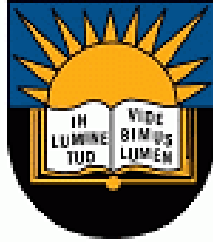


**MATHEMATICAL MODELLING OF BIOGAS YIELD FROM A GREENHOUSE
BIOGAS DIGESTER FED WITH COW DUNG**

Mzobotshe Mandilakhe



University of Fort Hare
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A dissertation submitted in fulfilment of the requirements for the degree of



MASTER OF SCIENCE
University of Fort Hare
Together in Excellence
IN

PHYSICS

.....

In the Faculty of Science and Agriculture at the University of Fort Hare

Supervisor: Prof Patrick Mukumba

Date: July 2024

DECLARATION

I, Mandilakhe Mzobotshe, student number 201716588, declare that this dissertation titled “Mathematical modeling of biogas yield from a greenhouse biogas digester fed with cow dung” submitted for the award of Master’s Degree, at the University of Fort Hare in the Faculty of Science and Agriculture is my original work and has never been submitted to this or any other university for consideration for another degree.

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DEDICATION

My beloved parents, you have been my pillars of strength and guiding light throughout this journey. Because of your sacrifices and unwavering support, I have been able to achieve this accomplishment. Your belief in me has been the foundation of my success.



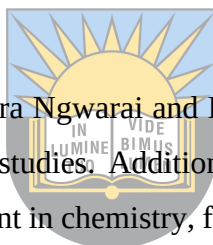
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In addition, I am grateful to Dr Shambira Ngwarai and Dr. Stephen Tangwe for teaching me the MATLAB abilities that I used in my studies. Additionally, I would like to acknowledge Mr. Kwanele Tshaphu, the senior lab assistant in chemistry, for providing me with the lab skills I need to characterize the physiochemical properties of the substrate.



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I would also like to thank my sister, Zenande Mzobotshe, for her constant cheer and confidence in my abilities. Your companionship has always brought me comfort and joy.

Lastly, I want to thank all my friends for their support, encouragement, and understanding throughout this journey

.

ABSTRACT

This study investigated biogas optimization using a solar greenhouse digester with cow manure feedstock. The methodology involved physicochemical analysis of feedstock, continuous monitoring of operational parameters, and development of mathematical models. A thermal analysis of the system was conducted. The temperature sensors were strategically positioned within the balloon digester and greenhouse envelope, while meteorological factors were measured using a pyranometer and weather sensors.

The results demonstrated optimal performance at mesophilic temperatures ($35\pm 1^\circ\text{C}$) and pH range of 6.8-7.2. Over the 39-day retention period, the system produced 18.269 m^3 of biogas, comprising 58% methane (CH_4) and 41% carbon dioxide (CO_2). The process achieved a chemical oxygen demand (COD) destruction rate of 56.31%. The low COD destruction rate can be attributed to the system's lack of a stirring mechanism, which affected the biogas yield and its composition. The multiple linear regression model for temperature prediction achieved an R-squared value of 0.985, and with a root mean square error (RMSE) of 0.341 while the non-linear response surface model for biogas yield reached 0.986 with a root mean square error (RMSE) of 0.0239.

The greenhouse enclosure effectively maintained optimal conditions, enhancing microbial activity and biogas production efficiency. These findings advance the understanding of solar-assisted biogas systems for sustainable energy production.

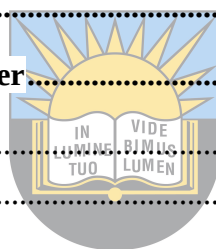
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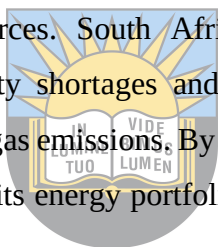


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CHAPTER 1 – INTRODUCTION

1.1 Background of the Study

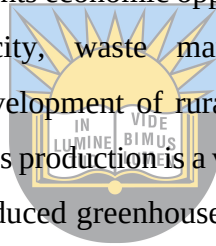
South Africa faces severe constraints on its national grid as demand in the national grid exceeds generation, and the base load is derived from fossil fuels. The process of transforming organic waste into energy has garnered considerable interest because of growing environmental concerns and the escalating costs of energy resources (Mutungwazi et al., 2020). The exploration of alternative energy sources is of growing significance, considering the persistent dependence on fossil fuels and their contribution to the escalating global warming crisis. South Africa's government has recognized the adverse consequences and substantial long-term costs associated with inadequate waste disposal, prompting them to pursue biogas generation as a feasible remedy to address the insufficiency in energy generation required to meet the demand. In the South African context, the utilization of biogas presents considerable importance owing to the country's ample agricultural and organic waste resources. South Africa is confronted with urgent energy challenges, such as recurrent electricity shortages and a substantial reliance on coal, which significantly contributes to greenhouse gas emissions. By harnessing the potential of biogas, South Africa has the opportunity to diversify its energy portfolio, decrease its dependence on coal, and address environmental pollution.



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Biomass-derived energy fuel is widely regarded as a favourable form of renewable energy. The production of biogas has emerged as a significant renewable energy solution, effectively tackling both environmental and energy-related issues (Mignogna et al., 2023). Biogas is a renewable energy source that is produced by microorganisms through the anaerobic digestion of organic matter in the absence of oxygen. This process involves breaking down various types of waste, including agricultural waste, manure, municipal waste, plant material, sewage, and food waste. The anaerobic digestion process consists of several stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During these stages, complex organic compounds are broken down into simpler molecules, which are then converted into methane (CH_4) and carbon dioxide (CO_2), along with small amounts of other gases like hydrogen sulphide (H_2S) and moisture. The resulting biogas primarily consists of 50-70% methane and 30-50% carbon dioxide, depending on the substrate type used and the process's management (Kabeyi et al., 2022). This makes biogas a valuable energy source that can be used for electricity and heat generation, transportation fuel, and cooking. This

process offers a sustainable substitute for conventional fossil fuels and contributes to the efficient management of waste by transforming organic waste into a valuable energy resource. However, further research studies must be conducted to establish its technical and economic viability as a dependable energy source (Saleem et al., 2022). The government aims to tackle this challenge by devising a plan to move towards an environmentally sustainable economy (DEA, 2016). Although biogas has impressive potential to supplement the grid energy demand, it is still in its development stage and partially contributes to the global bio-energy sector (Sawyerr, Trois, Workneh, & Okudoh 2019). The method of biogas production offers numerous advantages, such as the mitigation of environmental pollution, the establishment of localized energy self-sufficiency, and the generation of nutrient-rich organic fertilizer for agricultural purposes (Putatunda et al., 2020). The utilization of biogas not only helps to prevent deforestation but also provides a clean energy alternative and addresses sanitation concerns, particularly in rural areas (Singh et al., 2023). The production of biogas in rural areas presents economic opportunities by serving as a source of clean cooking fuel, decentralized electricity, waste management, and agricultural benefits. Consequently, it contributes to the development of rural areas while promoting environmental sustainability (Singh et al., 2023). Biogas production is a versatile fuel source with electricity, heat, and cooling applications. It leads to reduced greenhouse gas emissions and supports sustainable agriculture (Singh et al., 2023).



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The ratio of inoculum to substrate, retention period, pH level, C/N ratio, agitation, chemical oxygen demand (COD), ambient and slurry temperature, as well as the contents of volatile solids (VS) and total solids (TS), are all important variables in the methanogenic activities during the anaerobic digestion process. Regarding the biogas generation rate, the temperature set in the digester is a crucial factor for an economically viable fermentation process. This phenomenon occurs because temperature is positively correlated with the rate of microbial growth, digestion, and gas production. Therefore, it is necessary to implement bio-digester heating to enhance these processes (Makamure et al., 2021). The type of digester utilized exerts a considerable influence on the production of biogas. The selection of a digester carries implications for biogas production's efficiency, operational convenience, and sustainability, as each type possesses distinct components and processes. Among the different types of biogas digesters, it has been observed that numerous small-scale anaerobic digesters in developing nations encounter failure due to design inefficiencies, inadequate maintenance, the high capital cost of construction, operational

difficulties, and the unavailability of construction materials (Khoshnevisan et al., 2021). Balloon digesters have garnered attention due to their flexibility, ease of installation, and cost-effectiveness. However, these systems frequently face challenges in maintaining optimal temperatures for the anaerobic digestion process. The integration of solar energy into these systems, commonly referred to as solar-assisted digesters, presents a promising solution. Solar energy aids in sustaining the necessary temperatures, thereby enhancing microbial activity and augmenting biogas yields. Therefore, the research needs to address a critical knowledge gap in the understanding of how heat interact and influence biogas production in a controlled greenhouse environment. By doing so, it aims to enhance the efficiency and reliability of biogas systems, thereby contributing to the advancement of sustainable renewable energy technologies and providing valuable insights for the optimization of biogas production processes. Furthermore, the study aims to develop robust and predictive mathematical models that optimize biogas production by accurately relating key operational parameters such as chemical oxygen demand (COD), slurry temperature, and pH to the volume of biogas yield. The study also seeks to develop a multiple linear regression model to predict slurry temperature using environmental variables like ambient temperature, greenhouse temperature, solar irradiance, and relative humidity.

1.2 Problem Statement

The global shift towards renewable energy sources has brought attention to the potential of biogas as a sustainable alternative to fossil fuels. The widespread adoption of biodigesters worldwide has resulted in increased biogas production. Specifically, biogas production from agricultural waste, such as cow dung, offers significant environmental and economic advantages, including waste management and energy generation. Nevertheless, the anaerobic digestion process has certain technical limitations, including low yields and slow reaction rates. Various technologies have been utilized to improve biogas production from organic waste fractions, including temperature regulation. Installing conventional digester types in a harsh and steep area is also impractical. This indicates that even though these communities have the substrates needed to produce biogas, they are unable to benefit from biogas energy. Traditional biogas digesters often struggle to maintain optimal operating conditions, leading to inefficiencies in biogas production. It is believed that solar energy can play a vital role in raising the temperature within the biodigester. The integration of greenhouse technology with biogas digesters presents a promising solution by creating a controlled environment that can enhance microbial activity and, consequently, increase biogas yield.

The efficiency and optimization of biogas production from greenhouse biogas digesters fed with cow dung pose significant challenges in the pursuit of sustainable renewable energy sources. However, the application and optimization of balloon solar-assisted systems within greenhouses remain largely unexplored and insufficiently understood. Despite the potential of biogas as a clean energy alternative, there are no comprehensive models that accurately predict and optimize biogas yield based on varying operational parameters and environmental conditions. Existing studies lack comprehensive models and experimental data to determine the optimal design and operational parameters that maximize the benefits of such systems. The primary challenges include understanding the interaction between the balloon solar-assisted system and the microclimate of the greenhouse, optimizing energy capture and temperature distribution, and evaluating the temperature and overall greenhouse effect on the balloon digester. Current practices often fail to fully exploit the potential of biogas digesters due to an inadequate understanding of how factors such as COD, slurry temperature, pH, ambient temperature, greenhouse temperature, solar irradiance, and relative humidity influence biogas production. This gap limits the scalability and practical implementation of such systems in rural settings.

By addressing these gaps, the study aims to provide a comprehensive analysis of the physiochemical properties of cow dung in relation to biogas production, evaluate the performance of solar greenhouse digesters under different environmental conditions, and develop predictive models tailored to such systems. This research not only contributes to optimizing biogas production processes but also supports sustainable energy solutions for rural and semi-urban communities.

1.3 Research Aim

The aim is to develop a non-linear response surface mathematical model that will determine the operational parameters (COD, slurry temperature, and pH) of solar-assisted biogas production by relating input factors with the volume of biogas production and a multiple linear regression model with input parameters being (ambient temperature, greenhouse temperature, solar irradiance, and relative humidity) for the desired output being (slurry temperature).

1.4 Research Objectives

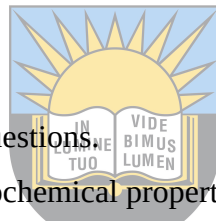
- i. To assess the physiochemical properties of dairy cattle manure feedstock, including volatile solids (VS), total solids (TS), COD, and pH.

- ii. To measure the meteorological factors affecting the performance of the biodigester, namely, solar irradiance, relative humidity, and ambient temperature
- iii. To measure both the temperature of the slurry and the temperature inside the greenhouse structure.
- iv. To quantify biogas production, analyze its composition, and compute the total biogas equivalent over the entire anaerobic digestion period.
- v. To determine how the greenhouse envelope affects the production of biogas produced by the solar-assisted biodigester.
- vi. To develop a multiple linear regression model that predicts slurry temperature using factors like relative humidity, sun irradiation, greenhouse temperature, and ambient temperature.
- vii. To develop a non-linear multiple response surface model (Hougen Watson) to anticipate the volume of biogas produced, using input variables such as COD, slurry temperature, and pH.

1.5 Research Questions

The study has the following research questions.

- i. What is the impact of the physiochemical properties on biogas production?
- ii. How do these meteorological factors affect biogas production?
- iii. What is the average temperature of the greenhouse envelope, and how does it affect the slurry temperature?
- iv. What is the quantity of biogas generated, and what is the composition of the biogas produced?
- v. How does the greenhouse envelope contribute to maintaining optimal environmental conditions for biogas production?
- vi. How can a multiple linear regression model be effectively employed to forecast slurry temperature by considering variables such as relative humidity, solar irradiation, greenhouse temperature, and ambient temperature?
- vii. Can these developed models accurately forecast the desired outputs?



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1.6 Study Rationale

This research is of utmost importance in advancing the implementation of biogas systems in rural areas, among farmers, and in agricultural regions. It aims to promote sustainable energy production and make a significant contribution to global initiatives in reducing greenhouse gas emissions. The role of biogas technology in enhancing sustainable energy solutions cannot be overstated. By employing anaerobic digestion, organic materials such as agricultural waste, food scraps, and municipal solid waste are converted into biogas, a renewable energy source that mitigates the adverse impacts associated with traditional waste management practices. This process not only addresses waste disposal challenges but also reduces greenhouse gas emissions, promoting environmental health. Moreover, as biogas technology matures, its integration with mathematical modelling will facilitate more efficient resource allocation and operational strategies, further optimizing biogas production and reinforcing its importance within the broader energy landscape (Bergström et al., 2024).

The development of a rigorous mathematical model in this study will serve as a basis for enhancing the design and operation of greenhouse solar-assisted biogas digesters. Ultimately, this will facilitate the wider adoption of biogas technology in diverse settings. Developing a model would help anticipate practical constraints of solar-assisted biogas production within a limited timeframe for conducting experiments. Models provide a comprehensive understanding of the complex system, facilitating smoother operation and design of the process while reducing costs. Predicting a system's behaviour simplifies production optimization and prevents any process failures.

