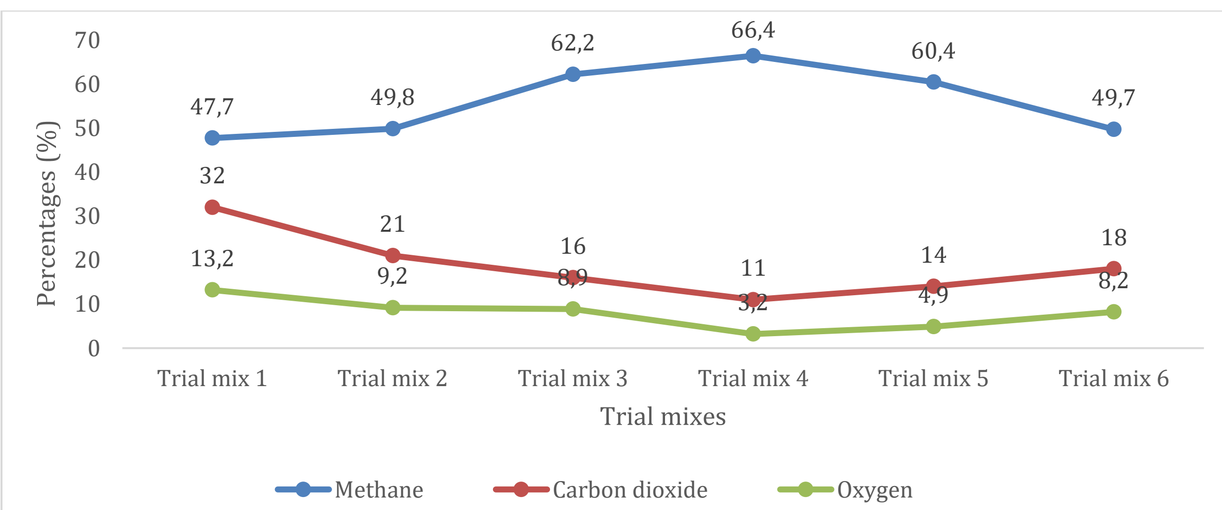



*Figure 6: Graph of optimal trial mix for biogas components in percentages*

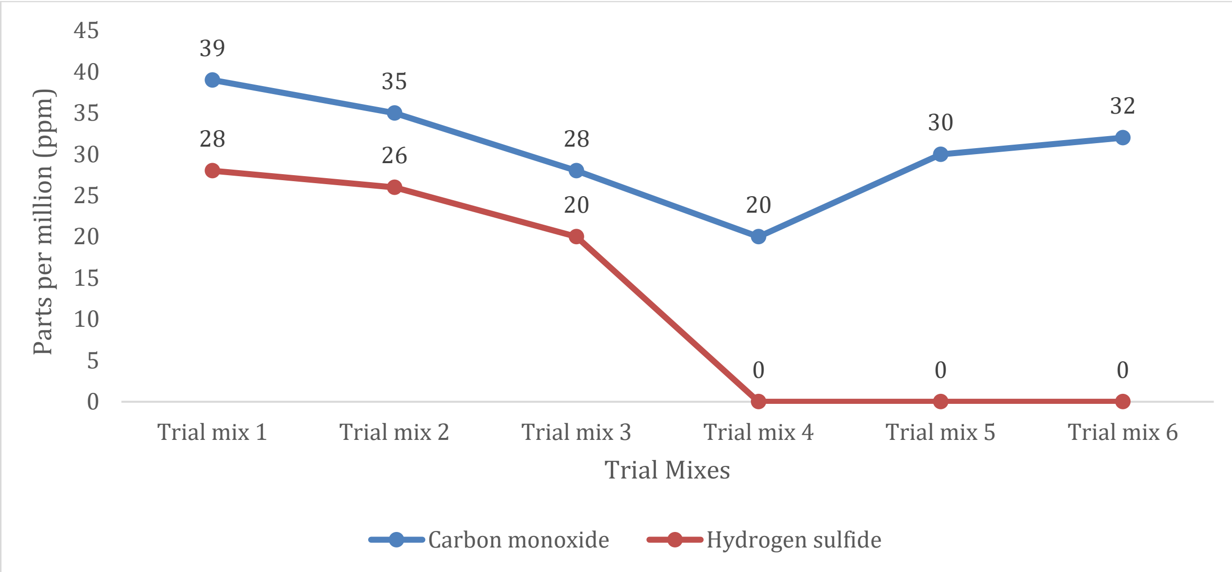



*Figure 7: Graph of optimal trial mix for biogas components in ppm*

From **figure seven** above, the gas impurities measured in parts per million depict a significant reduction in carbon monoxide levels to 20 ppm, highlighting the effectiveness of adsorbents. Additionally, hydrogen sulfide is seen to significantly reduce with increase in adsorbent material proportions until full removal, both from the fourth trial mix of 600:600 scoria and steel slag respectively.

Refer to **Table ten** in the appendix which shows the average results obtained from the three best performing trial mixes (500:500, 600:600, 600:700) across the three farms.

**Conclusion**

In a nutshell, across all farms, trial mix four (600g:600g) of scoria and steel slag respectively exhibited the highest methane, lowest carbon dioxide, zero hydrogen sulfide and significant reduction in oxygen and carbon monoxide. These results therefore confirm that trial mix four (600g:600g) is the optimum concentration of scoria and steel slag, necessary for achieving the highest methane yield, while effectively reducing the impurities and is therefore to be used in the design of a purification unit for biogas purification.

## 4.3 RESULTS: OBJECTIVE THREE

Designing and fabricating a purification system for the biogas.

The purpose of this objective was to design a cleaning and purification unit that effectively reduces primarily the impurities of carbon dioxide, hydrogen sulfide and additionally carbon monoxide and oxygen while simultaneously increasing the methane content of the gas. The design majorly focused on the use of an optimal concentration of scoria and steel slag for effective adsorption and different considerations were taken.

**Design considerations:** An optimum concentration of 600g:600g of scoria and steel slag respectively which was ascertained through performing a series of trial mixes was considered for design of the unit.

Volume considerations were also made to maximize adsorbent-gas interactions. Determining the proper volume for adsorbents and void space for gas flow ensures that biogas has sufficient contact with materials, maximizing impurity adsorption.

Hence Mass of scoria = 600g

Bulk density of scoria = 0.8 g/cm$^3$

Volume Occupied by scoria= $\frac{600}{0.8}$ = 750 cm$^3$

Mass of steel slag = 600g

Bulk density of steel slag= 1.2g/$cm^3$

Volume occupied by steel slag = $\frac{600}{1.2}$ = 500 $cm^3$

Total Volume of adsorbents = 750+500 = 1250 $cm^3$

A void fraction of 20% of adsorbent volume was considered to ensure uniform gas flow, while maintaining contact with adsorbents to minimize channeling as well as to ensure uniform and even compaction of materials on respective meshes. According to research, **(Abd et al., 2021); (Junfeng & Mingyang, 2018),** for packed bed reactors, a void fraction between 10-30% effectively balances gas flow and adsorption efficiency, making 20% optimal.

Therefore, Volume of space for gas flow = 0.2x 1250 = 250 $cm^3$

Volume of the packed chamber = 1250+250 = 1500 $cm^3$

Considering biogas flow rate of 0.5L/min and contact time of 5 minutes.

Volume of gas to be treated per cycle= 0.5x5 =2.5L=2500 $cm^3$

Since the adsorbents take up 1250 $cm^3$, the remaining volume for gas flow;

Volume for gas space = 2500−1250= 1250 cm3

Total Volume of chamber required = 1250+1250= 2500 cm3

Assuming an internal diameter of 8cm, $V=\pi r^2 h$

Height of the chamber= $2500/\pi(4)^2$ = 49.7 cm

Therefore, required dimensions of the chamber are diameter of the chamber of 8cm and height of 49.7cm.

