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APPLICABILITY AND FEASIBILITY OF LOCALLY AVAILABLE BIOGAS PURIFICATION OPTIONS IN UGANDA

BY

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A DISSERTATION SUBMITTED TO MAKERERE UNIVERSITY BUSINESS SCHOOL (FACULTY OF GRADUATE STUDIES AND RESEARCH) IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENERGY ECONOMICS AND GOVERNANCE OF MAKERERE UNIVERSITY

PLAN A

DECEMBER, 2025

DECLARATION

I hereby declare that this Dissertation is a result of my original ideas, and it has never been presented anywhere for academic purposes.

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APPROVAL

This thesis report has been submitted with the approval of my supervisors, whose signatures are appended against their respective names below;

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Dedication

This thesis is dedicated to the resilient rural communities of Uganda, whose ingenuity and perseverance inspire the pursuit of sustainable energy solutions. I also dedicate this thesis to my beloved family, whose boundless love, sacrifices, and encouragement have been the bedrock of my academic journey. Finally, I offer this work in honor of the visionaries striving for energy equity and environmental stewardship across Africa, in pursuit of a world where every household thrives under the glow of renewable energy.

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List of Abbreviations

CAPEX Capital Expenditure

CBA Cost-Benefit Analysis

CDM Clean Development Mechanism

CH_4 Methane

CO Carbon Monoxide

CO_2 Carbon Dioxide

EF Emission Factor

GGDS Green Growth Development Strategy

GHG Greenhouse Gas

GWP Global Warming Potential

GWP_{100} Global Warming Potential over a 100-year horizon

H_2CO_3 Carbonic Acid

H_2O Water

H_2S Hydrogen Sulfide

H_2SO_4 Sulfuric Acid

HCO_3^- Bicarbonate Ion

HS^- Bisulfide Ion

IEA International Energy Agency

IPCC Intergovernmental Panel on Climate Change

LCA Life Cycle Assessment

LCOBP Levelized Cost of Biogas Purification

MEMD Ministry of Energy and Mineral Development

N_2 Nitrogen

NDCs Nationally Determined Contributions

NH_3 Ammonia

NOx Nitrogen Oxides

NPV Net Present Value

O&M Operations and Maintenance

O_2 Oxygen

OPEX Operational Expenditure

RBV Resource-Based View

SDG Sustainable Development Goal

SO_2 Sulfur Dioxide

SO_3 Sulfur Trioxide

TAN Total Ammonia Nitrogen

UNFCCC United Nations Framework Convention on Climate Change

VMSs Volatile Methyl Siloxanes

VOCs Volatile Organic Compounds

WHO World Health Organization

Abstract

This study rigorously evaluated the techno-economic and environmental performance of two locally accessible biogas purification methods namely activated carbon adsorption and water scrubbing in the context of rural Uganda, where energy access remains limited. Biogas, primarily methane (CH_4), is often contaminated with impurities such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S), which diminish its calorific value and pose health, environmental, and infrastructural risks. Employing a quantitative experimental design at Makerere University Business School's Green Unit Laboratory, the study assessesed purification efficiency, cost-effectiveness, and environmental impacts using locally sourced materials. Results indicated that water scrubbing achieves a higher methane concentration (81.33% vs. 79.00%) and CO_2 removal efficiency (63.57% vs. 58.58%), while activated carbon excels in H_2S removal (68.42% vs. 42.11%), critical for corrosion prevention and safety. Techno-economic analysis revealed water scrubbing's lower Levelized Cost of Biogas Purification (LCOBP) ($0.46/m³ vs. $0.71/m³), driven by reduced capital and operational expenditures, with sensitivity analyses confirming cost advantages at scale (LCOBP: $0.31/m³ at 2,600.63 m³/year). Environmentally, water scrubbing avoided 14.94 kg CO_2-equivalent emissions annually, slightly outperforming activated carbon (13.86 kg CO_2-eq/year), though the latter's superior H_2S removal yields greater climate benefits when Global Warming Potential (GWP_{100} = 13) is considered (236.6 vs. 144.3 kg CO_2-eq/year). Grounded in the Resource-Based View (RBV) framework, the study highlights the competitive advantage of leveraging local resources (water, agricultural waste) for sustainable biogas production. Recommendations include prioritizing water scrubbing for cost-sensitive rural applications, using activated carbon for H_2S-heavy feedstocks, and exploring hybrid systems to optimize performance. These findings align with Uganda's National Biogas Strategy (2023–2030) and Sustainable Development Goals (SDGs 7, 13, 1), offering a scalable model for enhancing energy security, environmental sustainability, and rural livelihoods through community-driven biogas purification.

Keywords: Biogas purification, activated carbon, water scrubbing, techno-economic feasibility, environmental impact, Uganda, sustainable energy, Resource-Based View, SDGs

CHAPTER ONE

1.0 Background

1.1 Introduction

This section introduces the significance of biogas purification in Uganda, focusing on the country's energy challenges and the potential of biogas as a renewable energy source. It highlights the impurities present in biogas and their environmental and health impacts. Additionally, it studies the existing research on purification methods using locally available materials and the need for further optimization to make biogas purification economically feasible and accessible to rural communities. It provides a benchmark for the phenomenon under study.

Fossill fuels are currently the most utilized energy source globally with over 80% of the global energy needs relying on this non-renewable source (Ahmed et al., 2021; Jefferson, 2015). Fossil fuels are depleting and emitting greenhouse gases, which pose serious challenges. The most abundant greenhouse gas is carbon dioxide (CO_2), which is responsible for global warming and frequent natural disasters. These phenomena may lead to the displacement of people from their households and regions. Therefore, technologies that remove CO_2 from the atmosphere, such as carbon capture and storage, and conversion, are being developed and studied constantly (Werkneh, 2022). However, these technologies are not widely applied because they are not economically viable. Moreover, for the sake of sustainability and economic growth, there should be a shift from fossil fuels to renewable energy sources that have low or zero carbon emissions. To satisfy global energy needs, renewables should have a bigger share of the energy mix by 2050, but the current pace of development is too slow due to both technological and economic factors (Ahmed et al., 2021).

The growing scarcity of these fossil fuels, climate change, and energy needs require locally available and economically viable renewable energy interventions, for which biofuels namely, biogas, biodiesel, and bioethanol, have been found suitable for the purpose (Werkneh, 2022; Ahmed et al., 2021; McCord et al., 2019). The production of biofuels is currently experiencing commendable research, development, and innovation to cover the growing global demand for energy. According to Ahmed et al., (2021), Biofuels are expected to supply close to one-fourth of the primary energy within the next three decades across the globe. Similarly, Biogas is also expected to continue leading the trend as an emerging market for renewable energy. Cooking, transportation, heating, and power are some of the areas where biogas energy should be extended in both developed and developing economies.

Biogas production through anaerobic digestion contains impurities such as carbon dioxide, hydrogen sulfide, and moisture. Most of these impurities have adverse effects for instance; Carbon dioxide, in the ranges of 20-50%, contributes to global warming, exacerbating climate change. Global CO_2 emissions from the energy sector reached a record high of 36.3 $GtCO_2$ in 2021, with the power sector contributing the most (72%). Hydrogen sulphide exists in the ranges of 0.1-5%; this is a highly toxic gas, harmful to human health and ecosystems. H_2S emissions from biogas plants contribute to acid rain and can harm aquatic life . Nitrogen oxides also exist in the ranges of 0.5-2%, these contribute to smog formation and acid rain, impacting air quality and ecosystems. NOx emissions from biogas combustion, though lower than conventional fuels, still add to the overall burden. Ammonia that exists in the ranges of 0-2% contributes to eutrophication in water bodies, harming aquatic ecosystems. Ammonia emissions from biogas plants can have localized air quality impacts and contribute to nitrogen pollution in nearby water bodies (Jorgenson et al.,

2013). These impurities need to be removed to make the gas suitable for various applications including electricity generation, heating, and cooking (McCord et al., 2019).

Several technologies including; physical, chemical, and biological treatment methods (Adnan et al., 2019) are used to remove such impurities in a process known as biogas purification/upgrading. Physical methods involve processes such as compression and cooling of activated carbon to separate the impurities from the biogas. Chemical methods use various solvents to selectively absorb and remove the impurities. Membrane separation is another method used in biogas purification, where a selective membrane is used to separate the impurities from the biogas. In addition to these traditional methods, microalgal purification has emerged as a promising alternative to biogas purification.

Uganda's National Biogas Strategy and Action Plan (2023-2033) underscores the potential impact of biogas adoption and purification efforts. According to the strategy, biogas is expected to contribute significantly to Uganda's energy mix, with projections indicating an increase in the number of biogas plants across the country. The strategy envisages that about 28,000 biogas plants would have been installed by 2030, serving approximately 140,000 households. These installations are anticipated to generate about 1.5 million cubic meters of biogas daily, highlighting the scale of energy production achievable through biogas technology. Moreover, the strategy emphasizes the need to integrate such energy to the national grid. It is imperative to note that biogas in its raw form is not suitable for electricity production for national grid integration due to low efficiency and thus the need for upgrading through purification (Ahmed et al., 2021). Purified biogas also offers socio-economic benefits as highlighted in the strategy. It is anticipated that efficient production and use of biogas could lead to substantial savings in household energy expenditures

thereby improving disposable incomes and reducing poverty levels, particularly in rural areas where biogas production is prioritized (MEMD, 2023b).

Also, in Uganda; the rural access to modern energy is at only 8% (MEMD, 2023a). Biogas offers these communities a glimmer of hope for cleaner energy but its potential hinges on overcoming the hurdle of purification as demonstrated by (Mukisa et al., 2022). Literature highlights the abundance of agricultural waste materials in Uganda, presenting a potential treasure trove for low-cost purification solutions. Scholars such as Awe et al., (2017) have explored methods like activated charcoal from crop residues and biochar from animal waste, showcasing their effectiveness in removing harmful impurities like H_2S and CO_2. However, challenges remain in applicability and feasibility within rural contexts. Therefore, this study is crucial to bridge this gap and unlock the true potential of biogas for a cleaner, healthier future in Ugandan communities.

1.2 Problem statement

According to (MEMD, 2023b), biogas plants have seen significant development with 10,000 domestic biodigesters installed; these are primarily used for cooking as a replacement of solid biofuels. However, the national biogas strategy emphasizes that for advanced usage like electricity generation, biogas has to be purified to about 70-80% biomethane. This process is often complex in terms of technology used, resources needed, and is only economically viable at a large scale with a high demand for biomethane (Xie et al., 2018). To date, there is scanty evidence that explicitly studies the applicability of the locally available purification technologies in Uganda households. The limited information hinders the widespread adoption of biogas as a clean energy source, thereby impeding its potential to contribute to energy security (SDG7), environmental protection, and rural livelihoods (SDG1) (Meidiana et al., 2018). This study investigated the applicability of locally available purification methods of biogas in Uganda.