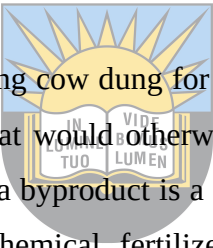
1.7 Assumptions

Some assumptions will be made regarding the volume of biogas yield from a solar greenhouse digester fed with cow dung. Firstly, the use of a biogas digester built from composite material can lead to cost-effectiveness and economic benefits, as higher net present value (NPV) leads to greater economic benefits (Obileke et al., 2022). Secondly, solar energy can significantly contribute to biogas production, with up to 75.21% contribution observed in some settings (Darwesh et al., 2021). Effective temperature regulation can enhance the methane content within biogas. Lastly, the anaerobic digestion of cow manure under mesophilic conditions can result in a higher destruction of pathogens (Oliveira et al., 2021). Therefore, it can be assumed that using a solar

greenhouse digester fed with cow dung can lead to efficient and sustainable biogas production with potential economic and environmental benefits.

1.8 Justification of Cow dung as a Primary Feedstock

Cow dung is an ideal primary substrate for biogas production due to its abundant availability, renewable nature, and alignment with sustainability goals, particularly in rural settings. In areas where livestock farming is prevalent, cow dung is consistently available throughout the year, providing a reliable and cost-effective feedstock for biogas plants (Shaibur et al., 2021). Its balanced carbon-to-nitrogen ratio (C/N ratio) of approximately 25:1 makes it highly suitable for anaerobic digestion, optimizing methane production. Moreover, the high moisture content and biodegradability of cow dung reduce the need for extensive preprocessing, making it especially practical in rural areas with limited technical resources.



From an environmental perspective, using cow dung for biogas production mitigates greenhouse gas emissions by capturing methane that would otherwise be released from untreated manure. Additionally, the digestate produced as a byproduct is a nutrient-rich fertilizer that enhances soil health and reduces dependency on chemical fertilizers, promoting sustainable agricultural practices (Onwosiet al., 2022). Socio-economically, cow dung-based biogas systems address rural energy needs by providing a decentralized energy source for cooking, lighting, and heating. Studies have shown that adopting biogas reduces firewood consumption, improving indoor air quality and alleviating the labour burden on women who traditionally collect firewood.

Furthermore, cow dung's consistent availability ensures a stable feedstock supply, reducing operational uncertainties often associated with crop residues or seasonal agricultural waste. This reliability is critical for the uninterrupted operation of small-scale biogas plants in rural areas. In summary, cow dung's accessibility, environmental benefits, and socio-economic advantages underscore its selection as a primary substrate for biogas production, contributing to sustainable energy development and improved rural livelihoods.

Cow dung is considered an ideal feedstock for biogas production due to its high moisture and volatile solids content (Washaya et al., 2023). Additionally, it contains a diverse array of

microorganisms that play vital roles in the anaerobic digestion process. For instance, the microbial composition of cow dung includes various bacterial species such as *Bacillus spp.*, *Corynebacterium spp.*, *Lactobacillus spp.*, *Citrobacter koseri*, *Enterobacter aerogenes*, *Escherichia coli*, *Klebsiella oxytoca*, *Klebsiella pneumoniae*, *Kluyvera spp.*, *Morgarella morganii*, *Pasteurella spp.*, *Providencia alcaligenes*, *Providencia stuartii*, and *Pseudomonas spp.*, along with protozoa, yeast (*Saccharomyces* and *Candida*), lignocellulolytic fungi, and archaea (Liang et al., 2024 & Liang et al., 2021). Biogas, a renewable energy source and potential substitute for fossil fuels, is generated when animal manure undergoes anaerobic digestion facilitated by methanogenic bacteria. The resulting biogas typically contains 45–70% methane, 25–40% carbon dioxide, and trace amounts of hydrogen sulphide (<10 ppm), nitrogen (<3 ppm), and hydrogen (<1 ppm), with the exact composition varying based on the source of the manure (Washaya et al., 2023).

1.9 Thesis Synopsis

Chapter 1: This chapter concisely introduces the dissertation, including the necessary background information and the motivations behind the research. It outlines the problem statement, research aims and objectives, study rationale and assumption, and the synopsis of the thesis.

Chapter 2: This chapter reviews the anaerobic digestion process and its stages of operation, the different biogas production processes, and factors that can affect biogas production. Additionally, the relationship between biogas production and thermal efficiency was also discussed. The chapter provides an overview of the various types of biogas digesters and their limitations. The effect of heat accumulation within the greenhouse enclosure was presented. The chapter concluded by looking at the mathematical model employed in predicting biogas yield.

Chapter 3: The methodology for empirically monitoring the digester's performance evaluation is the main focus of this chapter. In addition to modelling the performance of a field-scale solar hybrid biogas balloon digester, the determination of the feedstock characteristics and the mode of feeding was also provided.

Chapter 4: The outcomes of the solar-assisted balloon biodigester system are presented.

Chapter 5: The mathematical models developed for the experiments are presented in this Chapter. The chapter also looks at the effect of the ANOVA ONE-WAY test as a tool to determine the significant differences between target validation data and predicted values produced by the

mathematical models, as well as the target testing data and model outputs. The chapter describes how the input parameters of each model are ranked.

Chapter 6: The research findings, summary, and suggestions for improving the greenhouse envelope's insulation qualities through concrete use are outlined. Additionally, the system as a whole is optimized for increased efficacy.



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CHAPTER 2 – LITERATURE REVIEW

2.1 Introduction

This chapter provides an in-depth exploration of biogas production, examining the various factors that influence its efficiency and effectiveness. It emphasizes the importance of thermal efficiency in enhancing both the quantity and quality of biogas generated. Beginning with an introduction to biogas, the chapter discusses its environmental, social, and economic benefits. It then critically evaluates different types of biogas digesters, highlighting their advantages and limitations. Strategies for improving biogas production are explored, followed by a thorough analysis of temperature regulation methods in digesters, including their strengths and weaknesses.

The concept of a solar greenhouse digester, which utilizes solar energy for heating to enhance biogas production, is presented as an innovative technology. The chapter further explores the potential of biogas systems by focusing on the role of mathematical modelling in their design and operation. These models are crucial for predicting performance, optimizing efficiency, and minimizing environmental impacts. By consolidating discussions on mathematical modelling, the chapter aims to facilitate better collaboration among researchers, engineers, and policymakers, enabling more effective and innovative biogas system applications. This mathematical focus transforms biogas technology from a conceptual idea into a practical solution for modern energy challenges, while also providing a detailed overview of biogas production quantification from solar greenhouse digesters using cow manure as feedstock.

Despite advancements in the field, significant research gaps remain. For instance, there is limited understanding of how specific physiochemical properties such as volatile solids (VS), total solids (TS), and chemical oxygen demand (COD) affect biogas yields under greenhouse conditions, particularly when dairy cattle manure is used. Although these factors have been individually studied, their interactions and combined impacts on biogas production are not well understood.

Additionally, the influence of meteorological factors such as solar irradiance, relative humidity, and ambient temperature on biodigester performance is underexplored. While these variables are known to affect the thermal dynamics of biodigesters, their specific effects on slurry temperature and biogas production within solar-assisted greenhouse systems remain insufficiently quantified.

Similarly, although the thermal regulation provided by greenhouse envelopes has been studied qualitatively, there is a lack of quantitative data on their ability to stabilize slurry temperatures and enhance biogas yields across varying climatic conditions.

Another critical gap lies in the absence of reliable predictive models for biogas yields and slurry temperature. Existing models often rely on linear relationships or require significant computational resources, limiting their practicality for real-time biodigester management. Advanced non-linear models, such as response surface methodologies, have not been widely applied to predict biogas production based on variables like COD, slurry temperature, and pH, especially in solar-assisted systems.

This study aims to address the identified research gaps and make substantial contributions to the existing body of knowledge. First, it will comprehensively analyze the physiochemical properties of dairy cattle manure feedstock and their correlation with biogas production, offering a deeper understanding of the substrate's potential for energy generation. Second, it will quantify the influence of meteorological factors and greenhouse envelope designs on maintaining optimal environmental conditions for biogas production. This will provide valuable insights into the integration of these factors to enhance biodigester efficiency. Finally, the study will focus on developing and validating predictive models, including a multiple linear regression model for forecasting slurry temperature and a non-linear response surface model for estimating biogas yields. These models, specifically tailored to solar-assisted greenhouse biodigesters, will enable more accurate and practical forecasting for researchers and practitioners. By addressing these gaps, the study not only advances the understanding of solar-assisted greenhouse biodigesters but also establishes a framework for optimizing biogas production in rural and semi-urban contexts, ultimately contributing to the development of sustainable and efficient renewable energy solutions.

2.2 Background of Biogas Technology

The role of biogas technology in enhancing sustainable energy solutions cannot be overemphasised. By employing anaerobic digestion, organic materials such as agricultural waste, food scraps, and municipal solid waste are converted into biogas, a renewable energy source that mitigates the adverse impacts associated with traditional waste management practices. This process not only addresses waste disposal challenges but also reduces greenhouse gas emissions, promoting environmental health. In the context of Integrated Solid Waste Management (ISWM), the scalability and adaptability of biogas systems can significantly enhance material recycling and

energy recovery efforts within urban settings, particularly in regions like Nairobi, where waste volumes are high and management systems are often underdeveloped (Kasozi et al., 2010). Moreover, as biogas technology matures, its integration with mathematical modeling will facilitate more efficient resource allocation and operational strategies, further optimizing biogas production and reinforcing its importance within the broader energy landscape (Bergström et al., 2024).

The ability of biogas to lower greenhouse gas emissions and offer sustainable energy solutions has made it a prominent renewable energy source. According to Mukumba et al. (2017), biogas technology offers several advantages that improve user welfare, social welfare, and the economy. These advantages include promoting agricultural development, raising rural income, enhancing rural environmental conditions, streamlining energy consumption patterns, and improving the standard of living in rural and agricultural areas. Because it burns cleanly and produces less ash than other gas fuels like natural gas, biogas has the alluring benefit of being a clean energy source. This is because its shorter carbon chain length results in lesser carbon dioxide emissions during combustion (Mignogna et al., 2023). Along with these benefits, advanced sanitation is enhanced, bacteria and disease transmission are decreased, energy production costs are lowered, and greenhouse gas emissions, siloxanes, hydrogen sulphide, and nitrous oxide are reduced (Werkneh et al., 2022). In addition to being smoke-free, biogas minimizes odours and offers a healthier cooking environment (Pokhrel et al., 2023), making it a green energy source.

One device that has been suggested to increase biogas output is the solar greenhouse digester, which heats the digester using sun radiation. The purpose of this review of the literature is to give a broad overview of the studies that have been done on the amount of biogas produced by a solar greenhouse digester that is fed cow manure.

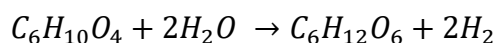
2.3 Biogas Process

Methanogens are microorganisms that produce methane and, at a particular temperature, are active, thereby producing biogas. It usually consists of a mixture of carbon dioxide (CO_2) and methane (CH_4), though the amounts might change depending on the digestive process and the chemical makeup of the source waste. Methane normally makes up 50–70% of the volume, while carbon dioxide accounts for 30–50%. Smaller amounts of nitrogen gas (N_2), ammonia (NH_3), hydrogen sulphide (H_2S), and other chemicals are also present. Furthermore, biogas can supply enough

energy for cooking in a family of five people because it is often saturated with water vapour (H₂O) and has a calorific value of 6 kWh/m³ (Obileke et al., 2020; Mukumba et al., 2018). Specifically, the anaerobic cycle has four syntrophic arrangements: methanogenesis, acetogenesis, hydrolysis, and acidogenesis (Kumar et al., 2019). Strict anaerobes like bactericides and facultative bacteria like streptococci carry out the first stage, hydrolysis. During this process, fermentative bacteria release enzymes like amylase and protease, which break down big, complicated macromolecules into smaller, organic components that can dissolve.

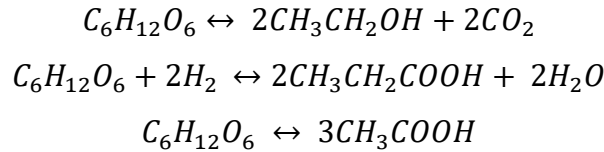
2.3.1 Hydrolysis

The hydrolysis process frequently encounters a bottleneck when dealing with a lot of organic wastes, mostly due to the difficulty in breaking down some complex polymers and the restricted access of hydrolytic microbes to soluble molecules (Nwokolo et al., 2022). To enable passage through microbial cell layers, the insoluble complex organic substance is divided into soluble components in this process (Uddin et al., 2021). Hydrolytic substances carry out the process of hydrolysis. Initially, fermentative bacteria break down proteins, cellulose, and lipids into amino acids, soluble sugars, and fatty acids (Weiland et al., 2010). Certain types of bacteria can produce enzymes called xylanases. These enzymes can break down complex carbohydrates such as cellulose and xylose into simpler sugars like glucose and xylose. On the other hand, proteolytic bacteria release proteases that break down proteins into amino acids. In addition, lipases produced by lipolytic bacteria have the ability to convert lipids (fats and oils) into glycerol and fatty acids with long chains (Kangle et al., 2012).



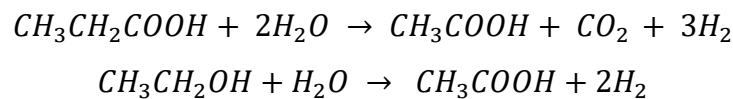
2.3.2 Acidogenesis

A distinct group of microorganisms ferments the breakdown products into acetic acid, hydrogen, carbon dioxide, and other volatile organic acids with lower molecular weights, like butyric acid and propionic acid, during the second stage, which is referred to as acidogenesis (VFAs, for example, liquor (ethanol) and lactic corrosive (Uddin et al., 2021).



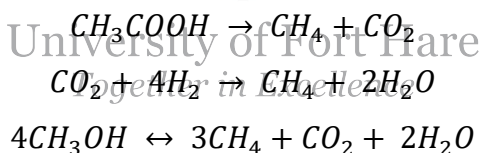
2.3.3 Acetogenesis

Acetate, CO₂, and H₂ are produced by acetogenic bacteria from the by-products of the acidogenesis phase and certain long-chain fatty acids from the hydrolysis phase. When the partial pressure of H₂ surpasses 10⁻⁴ atm, the processes that take place during acetogenesis are not beneficial from an energy perspective. Methanogenic bacteria, on the other hand, use the H₂ they produce to assist in lowering this partial pressure. Because H₂ is fundamentally made up of a proton (H⁺) plus an extra electron, the exchange of H₂ between different species is analogous to the transfer of electrons. The total pace of digestion may be significantly impacted by the rate at which this electron transfer takes place (Uddin et al., 2021). The process of acetogenesis converts various by-products of acidogenesis, including long fatty acids, VFAs that have numerous carbon atoms, propionate, butyrate, valerate, alcohols, and fragrant unsaturated fatty acids into acetic acid and hydrogen. Hydrogen-producing bacteria carry out this transformation (Rajagopal et al., 2021). During this phase, bacteria with acetogenic properties transform the outcomes of the primary stage into simple acids that are organic, carbon dioxide, and hydrogen (Lee et al., 2022). The main acids delivered are acetic corrosive (CH₃COOH), propionic corrosive (CH₃CH₂COOH), butyric corrosive (CH₃CH₂CH₂COOH), and ethanol (C₂H₅OH) (Zhu et al., 2022). In any case, a large portion of the acetic acid derivation is made by hydrogen-creating acetogenic bacteria (Rajagopal et al., 2021).