These calculations were used for drawing of the cleaning and purification unit in CAD software as displayed on the next page.

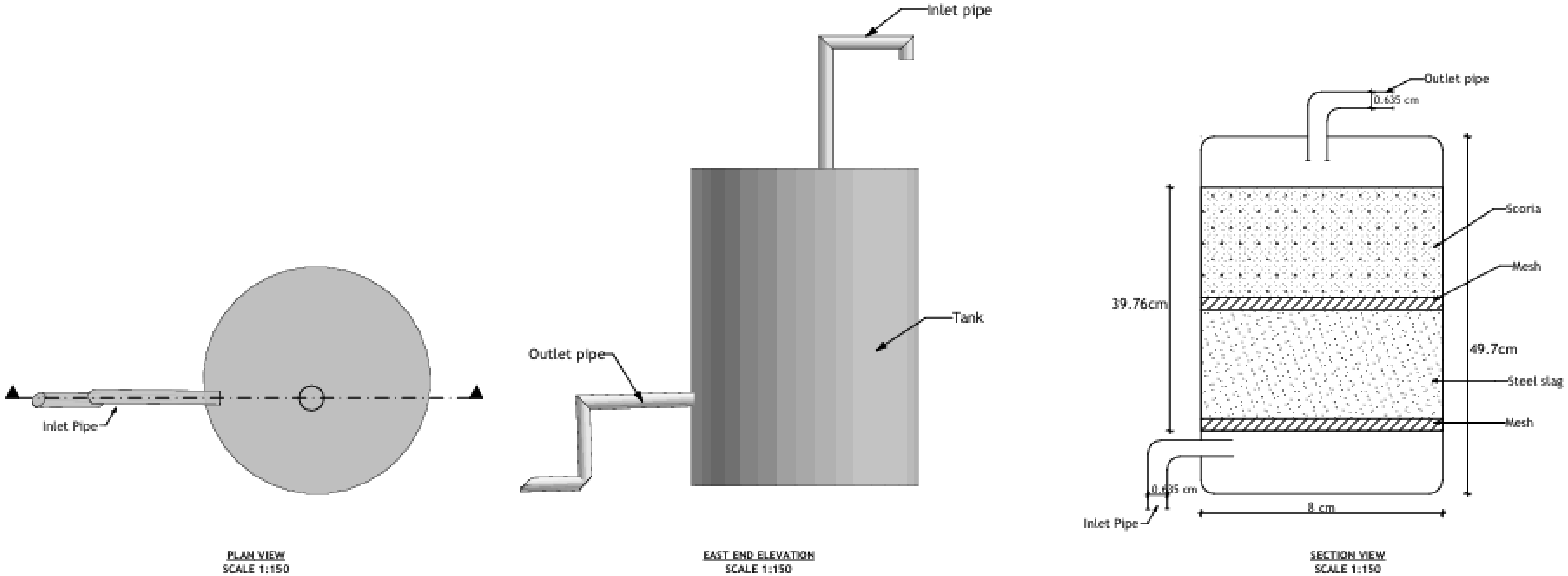
Efficiency reduction and improvement calculations were also done to determine the effectiveness of the unit through quantifying the impurity reduction and how methane content improved as shown below.

$CO_2$ efficiency reduction = $\frac{34.4-9.7}{34.4}*100 = 71.8\%$

$H_2S$ efficiency reduction = $\frac{37.5-0}{37.5} * 100 = 100\%$

Methane increment = 64.2 – 49.1= 15.1%

## DESIGN DRAWINGS




0. CLEANING & PURIFICATION UNIT (1) 1:100

**PROJECT : ASSESSING THE USE OF SCORIA AND STEEL SLAG IN THE PURIFICATION OF BIO GAS**

**DRAWING TITLE: CLEANING AND PURIFICATION UNIT**

**AUTHOR: KIZZA LINAH & AMARA TRACY**

**REG NUMBER: S21B32/071 & S21B32/049**

**Fabrication of purification unit**

In addition to the above, various considerations were made in fabrication to ensure effective operation of the purification system through precise flow, pressure control, material selection and component integration.

Under material selection, a high-density polyethylene (HDPE) drum was used due to its chemical inertness, durability and corrosion resistance. Mesh supports were used to support and evenly distribute material within the drum. Quarter inch (6.35mm) pipes were considered for inlet and outlet pipes to promote laminar flow, a more controlled and consistent distribution of gas, minimizing the risk of channeling.

For precise flow and pressure control, valves were incorporated at each piping junction, preventing backflow or pressure surges, essential for safety and maintaining optimal operating conditions during purification.

A bottom inlet and top outlet design was established to create an upward flow configuration, leveraging the lower density of biogas to ease its upward movement. This arrangement guarantees uniform gas dispersion as gas is pushed through the adsorbent beds allowing maximum contact with the reactive surfaces. Additionally, a layered configuration with steel slag at the bottom was done to enable the heavier gas, carbon dioxide, settle at the bottom and enable lighter gas to rise to contact with scoria capturing lighter impurities, and prevent slow gas movement and enhance overall purification efficiency.

Raw biogas was then passed through the fabricated purification unit across the three farms in triplicates and average values were obtained. The average values were then compared with the average values of biogas before purification as indicated in **table twelve** in the appendix.

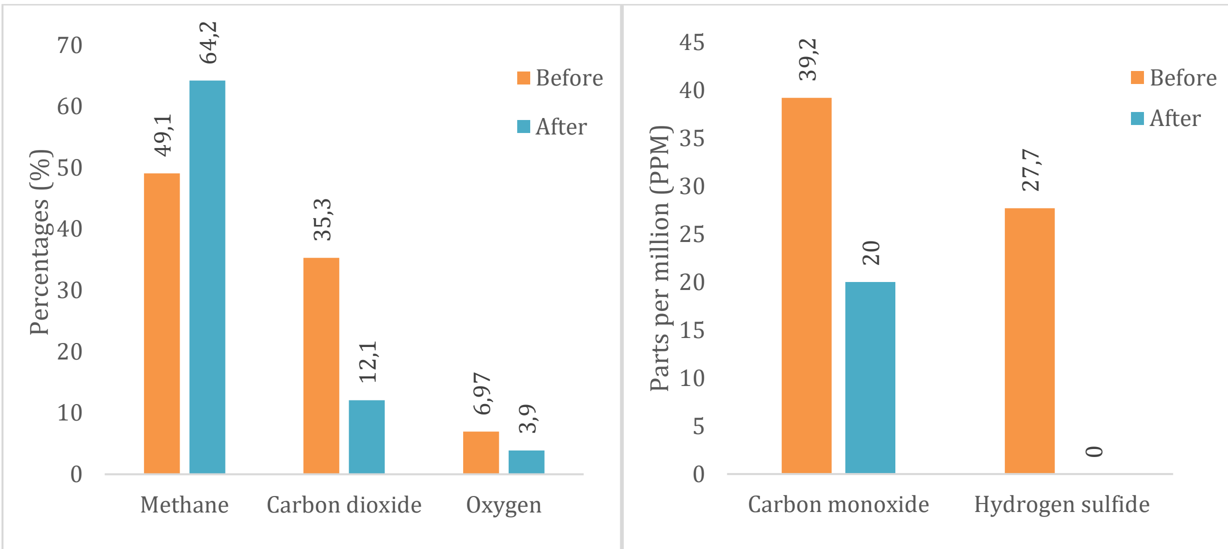



*Figure 8: Comparison before and after purification for farm 1 in percentages and ppm*

From **figure eight** above, Farm 1 relying solely on cow dung feedstock shows a significant reduction in carbon dioxide and an improvement in methane, implying that the reduction of carbon dioxide increased the calorific value of biogas. A reduction is also noted in oxygen, and for the impurities measured in parts per million, there is a significant reduction in carbon monoxide and hydrogen sulfide is reduced to zero.