1.3 Research objectives

1.3.1 Purpose of the study

To investigate the applicability and feasibility of locally available biogas purification options

1.3.2 Study objectives

i. To evaluate the effectiveness of the different locally available methods for biogas purification
ii. To assess the techno-economic feasibility of locally built-biogas purification systems
iii. To investigate the environmental impacts of implementing locally available biogas purification

1.4 Research Questions

i. What is the effectiveness of the different locally available methods for biogas purification in Uganda?
ii. Are locally built biogas purification systems in Uganda techno-economically feasible?
iii. What are the environmental impacts of implementing locally available biogas purification methods?

1.5 Significance of the study

Boost Energy Security: By lowering reliance on fossil fuels and alleviating energy shortages, biogas has the potential to offer rural Ugandan households a dependable and sustainable energy source.

Encourage environmental sustainability: By producing and using biogas as a low-carbon, renewable substitute for conventional energy sources, greenhouse gas emissions are reduced hence minimizing and mitigating climate change effects.

Enhance Rural Livelihoods: Having access to biogas can provide rural communities with more economical and clean energy sources. These include better cooking facilities, the ability to generate income from biogas production, and increased agricultural productivity from biogas byproducts.

Promote Economic Development: Improving biogas purification techniques can encourage innovative and entrepreneurial activity in the community, opening up new markets for small-scale biogas enterprises and promoting Uganda's economic expansion.

1.6 Justification of the study

Biogas produced in Uganda was found to be 58.8% of Methane which I well below the global aspirations of 95% methane for it to be used efficiently (Irene & Joachim, 2024). The pressing need to investigate and optimize locally accessible biogas purification techniques in Uganda is the rationale for this study, which aims to improve rural livelihoods, increase environmental sustainability, boost energy security, and stimulate economic growth.

CHAPTER TWO

2.0 Literature review

Introduction

This section involved the study of various purification methods that are employed in the biogas purification process. Various scholarly sources were reviewed for both empirical and theoretical findings to provide more insight into the topic under study. The section also exposed the potential research gaps some of which were adopted for the study.

2.1 Theoretical framework

The Resource-Based View (RBV) theory was used as a framework for this study. RBV, originally developed by Jay Barney, focuses on leveraging unique and valuable resources to achieve a competitive advantage (Luján Salazar, 2017). In this study, the locally available materials and technologies for biogas purification are considered valuable resources that can potentially confer a competitive advantage in promoting sustainable and effective biogas production. By applying RBV in the research context, the study aimed at determining whether the locally available materials for biogas purification can serve as unique and valuable resources that contribute to a competitive advantage in sustainable and efficient biogas production. It provided a strategic lens to assess the distinctiveness of the chosen purification methods, their impact on biogas quality, and their alignment with the broader goals of environmental sustainability and community engagement. The dependent variables will include the; Purity level of biogas (percentage of methane after purification) and the removal efficiency of impurities (CO_2 and H_2S). The independent variable includes, purification method used and parameters specific to each method, and locally available materials that are used in the purification method.

2.2 RBV Analysis of Biogas Purification Methods in Uganda

This study utilized the Resource-Based View (RBV) framework to explore the competitive advantage offered by different locally available materials and technologies for biogas purification in Ugandan communities. While previous studies have examined RBV and sustainable biogas production, this research shifts the lens to compare and contrast the competitiveness of various local methods themselves.

2.3 Empirical Review

2.3.1 Impurities in Biogas

According to Werkneh, (2022), the main components of biogas are carbon dioxide (CO_2) and methane (CH_4), in different proportions based on the type of substrate, production location, weather, and digestion technique. Smaller amounts of other substances are also present, such as water vapor (H_2O), nitrogen (N_2), oxygen (O_2), ammonia (NH_3), hydrogen sulfide (H_2S), carbon monoxide (CO), volatile organic compounds (VOCs), and volatile methyl siloxanes (VMSs). Biogas composition varies greatly. Ratola et al., (2020) for instance, discovered notable variations in the composition of biogas produced from various biomass sources. Biogas's calorific value is influenced by the amount of methane it contains; a higher methane content produces a higher heating value. To fulfill quality requirements for a range of applications, including heating, power generation, car fuel, and natural gas grid injection, methane concentration in biogas may need to be increased through upgrading technologies. For example, methane content should ideally be higher than 90% in biogas meant for internal combustion engines.

According to European regulations, biogas that is injected into natural gas grids as biomethane (biomethane) must contain more than 95% methane and less than predetermined thresholds of CO_2, O_2, H_2S, and NH_3 (Rosiak et al., 2014). In several energy sectors, biogas cannot completely

replace fossil fuels until several quality requirements are satisfied (Ratola et al, 2020). High CO_2 concentrations, usually more than 40%, lower the calorific value and density of biogas. In a similar vein, these qualities can also be diminished by the presence of H_2 and N_2, albeit usually at lower levels.

Scholars like (Werkneh, 2022; Karlsson et al., 2014; Rosiak et al., 2014) have studied water vapor in biogas and found that it is problematic because it can react to form acid substances with other impurities like H_2S, NH_3, O_2, CO_2, or volatile methyl siloxanes VMSs, which can lead to corrosion in the biogas equipment. Furthermore, it is strongly advised to remove it from biogas to prevent water condensation, which will enhance engine energy efficiency and lengthen the life of biogas purification technology. Indicators of air intrusion in the biogas collectors and/or transportation system include oxygen and Nitrogen. Oxygen is thought to be safe at low concentrations, but depending on the temperature of the biogas, concentrations above 6% have the potential to be explosive (Petersson et al., 2009). Humans and some microorganisms involved in the production of CH_4 in digesters are toxic to carbon monoxide, which can lower the calorific power of biogas. It is present in landfill biogas as a consequence of bacterial activity, as well as abiotic processes of organic matter degradation.

Hydrogen sulfide (H_2S) and sulfur compounds are not only offensive-smelling, but they also present serious health and environmental hazards to people and animals. H_2S can irritate the eyes and respiratory tract and cause breathing difficulties in asthmatics even at low concentrations (about 70 mg/m3). When concentrations surpass 700 mg/m3, inhalation can result in serious side effects like unconsciousness, coma, respiratory paralysis, convulsions, and fatality (Rosiak et al., 2014). In addition, engine structures may be corroded by sulfuric acid (H_2SO_4), which is produced when H_2S and other sulfur compounds oxidize. Alkaline parts of engines, pipelines, compressors,

and instruments are easily subjected to this reaction, which causes corrosion and poisons the catalyst. Moreover, H_2S is transformed into other corrosive and damaging chemicals for the environment, like sulfur dioxide (SO_2) and sulfur trioxide (SO_3), during the biogas combustion process (Zhao et al., 2010). Halogens and volatile organic compounds (VOCs) have potent smells and are toxic as well. Fuel cell electrolytes may be negatively impacted by substances that are known to be caustic, such as dichlorobenzene and tetrachloroethylene.

Ammonia (NH_3) is another significant impurity in biogas. Although NH_3 is an essential source of nitrogen for anaerobic microorganisms, methane production can be significantly suppressed by high concentrations of NH_3 (>1.54 g/L, as total ammonia nitrogen, or TAN) (Rosiak et al., 2014). Studies have shown that raising TAN levels from 1.7 to 14 g/L reduced methane production by 50%. Elevated levels of free NH_3 can upset the proton balance and interfere with microorganisms' enzymatic metabolism. Furthermore, it demonstrates corrosive qualities when wet. Consequently, NH_3 has a strong inhibitory effect in anaerobic digesters, which lowers the production of methane and biogas. Moreover, when biogas is burned, NH_3 can produce aerosols and slightly increase nitrogen oxide (NOx) emissions (Omer, 1996).

The literature provides proof of the various substances, origins, and concentrations of impurities that must be eliminated to improve biogas's efficiency for use as a clean energy source. It is difficult to remove all of these different impurities at once, and a single method might not be able to do so. Due to such impurities, green energy accelerators like proper packaging techniques are jeopardized. Additionally, since the population as a whole must be involved in the shift to clean energy technologies, it is critical to investigate the local applicability of various biogas purification technologies, among many advantages that will provide more guidance to policymakers on how much people can be supported as this has not yet received enough attention.

2.3.2 Purification Methods

Biogas, a renewable energy source derived from organic matter through anaerobic digestion, typically consists of methane and carbon dioxide, along with trace impurities. Effective purification of biogas is crucial for enhancing its energy content and ensuring compliance with quality standards. Various empirical studies have explored different purification methods to address the challenges associated with biogas impurities.

One commonly investigated method for removing impurities, particularly hydrogen sulfide (H_2S), from biogas is adsorption. Activated carbon, zeolites, and silica gel are commonly used as adsorbents. Studies, such as those by Mwacharo et al. (2020) and Zhao et al. (2010), have focused on optimizing adsorption parameters, including material selection, regeneration techniques, and adsorption capacity (Mwacharo et al., 2020; Zhao et al., 2010).

Liquid absorbents, notably amines, have been extensively studied for their effectiveness in absorbing carbon dioxide and other acidic gases present in biogas. The empirical investigations conducted by researchers such as Mater et al., (2014) and Rashed & Mamun, (2017) have provided valuable insights into various aspects of this purification method. These studies delve into the selection of absorbent types, exploring the specific characteristics that make certain amines more efficient in capturing acidic gases; these scholars have also investigated the impact of varying concentrations of absorbents, aiming to identify the optimal range that ensures maximal absorption efficiency. Furthermore, the empirical research has focused on scrutinizing process parameters associated with the absorption technique. This includes studying factors such as temperature, pressure, and contact time between the biogas and the absorbent solution. The investigations underscore the importance of understanding these parameters to improve the absorption process and ultimately the purification process (Rashed & Mamun, 2017).

Mwacharo et al., (2020), has studied the Pressure Swing Adsorption method for upgrading biogas purity; the study examined the effects of pressure swing cycles, adsorbent characteristics, and operating conditions on the removal of impurities, particularly carbon dioxide. The method was found to be effective for the removal of Carbon dioxide with more than 95% purity (Mwacharo et al., 2020).

Chemical scrubbing, involving the use of alkaline solutions, has been explored for removing acidic gases from biogas. A study by Zhao et al., (2010) has investigated scrubbing agents, their concentrations, and overall efficiency in removing impurities from biogas. The study offers valuable insights into scrubbing agent selection, concentrations, and overall efficiency in impurity removal. Chemical scrubbing methods provide purity levels of up to 98% compared to other conventional methods.

Biological upgrading methods, such as microbial methanation, have gained attention for improving methane content in biogas. Studies by Rashed & Mamun, (2017) and Mater et al., (2014) have explored microbial communities, reactor configurations, and operational conditions to enhance the biological upgrading process. Findings indicate that optimizing microbial communities, reactor configurations, and operational conditions significantly contribute to the efficacy of the biological upgrading process (Mater et al., 2014; Rashed & Mamun, 2017).