2.3.4 Methanogenesis

At the final stage of the anaerobic process called methanogenesis, certain microorganisms can transform simple organic compounds such as hydrogen, acetate, and carbon dioxide into methane and carbon dioxide (Zhu et al., 2021). This phase is essential to the overall effectiveness of the production of biogas and anaerobic digestion. Since no single species of methane-producing bacteria is able to break down every substrate that is accessible, a varied variety of these bacteria is essential for anaerobic digestion systems. Archaea bacteria are among these methanogenic bacteria (Kangle et al., 2012). Acetate consumers and H₂/CO₂ consumers are the two categories into which methanogens are separated. Due to their ability to absorb both acetate and H₂/CO₂, *Methanobacterium thermoautotrophicum*, commonly referred to as *Methanosaeta*, is crucial for anaerobic digestion (Weiland et al., 2010). About 70% of methane is created from acetate, with the remaining 30% coming from hydrogen and other electron donors, reducing carbon dioxide (Sawyer et al., 2019). Methanogens are members of the Archaea domain that create carbon dioxide and methane by using hydrogen, acetate, carbon dioxide, methanol, methylamines, and formate. Methanogenesis serves as an indicator of biological activity within an anaerobic system and reflects the state of the digestion process. Higher methane production suggests greater system stability and efficiency.



2.4 Factors Affecting the Anaerobic Digestion Process

The effectiveness of the anaerobic digestion process is influenced by various factors, such as the substrate's physiochemical characteristics, the design of the digester's operating conditions, and the digester's design (Meegoda et al., 2018). A well-designed anaerobic digester system ensures efficient decomposition of organic matter, prevents digestion failures, and enhances the methane content of the biogas produced. During the anaerobic digestion process, the growth rate of microorganisms is essential for attaining large biogas production (Harirchi et al., 2022). Strict adherence to operating parameter ranges, including temperature, pH, volatile solids (VS), total

solids (TS), substrate loading rate, and periodic mixing, can help create a favourable microbial environment in a digester (Westerholm et al., 2019).

In order to enhance microbial activity and optimize the efficiency of anaerobic degradation, it is necessary to carefully control specific operational parameters of the anaerobic process. These operating factors are covered in detail in the following section.

2.4.1 Hydraulic Retention Time (HRT)

The hydraulic retention time (HRT) is the average period during which solids and liquid wastes stay in a digester, allowing them to interact with the microbial biomass (feedstock). Extended hydraulic retention time often results in improved removal efficiency. It provides ample opportunity for the biomass to interact effectively with the waste, removing larger quantities of contaminants from the treated waste. The duration of temperature also affects retention, as higher temperatures result in shorter retention times, particularly up to 35°C (Li et al., 2020). The optimal length of time needed for complete digestion in a particular system depends on factors such as the technology employed, system temperature, feeding mechanism, and properties of the substrate. As an illustration, the retention periods in mesophilic digesters typically range from 10 to 40 days. On the other hand, digesters that operate in the thermophilic range need shorter retention periods (Shi et al., 2021). Ensuring the complete degradation of volatile solids is of utmost importance when designing reactors with adequate retention times. In flow-through systems like the Continuous Stirred-Tank Reactors (CSTRs) used in Phase II, the hydraulic residence time (HRT) and the retention time of the microbial biomass or sludge (SRT) are the same. When dealing with streams with high concentrations of solids, it becomes essential to increase the retention times to optimize bioenergy production (Sawyer et al., 2019). By increasing the solids retention time (SRT), the efficiency of the digestion process is enhanced, resulting in reduced sludge production and increased completion of anaerobic digestion reactions. This leads to improved biogas production. Having an excessively long SRT can result in a nutrient-deficient system, whereas an SRT that is too short leads to inefficient resource wastage (Li et al., 2014).

2.4.2 Total Solids (TS)

The amount of solid material contained in the substrate used for anaerobic digestion is referred to as total solids (TS) in the context of biogas production. Both organic and inorganic solids are included in this. Because it influences both the overall process efficiency and the biogas yield, TS is a crucial element in the production of biogas. Increased TS concentration may result in reduced substrate digestibility and process instability, but it may also increase organic loading rates and possibly biogas output (Luo et al., 2021). Total solids (TS) are the remaining solid materials in a substrate following a 24-hour heating process to 105°C and total moisture removal. Less than 10% TS is normally present in low solids (LS) anaerobic digestion systems, 15% to 20% in medium solids (MS) processes, and 22% to 40% in high solids (HS) processes (Sun et al., 2018).

2.4.3 Volatile Solids (VS)

VS represents the organic components within a substrate that are capable of being transformed into gas through anaerobic digestion. These components encompass substances like carbohydrates, proteins, and lipids, which microorganisms can decompose to generate biogas. The content of a substrate is of great importance in various applications in anaerobic digestion, as it directly influences the potential biogas output and the efficiency of the overall process (Hassan et al., 2021). The waste that remains after all debris has been removed and combustion has finished is referred to as the VS content in organic wastes. As per the research conducted by (Das et al. 2023), there are two main categories of volatile solids: biodegradable volatile solids (BVS) and recalcitrant volatile solids (RVS). Having a good grasp of the BVS component of the substrate is crucial for evaluating waste being biodegradable biogas age, organic loading rate, and C/N ratio. Some waste products that fall under the category of RVS, which are high in volatile and low in biodegradable matter, are cow dung and pig fertilizer. The biogas produced from these wastes can be generated in a significantly shorter period (around 7 days) compared to other digester substrates. This characteristic makes them highly suitable for promotion treatment (Prasad, 2012).

(Patel et al., 2023) highlighted that while VS content is often used as an indicator of a feedstock's biogas potential, the relationship between VS and methane yield is not always linear and can be affected by the chemical composition of the substrate. For example, high lignin content in certain feedstocks, such as agricultural residues, can reduce the biodegradability of VS, leading to lower methane production. This discrepancy points to the need for more research into how different

feedstock compositions, including their lignocellulosic content, protein, and carbohydrate profiles, interact with microbial communities during digestion and influence VS degradation.

Moreover, pretreatment methods, which are commonly employed to enhance the digestibility of feedstocks, can also have varying effects on VS degradation. (Ahmed et al., 2022) discussed the potential of physical, chemical, and biological pretreatments to increase the solubility and accessibility of organic material, thereby improving the degradation of VS and biogas yield. However, the efficiency of these methods is highly dependent on the type of feedstock and the pretreatment conditions, such as temperature, duration, and chemical concentration. For instance, alkaline or thermal pretreatment has been shown to improve the breakdown of lignin in lignocellulosic materials, but (Jankovičová et al., 2023) pointed out that such treatments may also lead to the loss of volatile fatty acids, which are essential intermediates in methane production. This indicates a gap in understanding the optimal conditions for pretreatment methods that maximize VS degradation while minimizing the loss of valuable byproducts.

Additionally, the interaction between VS concentration and operational factors such as hydraulic retention time (HRT) and organic loading rate (OLR) has not been fully explored in relation to specific feedstock types. (Shi et al., 2023) suggested that variations in HRT can influence the extent to which VS is converted into biogas, with shorter HRTs leading to incomplete degradation of the organic matter. However, how this effect varies across different feedstock compositions, especially those with high or low VS content, remains poorly understood. These gaps indicate the need for further research into the specific roles of feedstock composition and pretreatment methods in enhancing VS degradation, as well as the development of more tailored strategies to optimize biogas production from a diverse range of organic materials.

2.4.4 Chemical Oxygen Demand (COD)

The Chemical Oxygen Demand (COD) in biogas is determined by the amount of oxygen required for the chemical oxidation of organic compounds present in the biogas sample. It is an important parameter in biogas production because it indicates the organic load or pollution level of the substrate being digested (Kalia et al., 2019). Monitoring COD levels helps assess the efficiency of the anaerobic digestion process and the extent of organic matter degradation.

2.4.5 pH

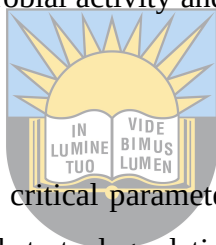
The ideal pH for biogas is accomplished when the pH of the slurry mix in the digester is in the scope of 6 and 7 (Muñoz et al., 2020). In the fundamental time of development, as a ton of organic acids are made by corrosive-forming bacteria, the pH inside the digester can lessen to under 5. This controls or even stops the maturing or digestion measure. Methanogenic microorganisms are incredibly sensitive to pH and don't prosper under a value of 6.5 (Munoz et al., 2020). The anaerobic digestion process is facilitated by a diverse range of microorganisms, including acidogens and methanogens. These microorganisms thrive within a specific pH range, with methanogens typically preferring a neutral pH environment. Maintaining the optimum pH ensures optimal microbial activity and biogas production rates. Optimal pH levels encourage effective matter breakdown and biogas production. By keeping the pH within the prescribed range, there is a need to increase the biogas yield, reduce retention periods, and improve overall process stability. Extreme pH levels, whether acidic or alkaline, can impede microbial activity and disturb anaerobic digestion. Acid inhibition can lead to low biogas output and process instability. As a result, keeping pH within the optimal range helps minimize acidification while ensuring process stability. Maintaining the optimum pH for biogas production is crucial for maximizing microbial activity, preventing acid inhibition, optimizing methane content, and ensuring overall process efficiency and stability. The pH control is an essential parameter in anaerobic digestion systems and is carefully monitored and regulated to achieve optimal biogas production performance.

2.4.6 Stirring

Stirring promotes the dispersion of microorganisms, enhances contact between bacteria and substrate, and prevents substrate layering, thereby boosting biogas production and accelerating organic waste decomposition. Additionally, stirring helps to maintain uniform temperature distribution and optimal pH levels and prevents the formation of crust or scum on the digester's surface, which could hinder gas production. (Li et al., 2020) A recent study investigated the impact of varying stirring frequencies on biogas production in anaerobic digestion processes. According to the study, increasing the frequency of stirring enhanced substrate usage and mixing efficiency, which increased biogas production. When stirring frequency was improved, the researchers saw a considerable rise in methane output, underscoring the significance of efficient mixing techniques in raising the efficiency of biogas generation.

2.4.7 Inoculum

The inoculum, typically comprising microorganisms sourced from a pre-established anaerobic digestion system, is vital for initiating and expediting biogas production. Inoculum serves as a source of active microbial populations necessary for the breakdown of organic matter and the production of biogas. During its introduction into a new anaerobic digestion system, inoculum jumpstarts the fermentation process by providing an array of anaerobic bacteria and archaea thrive in this community, skilfully breaking down intricate organic substances into more manageable compounds like volatile fatty acids and methane. In a study conducted by Wang et al. (2021), the impact of different sources of inoculum on biogas production in a pilot-scale anaerobic digestion system was examined. The findings revealed that inoculum obtained from stable and high-performing digesters yielded quicker start-up times and superior biogas production compared to inoculum sourced from less stable systems. Specifically, the study highlighted that the utilization of high-quality inoculum bolstered microbial activity and enhanced process stability, resulting in more efficient biogas production.



2.4.8 Carbon/Nitrogen(C/N) Ratio

The carbon-to-nitrogen (C/N) ratio is a critical parameter in anaerobic digestion processes as it directly influences microbial activity, substrate degradation, and biogas production efficiency. The C/N ratio indicates the substrate's balance between nitrogen-rich and carbon-rich compounds. Optimal microbial growth and activity and effective decomposition of organic matter hinge upon maintaining an appropriate C/N ratio. Enhanced biogas production rates are achieved through the synthesis of enzymes essential for substrate breakdown, a process facilitated by maintaining a well-balanced C/N ratio. Han et al. (2021) examined the effects of various C/N ratios on the generation of biogas in anaerobic digestion systems that handle organic waste. The results showed that an optimum C/N ratio greatly impacted biogas production rates and the amount of methane. The study revealed that, within a specific range, increasing the C/N ratio will result in higher methane concentrations and biogas outputs. However, deviating from the ideal C/N ratio changed the microbial population's dynamics and reduced biogas output. To maximize biogas production efficiency and process stability in anaerobic digestion systems, the researchers concluded that maintaining a balanced C/N ratio is crucial.

2.4.9 Ammonia

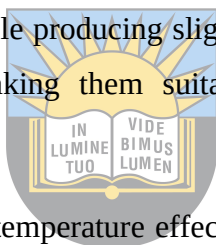
Ammonia is primarily generated during the anaerobic digestion process's breakdown of nitrogen-containing organic compounds (proteins and amino acids). Under elevated temperatures, specific microbial groups responsible for ammonia production and consumption may respond differently, affecting the overall dynamics of ammonia in the system. A major obstacle to aerobic digestion is the high ammonium release from manure, which hinders microbial activities and prevents the creation of biogas (Li et al., 2023). Temperature elevation can affect ammonia in the anaerobic digestion process in several ways. Generally, increasing temperature can enhance the rate of biogas production and the efficiency of organic matter degradation. However, high temperatures can also influence the balance of microbial populations in the digester, potentially favouring certain species over others, which may impact ammonia conversion rates (Yu et al., 2020).

2.4.10 Temperature

Temperature plays a vital role in ensuring biogas digesters' optimal performance, as (Kafle et al. 2021) highlighted. The physical and physiological properties of the mixing within the digester are impacted, along with the energy and thermodynamics of the biological processes. The study was conducted by (Zhu et al. 2021). There are two main temperature ranges, known as mesophilic and thermophilic, that provides ideal conditions to produce methane during digestion. These temperature ranges are named after the microorganisms that thrive in them. An optimal temperature range for mesophilic digestion is typically between 35–40°C or can be at temperature conditions varying between 20 and 45°C. On the other hand, thermophilic digestion thrives in a slightly higher temperature range of 40–55°C or even at augmented temperatures of up to 70°C (Li et al., 2021). Temperature discrepancies are influenced by various factors, such as the type and quantity of waste utilized, the design of the digester, the thickness of the walls and floor of the biogas digester, and the ambient air temperature (Mukumba et al., 2015). Moreover, warmer temperatures quicken the rate at which organic waste decomposes, shortening the retention period and increasing the economy. Methanogens, however, are extremely sensitive to temperature fluctuations. According to (Surendra et al. 2013), it has been found that mesophilic bacteria can withstand temperature fluctuations of up to 2.8°C. In contrast, thermophilic bacteria can only tolerate temperature changes of up to 1°C. Foam formation can result from large temperature swings in the digester, which substantially affects the total biogas generation (Zhang et al., 2021). In thermophilic digestion, it is imperative to maintain a constant operating temperature. Deviations

of more than 0.5°C/day are advised to avoid negative effects on biogas production (Jin et al., 2021). Reducing temperature changes can be achieved by putting protective measures for the digester into place. Due to its significantly low thermal conductivity value of 0.08 W/m·K, sawdust has been employed as an effective insulating barrier. Research has shown that using fertilizers from animals like cows, chickens, and pigs can result in the highest biogas output within a certain temperature range. This is true even though biogas production tends to increase with higher temperatures (Prasad, 2012). Temperature fluctuations are essential to produce methane by specific microbes (Mukumba et al., 2015). Gas production comes to a halt when the temperature drops below 10°C.