Under farm 2, **figure nine** below shows that after purification, the biogas quality was significantly enhanced and carbon dioxide and oxygen decreased greatly from 33.1% to 11.4% and 5.6% to 3.9% respectively, improving the fuel’s energy content. Additionally, components of carbon monoxide were significantly reduced and hydrogen sulfide completely removed, reducing corrosion risks.

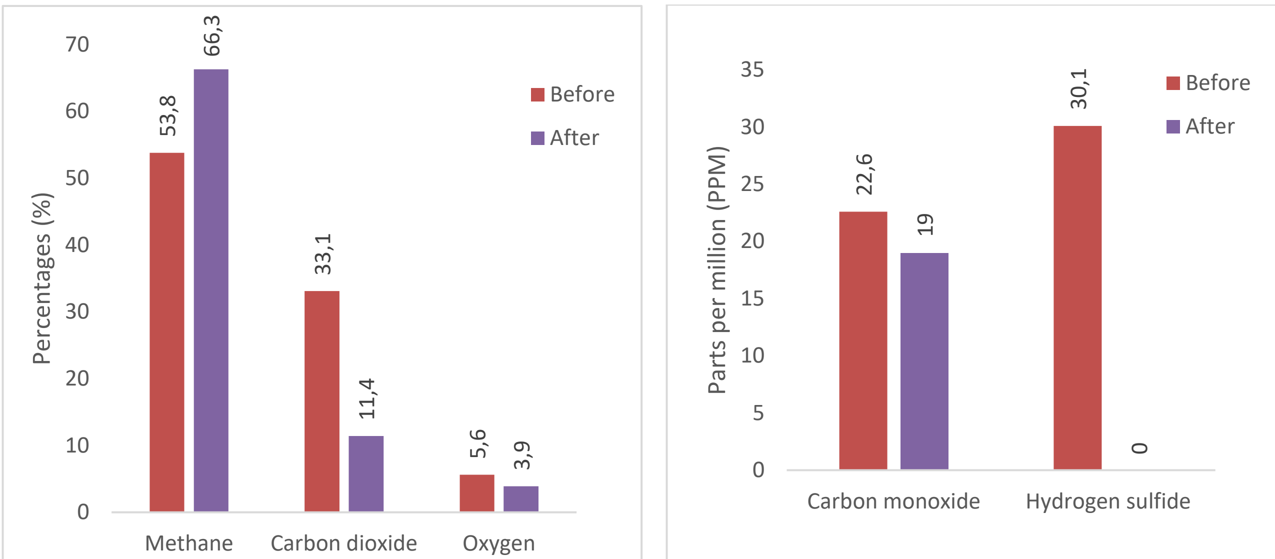



*Figure 9: Comparison before and after purification for farm 2 in percentages and ppm*

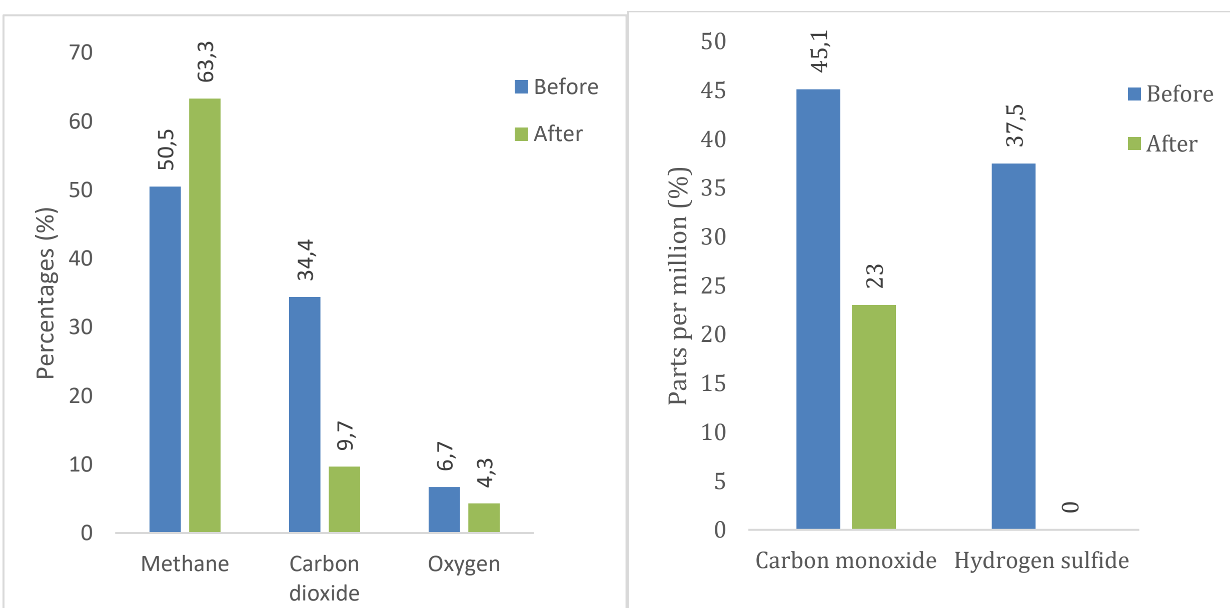



*Figure 10: Comparison for farm 3 before and after purification in percentage and ppm*

From **figure ten above**, the observed changes under farm 3, indicate an increase in methane content and a significant reduction in all impurities, that is, carbon dioxide is lowered from 34.4% to 9.7%, complete removal of hydrogen sulfide and oxygen and carbon monoxide are lowered significantly from 6.7 to 4.3% and 45.1 to 23ppm respectively.

**Conclusion**

In a nutshell, the detailed design and fabrication of the biogas purification unit was grounded in careful calculations, involving the use of the optimal mix obtained from objective 2, as well as integration of considerations such as material selection, configurations of flow, pressure, among others for fabrication of the unit. Experimental results across the three farms demonstrated a significant improvement in methane and significant reduction of impurities especially carbon dioxide and hydrogen sulfide. These outcomes confirmed the reliability of the design and effectiveness of the unit in enhancing the overall quality of biogas and demonstrates a scalable approach to biogas purification for medium scale farmers.

## 4.4 RESULTS: OBJECTIVE FOUR

Performing a Cost Benefit analysis for the use of scoria and steel slag in comparison to other purification materials.

Performance of scoria and steel slag in biogas purification

To assess the performance of scoria and steel slag in terms of effectiveness and longevity, the purification unit was run and tested over a period of one month. During this period, biogas samples were continuously collected and analyzed to monitor the depletion rate of materials and establish a feasible replacement interval for long term operational planning. The findings obtained were used to determine the ideal replacement schedule and incorporated in the cost benefit analysis (CBA), comparing scoria and steel slag with other purification materials.