The synergistic effects of combining multiple purification techniques have been investigated. Integration of adsorption with membrane separation or absorption with biological upgrading has been explored. Research by Rosiak et al., (2014) has examined the benefits of such hybrid approaches in terms of efficiency and cost-effectiveness. The integration of adsorption with membrane separation or absorption with biological upgrading has shown promise in terms of

enhanced efficiency and cost-effectiveness. These findings underscore the potential of hybrid approaches in optimizing biogas purification (Rosiak et al., 2014).

As shown in the literature, the purification of biogas holds significant importance in addressing energy poverty, promoting environmental sustainability, and fostering economic development. With a predominantly rural population and high levels of agricultural waste, biogas production presents a viable solution to meet the energy needs of rural communities while reducing reliance on traditional biomass fuels. However, these impurities present in biogas, pose health and environmental risks and limit its usability. Efforts to purify biogas in Uganda have gained momentum, driven by government initiatives, international partnerships, and grassroots organizations. Pilot projects and research studies have demonstrated the feasibility and effectiveness of various purification technologies, including physical, chemical, and biological methods, tailored to the local context. Scaling up efforts is essential to unlock the full potential of biogas as a clean and sustainable energy source in Uganda, contributing to energy access, environmental conservation, and socio-economic development in rural areas.

CHAPTER THREE

3.0 Methodology and Methods

Introduction

This chapter shows the steps that were taken to achieve each of the set specific objectives. The chapter also presents the material and methods that were used throughout the study; including the purification systems that are involved.

3.1 Research design

The study used a quantitative approach where numerical data was collected and consequently analyzed against the phenomenon under study. In this, the researcher conducted experiments in the Green Unit Laboratory at Makerere University Business School under the Department of Energy Sciences and Technologies (DEST) to collect the numerical data from the identified purification methods. The data was optimized to ascertain the best purification methods.

3.2 Objective one

3.2.1 Inclusion and Exclusion criteria

To decide on the methods to use for this study, the advantages of biogas purification methods within the local context were assessed. The methods assessed were mainly adsorption, absorption, membrane separation, and biological upgrading as they are the most common biogas purification methods (Rashed & Mamun, 2017).

In the adsorption process, contaminants from biogas, particularly hydrogen sulfide (H_2S) and Carbon dioxide, are removed using solid materials like silica gel, zeolites, or activated carbon. This method has the advantages of being widely available, easy to use, and effective. The drawbacks include the need for regular adsorbent regeneration or replacement, the potential for methane (CH_4) loss, and higher biogas purification costs.

The absorption technique removes impurities from biogas, particularly carbon dioxide (CO_2) and H_2S, by soaking them in liquid solvents like water, amines, or alkaline solutions. This method has the advantage of recovering and achieving high-purity CH_4, and it can be combined with other processes like biological upgrading. Its use of dangerous chemicals and high energy usage are the major drawbacks.

The membrane separation method extracts impurities, particularly CO_2, from biogas using selective membranes made of polymeric, ceramic, or composite materials. This method has the advantages of being modular, flexible, and efficient. The drawbacks include the need for high pressure, specialized tools, and biogas pre-treatment to extract water vapor and H_2S.

In the biological upgrading process, CO_2 and H_2S are changed into CH_4 and biomass, respectively, by microorganisms like bacteria, archaea, or algae. This technique offers the benefits of being inexpensive, self-regenerating, and environmentally benign. Its shortcomings include low efficiency, being in the experimental stage, and needing control and ideal conditions.

Therefore, from the reviewed literature, activated carbon and water scrubbing methods fit the purpose of this study for the local context in Uganda. These techniques can be applied to locally accessible resources, like water and agricultural waste, and are straightforward, economical, and efficient. Additionally, by removing CO_2 and H_2S from biogas, these techniques can enhance the material's quality and utility. In rural areas, where biogas production is most prevalent and necessary, these methods are also simple to implement and operate.

3.2.2 Using Activated carbon method

Raw biogas from the biodigester was moved to the purification tank through a hose pipe. The Purification tank contains a semi-permeable (filter) membrane to hold the impregnated activated

carbon particles. To improve the efficacy, impregnated activated carbon was used in this experiment. One (1) kilogram of the impregnated activated carbon was packed at different heights in the purification tank to further improve the purification efficacy. Consequently, Raw biogas was fed into the tank and allowed to flow through the impregnated activated carbon particles for purification. The pressure inside the tank was monitored to have the experiment under control. The raw biogas was measured upon entry at various intervals and results recorded; upon purification, the Purified biogas was measured with the help of the gas analyzer fixed at the outlet of the hose pipe. By this, the purity of the biogas was ascertained and hence recorded at each time. The removal efficiency of the impurities over time was also be determined by monitoring the concentrations of H_2S at both the inlet and outlet during various time intervals. The ratio of outlet concentration to initial concentration against operational time was obtained by monitoring the concentration of hydrogen sulphide and Carbon dioxide in the mixer. Using Equation (1), the efficiency of the method was evaluated;

$$\eta = \left(\frac{C_{inlet} - C_{outlet}}{C_{inlet}}\right) * 100 \qquad (1)$$

where, η is the efficiency of the purification method, C_{inlet} is the intial concentration of the raw biogas; C_{outlet} is the final concentration after purification. For any given method, the efficiency for the removal of any of the impurities was determined by measuring η.

Iron oxide reacts with hydrogen sulphide to produce iron sulphide as shown in Equation (2); Iron sulphide is a stable compound under normal condition of temperature and pressure.

$$Fe_2O_{3(s)} + 3H_2S_{(g)} \rightarrow 2FeS_{(s)} + 3H_2O_{(g)} \qquad (2)$$

A physical adsorption reaction occurs between Methane, activated carbon, and carbon dioxide. Methane (CH_4) is not as desirable to activated carbon as carbon dioxide (CO_2). Because CO_2

molecules are larger and more drawn to the carbon surface. They can create stronger bonds with the functional groups on the surface of activated carbon, such as hydroxyl (-OH) or carboxyl (-COOH) groups, due to their larger size and electrical characteristics (polarity). In essence, CO_2

adheres to activated carbon more readily than CH_4. Figure 1 shows the experimental setup for the activated carbon method for biogas purification as utilized in the laboratory.

3.2.3: Preparation of materials used

Activated carbon was prepared by hitting Sodium chloride with Charcoal pellets to help in the formation of micro and meso pores on the carbon. According to (Masuduzzaman et al., 2017) the micro pores are responsible for the adsorption of both Hydrogen sulphide and carbon dioxide while the meso pores help in allowing movement of the gas towards the micro pores whilst capturing other bigger impurities like water vapor. The steel wool was dampened in water to improve on its reaction properties.

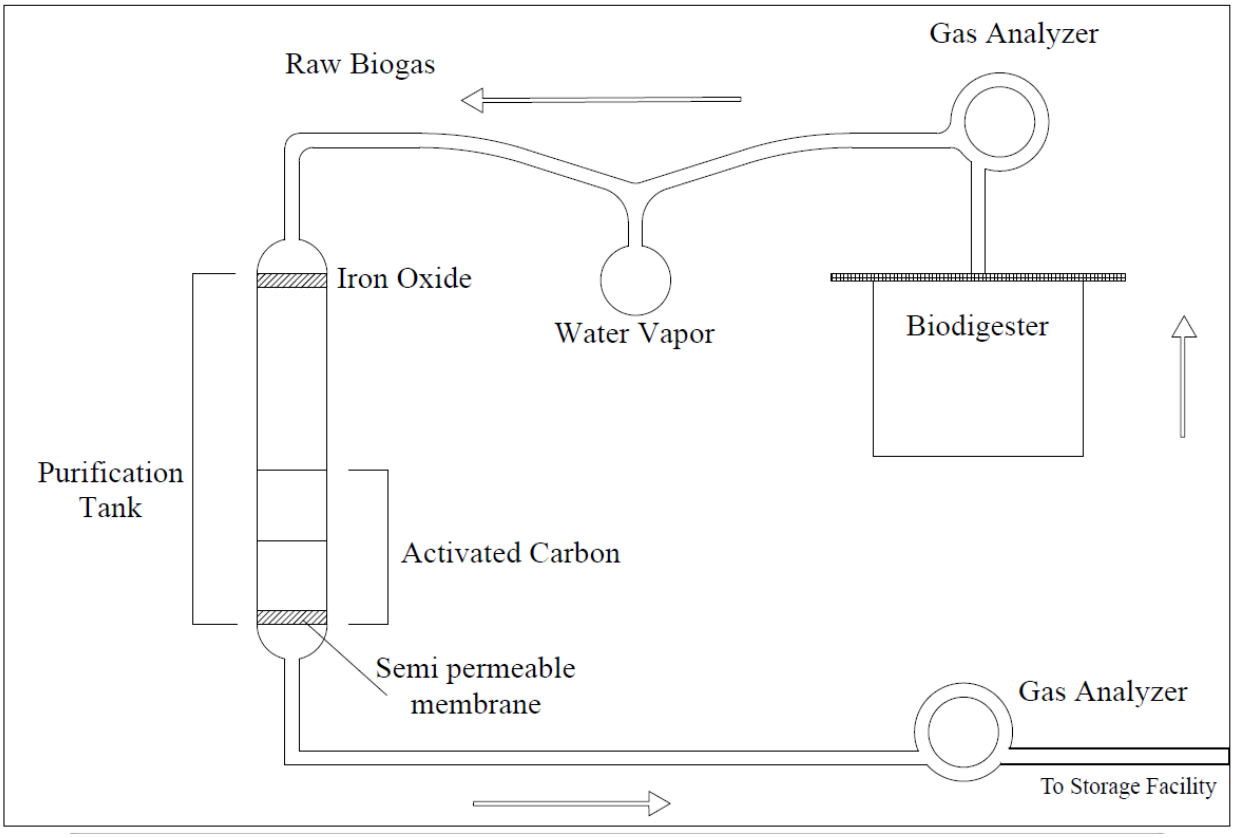

Figure 1: Experimental setup for the activated Carbon method (source: Researcher original work)

3.2.3 Water scrubbing

Experimental setup

Figure 2 shows the experimental set up for water scrubbing system as used in the laboratory.