(Zhou et al. 2023) found that thermophilic digestion of dairy manure led to a 20–30% increase in methane production compared to mesophilic conditions. However, other studies have pointed out the trade-offs associated with thermophilic digestion, such as higher energy requirements for maintaining elevated temperatures and potential system instability (Abdelrahman et al., 2025). Conversely, mesophilic conditions, while producing slightly lower biogas yields, are considered more stable and energy-efficient, making them suitable for small-scale rural applications (Alworais et al., 2023).



Research also highlights variability in temperature effects depending on feedstock composition. For example, (Hossain et al. 2022) observed that lignocellulosic feedstocks, such as crop residues, benefit more from thermophilic conditions due to improved hydrolysis of complex polymers, whereas feedstocks like cow dung showed less pronounced differences in yields between temperature ranges. Furthermore, studies by (Maxhayi et al. 2024) emphasize the importance of maintaining temperature uniformity within the digester. Fluctuations can disrupt microbial communities, leading to reduced methane yields and increased production of intermediate compounds, such as volatile fatty acids.

Despite these findings, gaps remain in understanding the interplay between temperature and other factors, such as pH, substrate composition, and hydraulic retention time (HRT). While some researchers advocate for temperature optimization through advanced control systems, such as solar-assisted greenhouses (Wang et al., 2023), others argue for the need to integrate temperature effects with other digester design parameters to develop holistic, cost-effective solutions. These

contrasting insights underscore the need for further studies to quantify temperature impacts across diverse operational and environmental conditions, particularly in low-resource settings.

2.5 Biogas Digester

Anaerobic digesters, sometimes called biogas digesters or biodigesters, are sealed systems or containers intended to aid in anaerobic digestion (Obileke et al., 2020). A biogas digester typically includes a tank or chamber that contains organic materials, like food waste, sewage solids, animal manure, or crop residue. Microorganisms, including anaerobic bacteria, can break down organic components and generate biogas. This biogas primarily comprises carbon dioxide (CO₂) and methane (CH₄). There are several different types of biogas digesters, each with specific benefits and uses, including batch, continuous stirred tank, plug-flow, and fixed-dome digesters. Some digesters may include additional components like heating systems, mixing mechanisms, and gas storage facilities to optimize biogas production and utilization. According to a study conducted by SANEDI, South Africa has approximately 350 small-scale biogas digesters installed, while Kenya, Uganda, and Ethiopia have significantly higher numbers, with 14,000, 11,000, and 10,000 installations, respectively (Sawyerr et al., 2019). Innovative designs that reduce costs, enhance durability and functionality, and streamline construction, operation, and maintenance will drive the widespread adoption of biogas plants. This study endeavours to examine the thermal efficiency of a previously proposed methodology for enhancing biogas production by delivering a comprehensive analysis of diverse biogas digester designs employed worldwide, with a specific emphasis on those executed in South Africa for domestic or small-scale intentions.

2.6 Characterisation of Biogas Digester

Biogas digesters can be categorized using various approaches, including:

2.6.1 Solids Retention Time (SRT)

a) *Passive systems*: Biogas digesters with passive systems for solid retention time allow solids to settle or be kept naturally inside the digester without the need for external mechanical agitation or intervention (Tjutju et al., 2024). A waste treatment facility currently utilises biogas recovery but has limited control over the method of anaerobic digestion.

b) *Low-rate systems*: Longer solid material retention periods are achieved by allowing for a slower solids turnover in low-rate systems for solid retention time in biogas digesters. These systems are

renowned for their capacity to guarantee effective biogas production and preserve a constant level of microbial activity (Tjutju et al., 2024). The primary source of methane-forming microbes in anaerobic digesters is manure waste. After the solids retention time (SRT) and hydraulic retention time (HRT) are equal, the waste travels through the digester, and only then does it depart.

c) *High-rate systems*: For biogas digesters, high-rate solid retention time (SRT) devices are made to enable quick, solid material turnover inside the digester. By effectively using microbiological activity to break down organic matter, these systems encourage the creation of more biogas. In addition, the presence of methane-producing microbes in the system enhances the efficiency of generating biogas involves the conversion of biodegradable material through a digester (Hamilton, 2014).

2.6.2 Feed Method

a) *Batch method*: Digesters become full and are subsequently emptied after a specific duration, indicating the completion of the reaction. This approach offers flexibility in handling various types of feedstocks and ensures better control over the digestion process.

b) *Continuous method*: Involves adding organic feedstock into the digester in a continuous manner, which ensures a steady flow of material for anaerobic digestion. These systems allow for a consistent biogas production rate and are commonly employed in large-scale biogas facilities with a constant organic material supply (Gadirli et al., 2024).

2.7 Biogas Digester Design

This section provides descriptions and explanations of different existing digester designs and their respective strengths and weaknesses.

2.7.1 Fixed Dome Digester

A fixed dome digester is an underground biogas plant shaped like a dome and made of brick, concrete, or reinforced cement (Wanjohi et al., 2022). Skilled masons are required for construction to prevent cracking and gas leakage. After the digester chamber is sealed, a slurry is formed by combining organic materials, such as kitchen scraps and animal dung, with water. An intake line is then used to feed this slurry into the chamber. When oxygen is unavailable, the organic material in the digester is broken down by anaerobic bacteria, which leads to biogas. This biogas, primarily consisting of carbon dioxide and methane, accumulates in the top dome.

Gas pressure head generation is caused by the difference in slurry levels between the expansion chamber and the digester (Tangwe et al., 2022). As gas is removed, the slurry returns to the reactor. Transporting biogas through pipes is made easier by the dome's constant volume pressure (Spuhler et al., 2014). The gas is directed out through a gas outlet pipe for various purposes such as cooking, heating, or generating electricity. Constructing the slurry chamber underground mitigates temperature fluctuations and withstands gas pressure. Shielded from low night-time temperatures and cold seasons, the underground digester warms up slowly during sunny and warm periods. This absence of temperature fluctuations benefits bacteriological processes (Tangwe et al., 2022). Advantages of the fixed dome digester include low initial and maintenance costs due to the absence of moving or metallic parts susceptible to rust (Obileke et al., 2020). The digested slurry, a nutrient-rich by-product, has the potential to be utilized as a fertilizer. Cost-effective, durable, and requiring minimal maintenance, the fixed dome design does need skilled construction to ensure gas tightness and efficient operation. This type of digester is particularly useful for households, small farms, and communities in rural and developing regions as it provides a sustainable method of waste to renewable energy production. However, the design also has limitations. The gas pressure delivered can vary because the gas storage dome has a fixed volume, and there is no mechanism to maintain a steady pressure flow once the gas is used. Fig 2.2 shows a standard brick-and-mortar fixed-dome digester. As a result, the gas pressure might not be enough to run different biogas equipment, like lights, gas water heaters, and generators.

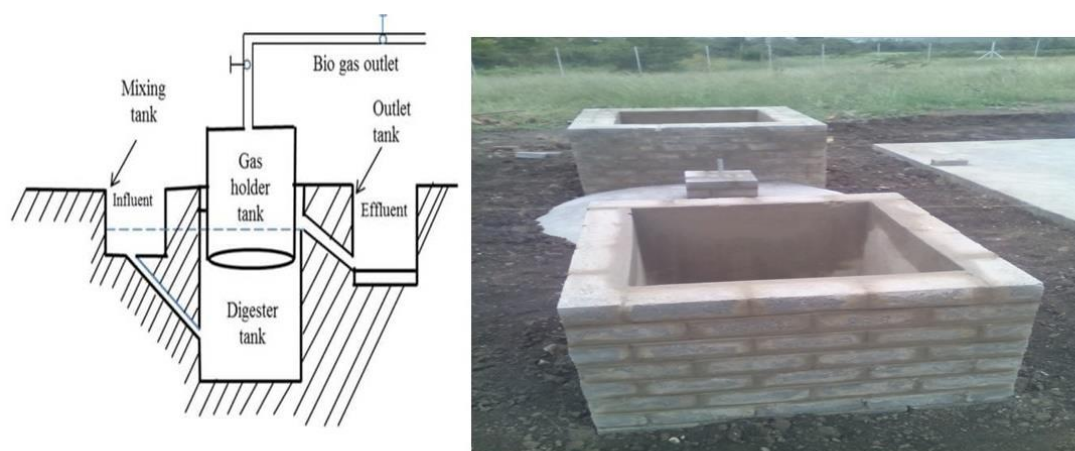


Figure 2. 1. Fixed dome digester adapted from (Rahman et al., 2017)

Fixed dome plants can produce just as much gas if sealed tightly as floating drum plants. However, because of the large variations in gas pressure, their gas utilization efficiency is lower (GTZ, ISAT, 2007). Because the building material is prone to cracking, it requires highly trained labour, which can be time-consuming and in short supply at times. Fixing leaks can be quite difficult, as records indicate that cracks that develop during the cement curing process or due to unstable ground conditions are the primary reasons for failures in fixed dome digesters. In fact, more than 50% of these digesters have a lifespan of less than 3 years, according to Cheng et al. (2014). This design is not suitable for rocky terrains due to the need for excavation. Additionally, solid deposition can occur if the agitation is poor, making maintenance and cleaning challenging. However, the plant has a 20-year or longer estimated operational life, which is partly due to the lack of rust-prone steel sections (GTZ, ISAT, 2007). Furthermore, because the amount of gas in the digester is invisible, operating a household can be difficult (Rowse, 2011).

2.7.2 Floating Drum Digester

A steel gas holder in a floating drum reactor is located above an underground digester pit, and its position is adjusted based on the production and extraction of gas (Alibe, Kallamu & Hammajam, 2022). By implementing a secure framework, the gas drum remains stable, allowing the gas holder to either rest directly on the fermenting slurry or be placed inside a waterproof container. Even on a surface with a high solid content, the drum will not get stuck as long as it is floating in a water jacket. Due to the reliance on the gas holder's weight, floating drum digesters are able to maintain a consistent gas pressure, which is advantageous. The building of the digester is quite straightforward, and small construction mistakes usually do not have a major effect on its operation or gas production. In addition, determining the volume of stored gas is a simple task, and operating the digester is a straightforward process (Rungthong & Nirunsin, 2024). It is important to note that the steel drum can be quite pricey because of the materials used, and it is also crucial to remember that steel components can be susceptible to corrosion. Regular maintenance is crucial to prevent corrosion and prolong the lifespan.

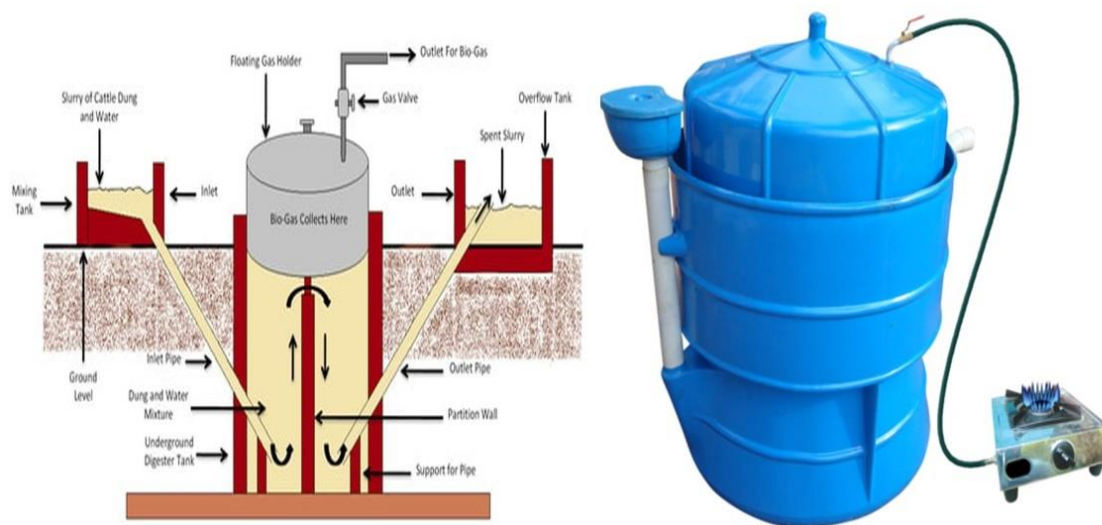


Figure 2. 2. Floating-drum digester adapted from (Godwin et al., 2021)

Figure 2.2 depicts a standard floating drum biogas plant, with sizes ranging from 1 to 10m³. In regions with high humidity, a well-maintained floating drum typically remains functional for approximately 3–5 years, while in arid climates, its lifespan extends to around 8–12 years. (Tangwe et al., 2022). When fibrous substances are used, the gas holder adheres to the floating scum (GTZ, ISAT, 2007). Although they cost more to build than steel, floating drums made of high-density polyethylene and glass-fibre-reinforced plastic have shown to be successful. It is imperative to limit the formation of fibrous debris in the slurry since it can impede the digester gasholder's movement when present, as is frequently the case (Mostajir et al., 2013). It has been observed that this restriction further reduces the effectiveness of slurry agitation, which the gasholder would normally aid with. Furthermore, while this design efficiently inhibits scum formation on the slurry surface, it has been found to be poor at stirring the slurry to prevent solids deposition and expose the substrate to microorganisms. Because of the sliding mechanism's need for a somewhat specialized design, the building is expensive, and regular maintenance is necessary. With this construction, it is not possible to use insulating materials like straw to reduce temperature swings, a practice observed in some designs, such as the permanent dome. As a result, additional heat will inevitably escape from the gasholder as it floats in the water slurry or around

its perimeter. Nonetheless, according to (Mutungwazi et al. 2018), the digester is resistant to gas leakage.

2.7.3 Balloon/Bio-bag Digester

In order to overcome certain limitations, bio-bag digesters—also referred to as balloon digesters—were created as an alternative to brick-and-metal digesters. The goal was to develop a low-maintenance, inexpensive, and simple-to-install solution (Bodhe et al., 2023). The balloon digester consists of a large inflatable PVC bag that acts as the digester chamber. The bag is divided into sections for the inlet and outlet, each equipped with waterproof manholes positioned at various depths to ensure the proper flow of the substrate. Through the input, water and organic waste are supplied into the digester. Anaerobic bacteria in the chamber decompose the organic matter to produce biogas, which gathers in the upper portion of the bag. By adjusting the height of the pipe that ends in the outlet manhole, the slurry level in the Bio-bag can be kept at around 2/3 of its capacity. The remaining capacity of the Bio-bag is reserved for storing biogas. In order to give enough pressure for gas propulsion to appliances, the gas can be delivered at the necessary pressure via a pressure pump or by adding weights to the top of the Bio-bag.