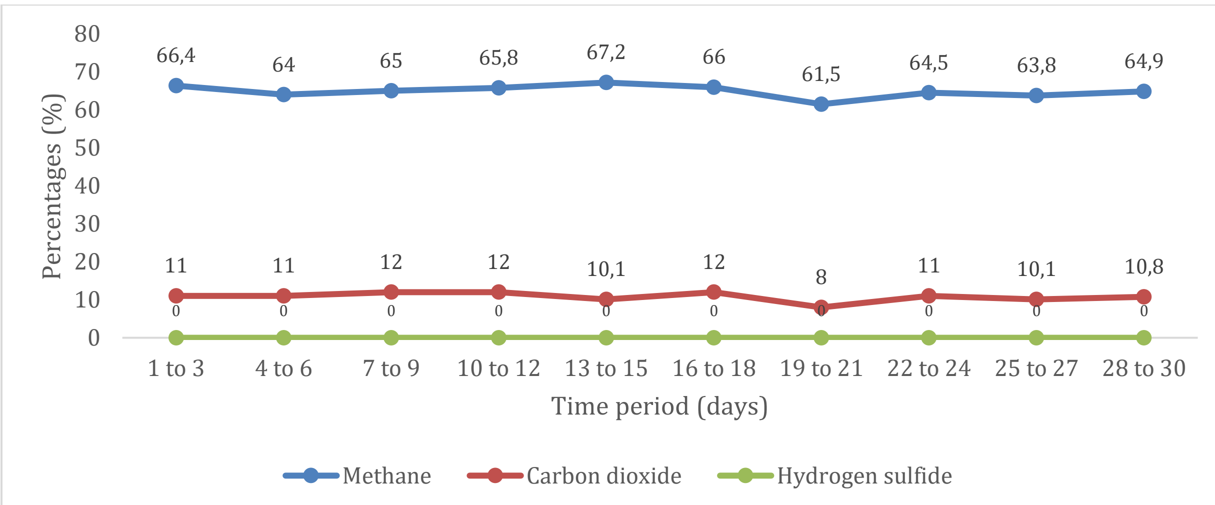



Figure 11: Performance of scoria and steel slag in biogas purification over a period of one month

As seen from figure **eleven** previously, over this period, carbon dioxide content which started from 11% gradually fluctuated and ultimately decreased to 10.8% by the end of the trial. This downward trend suggests that the steel slag continuously adsorbs and reduces the carbon dioxide content from the biogas. Hydrogen sulfide impurities as seen from graph in **figure eleven** remains zero or non-existent throughout the one-month analysis period, implying that the scoria sustained its purification performance.

Methane concentration remains relatively high and stable, starting from 66.4% and gradually fluctuating between 61.5% to 67.2%. This indicates that both scoria and steel slag effectively reduced unwanted impurities like carbon dioxide which would dilute its calorific value, thereby increasing the relative methane content in biogas.

Therefore, a gradual decline in $CO_2$ and $H_2S$ over the period, coupled with consistent methane implied that scoria and steel slag remained effective and did not reach saturation within the first thirty days, suggesting that the system would maintain optimal purification efficiency for a considerably longer period.

**Economic Evaluation of purification materials**

This section presents a comprehensive cost benefit analysis of the materials over a discounted five-year period. This incorporates the direct costs as well as associated benefits. This is to determine the economic viability of using scoria and steel slag in biogas purification, compared to other materials, looking at which one offers a better economic performance considering various factors as discussed in detail below.

**Key parameters**

Analysis period, t: Five years (March 2025 to March 2030)

Discount rate, r: A discount rate of 3% was applied to account for the time value of money.

Replacement interval: Based on the depletion analysis, a replacement interval every six months was considered to maintain its effectiveness.

Cost and benefit considerations

Costs: Acquisition costs, transport costs, preparation, operational costs were considered for all materials.

Material costs: Material prices, LPG costs, landfill costs were based on the prevailing market rates at the time of study.

Benefits: Benefits associated with savings in waste management, extended equipment lifespan, savings in chemical treatment, as well as LPG savings considering that LPG gas is used as the substitute for cooking.

Formulae used:

Discount Factor, DF = $\frac{1}{(1+r)^\wedge t}$

Where r=3% and t=5 years

Discounted Benefit=Benefit × DF

Net Benefit=Total Discounted Benefits−Total Costs

*Table 4: Detailed Cost Benefit Analysis of steel slag*

| Item | Nominal Value | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Total (Discounted) |
|---|---|---|---|---|---|---|---|
| Direct Costs (Steel Slag) | | | | | | | |
| Material Acquisition | 15,000 | 14,563 | 14,139 | 13,725 | 13,332 | 12,945 | 68,704 |
| Transport costs | 80,000 | 77,670 | 75,360 | 73,121 | 71,192 | 68,908 | 366,251 |
| Preparation | 30,000 | 29,127 | 28,215 | 27,421 | 26,698 | 25,841 | 137,302 |
| Operational Costs | 100,000 | 97,087 | 94,260 | 91,514 | 88,849 | 86,261 | 457,971 |
| Total Costs (Steel Slag) | 225,000 | 218,446 | 212,085 | 205,907 | 199,800 | 194,087 | 1,030,225 |
| Benefits (Steel Slag) | | | | | | | |
| Annual LPG savings | 694,000 | 673,786 | 653,737 | 634,210 | 616,000 | 598,000 | 3,175,733 |
| Reduced Maintenance Costs | 150,000 | 145,631 | 141,389 | 137,271 | 133,273 | 129,391 | 686,955 |
| Saving in waste management | 25,000 | 24,272 | 23,565 | 22,879 | 22,212 | 21,565 | 114,493 |
| Total Benefits (Steel Slag) | 869,000 | 843,689 | 818,691 | 794,360 | 771,485 | 748,956 | 3,977,181 |
| Net Benefit (Steel Slag, Discounted) | | | | | | | 2,946,956 |
| BENEFIT COST RATIO FOR STEEL SLAG | | | | | | | 3.86 |

*Table 5: Comparison analysis of purification materials used in carbon dioxide removal*

| Material | Acquisition cost (UGX) | Replacement Frequency (per year) | Additional Costs (UGX) | Annual Cost (UGX) | Total Discounted 5-Year Cost (UGX) | Associated Benefits (UGX) | Total Benefits discounted (UGX) | Net Benefits (Discounted) UGX | Benefit Cost ratio |
|---|---|---|---|---|---|---|---|---|---|
| Steel Slag | 15,000 | 2 | 195,000 | 225,000 | 1,030,435 | 869,000 | 3,982,000 | 2,951,565 | 3.87 |
| Clay Pellets | 45,000 | 2 | 250,000 | 340,000 | 1,557,101 | 825,000 | 3,777,000 | 2,219,899 | 2.43 |
| Lime | 110,000 | 3 | 175,000 | 505,000 | 2,313,790 | 790,000 | 3,619,000 | 1,305,210 | 1.56 |
| Activated Carbon | 10000 | 3 | 270,000 | 300,000 | 1,373,913 | 465,000 | 3,182,000 | 1,808,087 | 2.32 |

**Steel slag Cost Benefit Analysis**

A cost benefit analysis was firstly conducted for steel slag to determine its economic viability by estimating its associated annual costs and benefits, the discounted five-year costs and benefits and benefit cost ratio.

As seen from **table five** previously, for steel slag the total discounted benefits over the analysis period out-way the total discounted costs. With a Benefit/Cost Ratio of 3.86, steel slag offers a great return on investment, as every shilling invested generates nearly four times the benefits over the five-year period. Steel slag is then compared with other purification materials used in the removal of carbon dioxide in biogas as depicted in **table six** on the previous page.

The comparison table in table six above extends the analysis to include other purification materials used for removal of carbon dioxide. The table shows that steel slag outperforms the alternatives with the highest benefit cost ratio (3.86) and highest net benefit (UGX 2,951,565), demonstrating that steel slag has the highest economic viability by offering significant financial returns relative to the costs. This competitive advantage makes it an optimal, sustainable choice for medium scale farmers as it maximizes savings and benefits overtime.