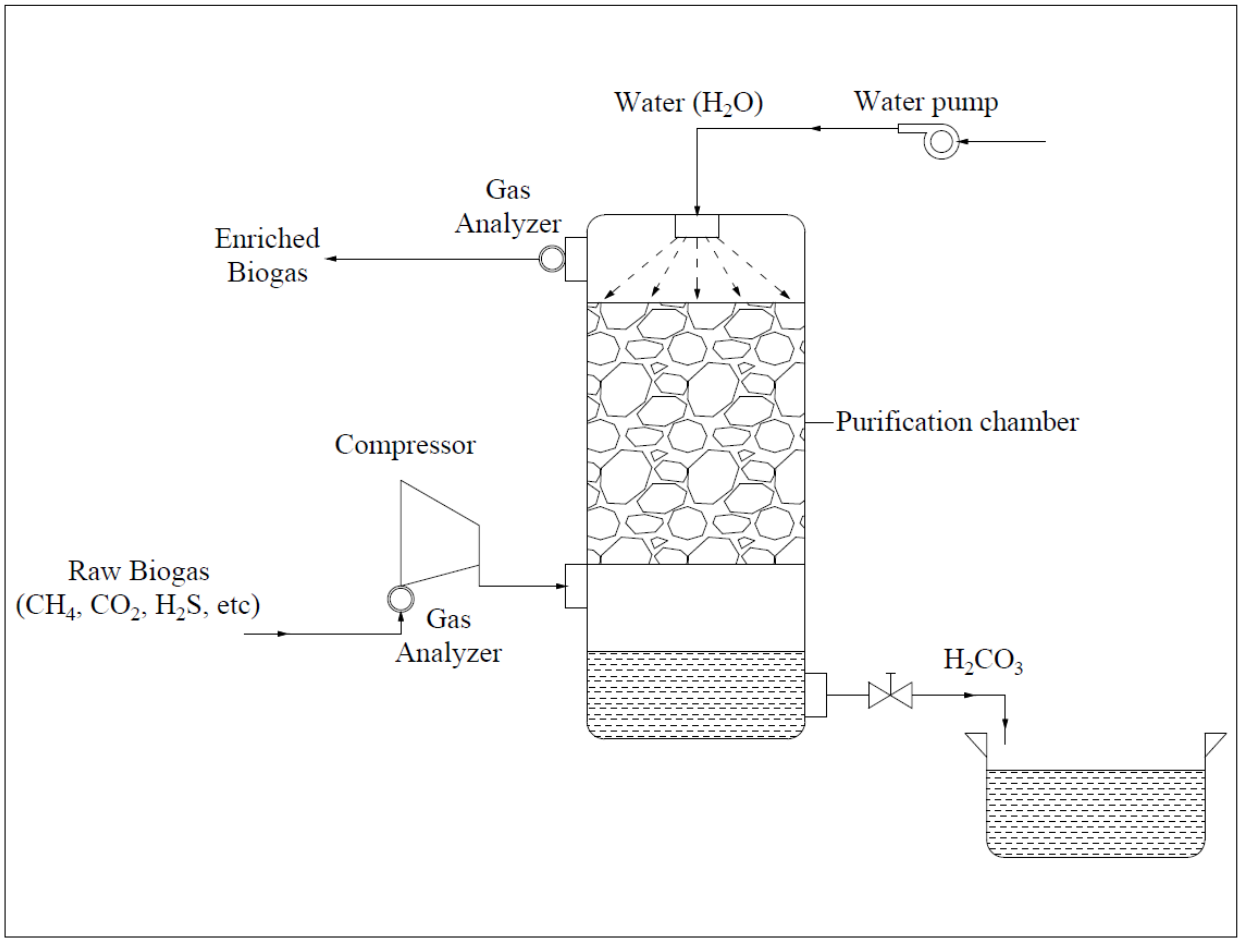

Figure 2: Set up for a water scrubbing system (source: Researcher original work)

Procedure

1. Identify the biogas source and determine the composition of impurities, such as carbon dioxide (CO_2) and hydrogen sulfide (H_2S).
2. Set up the water scrubbing system, including tanks, scrubbers, pumps, and plumbing connections.

3. The raw biogas is fed into the scrubber system, where it comes into contact with a countercurrent flow of water. The water acts as a solvent and absorbs the impurities present in the biogas, including CO_2 and H_2S.
4. As the biogas passes through the water, chemical reactions occur between the impurities and the water, forming soluble compounds.
5. Equations (3) and (4) indicate the chemical reaction between the main impurity and water.

Carbon dioxide reacts with water to form carbonic acid (H_2CO_3), which dissociates into bicarbonate ions (HCO_3^-) and hydrogen ions (H^+) through a continuous reaction.

$$CO_{2(g)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)} \quad (3)$$

$$H_2CO_{3(aq)} \rightleftharpoons HCO_3^-{}_{(aq)} + H^+{}_{(aq)} \quad (4)$$

Hydrogen sulfide reacts with water to form hydrosulphuric acid (H_2S), which dissociates into bisulfite ions (HS^-) and hydrogen ions (H^+) as illustrated in Equations (5) and (6).

$$H_2S_{(g)} + H_2O_{(l)} \rightleftharpoons H_2S_{(aq)} \quad (5)$$

$$H_2S_{(aq)} \rightleftharpoons HS^-{}_{(aq)} + H^+{}_{(aq)} \quad (6)$$

The soluble bicarbonate and bisulfide ions remain dissolved in the water solution. Separate the purified biogas from the water solution using separation techniques such as settling or filtration. Collect the purified biogas for further processing or utilization, while the water solution containing the dissolved impurities is discharged. The performance of the water scrubbing system will be determined by measuring concentrations of impurities. Control the operation of the scrubber system to optimize efficiency and effectiveness in removing impurities from the biogas. The

environmental implications of the water scrubbing method, including water usage, wastewater disposal, and potential emissions of greenhouse gases will be assessed.

3.3 Objective two

A cost-benefit analysis (CBA) was performed on all the methods to ascertain their competitive advantages.

3.3.3 Levelized cost of gas purification (LCOGP)

The levelized cost of purifying biogas makes it possible to compare power systems of different generation and cost structures with each other. It is the ratio of the sum of all accumulated costs for constructing and operating a system to the sum of the annual energy generation of the power plant throughout its lifetime. Average LCOGP is calculated based on the net present worth method, in which the expenses for investment and the payment streams from earnings and expenditures during the plant's lifetime are calculated based on discounting from a shared reference date (US Department of Energy, 2013).

The LCOGP of a new system is calculated using the Equation (7);

$$LCOGP = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{G_t}{(1+r)^t}} \qquad (7)$$

where, $LCOGP$ is the Levelized cost of biogas purification (dollar/kWh); I_t is investment expenditures in year t (including financing); M_t is operations and maintenance expenditures in year t; G_t is gas purified in year t; r is the discount rate; and n is the life of the system.

3.4 Objective three

To ascertain the environmental impact of each method, emissions that are avoided through the purification process were calculated through the formula; to calculate the emissions released from biogas purification, Equation (8) was used as seen below:

$$E = A * EF \quad (8)$$

where, E is the number of emissions avoided; A is the amount of pollutants removed; and EF is the Emission factor.

Emission Factor (EF): The emission factor represents the quantity of pollutant emissions per unit of activity or substance. This factor varies depending on the type of pollutant under study. The emission factor data for each pollutant was sourced from the IPCC – Emission Factor Database, which provides standardized emission factors for various activities and processes.

IPCC – Emission Factor Database: The IPCC – Emission Factor Database is a comprehensive resource that provides emission factors for various greenhouse gases and air pollutants associated with different industrial processes, including biogas purification. It offers standardized emission factors based on scientific research and data analysis.

Interpretation: The calculated emissions avoided for each purification method provided insights into their environmental impact in terms of reducing air pollutants and greenhouse gas emissions. This information is crucial for evaluating the environmental sustainability of each method and making informed decisions regarding its adoption and implementation. Emission factors considered as presented by (Mukisa, 2016);

i. Carbon dioxide (CO_2) $EF_{\boldsymbol{CO_2;biogas}} = 0.025254\ \mathrm{kg}_{\boldsymbol{CO_{2eq}}}\ .\ ton_{biogas}{}^{-1}$

ii. Methane (CH_4) $EF_{\boldsymbol{CH_4};\boldsymbol{biogas}} = 3.88 \times 10^{-5}\ \mathrm{kg}_{\boldsymbol{CO_{2eq}}} . ton_{biogas}{}^{-1}$

iii. Hydrogen sulphide (H_2S) $EF_{\boldsymbol{H_2S};\boldsymbol{biogas}} = 0.0035\ \mathrm{kg}_{\boldsymbol{CO_{2eq}}} . ton_{biogas}{}^{-1}$

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

Introduction

This section presents the findings obtained from the experimental evaluation of two different purification methods and consequently their implications on biogas quality, and use. The section also shows the materials used for both methods and their availability. The discussion that follows interprets the results in terms of the efficiency of each purification method, their suitability for different applications, and their potential for scalability and cost-effectiveness in Uganda. By comparing the performance of activated carbon adsorption and water scrubbing, this section aims to identify the most effective and practical approach for biogas purification in Uganda, where access to clean and affordable energy remains a significant challenge. The Environmental gain in terms of captured caborndioxide is also studied to realize the full benefits of biogas purification.

4.1 Biogas Purification

Laboratory set up

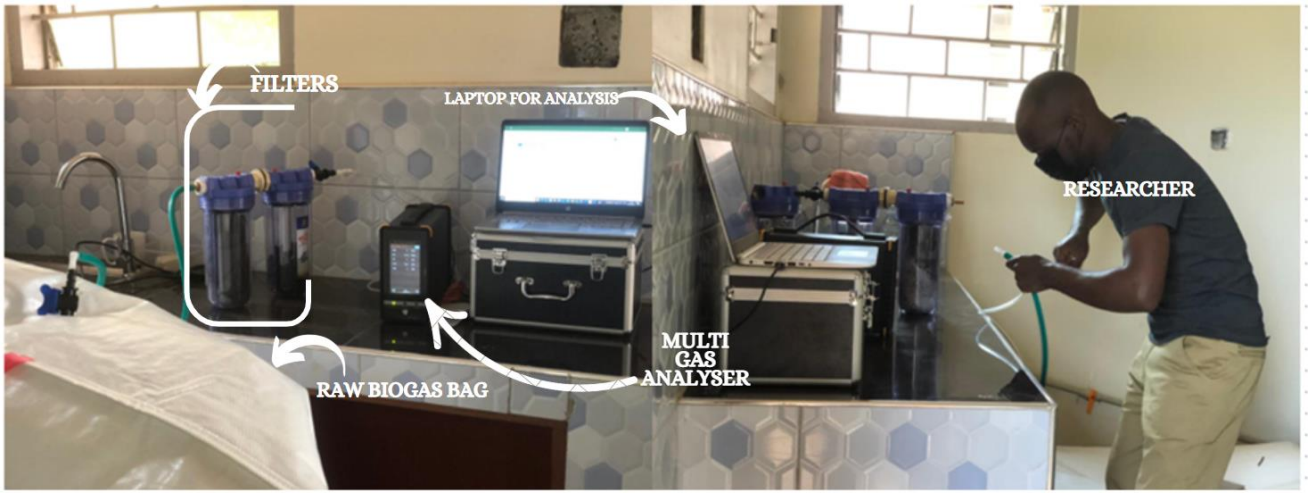

Figure 3: System Set up at the Laboratory

Three readings were taken in a period of 10 minutes of purification as this time allowed the system attain stable state conditions for accurate readings on the gas analyzer, the corresponding average of the readings was calculated as shown in table. ***(Source Biogas Analyser)***

Raw biogas

Table 1: Results obtained from raw biogas.