A Bio-bag digester that operates at mesophilic temperatures can be partially buried, covered with straw, or enclosed in a greenhouse envelope. The Bio-bag can operate without maintenance for up to 15 years because it is made of reinforced PVC material that is flexible and resilient (OME BD, 2014). In rural communities, the Bio-bag digester can be installed by oneself because it is easy to build and requires little expertise. Balloon digesters are less expensive and simpler to build and maintain than fixed dome digesters. However, fixed dome digesters are more durable and better suited for long-term, large-scale applications. Fixed dome digesters also provide more stable gas pressure but require skilled labour for construction and are more difficult to repair if damaged. Floating drum digesters offer the advantage of providing constant gas pressure, which balloon digesters lack. However, the steel parts of floating drum digesters are prone to corrosion, leading to higher maintenance costs and shorter lifespans. On the other hand, balloon digesters eliminate the issue of corrosion but sacrifice consistent gas pressure. Figure 2.3 illustrates a bio-bag digester.

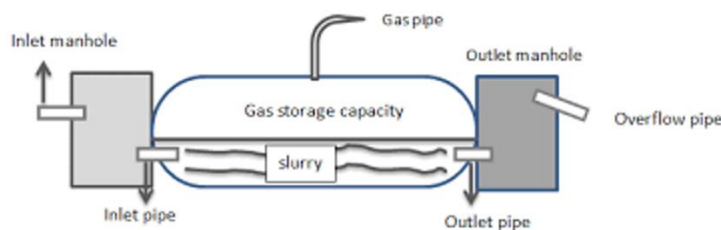


Figure 2. 3. Picture and diagram of the balloon digester

Some of the benefits of the bio-bag digester are its cost-effectiveness due to standardized prefabrication, its shallow installation, which is ideal for areas with high groundwater levels, the system's capability to achieve higher digester temperatures in warmer climates, its straightforward cleaning, emptying, and maintenance procedures, and its impressive efficiency in breaking down difficult substrates like water hyacinths.

The Bio-bag digester design, although simple to install and equipped with various safety and biogas-boosting features, has a number of flaws. These include the plastic material's high cost, susceptibility to breakage, and sensitivity to temperature fluctuations in the surrounding environment. Moreover, the low pressure of the gas generated inside the bio-bag calls for a pump. In addition, there have been frequent observations of issues with gas pipe connections in bio-bag installations conducted in South Africa. These issues include non-airtight connections resulting from errors during inflation and deflation; there appeared to be an issue with the plastic not being securely clamped onto the outlet and inlet pipes because of the limited working space. Additionally, gas was escaping through the pipes because they were not adequately covered under the slurry. (Mutungwazi et al., 2020).

Many stakeholders overlook how crucial it is to run the digesters efficiently, which calls for constant slurry level monitoring to stop methane leaks. Even those who understand the necessity of maintaining the correct slurry level often struggle due to improper sizing of the digesters. Instead

of being appropriately sized for family needs, they are often oversized, making it burdensome for stakeholders to ensure that the slurry level is consistently filled and maintained above the inlet pipe. A drawback is the lack of coverings for the digesters, allowing children to inadvertently damage the plastic by throwing stones and twigs inside. Another limitation of this design is the absence of agitation, leading to potential issues such as scum formation and clogging within the digester. While semi-continuous feeding can mitigate this risk, it does not entirely prevent system failure. Furthermore, the typical lifespan of this digester design rarely exceeds 2-5 years (Tangwe et al., 2022).

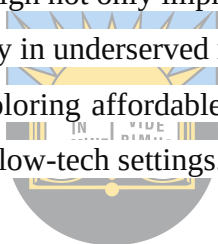
Among biogas digester designs, balloon digesters housed inside greenhouse envelopes present distinct advantages over fixed dome and floating drum digesters in terms of temperature regulation. Fixed dome digesters, typically constructed underground, often mirror ambient temperatures, which can hinder microbial activity in cold climates. Floating drum digesters, while effective in visual monitoring of gas production, also suffer from temperature instability and higher maintenance due to corrosion and mechanical wear (Patel et al., 2023). Conversely, balloon digesters, made of flexible polyethylene materials, are cost-effective and easier to install. When housed in a greenhouse envelope, they benefit from passive solar heating, which stabilizes internal temperatures, creating a favourable environment for anaerobic digestion.

Low-cost and easy-to-build passive solar heating methods can be utilized to warm biogas digesters effectively. In New Delhi, India, the construction of a gridded solar greenhouse resulted in an increase in ambient temperature within the digester by approximately 19°C, with a 15–20% rise in gas production compared to traditional setups (Bansal et al., 1985). For instance, while a traditional balloon digester maintained an average annual temperature of 22.4°C and produced 34.6 kg of gas per day, an experimental balloon digester housed within a solar greenhouse achieved an average temperature of 26.3°C and a daily gas output of 39.1 kg (Kumar et al., 2008). The temperature in reactors equipped with solar greenhouses showed an increase of 7.6–13.5°C compared to those installed traditionally. The use of solar greenhouses significantly raises the temperature of the digestion liquid, thereby enhancing biogas output. Although experimental studies have demonstrated the advantages of passive solar-assisted biogas systems under specific conditions, theoretical research in this area remains limited. Related studies, such as those on solar

dryers, highlight similar advancements. For instance, (Capossio et al. 2022) developed computational models of the solar drying process and applied them to brewer's spent grains.

The greenhouse mechanism also prevents extreme temperature variations by buffering against nighttime cooling or overcast conditions, a critical feature absent in fixed dome or floating drum systems. Furthermore, balloon digesters' lightweight design allows for better thermal stratification, enhancing microbial efficiency throughout the digester's volume. However, the reliance on greenhouse envelopes requires careful consideration of insulation materials, such as double-layer polyethylene, to maximize thermal retention while minimizing costs.

In conclusion, while fixed dome and floating drum digesters have proven effective under stable environmental conditions, balloon digesters housed in greenhouse envelopes provide superior temperature control, making them more suitable for resource-constrained rural areas with significant climatic challenges. This design not only improves biogas yields but also enhances the feasibility of adopting biogas technology in underserved regions. Future research should focus on optimizing greenhouse designs and exploring affordable insulation solutions to further enhance the performance of balloon digesters in low-tech settings.



2.8 Digester Heating Advances

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Insufficient temperatures or abrupt temperature fluctuations during biomass anaerobic fermentation can diminish the gas production efficiency and the methane content in the biogas (Shao et al., 2021). Biogas generation and raw material decomposition rates are often low in regions where the ambient temperature stays in the psychrophilic range for prolonged periods. Thus, it's critical to put in place economical and effective methods to maintain and warm the heat during the fermentation of biogas. Numerous techniques have been investigated to raise the biodigesters' operating temperature. These techniques include ground source heat pump (GSHP) heating, electric heating, biomass heating, coal boiler heating, hybrid solar heating, solar warming, active solar energy heating, and integrated warming technologies. Electric heating is costly even though it works well. Due to fuel combustion, both the biomass boiler and coal boiler heating systems have very low thermal energy conversion rates and contribute to air pollution (Li et al., 2015). However, the digester temperature can be raised approximately four times using the waste heat technology of biogas generators, which uses the heat from the exhaust and cooling system of

the biogas engine to raise the digester temperature (Luo et al., 2005). However, this method might not be appropriate in all circumstances and is only appropriate for biogas electricity production projects.

2.8.1 Solar Heating

Two methods of utilizing solar heating in anaerobic digestion (AD) are direct and indirect. Direct utilization involves using solar energy to heat the digester or the surrounding area. On the other hand, indirect solar heating involves transferring solar energy through a medium to the desired location (Makamure et al., 2021). However, due to the elevated levels of free ammonia observed at higher temperatures, the integration of solar heating into the anaerobic digestion process could potentially compromise process stability during thermophilic anaerobic digestion and increase the likelihood of inhibition (Wang et al., 2019).

2.8.2 Direct Heating

The two biogas heating techniques are direct heating in steaming hot water or steam and aberrant heating using exchange, where the heating medium is commonly boiling water. Direct steam heating has the huge weakness of requiring a complex steam-age framework (counting desalination and particle exchange as water pre-treatment) and can likewise bring about nearby overheating. The addition of hot water increases the slurry's water content and should only be used when necessary to weaken the mixture. Heat exchangers positioned inside or outside the digester are utilized to attain unconventional heating, contingent upon the condition of the vessel, the substrate type employed, and the operational mode concept (Makamure et al., 2021). The digester can be heated on the floor, in-vessel, on-vessel, and ex-vessel to accomplish atypical heating.

2.8.3 Ground Source Heat Pump (GSHP)

Medium-temperature fermentation processes benefit greatly from the steady, low-temperature heat source provided by the Ground Source Heat Pump (GSHP) heating technology. It has many benefits, including excellent efficiency, low energy consumption, and environmental friendliness. The requirement to drill wells and install subterranean pipes, which results in comparatively high costs and technical demands, is a disadvantage. It is also inappropriate for high-temperature fermentation systems that need to be heated year-round and may be limited by regional differences

in geological water quality. Furthermore, during the summer months, no heat is returned to the soil; instead, it is taken from it in the winter to warm the methane digester. The long-term sustained and stable operation of the GSHP system is thus impacted by an imbalance in the heat extracted or discharged from the soil between winter and summer (Zhang et al., 2011).

2.8.4 Use of a Greenhouse as a Temperature Regulator

An efficient approach to addressing the issue of fluctuating temperatures during the anaerobic digestion process involves the utilization of a greenhouse enclosure. This can enhance gas output and improve its quality. The greenhouse enclosure ensures that the slurry is warmed to the ideal anaerobic digestion temperature, helping regulate the overall temperature. The temperature conditions within the greenhouse, facilitated by a radiation-absorbing arrangement, allow for an exceptionally efficient transfer of energy. Various external factors, including humidity, wind speed, the outside sky temperatures, and total solar radiation, can influence the energy transfer process.

Using a solar greenhouse to heat the methane digester is one method of using greenhouse heating technology. A solar greenhouse is inexpensive to build, operate, and maintain (Shao et al., 2021). It is also simple to erect. Kumar et al. (2019) studied the use of plastic as an insulation material on a methane digester in a solar greenhouse near Nilgiris, India, as an alternative to conventional brick and stone. In comparison to a conventional digester, the experimental biogas digester with plastic insulation generated 34.6 kg/d of gas and had an inside temperature of 22.4°C. The experimental biogas digester's annual average temperature increased to 26.3°C, which resulted in a 39.1 kg/d increase in gas production. The greenhouse's design and control systems, such as its ventilation system, affect how energy is transferred throughout the greenhouse (Lau and Staley, 1989). When sunlight, particularly ultraviolet (UV) radiation, passes through a greenhouse cover, it generates the greenhouse effect within the greenhouse structure. The choice of cover material significantly impacts the amount of radiation that can penetrate the greenhouse. The incoming radiation entering the greenhouse through the cover is relatively low. The remaining energy is either released into the atmosphere or absorbed by the cover. Radiant energy within the greenhouse is absorbed by parts of the greenhouse envelope, including the flooring. After that, the longwave infrared (IR) radiation from these absorbing surfaces heats up and enters the greenhouse. Since the energy of

warm radiation is lower, it cannot escape into the atmosphere through the greenhouse cover. Consequently, the enclosed greenhouse environment experiences an increase in thermal energy (Conradie et al., 2010; Kalogirou et al., 2014).

Mutungwazi et al. (2020) designed and constructed a 100L, agitated portable carbon steel biogas digester that was deployed inside a greenhouse. The temperature was automatically maintained at $35\pm 1^{\circ}\text{C}$ using an electronic circuit to control ventilation through a suitable window. In contrast to the 50% methane and 28% COD destruction stated in the (Mukumba et al., 2019) for a permanent dome insulated with sawdust, the system achieved 55% methane and 61% destruction of COD. A study on the impact of biogas fermentation in a basic solar-assisted greenhouse was carried out by Shao et al. in 2022. They examined the process of fermentation temperature and a heat transfer model for biogas fermentation using a semi-buried balloon digester. According to the authors, the heat transfer model had a maximum deviation of 2% from the actual temperature. They also observed that the use of a basic greenhouse improved methane fermentation in different climate zones, including cold areas, hot summers, and cold winters. The heat transfer model and temperature-based biogas production rate prediction were found to be applicable in these scenarios. The results showed that the biogas production rate was higher than that of underground digesters.



Mao et al. (2015) reviewed recent advances in anaerobic digestion related to biogas production. They discussed the variables influencing digesters, the anaerobic digestion process, and the efficiency based on the characteristics of the substrate. Various studies have been conducted on solar greenhouse digesters for biogas production. A solar greenhouse digester was built in a study by Liu et al. (2020) to process food waste and cow dung. Comparing the solar greenhouse digester to the conventional digester, the results revealed a noticeably higher methane yield in the former. The study found that increasing the efficiency of biogas generation could be possible using a solar greenhouse digester.

Yu et al. (2019) conducted a study to examine the influence of temperature on biogas production in a solar greenhouse digester utilizing cow manure as the primary feedstock. The results revealed a positive correlation between temperature and methane output. Consequently, the study inferred

that optimizing temperature control can significantly enhance biogas production in a solar greenhouse digester. Heat builds up inside the greenhouse design as a result of its exposure to the sun's short-wave, high-frequency radiation. It is possible to improve biogas production by using this heat.

2.8.5 Emerging Technologies and Recent Advances in Biogas Digester Systems

Recent technological innovations have significantly improved the operational efficiency and system performance of biogas digester systems. Zhang and Liu (2023) observe that the integration of smart monitoring systems into traditional digesters has brought an unprecedented revolution to process control by allowing live tracking of important parameters like temperature, pH, and gas production. Optimised operating conditions are responsible for an advancement that has resulted in 25-30% biogas yield increase. (Wang and Patel et al.,2024) also claim that in the delivery of advanced membrane materials, the gas separation efficiency has improved, culminating in higher methane concentration in the final biogas output and reduced system maintenance requirements. In recent years, the automation of biogas systems has become a very important step for industrial-scale systems. Sharma and Rodriguez 2023) report research that shows that automated feeding systems, in conjunction with artificial intelligence (AI) driven process control, can, in fact, lower operational costs by up to 40% and keep biogas production rates consistent. Machine learning algorithms optimise substrate mixing ratios and feed intervals for these systems. In addition, as well elaborated by Kumar and Thompson (2024), integrated automated temperature control systems based on weather prediction models and equipped with such promise in variable climatic zones, where up to 35% improvement in thermal efficiency was demonstrated compared to the conventional installations.