*Table 6: Detailed Cost Benefit Analysis of scoria*

| Item | Nominal Value | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Total (Discounted) |
|---|---|---|---|---|---|---|---|
| Costs (Scoria) | | | | | | | |
| Material Acquisition | 30,000 | 29126.2 | 28277.877 | 27454.25 | 26654.611 | 25878.264 | 137,391 |
| Transport | 350,000 | 339806 | 329908.57 | 320299.58 | 310970.47 | 301913.07 | 1,602,898 |
| Preparation | 30,000 | 29,126 | 28,278 | 27,454 | 26,655 | 25,878 | 137,391 |
| Operational Costs | 50,000 | 48,544 | 47,130 | 45,757 | 44,424 | 43,130 | 228,985 |
| Total Costs (Scoria) | 460,000 | 446,601 | 434,594.56 | 420,965.58 | 408,703.5 | 396,799.96 | 2,107,665 |
| Benefits (Scoria) | | | | | | | |
| Extended Equipment Lifespan | 114,286 | 110,957 | 107,726 | 104,588 | 101,542 | 98,584 | 523,397 |
| Savings in Maintenance | 150,000 | 145,631 | 141,389 | 137,271 | 133,273 | 129,391 | 686,955 |
| Savings in Chemical treatment | 300,000 | 291,262 | 282,779 | 274,542 | 266,546 | 258,783 | 1,373,912 |
| Total Benefits (Scoria) | 564,000 | 547,573 | 531,622 | 516,146 | 501,116 | 486,502 | 2,584,264 |
| Net Benefit (Scoria, Discounted) | | | | | | | 475,294 |
| COST BENEFIT RATIO FOR SCORIA | | | | | | | 1.226 |

*Table 7: Comparison analysis of purification materials used in hydrogen sulfide removal*

| Material | Acquisition cost (UGX) | Replacement Frequency (per year) | Additional Costs (UGX) | Annual Cost (UGX) | Total Discounted 5-Year Cost (UGX) | Associated Benefits (UGX) | Total Benefits discounted (UGX) | Net Benefits (Discounted) UGX | Cost Benefit ratio |
|---|---|---|---|---|---|---|---|---|---|
| Scoria | 30,000 | 2 | 400,000 | 460,000 | 2,107,665 | 564,000 | 2,584,264 | 475,294 | 1.23 |
| Iron Oxide Pellets | 340,000 | 1 | 200,000 | 540,000 | 2,473,640 | 570,000 | 2,610,230 | 136,590 | 1.06 |
| Activated Carbon | 10000 | 3 | 270,000 | 300,000 | 1,373,913 | 390,000 | 1,586,086 | 212,174 | 1.15 |
| Ferric Oxide | 225,000 | 1 | 250,000 | 475,000 | 2,177,373 | 500,000 | 2,289,855 | 112,482 | 1.05 |

**Scoria analysis**

Scoria was similarly analyzed, considering the same replacement frequency, the benefits and costs associated were evaluated to obtain the net benefits and benefit cost ratio over the analysis period as discussed in the results analysis below.

**Table seven** depicted previously, shows a detailed breakdown of the economic evaluation of the use of scoria for purification. The table shows that it yields a net benefit of UGX 475,294 and a cost benefit ratio of 1.23 over a period of 5 years. This demonstrates that scoria yields a good return on investment, contributing to operational benefits overtime. Scoria is then compared with other purification materials used in the removal of hydrogen sulfide in biogas to determine the most economically viable option.

When compared across the purification materials indicated in **table eight**, scoria demonstrates the highest benefit cost ratio (1.23) as compared to the activated carbon, ferric oxide and others. It therefore yields a competitive advantage against the alternatives, offering it as the best economical alternative for hydrogen sulfide removal by medium scale farmers in the long run.

In a nutshell, this analysis demonstrates that both steel slag and scoria offer economically sound solutions for biogas purification as they both depict the highest benefit cost ratios and net benefits, as compared to the other purification materials used in removal of carbon dioxide and hydrogen sulfide respectively. Together, these materials offer a cost effective and sustainable option for biogas purification.

## CONCLUSION AND RECOMMENTDATIONS

This section presents our conclusions and recommendations from this research project based on the experimental results obtained. It briefly discusses the findings obtained from biogas composition, optimal adsorbent mix, system design and cost benefit analysis, as discussed in detail below. These insights are aimed to guide further improvements and practical applications on medium scale farms.

Raw biogas obtained from these medium scale farms in Wakiso was confirmed through analysis, to contain a significant proportion of impurities, primarily carbon dioxide and hydrogen sulfide accompanied with low methane. There was also variability in biogas composition influenced by differences in feedstock and farm operational practices, which underscores the need for purification to enhance the biogas quality.

The various trial mixes performed, indicated that specific ratios of scoria and steel slag effectively removed hydrogen sulfide and reduced carbon dioxide, thereby increasing the methane concentration in the biogas. An optimum concentration of 600g:600g of scoria and steel slag respectively was obtained where the adsorbents performed together as scoria's porous nature effectively removed hydrogen sulfide and calcium rich steel slag captured carbon dioxide

Detailed design and fabrication of the purification unit was based on various considerations, careful design calculations and the optimum concentration Experimental results from running the unit at the farms showed a significant increase in methane and a notable reduction in impurities, primarily carbon dioxide and methane. These outcomes confirm the reliability of the design and demonstrate the unit's effectiveness in enhancing biogas quality, offering a scalable solution for medium scale farmers.

The cost benefit analysis revealed that the use of scoria and steel slag as purification materials offers a more affordable alternative to conventional adsorbents. Their effective performance, abundance and locally sourced nature in Uganda makes them economically viable for medium scale farms.

## RECOMMENDATIONS

Extended sampling durations can be done across different seasons to capture the full range of variations in raw biogas components.

Further research on the integration of additional purification stages or materials can be done to eliminate certain residual impurities further such as carbon monoxide.

Additionally, future research can be done to develop cost-effective regeneration techniques for the adsorbents, in order to increase their operational lifespan as well as to sustain the purification efficiency for longer time periods.

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## APPENDICES

## APPENDIX A: TABLES OF RESULTS

*Table 8: Results of raw biogas composition of medium scale farmers in Namulonge*

| COMPOSITION | FARM ONE | FARM TWO | FARM THREE | AVERAGE |
|---|---|---|---|---|
| Methane (%) | 49.1 | 53.8 | 50.5 | 51.13 |
| Carbondioxide (%) | 35.3 | 33.1 | 34.4 | 34.27 |
| Oxygen (%) | 6.97 | 5.6 | 6.7 | 6.42 |
| Carbon monoxide (ppm) | 39.2 | 22.6 | 45.1 | 35.63 |
| Hydrogen Sulfide (ppm) | 27.7 | 30.1 | 37.5 | 31.77 |

*Table 9: Results of average composition from trial mixes of scoria and steel slag conducted*

| Biogas composition | Mix 1(150:300) | Mix 2(300:300) | Mix 3(500:500) | Mix 4(600:600) | Mix 5 (600:700) | Mix 6 (700:800) |
|---|---|---|---|---|---|---|
| Methane | 47.7 | 49.8 | 62.2 | 66.4 | 60.4 | 49.7 |
| Carbon dioxide | 32 | 21 | 16 | 11 | 14 | 18 |
| Oxygen | 13.2 | 9.2 | 8.9 | 3.2 | 4.9 | 8.2 |
| Carbon monoxide | 39 | 35 | 28 | 20 | 30 | 32 |
| Hydrogen sulfide | 28 | 26 | 20 | 0 | 0 | 4 |