Biogas composition	**Readings (%)**			**Average (%)**
	1	**2**	**3**	
CH_4	47	53	52	**50.67**
CO_2	49	45	46	**46.67**
H_2S	2.0	1.0	1.0	**1.33**

The initial results from the gas analyzer indicate and average of 50.67% of methane in the biogas, this is a relatively low composition and therefore this necessitates the need for purification to increase the energy content. Raw biogas also contains other impurities like vapor, Nitrogen oxides, and other impurities that were not considered for this study but are accounted for in the overall composition of the biogas. Methane is the primary combustible component of biogas, and its concentration directly affects the calorific value**.** As illustrated by (Mwacharo et al., 2020) the presence of more than 40% carbon dioxide (CO_2) significantly dilutes the calorific value per unit volume of biogas, limiting its use in applications such as biofuel for transportation, lighting, and cooking and thus the need for purification. Additionally, 1.33% hydrogen sulfide (H_2S) is present, which is a toxic and corrosive impurity that must be removed to protect equipment and meet safety standards. The results are also consistent with the study by Irene and Joachim (2024), that shows the content of methane in biogas from Uganda was is between 50-60%.

Activated carbon method

Table 2: Results obtained after using activated carbon purification method

Biogas composition	**Readings (%)**			**Average (%)**
	1	**2**	**3**	
CH_4	79	80	78	**79.00**
CO_2	20	17	21	**19.33**
H_2S	0.42	0.43	0.42	**0.42**

The activated carbon method significantly enhances the methane concentration in biogas, increasing it from an average of 51.67% in raw biogas to 79.33%. This substantial improvement indicates the method's effectiveness in purifying biogas for energy production. Additionally, the method reduces carbon dioxide levels from 50% to 19.33%. This is achieved through a physical reaction between carbon dioxide and activated charcoal. Carbon dioxide particles are adsorbed on the surface of activated carbon and they remain attached until washed away in a regeneration process. The trapped carbon dioxide particles can be safely evacuated for storage in carbon capture processes. According to (Sharjeel, 2018) activated carbon method has a high efficiency in the removal of carbon dioxide particles from biogas and this is consistent with the results attained. The reduction in CO2 is crucial for improving the calorific value of the biogas. Almost all of the noncombustible portion of biogas is CO_2, which reduces the calorific value per unit volume of biogas; this limits biogas for uses such as biofuel for transportation, cooking, and lighting, where direct combustion technology is needed (Mwacharo et al., 2020). Similarly, hydrogen sulphide is eliminated to upto 70% of the mixture, this is attributed to the reaction between steel wool and hydrogen suphide as indicated in Equation (2). A study by (Zafa, 2024) indicates that steel wool can remove hydrogen sulphide from a mixture to upto 70-98% and results improve if used with

stable iodides like potassium iodide. The solid iron sulphide formed can be removed from the system after a significant usage period, in this study, 3 months changing period was used to maintain efficiency.

From eqn. (1) the efficiency of purification for activated carbon method is determined by substituting C_{inlet} and C_{outlet};

For Carbon dioxide

$$\eta = \left(\frac{46.67 - 19.33}{46.67}\right) * 100$$

$$= \quad 58.58\%$$

For Hydrogen Sulphide

$$\eta = \left(\frac{1.33 - 0.42}{1.33}\right) * 100$$

$$= \quad 68.42\%$$

Water scrubbing method

Table 3: Results obtained after using water scrubbing purification method

Biogas composition	**Readings (%)**			**Average (%)**
	1	**2**	**3**	
CH_4	81	83	80	**81.33**
CO_2	17	16	18	**17.00**
H_2S	0.7	0.8	0.8	**0.77**

The water scrubbing method also shows effectiveness in purifying biogas. It increases methane concentration to an average of 81.33%, slightly higher than the activated carbon method. This effectiveness is attributed to the solubility of Carbon dioxide in water. According to a study by

(Masuduzzaman et al., 2017), carbon dioxide is one of the most soluble gases in water and it reacts as shown in Equation (3) and (4). The higher solubility of CO_2 in water than CH_4 enables them to be separated by taking advantage of the difference in their solubility in water. At room temperature, the solubility of CO_2 in water is 26 times higher than that of CH_4 (Mwacharo et al., 2020). Therefore, this technique reduces CO_2 levels to 17.00%, which is comparable to the activated carbon method. However, it is less effective in removing hydrogen sulfide, reducing it to 0.77% compared to 0.42% with activated carbon, this is attributed to the slow flow rate of biogas and lower temperatures and pressure during the experiment; a study by (Moghadam & Banaeia, 2022) indicate that increasing the pressure and rate of gas flow significantly improves the efficiency of the removal of hydrogen sulphide from a biogas. However, the water scrubbing method offers the advantage that H_2S can be eliminated with the removal of CO_2 because the solubility of H_2S in water is higher than CO_2 and this saves the overall purification time (Mwacharo et al., 2020).

Similarly, Equation (1) was used to determine the purification efficiency for water scrubbing by substituting C*inlet* and *Coutlet*;

For Carbon dioxide

$$\eta = \left(\frac{46.67 - 17.00}{46.67}\right) * 100$$

$$= \quad 63.57\%$$

For Hydrogen sulphide

$$\eta = \left(\frac{1.33 - 0.77}{1.33}\right) * 100$$

$$= \quad 42.11\%$$

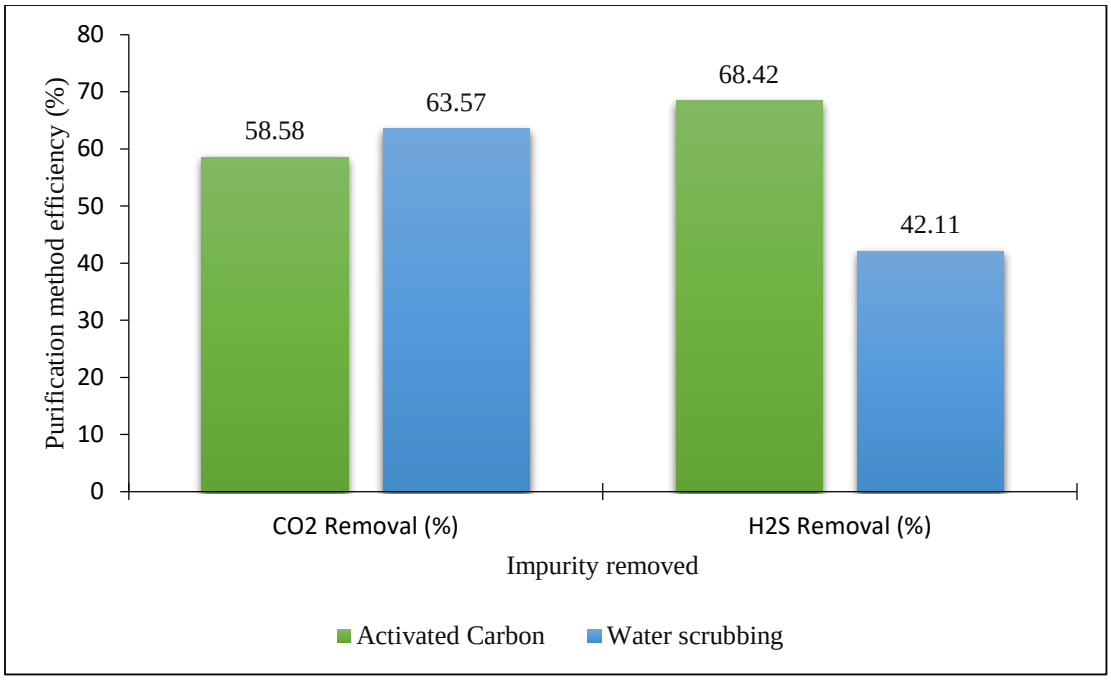

Figure 3: Removal efficiency for each method relative to the impurities

From the results obtained, both methods improve biogas quality but the activated carbon method is more effective in removing hydrogen sulfide, while the water scrubbing method generally achieves a higher methane concentration. The activated carbon method excels in reducing H_2S levels from 1.33% in raw biogas to 0.42%, which is essential for preventing corrosion and ensuring the safety of the biogas. The water scrubbing method, on the other hand, is advantageous for its higher methane recovery and the simultaneous removal of CO_2 and H_2S, although it requires a high initial investment and high energy demand during water regeneration (Zhao et al., 2010).

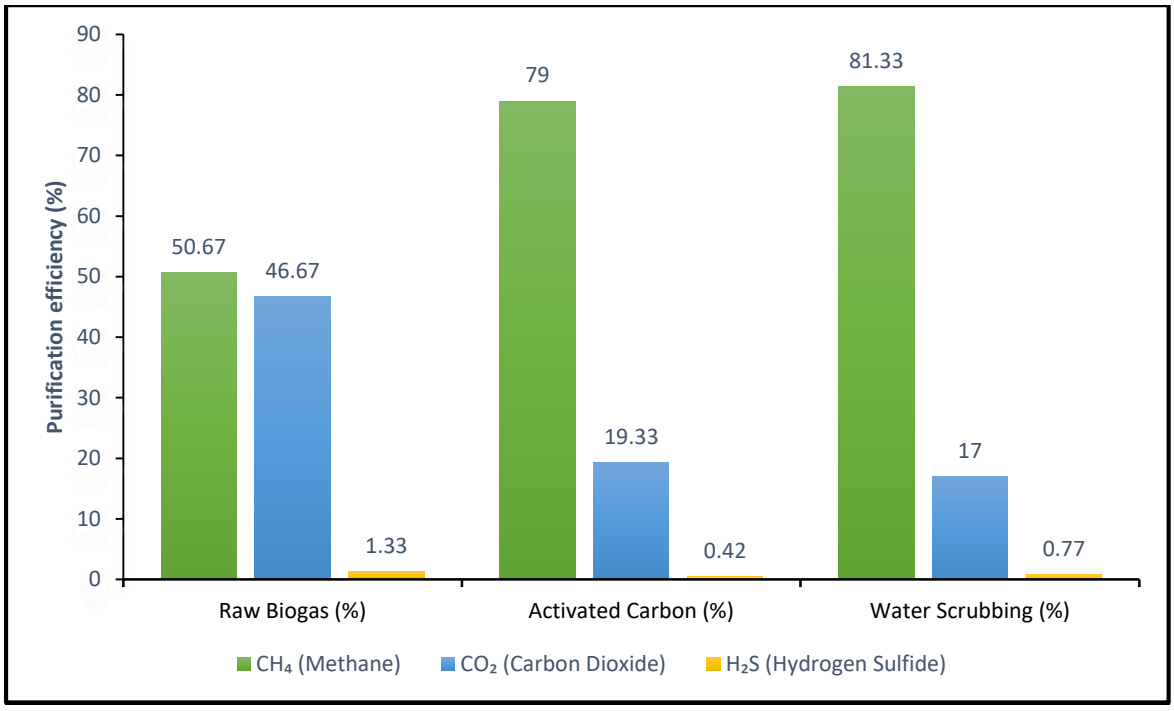

Figure 4: Comparative performance for each method

As illustrated in Figure (4), activated carbon method removes more hydrogen sulphide compared to water scrubbing; this is because there is a chemical reaction between iron and hydrogen sulphide as shown in Equation (2) to form a stable compound of iron sulphide and this remains trapped on the iron bed. This reaction is irreversible, the gas cannot be released back into the stream and thus increased efficiency of removal of hydrogen sulphide. Conversely, hydrogen sulphide is moderately soluble in water, this means a significant amount of the gas remains in the gas phase. Also, to improve the solubility of the hydrogen sulphide, there is need to alter the temperature and pH of the system, this experiment was performed at Normal temperature and pressure (NTP). Furthermore, once the saturation of hydrogen sulphide in the water increases, the efficiency drops requiring frequent replacement of the water or and control of the pH.