Another big advancement in the field is that biogas systems can also be integrated with other renewable energy technologies. As (Lee and Martinez 2023) have demonstrated, hybrid systems consisting of solar thermal collectors blended with biogas digesters maintain operational temperature stability in cold climates, leading to thermal efficiency improvement of up to 45%. This integration in agricultural applications has been particularly successful. Furthermore, Chen and Wilson document successful implementations of combined biogas and solar photovoltaic systems, using excess solar energy for digester heating when sunlight is low, resulting in a more dependable and efficient total system.

2.8.6 Practical Applications and Case Studies

In various scenarios, the biogas digesters are being implemented and have played a successful and effective role. Integrating greenhouse systems (greenhouse-assisted digesters), which buffer greenhouse gases from entering our atmosphere and use alternative energy to maintain optimal operating temperatures, has shown success in these cold climate regions where greenhouse-style digesters were unable to maintain optimal operating temperatures and increased gas production up to 40–50% in the winter vs. traditional systems (Mitchell and Wong 2023). For example, Kumar and Anderson (2024) demonstrate successful adaptations of floating drum designs for community-scale applications in the rural environment, where simplified maintenance features and visibly stored gas proved most advantageous for user acceptance and system longevity. This work has shown potential for significant economic and environmental benefits in large-scale agricultural applications.

Research conducted by Thompson and Garcia (2023) has shown that integrated farm-scale biogas systems that treat mixed agricultural waste can supply enough energy to become independent with reductions in greenhouse gas emissions by up to 70% compared with conventional waste management practices. Li and Martinez (2024) additionally document successful large-scale digester feeding systems automation that consistently produces gas and substantially reduces the necessary labour (up to 60%).

Small-scale implementations in developing regions have had promising results in addressing both the challenges of energy access and waste management. Wilson and Ahmed (2023) research community-scale projects seeking to capture the benefits of shower and wash sundries with locally made, modified fixed dome designs and achieve significant improvements to local sanitation and reliable energy access for previously underserved communities. Studies by Park and Santos (2024) also point to the success of simplified maintenance protocols and community-based operation models in ensuring the long-term sustainability of some projects, with some of these projects running continuously for over a decade and requiring minimal external support.

2.8.7 Economic Viability and Sustainability Analysis

The scale, location and implementation context influence the economic viability of biogas digester systems. Moreover, although the initial investment in small-scale biogas digesters in rural areas can range between \$300–1,000, ideally, these get recovered in 2–4 years as the efforts pay off from reduced energy costs and fertiliser production, suggests economic analyses (Henderson & Kumar 2023). Thompson and Liu (2024) find that although greenhouse-enhanced digesters are more expensive initially, these instalments pay back quicker and at higher rates over the long haul compared to conventional systems, where they are 15–20% more financially lucrative, driven largely by the ability to remain operational year-round and avoid disruptions to digesting.

Results across multiple studies show promising results for environmental sustainability metrics of biogas systems. Based on research by Martinez and Zhang (2023), modern biogas systems can potentially reduce carbon emissions by 60 – 85% when compared with conventional fossil fuel use while also providing opportunities to manage agriculture waste issues. The dual benefit of this is that it improves their sustainability profile. In addition, further (2024) Park and Johnson.

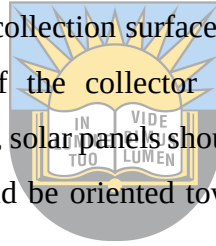
Significant socio-economic benefits have been identified in the adaptation of biogas systems for small-scale applications. Community-scale biogas projects are shown by Wilson and Ahmed's (2023) studies to generate employment locally while decreasing energy poverty with implemented projects resulting in a 30–40% decrease in household energy costs. On the other hand, Garcia and (Smith et al., 2024), in their research, show that properly scaled systems can supply energy security to rural communities, making extra income through sales of the surplus energy and organic fertiliser produced from biogas and building sustainable local economies around biogas infrastructure.

2.9 Solar Radiation

Solar radiation, quantified in kilowatt-hours per square meter (kWh/m^2), refers to the electromagnetic energy emitted by the sun over a given surface area. It includes a variety of wavelengths, ranging from visible and ultraviolet light to infrared energy. Diffuse, reflected, and direct solar radiations make up the total amount of solar radiation in the world. According to Colorado State College (1978), diffuse radiation is dispersed sunlight that reaches a surface from several directions. In contrast, direct radiation is sunlight that directly reaches a surface

perpendicular to the sun's rays. A pyranometer is commonly employed to quantify the overall solar irradiation. The production of methane is greatly impacted by solar radiation, as observed in a recent study (Obileke et al., 2021). The tilt angle of the collector can be utilized to ascertain the orientation of a photovoltaic (PV) panel, greenhouse, or any other variety of solar collector. It pertains to the inclination angle formed by the collector surface and the horizontal plane, or the angle formed by the sun's rays and the surface normal to the collector. According to Conradie et al. (2010), the optimal way to capture energy is by ensuring that the collector surface constantly faces the sun and maintains an angle perpendicular to the sun's beams. To achieve this, it would be necessary to track the sun's movement from east to west during the day and adjust the tilt angle daily. However, for greenhouse applications, this is not a viable option.

For optimal energy capture during peak months, positioning the collector nearly parallel to the sun's beams at solar noon would be a more practical approach, rather than constantly tracking the sun. This is achieved by adjusting the collection surface to a specific angle corresponding to the location's latitude. The orientation of the collector should be adjusted depending on the hemisphere. In the northern hemisphere, solar panels should be oriented toward the south, whereas in the southern hemisphere, they should be oriented toward the north (Colorado State College, 1978; Jim Dunlop Solar, 2012).



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2.10 Thermal Transfer Process Within Greenhouse

Normally, we obtain data on solar radiation for horizontal surfaces, but occasionally, we require it for inclined surfaces. In such cases, we frequently utilize the (Klein et al., 1977) method to calculate solar radiation on these surfaces.

$$I_t = I \times R \quad [2.1]$$

Where I_t is the solar radiation on the tilted surface (Wm^{-2})

I is the total radiation on the horizontal surface (Wm^{-2})

R is the ratio of the total radiation on the titled and horizontal surface

Where R is as follows

$$R = \frac{I_a}{I} \cdot R_b + \frac{I_s}{I} \cdot \frac{(1+\cos \alpha)}{2} + \frac{\beta(1-\cos \alpha)}{2} \quad [2.2]$$

Where I_a is the average daily amount of horizontal direct radiation per month ($\text{J} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$)

I_s is the average daily amount of horizontal scattered radiation per month ($\text{J} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$)

A is the roof angle

where R_b is the ratio of direct solar radiation on the titled and horizontal surface ρ is the ground reflection coefficient =0.2

$$R_b = \frac{\cos(\sigma - \alpha) \cos \vartheta \sin \varphi_o + \frac{\pi}{180} \varphi_o \sin(\sigma - \alpha) \sin \vartheta}{\cos \sigma \cos \vartheta \sin \varphi_o + \frac{\pi}{180} \varphi_o \sin \sigma \sin \vartheta} \quad [2.3]$$

Where σ is the local latitude

ϑ is the declination angle of the sun

φ_o is the sunrise and sunset hour angle on the south tilted surface

φ_o can be determined by

$$\varphi_o = \cos^{-1}(-tg(\sigma - \theta)tg\vartheta) \quad [2.4]$$

Where tg is the transmittance of the daylighting surface

Year-round declination varies from $23,45^\circ$ to $-23,45^\circ$, which can be calculated by

$$\vartheta = 23.45 \times \sin\left(360 \times \frac{284+n}{365}\right) \quad [2.5]$$

Where n is the serial number of the calculating day in a year

The solar radiation energy absorbed by the greenhouse can be calculated by

$$I_G = I_t \times D_L \times \tau_g \quad [2.6]$$

Where D_L is the actual daylighting area

τ_g is the transmittance of the daylighting surface

The lighting surface of the greenhouse was made of hollow PE film

The method given earlier can be used to calculate the amount of solar radiation that a greenhouse covering receives on its surface. When constructing a greenhouse, it is important to consider maximizing solar energy transmission. One way to do this is by aligning the collector surface at an angle corresponding to the greenhouse's latitude. By doing so, you can ensure optimal sunlight exposure for your greenhouse. Tilting the greenhouse to face either the north or the south can increase the amount of radiation absorbed. This adjustment will expand the surface area exposed to shortwave radiation. The net heat gain in the greenhouse is determined by the absorption of solar radiation and the loss of thermal radiation (Mutungwazi et al., 2020). The greenhouse's internal thermal radiation losses through conduction and coverings are caused by ventilation and

infiltration (Kalogirou et al., 2014). The temperature inside the greenhouse can be determined by the following:

$$C_{ga} \cdot \rho_{ga} \cdot V \cdot \frac{dT_{ga}}{dt} = Q_{sra} + Q_{cv,gb} + Q_{cv,cd,gc} - Q_{v,in-out} - Q_i \quad [2.7]$$

Where: $-\frac{dT_{ga}}{dt}$ is the rate of change of the greenhouse air temperature

C_{ga} is the specific heat capacity of air inside the greenhouse,

ρ_{ga} is the density of the air inside the greenhouse

V is the effective height of the greenhouse (greenhouse volume/base surface area)

Q_{sra} is the solar radiation absorbed by the air

$Q_{cv,gb}$ is the Heat transfer by convection of air with the greenhouse base.

$Q_{cv,cd,gc}$ is the Heat transfer by convection and conduction in the greenhouse cover between the inside and outside air

$Q_{v,in-out}$ is the Heat lost by natural ventilation from inside air to outside air

Q_i is the Heat lost by infiltration losses

The equation gives the solar radiation passing through the greenhouse absorbed by the air:

$$Q_{sra} = C_{sac} \cdot V_{srt} \quad [2.8]$$

Where C_{sac} is the shortwave absorption coefficient of the air inside the greenhouse

V_{srt} is the solar radiation transmitted through the cover into the greenhouse, and it's given by the equation:

$$V_{srt} = V_{gc,htc} \cdot I_G \quad [2.9]$$

Where $V_{gc,htc}$ is the short-wave heat transmission coefficient of the greenhouse cover

I_G is the global solar radiation

The temperature differential between the air and the greenhouse base determines the convective flux of air within the greenhouse. Here is an explanation of their connection.

$$Q_{cv,gb} = C_{cve}(T_{gb} - T_{ga}) \quad [2.10]$$

Where C_{cve} is the convection coefficient

T_{gb} is the temperature of greenhouse base

T_{ga} is the temperature of air inside the greenhouse

The temperature difference between the inside and outside air depends on how heat is transferred through conduction and convection in the cover.

$$Q_{cv,cd,gc} = C_{cv,cd,tl} \cdot (T_{ga} - T_{aog}) \quad [2.11]$$

Where $C_{cv,cd,tl}$ is a conductive and convective thermal loss coefficient

T_{aog} is the temperature of air outside the greenhouse

Currently, limited information on heat dissipation from digesters in greenhouses with concrete flooring is available. The linear interpolation model is considered inaccurate in this scenario. A digester inside a greenhouse becomes part of a complex heat transfer system involving fluid, pipes, and soil. Compared to air-based heat transfer, the transfer of heat from the methane digester to the concrete floor is significantly reduced. Heat transfer from the biogas digester to the concrete floor is often ignored to simplify calculations. The heat transport within the biogas digester is modelled using a simplified approach, assuming each element has a uniform temperature throughout its geometry. The thermal equilibrium equation for each element in the model is based on this assumption of constant temperature. The biogas fermentation liquid, which maintains consistent temperature, density, pressure, and specific heat capacity during the fermentation process, is approximated as water due to its low dry matter content.

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2.10.1 The digester's thermal equilibrium equation

A digester is a component of the highly complex fluid-pipe soil-linked heat transfer system found inside a greenhouse. The heat transfer from the methane digester to the concrete floor is significantly lower compared to the heat transfer in the air. For the sake of simplicity, the heat transfer from the biogas digester to the concrete floor was not considered. The heat balance of the equation can be derived by converting the process of transferring heat within the biogas digester as demonstrated below:

Every element's thermal equilibrium equation in the model is based on a single temperature sustained throughout the element's geometry. The liquid is referred to as water because there is less dry matter in the biogas fermentation liquid, which maintains a consistent temperature, density, pressure, and specific heat capacity throughout the process.

According to Perrigault et al. (2012), the biogas in the reactor is represented as a cube when it is fully inflated. Overlooked is the heat transfer from longwave radiation between the biogas

digester's outer surface and the greenhouse wrap's interior surface. Heat conduction from the biogas digester to the concrete floor is often overlooked. The importance of heat storage in the biogas digester is often overlooked. The heat generated by the biogas often goes unnoticed. The issue of heat generation in biological fermentation is often overlooked.

$$\rho_1 V_1 C_1 \frac{dT_1}{dt} + \rho_1 V_2 C_1 (T_1 - T_2) = (1 - r_r) I_t \cdot R \cdot F_r \cdot \tau_g + k_1 \cdot F_1 \cdot (T_a - T_1) \quad [2.12]$$

Where ρ_1 is the density of water (kg.m^{-3})

V_1 is the volume of the fermentation liquid (m^3)

C_1 is the specific heat capacity of water ($\text{J.kg}^{-1} \cdot \text{K}^{-1}$)

T_1 is the fermentation temperature ($^{\circ}\text{C}$)

t is the time (s)

V_2 is the volume flow rate of the input material ($\text{m}^3 \cdot \text{s}^{-1}$)

T_2 is the temperature of the input material ($^{\circ}\text{C}$)

r_r is the proportion of solar radiation absorbed by the air in the greenhouse

k_1 is the heat transfer coefficient of cylindrical lateral surface ($\text{W.m}^{-2} \cdot \text{K}^{-1}$)

Modelling the transfer of convective heat from the air inside the greenhouse to the cover of the digester.