*Table 10: Average composition of biogas from each trial mix for the three farms*

| Farms | Farm one | | | Farm two | | | Farm three | | |
|---|---|---|---|---|---|---|---|---|---|
| Trial Mixes | Mix 1(500: 500) | Mix 2(600: 600) | Mix 3 (600: 700) | Mix 1(500: 500) | Mix 2(600: 600) | Mix 3 (600: 700) | Mix 1(500: 500) | Mix 2(600: 600) | Mix 3 (600: 700) |
| Methane | 62.2 | 66.4 | 60.4 | 54 | 65.8 | 60.8 | 53.8 | 61.5 | 56.6 |
| Carbond ioxide | 16 | 11 | 14 | 22 | 12 | 17 | 26 | 8 | 15 |
| Oxygen | 8.9 | 3.2 | 4.9 | 5.4 | 3.7 | 5 | 5.8 | 4.6 | 6.6 |
| Carbon monoxid e | 28 | 20 | 30 | 23 | 16 | 24 | 29 | 22 | 26 |
| Hydroge n sulfide | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Table 11: Comparison of biogas components before and after purification*

| Gas | Farm 1 | | Farm 2 | | Farm 3 | |
|---|---|---|---|---|---|---|
| | Before | After | Before | After | Before | After |
| Methane | 49.1 | 64.2 | 53.8 | 66.3 | 50.5 | 63.3 |
| Carbon dioxide | 35.3 | 12.1 | 33.1 | 11.4 | 34.4 | 9.7 |
| Oxygen | 6.97 | 3.9 | 5.6 | 3.9 | 6.7 | 4.3 |
| Carbon monoxide | 39.2 | 20 | 22.6 | 19 | 45.1 | 23 |
| Hydrogen sulfide | 27.7 | 0 | 30.1 | 0 | 37.5 | 0 |

## APPENDIX B: PICTORIAL


*Figure 12: Bosean Gas Detector*


*Figure 13: Multi Tec 540*

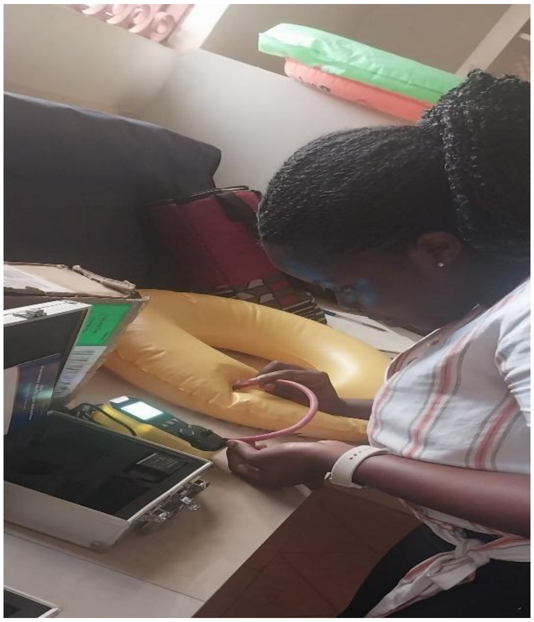

*Figure 14: Biogas Quality test being conducted*

*Figure 15: Crushing of steel slag*

*Figure 16: Weighing of steel slag after crushing*

*Figure 17: Layering of scoria in the unit*

*Figure 18: Fabrication of the purification unit*

*Figure 19: Setup of the cleaning and purification*

## APPENDIX C: LABORATORY TEST RESULTS

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**LABORATORY TEST REPORT**

| | | |
|---|---|---|
| **Certificate Number: A005** | | |
| **Client Name:** AMARA TRACY & KIZZA LINAH | **Sample Receipt Date:** 19/01/2025 | **Analysis Start Date:** 23/01/2025 |
| **Client Address and Contact:** UCU P.O Box 4, Mukono 0758307066 | | |
| **Lab Sample ID: A005/2025** | **Date of analysis completion** 23/01/2025 | **Date of issue of the certificate** 01/31/2025 |
| **Client Sample ID:** Biogas A3E | | |
| **Sample type and Location:** Biogas samples from Farms in Namulonge, Wakiso District | | |
| **State of the sample on delivery:** Gaseous in Enclosed Gas Bags | **Testing Conditions:** Ambient Temperature: 22°C | |
| | **Testing Methods:** IEC 60079-29 | |

**BIOGAS QUALITY TEST**

| Farm 1 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
|---|---|---|---|---|
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 45.4% | 46% | 42.4% | **44.6%** |
| Carbon dioxide | 29% | 28% | 30% | **29%** |
| Oxygen | 12% | 13.6% | 14% | **13.2%** |
| Carbon monoxide | 37 ppm | 38 ppm | 39 ppm | **38 ppm** |
| Hydrogen Sulphide | 32.6 ppm | 35 ppm | 33.2 ppm | **33.6 ppm** |

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| BIOGAS QUALITY TEST | | | | |
| --- | --- | --- | --- | --- |
| Farm 2 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 55.4% | 54% | 55% | **54.8%** |
| Carbon dioxide | 32% | 28% | 30% | **30%** |
| Oxygen | 9% | 8.3% | 7% | **8.1%** |
| Carbon monoxide | 12 ppm | 11 ppm | 10 ppm | **11 ppm** |
| Hydrogen Sulphide | 24 ppm | 22.5 ppm | 23.4 ppm | **23.3 ppm** |

| BIOGAS QUALITY TEST | | | | |
| --- | --- | --- | --- | --- |
| Farm 3 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 53.3% | 54% | 52% | **53.1%** |
| Carbon dioxide | 25% | 24% | 23% | **24%** |
| Oxygen | 15% | 13.8% | 12% | **13.6%** |
| Carbon monoxide | 22 ppm | 20 ppm | 18 ppm | **20 ppm** |
| Hydrogen Sulphide | 32 ppm | 29.1 ppm | 31.6 ppm | **30.9 ppm** |

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## LABORATORY TEST REPORT

| | | |
|---|---|---|
| **Certificate Number: A006** | | |
| **Client Name:** AMARA TRACY & KIZZA LINAH | **Sample Receipt Date:** 03/02/2025 | **Analysis Start Date:** 03/02/2025 |
| **Client Address and Contact:** UCU P.O Box 4, Mukono 0758307066 | | |
| **Lab Sample ID: A006/2025** | **Date of analysis completion** 03/02/2025 | **Date of issue of the certificate** 06/02/2025 |
| **Client Sample ID:** Biogas A3F | | |
| **Sample type and Location:** Biogas samples from Farms in Namulonge, Wakiso District | | |
| **State of the sample on delivery:** Gaseous in Enclosed Gas Bags | **Testing Conditions:** Ambient Temperature: 22$^0$C | |
| | **Testing Methods:** IEC 60079-29 | |

## BIOGAS QUALITY TEST

| Farm 1 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
|---|---|---|---|---|
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 52.4% | 50.7% | 51.3% | **51.5%** |
| Carbon dioxide | 46% | 39% | 32% | **39%** |
| Oxygen | 1.5% | 5% | 5.9% | **4.1%** |
| Carbon monoxide | 39.4 ppm | 40.4 ppm | 41.4 ppm | **40.4 ppm** |
| Hydrogen Sulphide | 30 ppm | 22 ppm | 21 ppm | **24.4 ppm** |

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| BIOGAS QUALITY TEST | | | | |
|---|---|---|---|---|
| Farm 2 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 51.6% | 49.3% | 52.6% | 51.2% |
| Carbon dioxide | 38% | 35% | 33% | 35.3% |
| Oxygen | 8.4% | 2.6% | 3.3% | 4.8% |
| Carbon monoxide | 16 ppm | 26 ppm | 40 ppm | 27 ppm |
| Hydrogen Sulphide | 27 ppm | 28 ppm | 25 ppm | 27 ppm |

| BIOGAS QUALITY TEST | | | | |
|---|---|---|---|---|
| Farm 3 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 48.8% | 45.6% | 50.1% | 48.2% |
| Carbon dioxide | 40% | 38% | 42.3% | 40.1% |
| Oxygen | 7% | 1.4% | 1.8% | 3.4% |
| Carbon monoxide | 73 ppm | 75 ppm | 72 ppm | 73.3 ppm |
| Hydrogen Sulphide | 37 ppm | 45 ppm | 37 ppm | 39.7 ppm |