4.2 Determining the Techno-economic Feasibility

This objective aimed at assessing the techno-economic feasibility of locally built-biogas purification systems. This was realized by calculating the levelized cost of biogas purification for each method and consequently compared overall costs

Activated carbon method.

The levelized cost of biogas purification is calculated using excel software from the gathered data in Table 4;

Table 4: Cost of materials used in activated carbon purification method

Item	**Quantity**	**Rate ($)**
Carbon charcoal	8 kg	2.7
Activator	Lumpsum	27
PVC pipe 6 inch	½ Pc	10.8
Cotton fabric	1 m^2	2.7
Iron (steel wire roll)	1 roll	2.7
PVC glue	I tin	8.1
TOTAL		**54**

As shown in **Table 4**, the Initial investment for setting up the entire system is $54

System considerations

The purification system can last for 10 years

A 5% discount rate was considered as per previous studies

$5m^3$ of biogas are purified daily, then (5*365) = $1825m^3$

Considering a maintenance downtime of 5%, the overall production is reduced by (0.05*1825) = $91.25m^3$. Therefore, the annual production is (1825-91.25) = $1733.75m^3$

The biogas was collected from Human waste as the feedstock for the Biodigester.

Maintenance

The steel wire (Iron) is changed 4 times a year

According to (Rashed & Mamun, 2017) it is recommended that the saturated activated carbon be changed at least twice a year, for more efficiency, this research used a changing period of 4 times a year. The cost of replacing activated carbon is and steel wire the total cost of maintenance is $21.6.

Levelized Cost of Biogas Purification Using Activated Carbon

The levelized cost of biogas purification (LCOBP) was calculated for the activated carbon method using discounted cash flow analysis over a 10-year project lifespan. Key input assumptions included a purification capacity of 1,733.75 cubic centimeters per year, a system capacity of 5 cc, capital expenditure of USD 48.6/m^3, and annual operating and maintenance (O&M) costs of USD 21.6. A social discount rate of 5% was applied, consistent with long-term energy investment assessments in Sub-Saharan Africa (IRENA, 2021; MEMD, 2023).

The net present value (NPV) of total capital expenditure (CAPEX) was computed to be USD 243, while the NPV of operating expenses (OPEX) over the analysis period was USD 40.50. This resulted into a computed LCOBP of USD 0.71 per cubic centimeter of purified biogas. This cost reflects both the amortized capital investment and the annual operational burden,

normalized over the entire purification output. The findings demonstrate that under ideal operating conditions and low-cost financing (5% discount rate), activated carbon offers a competitive purification cost.

Levelized Cost of Biogas Purification Using Water scrubbing method

Table 5: Indicates the cost of materials used water scrubbing purification method

Item	Quantity	Rate ($)
Gas Nozzle	4Pc	5.4
Nipples	2 Pc	5.4
PVC pipe 6 inch	½ Pc	10.8
Cotton fabric	1 m2	2.7
Water	4 liters	0.5
PVC glue	I tin	8.1
Funnel	4Pc	2
TOTAL		**34.9**

To evaluate the economic feasibility of biogas purification using the water scrubbing method, a levelized cost analysis was conducted based on the following parameters: a purification capacity of 1,733.75 cubic meters per year, a system capacity of 5 cubic meters, a capital expenditure (CAPEX) of $31.7 per cubic meter, and annual operation and maintenance (O&M) costs of $3.2. The analysis spans a 10-year period with a discount rate of 5%.

The net present value (NPV) of the costs was calculated, with the CAPEX occurring in year 0 and O&M costs distributed annually over the 10-year period. The NPV of the CAPEX is $0.11, while the NPV of the OPEX is $26.42. The NPV of the total purification volume over the analysis period is 58 cubic meters. Against this background, the levelised cost of biogas purification (LCOBP) was determined, as the ratio of the total NPV of costs (CAPEX and OPEX) to the NPV of the purification volume.

The resulting LCOBP is $0.46 per cubic meter. This metric provides a comprehensive measure of the cost-effectiveness of the water scrubbing method, accounting for both initial investment and ongoing operational expenses over the system's lifetime. The low LCOBP suggests that water scrubbing is also a cost-competitive approach for biogas purification, potentially supporting its adoption in sustainable energy systems and its potential for scalability and application in biogas upgrading projects.

The two methods indicate cost differences that would impact their choice. Water scrubbing reveals a LCOBP of $0.46 per cubic meter which makes it more cost effective compared to the activated carbon method that boosts $0.71 per cubic meter. The main difference in the costs is motivated by the CAPEX levels of each method with water scrubbing having a lesser CAPEX of 31.7$ and O&M $3.2 per year compared to activated carbon with $48.6 with a corresponding O&M of $21.6 per year. By this, the water scrubbing method presents a cheaper option at both the investment and operational levels. Notably, in circumstances where a higher removal efficiency of contaminants like H_2S and hence a stringent gas quality is desired, activated carbon is more competitive. However, for a system purifying 1,733 cubic meters of biogas annually, the financial burden of its higher operational costs makes it less attractive than water scrubbing, which provides a more balanced cost-performance ratio. Conversely, Awe et al., (2017) insists that the choice of purification technology should consider factors beyond cost, such as energy consumption, environmental impact, and resource availability. Water scrubbing, for example, requires a steady supply of water, which may be a limitation in regions with scarce water resources. On the other hand, activated carbon requires periodic replacement, adding to its recurring costs and waste management concerns. Ultimately, for projects prioritizing cost efficiency and scalability, water scrubbing emerges as the more viable purification option. However, if achieving ultra-pure

biomethane with stringent gas quality specifications is the priority, activated carbon might still be justified despite its higher LCOBP.

4.2.1 SENSITIVITY ANALYSIS

A one-way sensitivity analysis was conducted for each of the key parameters (discount rate and purification capacity). The direction of variation was selected based on practical and policy constraints. For example, discount rates below 5% are uncommon in Uganda's financing landscape. Hence, variation was applied in one direction only to reflect realistic and policy-relevant scenarios.

Activated Carbon

Table 6: Consolidated sensitivity analysis results for the activated carbon purification method.

Discount Rate (%)	LCOBP (USD/m^3)	Purification Capacity (m^3/year)	LCOBP (USD/ m^3)
5.0	0.71	1,733.75	0.71
7.5	1.06	1,907.13	0.65
10.0	1.41	2,080.50	0.59
12.5	1.76	2,253.80	0.55
15.0	2.11	2,427.25	0.51
—	—	2,600.63	0.48

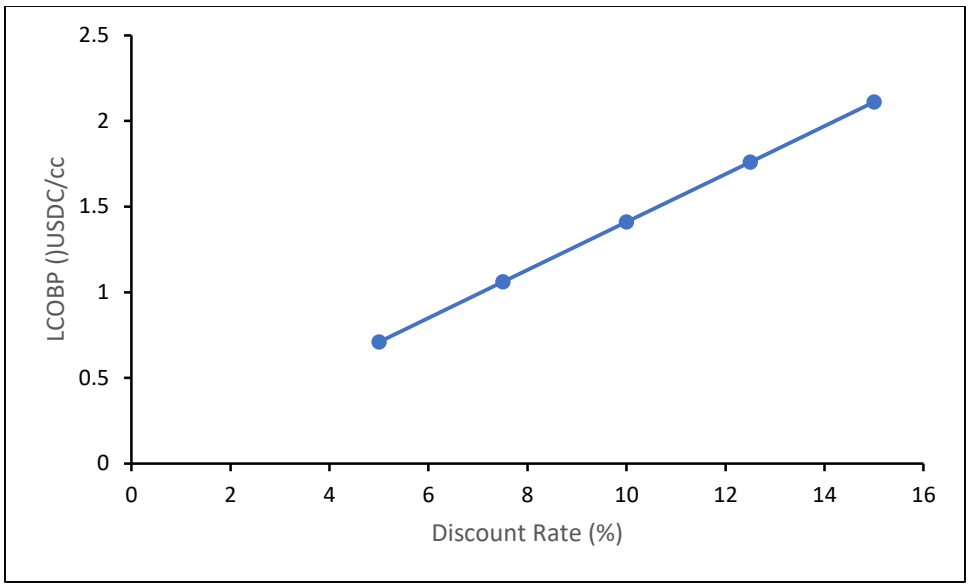

Figure 5: Sensitivity Analysis on Discount rate against LCOBP

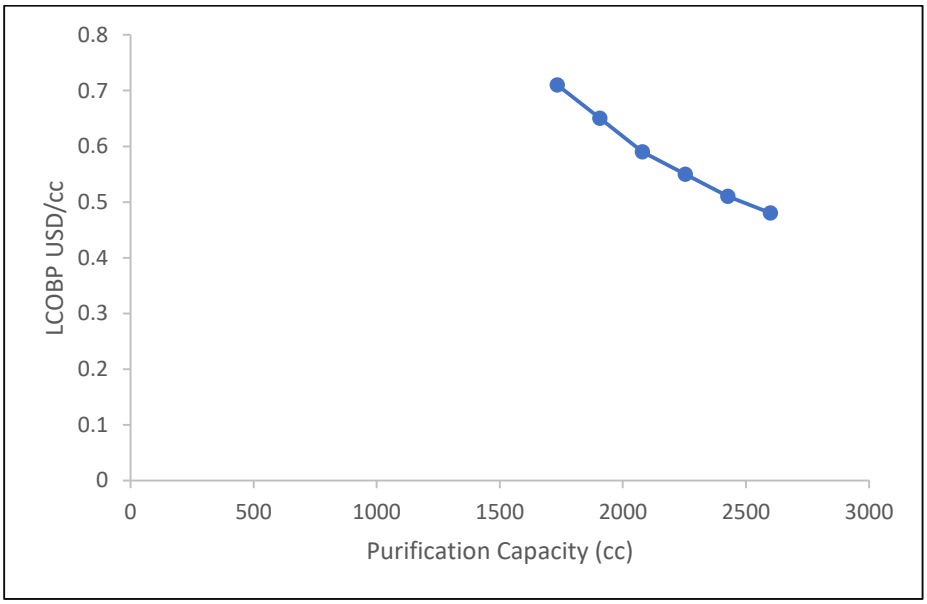

Figure 6: Sensitivity Analysis on Purification Capacity against LCOBP

From Table 6; As the discount rate increases, the LCOBP rises steadily from USD 0.71/cc at 5% to USD 2.11/ m^3 at 15%. In contrast, increasing the purification capacity by 10% at each step results in a steady decline in LCOBP from USD 0.71/ m^3 to USD 0.48/ m^3, indicating economies of scale and improved cost-efficiency.