As per the research conducted by Lienhard IV and Lienhard V in 2017, the convective heat transfer from the air inside the greenhouse to the cover can be described as follows:

$$Q_{c,ga-co} = C_{cv,ga-co} \cdot A_{di} (T_{gt} - T_{di}) \quad [2.13]$$

Where $Q_{c,ga-co}$ is the convective heat flux from the greenhouse air to the cover

$C_{cv,ga-co}$ is the convective heat transfer coefficient between the greenhouse and the digester

A_{di} is the area of the surface of the digester

T_{gt} is the greenhouse temperature ($^{\circ}\text{C}$)

T_{di} is the digester's surface temperature ($^{\circ}\text{C}$)

Given the protection provided by the polyethylene greenhouse, it is assumed that free convection takes place in this particular situation, as it shields the digester from external elements. Constructing a model to analyze the radiative heat transfer between the digester cover and digestate. The radiative heat transfer between the digester and the slurry was described using a

simple model involving two bodies, one encircling the other. Considering the flat surface of the slurry, we can calculate the net heat transfer using the formula provided by Lienhard IV & Lienhard V (2017):

$$Q_{rsa} = \sigma \frac{T_{co}^4 - T_{dg}^4}{\frac{1-\epsilon_{co}}{\epsilon_{co} \cdot A_{co}} + \frac{1}{A_{co}} + \frac{1-\epsilon_{dg}}{\epsilon_{co} \cdot A_{dg}}} \quad [2.14]$$

Where σ is the Stefan Boltzmann constant

ϵ_{co} is the thermal emissivity of the digester

ϵ_{dg} is the thermal emissivity of the digestate

A_{co} is the area of the inner surface of the digester

A_{dg} is the area of the slurry surface

The formula calculates the heat transfer between two surfaces based on their temperatures and emissivity. It considers the surface areas and emissivity of both surfaces (2.14). Given the protection provided by the polyethylene greenhouse, it is expected that free convection will take place in this situation, as it shields the digester from the elements. Constructing a model to analyze the radiative heat transfer between the digester cover and digestate. The radiative heat transfer between the digester and the slurry was described using a simple model of two bodies, one encircled by the other. Considering the flat surface of the slurry, we can calculate the net heat transfer using the formula provided by Lienhard IV & Lienhard V (2017).

$$Q_{cv,dg-co} = C_{cv,dg-co} \cdot A_{dg} (T_{dg} - T_{co}) \quad [2.15]$$

Where $Q_{cv,dg-co}$ is the convective heat transfer between the digestate and the inner digester cover

$C_{cv,dg-co}$ is the heat flux of the digestate and the inner cover of the digester

A_{dg} is the area of the digestate

T_{dg} is the temperature of the digestate

T_{co} is the temperature of the inner cover of the digester

The equation represents the relationship between heat transfer, specific heat capacity, area, and temperature difference. [2.15]. Investigating the heat transfer process from the slurry to the walls of the digester, the slurry provided insulation for both the floor and sidewalls. In addition, the temperature difference (T_D) between the walls of the digester and the insulation surrounding the reactor has been measured. It is anticipated to remain consistent across the walls and floors. Based on research conducted by Axaopoulos et al. in 2001, the transfer of heat through the ground can be explained using the concept of effective conductance. This can be computed using the formula:

$$Q_{dw} = \frac{W_b}{\mu_b} \cdot A_{b-i}(T_{dg} - T_i) \quad [2.16]$$

Where Q_{dw} is the heat transfer from the slurry to the digester walls

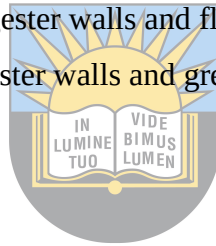
W_b is the reactor bag width (m)

μ_b is the reactor bag thermal conductivity

A_{b-i} is the contact area between the digester walls and floor

T_{dg} is the temperature between the digester walls and greenhouse

T_i is the temperature of the greenhouse

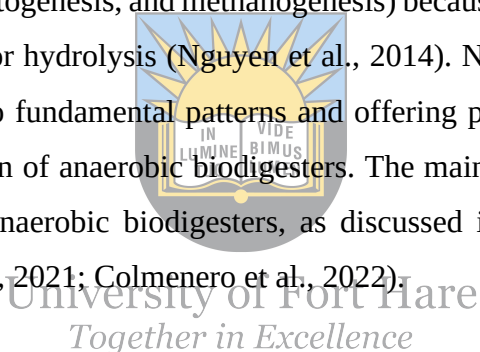


2.11 Mathematical Model

A mathematical model is a continuous loop that uses mathematics to describe real-world scenarios and their relationships (Cordero et al., 2022). It involves translating problems into numerical language, solving them symbolically, and testing them in the real system (Verschaffel et al., 2020). Mathematical models have input blocks, model blocks, and output blocks. Input blocks represent data or parameters, model blocks describe equations or algorithms, and output blocks display results or desired responses of the model, characterizing a real plant or process (Haefner et al., 2005). Biogas models are essential for designing, predicting, evaluating, and optimizing digester performance. They provide insights into the processes involved and enhance our understanding of anaerobic digestion dynamics at each stage.

Additionally, these models help identify opportunities for operational optimization within the system. The modelling of anaerobic digestion has undergone significant improvements in complexity over the past decade. Initially, early-stage models relied on single-stage kinetics to predict steady-state gas production and degradability. However, recent simulations have

introduced more intricate processes to account for the biodegradability of organic materials (Nguyen, H et al. 2014). The modelling of anaerobic digestion has undergone significant improvements in complexity over the past decade. Initially, early-stage models relied on single-stage kinetics to predict steady-state gas production and degradability. However, recent simulations have introduced more intricate processes to account for the biodegradability of organic materials (Nguyen et al. 2014). Currently, the most comprehensive model for AD processes is the Anaerobic Digestion Model 1 (ADM1). Due to its comprehensive coverage of physicochemical and biochemical reactions in AD, this resource is highly valued for both practical and academic applications (Poggio et al., 2016). The IWA Anaerobic Digestion Task Group collaborated with multiple experts to develop ADM1, a generalized model for AD. The model includes three primary analyses: biochemical, physicochemical, and transfer of mass reactions (Batstone et al., 2002; Nguyen et al., 2014). The disintegration step is included in ADM1 before the four stages of AD (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) because it is believed to come before them and supply substrates for hydrolysis (Nguyen et al., 2014). Numerical models are valuable tools for gaining insights into fundamental patterns and offering practical recommendations for the operation and optimization of anaerobic biodigesters. The main model seeks to elucidate the behaviour of solar-assisted anaerobic biodigesters, as discussed in recent studies (Valela and Muzenda, 2019; McGee et al., 2021; Colmenero et al., 2022).



2.11.1 The Role of Mathematical Modelling in Biogas Production

Mathematical modelling plays a pivotal role in optimizing biogas production processes by simulating and predicting the behavior of complex biological and chemical interactions within anaerobic digesters. This simulation capability allows researchers and engineers to explore various operational parameters, enhancing the efficiency of gas yields while minimizing environmental impact. For instance, as indicated in previous studies, computational models can be calibrated using experimental data, which provides insights into the mixing dynamics that are crucial for effective microbial activity and substrate conversion in digester systems (Borman et al., 2009). Furthermore, employing these models in practical applications facilitates the identification of optimal conditions to foster biogas production from municipal and industrial waste, addressing both energy generation and greenhouse gas emissions more effectively (Yazidi et al., 2018). Ultimately, these models not only streamline the technological discussion surrounding biogas but

also empower stakeholders to make informed decisions based on data-driven insights, enhancing the viability of sustainable waste management solutions.

In biogas systems, mathematical models play a pivotal role in optimizing production processes and enhancing operational efficiency. Key models include the Monod equation, which describes microbial growth dynamics and substrate consumption, allowing operators to predict the rate of biogas production based on varying feedstock concentrations. Additionally, stoichiometric models help to balance the chemical reactions occurring during anaerobic digestion, offering insights into the transformation of organic matter into biogas. Recent studies have highlighted the importance of integrating these models to address logistical challenges in biomass sourcing, particularly in establishing bio-hub facilities that streamline preprocessing and distribution (Bergström et al., 2024). Moreover, the development of simulation models assists in assessing the economic viability and environmental impacts of different biogas systems, ensuring that both capital investment and operational decisions align with sustainability goals (Uusi-Kinnala et al. 2023). Through these mathematical frameworks, stakeholders can make informed decisions that enhance overall system resilience and output efficiency.



Advancements in mathematical modelling are poised to revolutionize biogas technology, enhancing efficiency and expanding its applications. Techniques such as simulation and optimization can pinpoint the most effective operational conditions for biogas plants, allowing for real-time adjustments to maximize output. By integrating complex algorithms, researchers can better predict biogas production rates and digestate quality, leading to improved resource management and reduced waste. Furthermore, the application of statistical analysis can facilitate a deeper understanding of the variables affecting biogas yield, driving innovations that enable the energy sector to move towards sustainability. As these mathematical approaches become more refined, they will foster collaboration among engineers, scientists, and policymakers, ensuring that biogas technology not only meets current energy demands but also adapitates to future challenges in climate change mitigation and energy security. Emphasizing a mathematical focus will undoubtedly pave the way for a more sustainable and efficient biogas industry.

2.12 Practical Applications of Solar Radiation Principles in Biogas Systems

Practical application of solar radiation principles to biogas systems typically results in improved system performance. Chen and Thompson (2023) also report that optimised greenhouse orientation and design based on local solar radiation patterns improves average winter digester temperatures by 8–12°C, with corresponding improvements in gas production rate. Further studies by Martinez and Wilson (2024) show that strategically located thermal mass within a greenhouse-enhanced (GH) digester can effectively modulate temperature fluctuations, limiting thermal stress experienced by methanogenic bacteria and thereby enhancing system stability.

Innovative hybrid systems were developed by integrating solar thermal principles with digester design. Research by Kumar and Lee (2023) shows that a combination of passive solar heating through greenhouse effects and active solar thermal collectors has been particularly promising in cold climates where system temperatures were observed to be stable even when there is limited sunlight. Also, solar tracking greenhouse designs, as studied by Rodriguez and Park (2024), show as much as a 30% increase in winter thermal performance over conventional fixed orientation systems and are documented as positive design implementations. It allows for more efficient system design due to recent advances in thermal transfer modelling. As exhibited in Hassan and Smith's (2023) research, computationally modelled heat transfer to and within greenhouse-enhanced digesters using computational fluid dynamics improves air circulation and heat distribution within the digesters for optimised design with thermal performance enhanced by 25% – 35%. Accordingly, Taylor and Wang (2024) studies emphasise the significance of correct insulation and thermal stratification management to harness the full potential of solar heating and achieve steady operating temperatures with minimum demand on auxiliary heating.

2.13 Summary

Navigating the landscape of current biogas technology discussions reveals a plethora of challenges that hinder meaningful advancements. One significant issue is the lack of a unified approach in integrating various treatment technologies, as evidenced by the findings on anaerobic co-digestion (AcoD) and high-rate acidification. Research indicates that combining these methods with source-separated organics can yield substantial increases in biogas production, yet the inconsistency in adopting such integrative models across different wastewater treatment plants (WWTPs) remains

a barrier (Pritty et al., 2019). Furthermore, the optimization of biogas and hydrogen production through urban-industrial symbiosis illustrates the need for comprehensive modelling that addresses varied environmental and economic parameters (Butturi et al., 2023). These disparities in methodology not only obscure potential synergies but also complicate stakeholder engagement, underscoring the necessity for a more streamlined focus on mathematical modelling to facilitate clearer dialogues and actionable solutions in biogas technology advancements.

The literature has reviewed that a solar-assisted greenhouse digester, fed with cow dung, has the potential to enhance thermal efficiency and improve biogas production. The use of solar energy to heat the digester can play a significant role in biogas production and its quality, as temperature fluctuations can affect the activity and composition of methane-producing bacteria. Different species of methanogens have specific temperature ranges ideal for their growth and activity, and temperature fluctuations can impact their metabolic rates and overall performance in anaerobic digestion systems. Controlling the temperature can optimise biogas production in a solar greenhouse digester.

To address the identified gaps and set a clear direction for future research, this study aims to make significant contributions to the existing body of knowledge on biogas production, particularly in the context of solar-assisted greenhouse digesters using cow dung as a primary feedstock. Key research gaps include the limited understanding of the interactions between physiochemical properties, meteorological factors, and greenhouse designs on biogas yields, as well as the lack of robust, predictive models tailored to low-tech and resource-constrained settings. Biogas production models are valuable for developing, optimising, and enhancing resource efficiency. These models enable the effective use of resources such as feedstock, water, and digester energy. Understanding the connections between input variables and biogas production minimises waste and maximises overall efficiency. Additionally, production models provide a deeper understanding of dynamic processes, identify operational and optimisation opportunities, and contribute to biogas systems' efficiency, sustainability, and economic viability. Further research is needed to investigate the economic feasibility and scalability of a solar-assisted greenhouse balloon digester for biogas production.

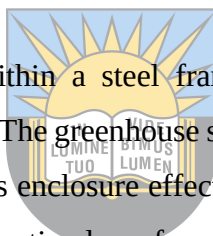
CHAPTER 3 – METHODOLOGY

3.1 Introduction

This chapter presents the greenhouse principles to increase the biogas yield during the anaerobic digestion process. Furthermore, it details with the experimental setup and monitoring of the performance of the biogas digester as well as the physicochemical properties of the cow dung. Part of the methodology chapter deals with the characterization and properties of the equipment used for the monitoring of the biogas digester and the substrate. The experimental design techniques and selection for identifying the crucial parameters for the development of the mathematical model were also presented.

3.2 Digester System

The balloon digester was enclosed within a steel frame wrapped in polyvinyl chloride PE, providing a sturdy and durable housing. The greenhouse structure surrounding the balloon digester membrane had a volume of 3.4 m^3 . This enclosure effectively shielded the digester from adverse temperature conditions, ensuring its optimal performance. The balloon digester itself was composed of PVC Tarpaulin material, ensuring its robustness. Its dimensions were as follows: height (195 cm), length (156 cm), and width (120 cm). The balloon digester was divided into two sections, namely the gas storage with a volume of 1.3 m^3 and the fermentation chamber with a volume of 1.7 m^3 , making the total volume of the balloon digester 3.0 m^3 . Fig 3.1 depicts the biogas digester used in the study.



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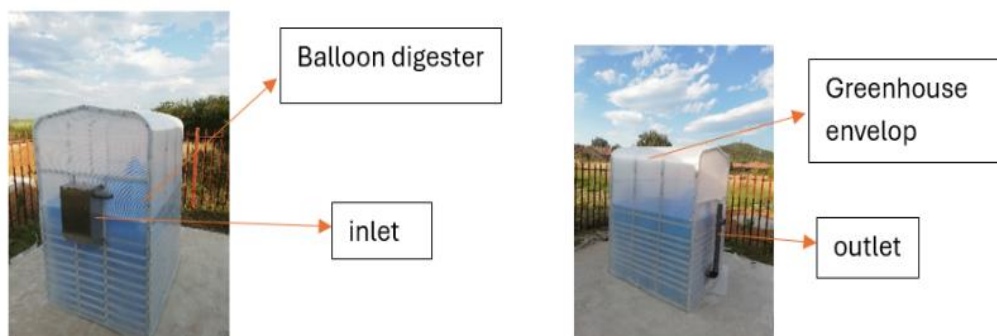


Figure 3. 1. Balloon digester inside a greenhouse structure

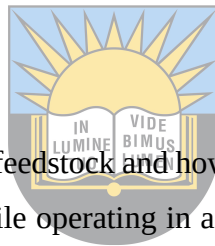
The balloon biogas digester was positioned on a concrete slab to improve the biogas process's efficiency, safety, and durability. Concrete slabs are known for their ability to provide a steady study foundation, which is crucial for supporting the weight of the digester and its contents. This prevents settling or shifting that could disrupt anaerobic digestion (Yadvika et al., 2004), thus ensuring the system's long-term viability. Furthermore, concrete possesses thermal mass properties that help maintain a consistent temperature inside the digester. This is highly important for promoting microbial activity and achieving optimal biogas production (Angelidaki et al., 2011). Additionally, the smooth and impermeable surface of concrete simplifies the cleaning and maintenance processes, thereby facilitating hygienic conditions around the digester (Brown et al., 2012). Moreover, the concrete slab acts as a barrier against groundwater infiltration, which could reduce the temperature of the slurry if in contact and disrupt the anaerobic process (Wellinger et al., 2013). Lastly, concrete slabs contribute to enhanced safety by minimizing the risk of subsidence, particularly in regions with varying soil conditions or seismic activity. This ensures that the digester remains securely in place (Deublein & Steinhauser, 2008). Figure 3.2 shows how the digester was positioned on the concrete slab.