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## LABORATORY TEST REPORT

| | | |
|---|---|---|
| **Certificate Number: A007** | | |
| **Client Name:** AMARA TRACY & KIZZA LINAH | **Sample Receipt Date:**<br>04/02/2025 | **Analysis Start Date:**<br>04/02/2025 |
| **Client Address and Contact:** UCU P.O Box 4, Mukono 0758307066 | | |
| **Lab Sample ID: A007/2025** | **Date of analysis completion**<br>04/02/2025 | **Date of issue of the certificate**<br>06/02/2025 |
| **Client Sample ID:** Biogas A3G | | |
| **Sample type and Location:** Biogas samples from Farms in Namulonge, Wakiso District | | |
| **State of the sample on delivery:**<br>Gaseous in Enclosed Gas Bags | **Testing Conditions:** Ambient Temperature: 22°C | |
| | **Testing Methods:** IEC 60079-29 | |

| BIOGAS QUALITY TEST | | | | |
|---|---|---|---|---|
| Farm 1 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 55.3% | 46.6% | 52.1% | 51.3% |
| Carbon dioxide | 37% | 38% | 38% | 38% |
| Oxygen | 5% | 3.3% | 2.6% | 3.6% |
| Carbon monoxide | 38 ppm | 39 ppm | 40 ppm | 39 ppm |
| Hydrogen Sulphide | 30 ppm | 22 ppm | 22 ppm | 25 ppm |

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| BIOGAS QUALITY TEST | | | | |
|---|---|---|---|---|
| Farm 2 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 55.4% | 56% | 55% | **55.5%** |
| Carbon dioxide | 28% | 38% | 36% | **34%** |
| Oxygen | 5.3% | 4% | 3.8% | **3.8%** |
| Carbon monoxide | 29 ppm | 30 ppm | 30 ppm | **30 ppm** |
| Hydrogen Sulphide | 37 ppm | 45 ppm | 37 ppm | **40 ppm** |

| BIOGAS QUALITY TEST | | | | |
|---|---|---|---|---|
| Farm 3 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | |
| | Test 1 | Test 2 | Test 3 | AVERAGE |
| Methane | 48.3% | 50.1% | 52.1% | **50.1%** |
| Carbon dioxide | 22% | 48% | 47% | **39%** |
| Oxygen | 8.2% | 1.1% | 0.2% | **3.1%** |
| Carbon monoxide | 40 ppm | 30 ppm | 35 ppm | **35 ppm** |
| Hydrogen Sulphide | 45 ppm | 50 ppm | 30 ppm | **42 ppm** |

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## LABORATORY TEST REPORT

| **Certificate Number:** A008 | | |
|---|---|---|
| **Client Name:** AMARA TRACY & KIZZA LINAH<br>**Client Address and Contact:** UCU P.O Box 4, Mukono 0758307066 | **Sample Receipt Date:**<br>07/02/2025 | **Analysis Start Date:**<br>07/02/2025 |
| **Lab Sample ID:** A008/2025<br>**Client Sample ID:** Biogas A3H<br>**Sample type and Location:** Biogas samples from Farms in Namulonge, Wakiso District | **Date of analysis completion**<br>07/02/2025 | **Date of issue of the certificate**<br>07/02/2025 |
| **State of the sample on delivery:**<br>Gaseous in Enclosed Gas Bags | **Testing Conditions:**<br>Ambient Temperature: 22°C<br>**Testing Methods:** IEC 60079-29 | |

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## BIOGAS QUALITY TEST

**Multitec 540 & Bosean gas detector**

| Biogas Sample sourced from Farm 1 | Trial mix one: Steel slag 150g : Scoria 300g | | | | Trial mix two: Steel slag 300g : Scoria 300g | | | | Trial mix three: Steel slag 500g : Scoria 500g | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **GAS** | **1** | **2** | **3** | **AVG.** | **1** | **2** | **3** | **AVG.** | **1** | **2** | **3** | **AVG.** |
| **Methane** | 45.4% | 49.2% | 48.5% | **47.7%** | 49.4 | 49.7 | 50.3 | **49.8%** | 63.4% | 60.5% | 62.7% | **62.2%** |
| **Carbon dioxide** | 32.7% | 30% | 33.3% | **32%** | 19.4 | 21.9 | 21.7 | **21%** | 13.9% | 17.5% | 16.6% | **16%** |
| **Oxygen** | 11.9% | 14.6% | 13.1% | **13.2%** | 9.3% | 8.5% | 9.8% | **9.2%** | 8.9% | 8.8% | 9.0% | **8.9%** |
| **Carbon monoxide** | 148ppm | 148ppm | 154ppm | **150ppm** | 150ppm | 147ppm | 144ppm | **147ppm** | 137ppm | 136ppm | 135ppm | **136ppm** |
| **Hydrogen Sulphide** | 32ppm | 29ppm | 24ppm | **28ppm** | 28ppm | 25ppm | 25ppm | **26ppm** | 19ppm | 22ppm | 19ppm | **20ppm** |

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## LABORATORY TEST REPORT

| | | |
|---|---|---|
| **Certificate Number: A008** | | |
| **Client Name:** AMARA TRACY & KIZZA LINAH | **Sample Receipt Date:** | **Analysis Start Date:** |
| **Client Address and Contact:** UCU P.O Box 4, Mukono 0758307066 | 18/02/2025 | 18/02/2025 |
| **Lab Sample ID: A008/2025** | **Date of analysis completion** | **Date of issue of the certificate** |
| **Client Sample ID:** Biogas A3G | | |
| **Sample type and Location:** Biogas samples from Farms in Namulonge, Wakiso District | 18/02/2025 | 18/02/2025 |
| **State of the sample on delivery:** Gaseous in Enclosed Gas Bags | **Testing Conditions:** Ambient Temperature: 22°C | |
| | **Testing Methods:** IEC 60079-29 | |

| **BIOGAS QUALITY TEST** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Farm 1 Biogas Sample** | **Multitec 540 & Bosean Gas Detectors** | | | | | | | | | | | |
| COMPOSITION | TRIAL MIX 1 600:600 | | | | TRIAL MIX 2 600:700 | | | | TRIAL MIX 3 700:800 | | | |
| | 1 | 2 | 3 | **AVG** | 1 | 2 | 3 | **AVG** | 1 | 2 | 3 | **AVG** |
| METHANE (%) | 67.2 | 66 | 66 | **66.4** | 60 | 60.4 | 61 | **60.4** | 52.2 | 48 | 49 | **49.7** |
| CARBON DIOXIDE (%) | 10 | 12 | 10 | **11** | 12 | 14 | 16 | **14** | 16 | 18 | 20 | **18** |
| OXYGEN (%) | 2.8 | 3.2 | 3.6 | **3.2** | 4.5 | 5.5 | 4.7 | **4.9** | 7.8 | 8 | 8.8 | **8.2** |
| CARBON MONOXIDE (ppm) | 20 | 19 | 21 | **20** | 29 | 31 | 30 | **30** | 30 | 32 | 34 | **32** |
| HYDROGEN SULPHIDE (ppm) | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** | 4 | 4 | 4 | [illegible] |