Water scrubbing

Table 7: Consolidated sensitivity analysis results for water scrubbing purification method

Discount Rate (%)	LCOBP (USD/ m^3)	Purification Capacity (m^3 /year)	LCOBP (USD/ m^3)
5.0	0.46	1733.75	0.46
7.5	0.69	1907.13	0.42
10.0	0.92	2080.50	0.38
12.5	1.14	2253.80	0.35
15.0	1.32	2427.25	0.33
—	—	2600.63	0.31

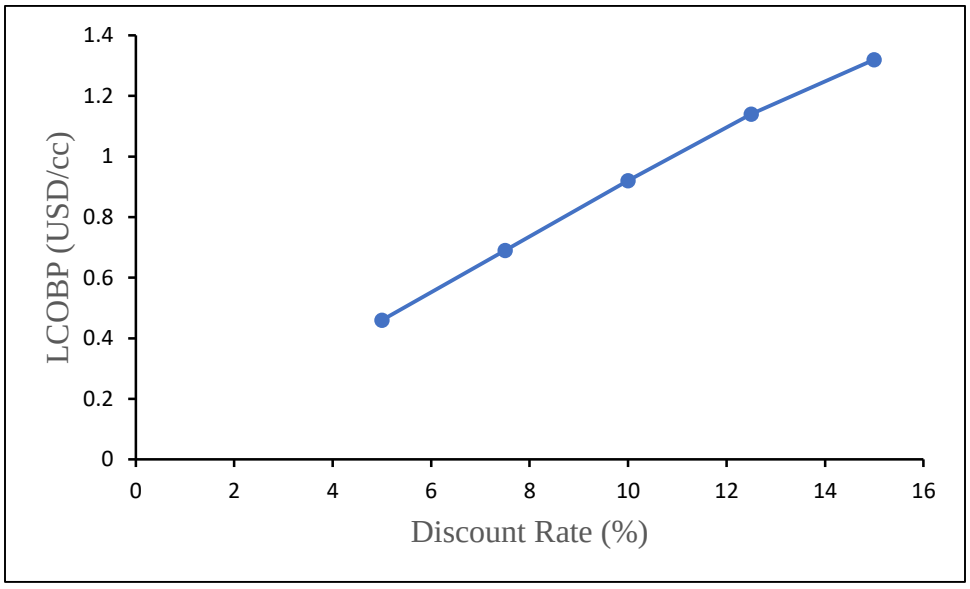

Figure 7: Sensitivity Analysis on Discount rate against LCOBP for water scrubbing method

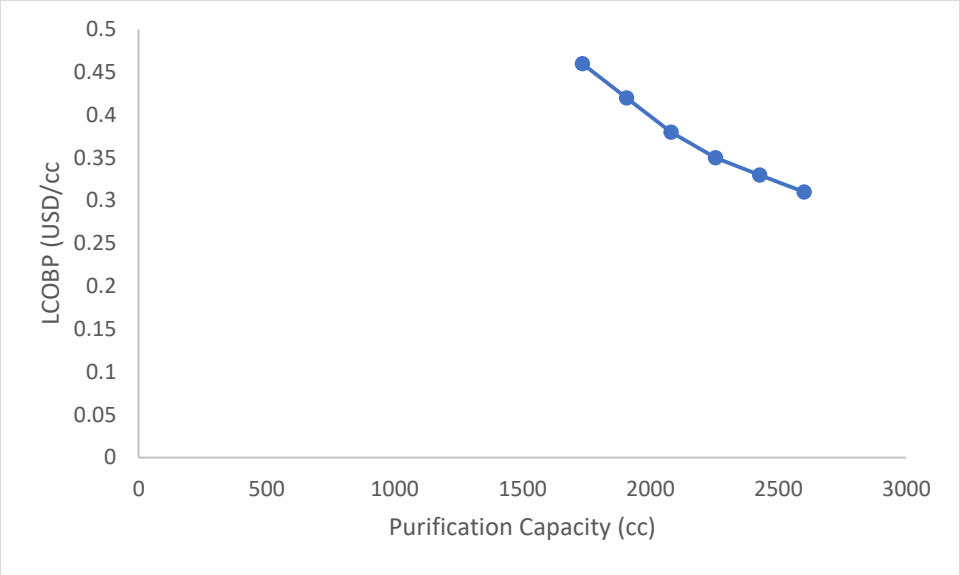

Figure 8 Sensitivity Analysis on purification capacity against LCOBP for water scrubbing method

The results in Table 7 illustrate the relationship between the discount rate, purification capacity, levelized cost of biogas production (LCOBP), using the water scrubbing method. They show how varying discount rates (5.0% to 15.0%) and corresponding purification capacities (1,733.75 to 2,600.63 cubic meters per year) impact the LCOBP. As the discount rate increases from 5.0% to 15.0%, the LCOGP rises from $0.46 to $1.32 per cubic meter, reflecting the higher cost of capital over time, which increases the present value of future costs relative to the biogas output. This trend indicates that higher discount rates amplify the economic burden of initial capital and operational expenses, making biogas purification less cost-competitive at higher rates.

Conversely, the LCOBP decreases from $0.71 to $0.31 per cubic meter as the discount rate increases and purification capacity grows. This decline suggests economies of scale in the purification process, where higher capacities (from 1,733.75 to 2,600.63 cubic meters per year) reduce the per-unit cost of purification. The lower LCOBP at higher discount rates may also reflect the reduced present value of future operational costs relative to the increased purification volume,

making the water scrubbing method more economically attractive at larger scales. While higher discount rates increase the cost of biogas purification, they are associated with lower purification costs due to increased capacity. This suggests that scaling up purification capacity could mitigate the economic impact of higher discount rates, enhancing the overall cost-effectiveness of the biogas purification process. These findings underscore the importance of optimizing system scale and carefully selecting discount rates in economic assessments to balance production and purification costs. The results also support the potential of water scrubbing as a cost-efficient purification method, particularly at higher capacities, which could also inform the design and implementation of biogas upgrading systems in sustainable energy applications.

The sensitivity analysis reveals that higher discount rates significantly increase the LCOBP, particularly for activated carbon systems (up to \$2.11/ m^3 at 15% discount rate). This sensitivity underscores the need for favourable financing mechanisms to support biogas projects in developing economies. Access to low-interest loans or grants could reduce the effective discount rate, making both methods more financially viable. Additionally, carbon financing mechanisms, such as those under the Clean Development Mechanism (CDM), could offset the higher CAPEX and O&M costs of activated carbon systems by monetizing emission reductions (UNFCCC, 2022). Governments and development agencies should prioritize policies that incentivize local manufacturing and provide technical training to ensure the long-term sustainability of these systems (IRENA, 2021).

4.3 Determining the Environmental Impact

This subsection presents the environmental impacts of two locally available biogas purification methods; activated carbon adsorption and water scrubbing assessed through avoided emissions and secondary effects. The investigation quantifies the removal of carbon dioxide (CO_2) and

hydrogen sulfide (H_2S) from biogas, which are major pollutants affecting climate and air quality using experimental data from Tables (1), (2), and (3).

4.3.1 Environmental Impact Assessment of Biogas Purification

Activated Carbon Method

Biogas purification serves dual functions; it improves the calorific value of the gas for energy generation and reduces the environmental and health hazards associated with gaseous pollutants. Among various methods, the activated carbon method is widely used due to its high adsorption capacity and selectivity for trace gases, especially hydrogen sulphide (H_2S). In this sub section, the study evaluates the environmental implications of this method by quantifying the avoided emissions of two major impurities of carbon dioxide (CO_2) and hydrogen sulphide (H_2S) against there emission factors.

To determine the environmental impact, quantification is determined by calculating emissions avoided, derived from the difference in pollutant concentrations before and after purification, scaled by the total volume of biogas treated annually. The resulting mass of pollutant removed (in tons/year) is multiplied by the respective emission factor (kg CO_2-equivalent per ton) to yield the avoided emissions in kg CO_2-equivalent/year. As per the IPCC; for CO_2, the emission factor is 25.254 kg CO_2-eq/ton of gas removed, accounting for indirect impacts such as global warming, acidification, and contribution to atmospheric loading. For H_2S, two aspects are considered: its emission factor (3.5 kg CO_2-eq/ton) and its Global Warming Potential (GWP_{100}) of 13 as per the IPCC guidelines due to its strong reactivity and indirect contribution to greenhouse effects through secondary aerosols and acid rain formation.

The density of raw biogas was taken as 1.15 kg/m³, based on observed values in the experimental setup and supported by literature for typical biogas mixtures containing 55–65% methane, 30–45% carbon dioxide, and trace impurities such as hydrogen sulphide and water vapor.

This density value was critical in converting volumetric concentrations of gaseous impurities into mass-based quantities for further analysis. Specifically, the mass of each impurity (in kg/m³) was computed by multiplying its volumetric concentration (expressed in m³ of impurity per m³ of biogas) by the biogas density, as shown in Equation (9).

$$\text{Mass of impurity } \left(\frac{\text{Kg}}{\text{m3}}\right) = \text{Concentration} * \rho \text{ Biogas} \quad (9)$$

Table 8: Avoided emissions using Activated Carbon

Impurity	**Initial Concentration (kg/m³)**	**Final Concentration**	**Mass Removed**	**Annual Mass Removed (tons/year)**	**Emission Factor (kgCO_2 eq/ton)**	**Emissions Avoided (kg CO_2 eq/year)**
	ACTIVATED CARBON METHOD					
CO2	0.537	0.222	0.315	0.546	25.254	13.8
H2S	0.0153	0.0048	0.0105	0.0182	3.5	0.0637
Total	-	-	-	-	-	13.86

From Table 8, purification through activated carbon results in the annual removal of 0.546 tons of CO_2, which corresponds to 13.8 kg CO_2-equivalent emissions avoided annually. This reduction contributes directly to global climate goals by lowering the amount of carbon released to the atmosphere from anaerobic digestion systems. While this figure may seem modest, it represents a meaningful contribution in the context of rural off-grid energy systems, where emissions are often unmonitored and cumulative impacts over multiple plants can be significant. Also, the results confirm that the activated carbon method is effective in reducing greenhouse gas emissions from

raw biogas streams. CO_2 removal remains the dominant contributor to avoided emissions, but H_2S removal, though lower in mass, has critical relevance due to its corrosive, toxic, and climate-altering properties. These findings align with Uganda's Nationally Determined Contributions (NDCs) under the Paris Agreement, which seek to reduce GHG emissions while promoting renewable energy access. Integration of activated carbon purification in community-level biogas systems can support SD7, SDG13, AND SDG 13.

Water Scrubbing Method

Water scrubbing is among the most commonly applied biogas purification techniques in Uganda due to its ease of use, and reliance on locally available materials. This method exploits the differential solubility of impurities like carbon dioxide (CO_2) and hydrogen sulphide (H_2S) in water under pressure, allowing for effective removal without complex equipment. This sub section evaluates the method's environmental benefits by estimating the emissions avoided based on standard emission factors and later incorporating Global Warming Potential (GWP_{100}) for H_2S.

Table 9: Avoided Emissions by using Water scrubbing method

Impurity	**Initial Concentration (kg/m^3)**	**Final Concentration**	**Mass Removed**	**Annual Mass Removed (tons/year)**	**Emission Factor ($kgCO_2$ eq/ton)**	**Emissions Avoided (kg CO_2 eq/year)**
	WATER SCRUBBING					
CO_2	0.537	0.196	0.341	0.591	25.254	14.9
H_2S	0.0153	0.0089	0.0064	0.0111	3.5	0.0389
Total	-	-	-	-	-	14.94

From Table 9, the purification of biogas using water scrubbing removes approximately 0.591 tons of CO_2 annually, which corresponds to 14.9 kg of avoided CO_2-equivalent emissions. Also, these results represent a tangible reduction in the climate impact of impure biogas, particularly for decentralized energy systems that often go unregulated. This total slightly exceeds that of the activated carbon method, indicating higher environmental efficacy in terms of avoided emissions. The majority of this benefit is attributed to CO_2 removal, although H_2S remains critical due to its high reactivity and contribution to acidification and indirect climate impacts.

These results indicate that water scrubbing is marginally more effective than activated carbon in reducing the total mass of impurities from biogas and consequently achieving greater emission reductions. CO_2 removal under water scrubbing is 0.591 tons/year, compared to 0.546 tons/year using activated carbon. Likewise, total avoided emissions are 14.94 kg CO_2-eq/year versus 13.86 kg CO_2-eq/year respectively. However, it is crucial to consider not only the quantity but also the nature of the removed pollutants. Activated carbon is more efficient in targeting hydrogen sulphide, a compound with higher potential for environmental and equipment damage. The lower H_2S removal (0.0111 tons/year for water scrubbing vs 0.0182 tons/year for activated carbon) may necessitate complementary measures when water scrubbing is deployed, especially in regions with high-sulphur feedstocks like animal dung.

Water scrubbing's superior overall performance in emission reduction positions it as a suitable method for low-cost climate-smart energy transitions in Uganda. The method aligns with the objectives of Uganda's Green Growth Development Strategy (GGDS) and Vision 2040, which prioritize environmental sustainability alongside energy access.

4.3.2 Global Warming Potential

Table 10: Global warming potential for Hydrogen Sulphide

Pollutant	GWP_{100} (CO_2-eq/ton)	Description
CO_2	1	Baseline reference gas
H_2S	13	High GWP due to sulphur-based acidification potential and indirect effects on tropospheric chemistry (EPA, 2022; Wang et al., 2019)

While most greenhouse gas assessments focus on CH_4, CO_2, and N_2O, recent studies have highlighted the need to account for the Global Warming Potential (GWP) of sulphur-containing gases, especially H_2S. The Intergovernmental Panel on Climate Change (IPCC) does not provide a standard GWP_{100} for H_2S, but literature values suggest an approximate GWP_{100} of 13**,** primarily based on its oxidation to SO_2 and its atmospheric lifetime. In this context, the present study evaluates the contribution of H_2S removal to climate mitigation using this value for comparative and sensitivity purposes.

Application of Global Warming Potential (GWP_{100}) in Assessing H_2S Removal

Although hydrogen sulphide (H_2S) exists in relatively low concentrations within biogas streams, its high Global Warming Potential (GWP_{100}) renders it a disproportionately important contributor to climate change. According to the Intergovernmental Panel on Climate Change (IPCC), H_2S possesses a GWP_{100} of 13, meaning its warming effect over a 100-year horizon is thirteen times that of carbon dioxide (IPCC, 2013). This study now applies the GWP_{100} metric to evaluate the emissions avoided by removing H_2S through two purification technologies: activated carbon filtration and water scrubbing.

Activated carbon demonstrated superior performance, removing approximately 0.0182 tons of H_2S annually. When adjusted for GWP_{100}, this equates to 236.6 kg CO_2-equivalent per year in avoided emissions. By comparison, the water scrubbing method removed 0.0111 tons of H_2S annually, translating to 144.3 kg CO_2-equivalent per year. These estimates are significantly higher than those derived from traditional emission factor models, which yielded just 0.0637 kg CO_2-eq/year and 0.0389 kg CO_2-eq/year for activated carbon and water scrubbing, respectively. The disparity over 3,000% in some cases suggests that emission factor-based frameworks may vastly understate the environmental benefits of biogas purification in H_2S-rich scenarios (Frey & Puppe, 2020; EPA, 2014).

The study further reveals that trace gases, despite their minor volumetric presence, can have disproportionately large climate impacts. Consequently, national emission inventories and life cycle assessments (LCA) that fail to incorporate trace gas GWPs risk underestimating the climate mitigation potential of biogas systems (Giuntoli et al., 2017). In low-income countries like Uganda, where biogas systems are being increasingly promoted as sustainable energy solutions, the integration of trace gas considerations into environmental reporting frameworks is particularly critical.

Moreover, the findings support the strategic selection of purification technologies. While water scrubbing is more effective at CO_2 removal, activated carbon significantly outperforms it in H_2S capture. A hybrid approach, combining both methods may provide the most effective and environmentally beneficial solution as also alluded to by Ryckebosch et al., (2011). Such configurations could maximize total greenhouse gas (GHG) reductions, thereby enhancing the overall sustainability profile of biogas in rural and peri-urban contexts.

CHAPTER FIVE

CONCLUSCIONS AND RECOMMENDATIONS

5.1 CONCLUSCIONS

This study investigated the applicability and feasibility of locally available biogas purification options in Uganda, focusing on the activated carbon and water scrubbing methods. The findings demonstrate that both methods effectively improve biogas quality, with water scrubbing achieving a higher methane concentration (81.33% vs. 79.00% for activated carbon) and CO_2 removal efficiency (63.57% vs. 58.58%), while activated carbon excels in H_2S removal (68.42% vs. 42.11%). Techno-economically, water scrubbing is more feasible, with an original LCOBP of \$0.46/m^3 compared to \$0.71/m^3 for activated carbon, and the sensitivity analysis suggests increase in production capacity will reduce the overall LCOBP in both methods and an increase in LCOBP once the discount rate in increased.

Considering the Resource-Based View (RBV) theory, both methods leverage locally available resources that is water for scrubbing and agricultural waste for activated carbon offering a competitive advantage in sustainable biogas production. Water scrubbing emerges as the more viable option for widespread adoption in rural Uganda due to its cost-effectiveness and scalability, despite the potential need for wastewater management, while activated carbon is better suited for specific applications where H_2S removal is critical. The study underscores the potential of biogas purification to enhance energy access, reduce environmental impact, and improve rural livelihoods in Uganda, provided that cost, scale, and resource constraints are addressed through targeted policy interventions and technological optimizations. Future research should explore hybrid purification systems and long-term environmental impacts to further unlock biogas's role in Uganda's renewable energy landscape.

5.2 RECOMMENDATIONS

Water scrubbing should be prioritized for small-scale rural applications due to its higher CO_2 removal efficiency and lower LCOBP making it more cost-effective for households with limited resources. In contrast, activated carbon should be considered in regions with high H_2S content, given its superior H_2S removal efficiency, particularly where air quality is a priority. To address the operational costs of activated carbon local governments and NGOs should promote recycling programs for spent activated carbon, utilizing Uganda's agricultural waste to minimize waste generation.

Hybrid approaches combining water scrubbing and activated carbon should be explored to optimize both CO_2 and H_2S removal while balancing costs. For example, using water scrubbing as the primary method for CO_2 removal, followed by a smaller activated carbon unit for H_2S polishing, could leverage the strengths of both methods. This hybrid system could be piloted in rural areas to assess its feasibility, with findings informing future policy and investment decisions.

Capacity-building programs should be implemented to train rural communities on the operation and maintenance of these purification systems, ensuring long-term sustainability and alignment with the study's goal of enhancing energy security (SDG 7), environmental sustainability (SDG 13), and rural livelihoods (SDG 1).

The Study recommends the use of an electric pump to help in improving the flow rate of biogas, by so doing, the results will be realized faster and a hybrid method will be supported.

The study also recommends that a similar study be done on different feedstocks to ascertain the level of disparity.

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Appendix A

Excel Analysis

Input					LEVELISED COST OF BIOGAS PURIFICATION USING ACTIVATED CARBON												
			Purification capacity	*cf/yr*	1733.75												
			System Capacity	*cc*	5												
			Capex	*usd/cc*	48.6												
			System O&M	*usd/yr*	21.6												
			Period of analysis	*yrs*	10												
			Discount rate	*%*	5												
Calculation																	
			Periods			0	1	2	3	4	5	6	7	8	9	10	
			PV CAPEX	*USD*	243	243	0	0	0	0	0	0	0	0	0	0	
			PV O&M	*USD*	21.6	0	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	21.6	
			Total Purification	*cubicmeters*	1733.75	0	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	
		NPV															
			OPEX	*USD*	USD 40.50												
			CAPEX	*USD*	USD 0.72												
			Purification	*cubicmeters*	58												
Results																	
			LCOBP	*USD/Cubicmeters*	USD 0.71												

Input					LEVELISED COST OF BIOGAS PURIFICATION USING WATER SCRUBBING METHOD												
			Purification capacity	*cf/yr*	1733.75												
			System Capacity	*cc*	5												
			Capex	*usd/cc*	31.7												
			System O&M	*usd/yr*	3.2												
			Period of analysis	*yrs*	10												
			Discount rate	*%*	5												
Calculation																	
			Periods			0	1	2	3	4	5	6	7	8	9	10	
			PV CAPEX	*USD*	158.5	158.5	0	0	0	0	0	0	0	0	0	0	
			PV O&M	*USD*	3.2	0	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	
			Total Purification	*cubicmeters*	1733.75	0	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	1733.75	
		NPV															
			OPEX	*USD*	USD 26.42												
			CAPEX	*USD*	USD 0.11												
			Purification	*cubicmeters*	58												
Results																	
			LCOBP	*USD/Cubicmeters*	USD 0.46												

Appendix B

Laboratory photos