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| BIOGAS QUALITY TEST | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm 2 Biogas Sample | Multitec 540 & Bosean Gas Detectors | | | | | | | | | | | |
| COMPOSITION | TRIAL MIX 1 500:500 | | | | TRIAL MIX 2 600:600 | | | | TRIAL MIX 3 600:700 | | | |
| | 1 | 2 | 3 | AVG | 1 | 2 | 3 | AVG | 1 | 2 | 3 | AVG |
| METHANE (%) | 56 | 54 | 52 | **54** | 64 | 68.6 | 65 | **65.8** | 61 | 60.8 | 60.5 | **60.8** |
| CARBON DIOXIDE (%) | 20 | 22 | 24 | **22** | 10 | 12 | 14 | **12** | 18 | 17 | 16 | **17** |
| OXYGEN (%) | 4.9 | 5.2 | 6.1 | **5.4** | 3.4 | 4.2 | 3.5 | **3.7** | 5 | 4 | 6 | **5** |
| CARBON MONOXIDE (ppm) | 23 | 25 | 22 | **23** | 14 | 16 | 18 | **16** | 22 | 23 | 28 | **24** |
| HYDROGEN SULPHIDE (ppm) | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** |

| BIOGAS QUALITY TEST | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm 3 Biogas Sample | Multitec 540 & Bosean Gas Detectors | | | | | | | | | | | |
| COMPOSITION | TRIAL MIX 1 500:500 | | | | TRIAL MIX 2 600:600 | | | | TRIAL MIX 3 600:700 | | | |
| | 1 | 2 | 3 | AVG | 1 | 2 | 3 | AVG | 1 | 2 | 3 | AVG |
| Methane (%) | 56 | 52.8 | 52.8 | **53.8** | 62 | 61 | 61.5 | **61.5** | 56 | 57 | 57 | **56.6** |
| Carbon dioxide (%) | 25 | 26 | 27 | **26** | 8 | 7 | 9 | **8** | 15 | 14 | 16 | **15** |
| Oxygen (%) | 5.9 | 5.8 | 5.7 | **5.8** | 4.6 | 4.7 | 4.5 | **4.6** | 6 | 6.6 | 6.8 | **6.6** |
| Carbon monoxide (ppm) | 28 | 29 | 30 | **29** | 20 | 24 | 22 | **22** | 28 | 24 | [illegible] | **26** |
| Hydrogen Sulfide(ppm) | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** | 0 | 0 | [illegible] | **0** |

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## LABORATORY TEST REPORT

| | | |
|---|---|---|
| **Certificate Number: A010** | | |
| **Client Name:** AMARA TRACY & KIZZA LINAH | **Sample Receipt Date:** | **Analysis Start Date:** |
| **Client Address and Contact:** UCU P.O Box 4, Mukono 0758307066 | 07/03/2025 | 07/03/2025 |
| **Lab Sample ID: A010/2025** | **Date of analysis completion** | **Date of issue of the certificate** |
| **Client Sample ID:** Biogas A3F | | |
| **Sample type and Location:** Biogas samples from Farms in Namulonge, Wakiso District | 07/03/2025 | 07/03/2025 |
| **State of the sample on delivery:** Gaseous in Enclosed Gas Bags | **Testing Conditions:** Ambient Temperature: 22°C | |
| | **Testing Methods:** IEC 60079-29 | |

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| BIOGAS QUALITY TEST | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm 1 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | | | | | | | | | |
| | | | | AVG | | | | AVG | | | | AVG |
| Methane | 67.2 | 66 | 66 | **66.4** | 63 | 64.1 | 65 | **64** | 64 | 66 | 65.1 | **65** |
| Carbon dioxide | 10 | 12 | 10 | **11** | 11 | 12 | 11 | **11** | 10 | 12 | 14 | **12** |
| oxygen | 2.8 | 3.2 | 3.6 | **3.2** | 3.3 | 3.4 | 3.6 | **3.4** | 4.1 | 4.3 | 5 | **4.4** |
| Carbon monoxide | 20 | 19 | 21 | **20** | 19 | 18 | 20 | **19** | 20 | 21 | 19 | **20** |
| Hydrogen sulfide | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** |

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## LABORATORY TEST REPORT

| | | | |
|---|---|---|---|
| **Certificate Number: A010** | | | |
| **Client Name:** AMARA TRACY & KIZZA LINAH | **Sample Receipt Date:** 07/03/2025 | **Analysis Start Date:** 07/03/2025 | |
| **Client Address and Contact:** UCU P.O Box 4, Mukono 0758307066 | | | |
| **Lab Sample ID: A010/2025** | **Date of analysis completion** 07/03/2025 | **Date of issue of the certificate** 07/03/2025 | |
| **Client Sample ID:** Biogas A3F | | | |
| **Sample type and Location:** Biogas samples from Farms in Namulonge, Wakiso District | | | |
| **State of the sample on delivery:** Gaseous in Enclosed Gas Bags | **Testing Conditions:** Ambient Temperature: 22°C | | |
| | **Testing Methods:** IEC 60079-29 | | |

| **BIOGAS QUALITY TEST** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Farm 1 Biogas Sample** | **Multitec 540 & Bosean Gas Detector** | | | | | | | | | | | |
| | | | | AVG | | | | AVG | | | | AVG |
| Methane | 67.2 | 66 | 66 | **66.4** | 63 | 64.1 | 65 | **64** | 64 | 66 | 65.1 | **65** |
| Carbon dioxide | 10 | 12 | 10 | **11** | 11 | 12 | 11 | **11** | 10 | 12 | 14 | **12** |
| oxygen | 2.8 | 3.2 | 3.6 | **3.2** | 3.3 | 3.4 | 3.6 | **3.4** | 4.1 | 4.3 | 5 | **4.4** |
| Carbon monoxide | 20 | 19 | 21 | **20** | 19 | 18 | 20 | **19** | 20 | 21 | 19 | **20** |
| Hydrogen sulfide | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** |

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| BIOGAS QUALITY TEST | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm 2 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | | | | | | | | | |
| Methane | 64 | 68.6 | 65 | 65.8 | 66.8 | 67.6 | 67 | **67.2** | 66.1 | 65 | 67 | 66 |
| Carbon dioxide | 10 | 12 | 14 | **12** | 10 | 9.3 | 11 | **10.1** | 12.3 | 11.8 | 12 | **12** |
| oxygen | 3.4 | 4.2 | 3.5 | **3.7** | 3.9 | 3.8 | 3.7 | **3.8** | 4.3 | 4.4 | 4.2 | **4.3** |
| Carbon monoxide | 14 | 16 | 18 | **16** | 19 | 20 | 21 | **20** | 22 | 21 | 20 | **21** |
| Hydrogen sulfide | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** |

| BIOGAS QUALITY TEST | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Farm 3 Biogas Sample | Multitec 540 & Bosean Gas Detector | | | | | | | | | | | |
| | 1 | 2 | 3 | AVG | 1 | 2 | 3 | AVG | 1 | 2 | 3 | AVG |
| Methane | 62 | 61 | 61.5 | **61.5** | 65 | 64 | 64.6 | **64.5** | 63 | 66 | 62.2 | **63.8** |
| Carbon dioxide | 8 | 7 | 9 | **8** | 10 | 11 | 12 | **11** | 10 | 11 | 9.3 | **10.1** |
| oxygen | 4.6 | 4.7 | 4.5 | **4.6** | 4.3 | 4.4 | 4.5 | **4.4** | 3.8 | 3.7 | 3.9 | **3.8** |
| Carbon monoxide | 20 | 24 | 22 | **22** | 24 | 22 | 26 | **24** | 22 | 24 | 20 | **22** |
| Hydrogen sulfide | 0 | 0 | 0 | **0** | 0 | 0 | 0 | **0** | 0 | 0 | | **0** |



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