Figure 3. 2. Digester position on the concrete slab

3.3 Study Slurry Preparation

Figure 3.3 shows the preparation of the feedstock and how it was fed into the digester. The balloon digester was monitored for 40 days while operating in a batch feeding system, where 1500 litres of the slurry was introduced in a ratio of 1:1 cow dung and water added from the inlet.



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Figure 3. 3. Slurry preparation and feeding of the digester

3.4 Experimental Setup for the Study

Figure 3.4 shows the schematic diagram of the actual experimental setup of the solar-assisted balloon digester, which has been enclosed under a greenhouse PVC membrane with sensors and data loggers installed at precise locations in the system.

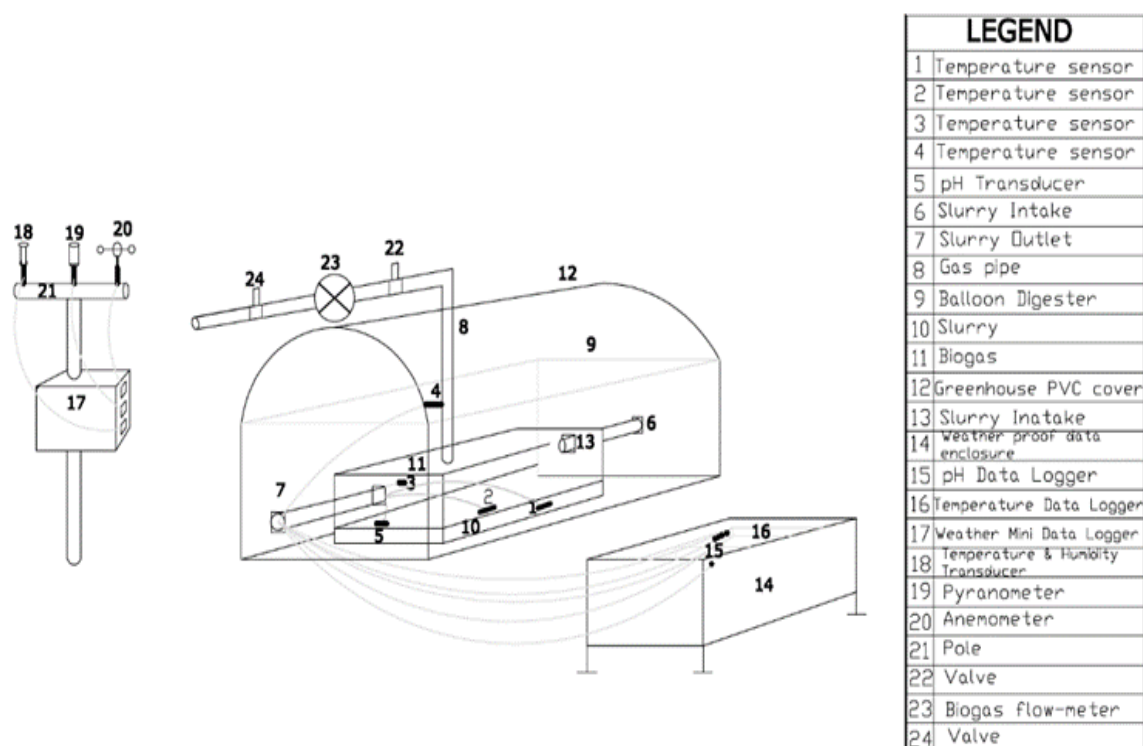
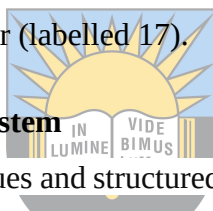


Figure 3. 4. Experimental set-up

Two temperature sensors (designated 1 and 2) at the bottom and middle of the slurry determine the average temperature. In contrast, the temperature inside the biogas storage compartment was measured by the temperature sensor numbered 3, while the temperature inside the greenhouse membrane was measured by the temperature sensor numbered 4. A four-channel data recorder with the number 16 was linked to each of the temperature sensors. A pH electrode numbered 6 embedded in the slurry was used to measure the slurry pH. The pH of the slurry was determined by connecting this electrode to the pH meter numbered 15. To regulate the flow rate of the biogas

from the balloon digester gas storage, there are two open and shut valves labelled 22 and 24 located along the gas pipe. These valves were kept closed to allow for biogas production, trapping, and gas pressure gain. A biogas flow meter (labelled 23) was used to determine the amount of biogas produced. This flow meter was installed between the two open and closed control valves along the gas pipe.

During the retention period, the valve (labelled 22) was opened in the evening of each day to determine the amount of biogas produced for that specific day. Additionally, a biogas analyzer was attached to the end of the gas line, and the two control valves were opened to determine the quality of the biogas produced. The biogas analyzer displayed the composition of biogas (methane, carbon dioxide, and hydrogen sulphide). Solar radiation was measured using a pyranometer (labelled 19), while a sensor (labelled 18) measured the ambient temperature and humidity. The wind speed was measured by an anemometer (labelled 20). The weather sensors were all connected to a waterproof mini weather data logger (labelled 17).



3.5 Performance Evaluation of the System

This section presents a series of techniques and structured processes utilized to assess and enhance the efficiency of the biogas digester outlined in the preceding sections. It encompasses gathering the substrate, detailing the equipment, reagents, and steps employed to evaluate the chemical and physical properties of the substrate prior to, during, and after digestion, monitoring operational parameters of the digester, analyzing the chemical composition of biogas, and storing data for further analysis. The performance evaluation flowchart is depicted in Fig 3.5.

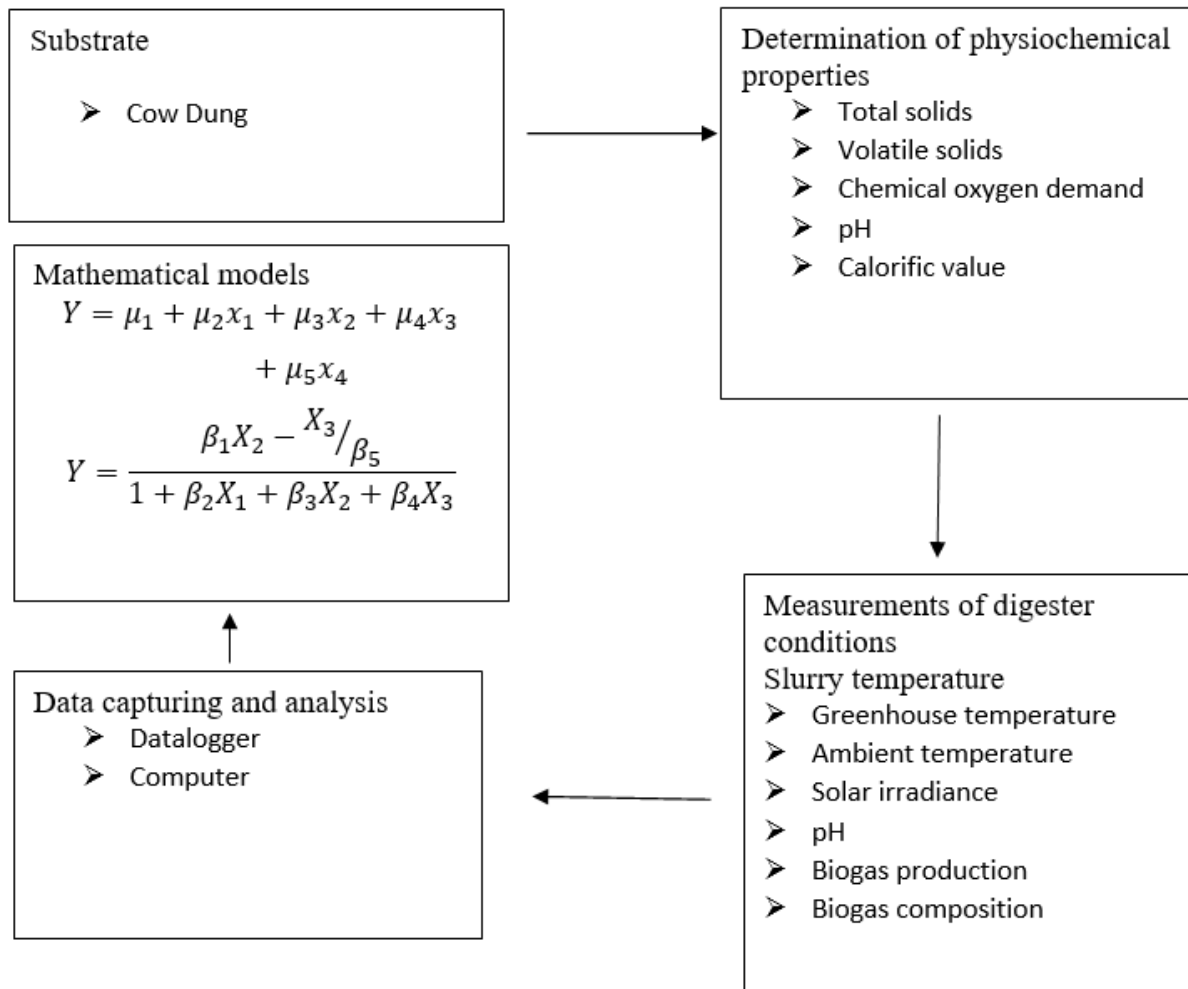


Figure 3. 5. Layout of proposed research design

Dairy cow dung was collected from the University of Fort Hare Dairy farm to be used as the substrate for the digester. Prior to and following its introduction into the digester, an analysis was conducted on the substrate to determine its TS, VS, pH, COD, and calorific value. The execution of all analytical determinations followed the standard procedures for the assessment of water and wastewater (APHA, 2023). A mixture containing water and cow dung from the University of Fort Hare dairy farm was pumped into the balloon digester. The moisture level of the cow manure was factored in when determining the optimal ratio of manure to water for creating the slurry. As per the guidelines published by Ahmadi-Pirlou et al. (2021) for improved biogas generation, the

substrates were combined with water until the total solids accounted for 5-10% of the fermentation slurry's volume.

3.6 Determination of Physiochemical Properties

3.6.1 Determination of total solids (TS)

Total solids, sometimes referred to as dry weight, are the weight of the dry material that remains in the sample after the water molecules have been removed. Bradley's method determined the proportion of total solids. The samples were weighed on a dish and dried in an oven set to 105°C for the entire night. The dish's weight and the sample before and after drying were measured using a mass balance. Equation 2.1, the standard for the APHA approach, was used to compute the percentage of total solids (APHA, 2023).

$$(TS)mg/L = \frac{A-B}{S} \times 1,000,000 \quad 3.1$$

Where A is the final 105°C weight of the dried residue + tared dish in(mg)

B is tared dish weight in mg

S is the volume of the sample



3.6.2 Determination of volatile solids (VS)

Materials classified as volatile solids either entirely evaporate from water at temperatures over 550°C or are part of dry matter left over after the inorganic component (raw ashes) is removed. These particles are frequently referred to as the water's organic content. The sample was weighed and burned for two hours at 550°C to 600°C in a muffle furnace to ascertain the total solids content. After cooling in a desiccator, the residue was weighed. Until there was a 50 mg weight difference, the igniting, cooling, desiccating, and weighing procedures were repeated. The ultimate weight was noted. A standard equation, 2.2, was used to determine the number of volatile materials (APHA, 2023).

$$\text{Volatile Solids } mg/L = \frac{A-B}{S} \times 1,000,000 \quad 3.2$$

Where A is the weight of residue + weight of dish before ignition in (mg)

B is the weight of residue + weight of dish after ignition in (mg)

S is the volume of the sample

3.6.3 Determination of other physicochemical parameters with AL450 aquatic photometer

The AL450 Aqualytic photometer was used to calculate the COD (Fig3.6). This cutting-edge, microprocessor-driven photometer has a large-format graphic display and an ergonomic keypad. It includes several pre-programmed techniques, such as VARIO Powder Packs, tube tests, liquid reagents, and AQUALYTIC tablet reagents. Users are also able to monitor their techniques. Six different wavelengths of interference filters are used by the filter photometer AL450. Its special optical design eliminates the need for any moving parts and enables automatic wavelength selection. This guarantees the maximum level of accuracy, along with the internal reference channel and dual beam technology. The AL450 photometer's LCD and function keys make up its user interface. Numerous analyses were carried out using these keys. The AL450 can also be carried around and is powered by seven common rechargeable batteries (Fig 3.6).



Figure 3. 6. AL450 aqualytic filter photometer

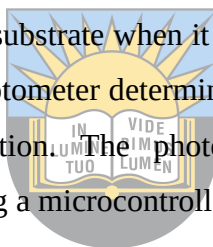
Selecting a photometer technique

Once the mode button is pressed, a menu will pop up displaying a range of options, including photometer conditions and other operations. One of the choices that will be available is the methods option. Choose a method to use. There are two choices for selecting the appropriate approach:

- a) Choose the method number directly or use the arrow keys to select the desired method from the list.
- b) Use the key to confirm.

The photometric principle

The hue of the substrate sample becomes proportionate to the concentration of the parameter being evaluated when certain reagents are applied. The photometer measures this colouration. A certain wavelength of light is absorbed by the substrate when it travels through the coloured sample and is reflected by the LED mirror. The photometer determines the sample's colour by measuring the wavelength's transmission or absorption. The photometer then computes the necessary concentration and shows the result using a microcontroller (Aqualytic®, 2015).



3.6.4 Determination of COD

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The COD measures the amount of oxygen needed to oxidize organic matter in a specific substrate volume (Yao, Liu, Chen, Zhou, & Xie, 2015). The method employed for calculating COD was as follows:

1. The AL450 photometer was fitted with an adaptor to accommodate reaction vials with a 16 mm diameter.
2. To serve as the blank, 0.2 ml of deionized water was poured into a reaction vial with a white cover.
3. For testing purposes, a separate white-capped reaction vial was used to introduce 0.2 ml of the substrate sample.

4. In order to completely mix the contents, the vials were carefully turned upside down multiple times and securely sealed. To prevent burns, a fresh, dry towel was used to handle the vials as they heated up during the mixing process.
 5. The contents had been heated for 120 minutes at 150°C in a reactor that had been preheated to aid in digestion. Following the heating process, the mixture was left to reach a temperature of 60°C. After being gently mixed by inverting, it was allowed to cool down to room temperature.
 6. After placing the empty vial into the test chamber, the adapter lid was firmly attached. Before being placed in the chamber, the vials, caps, and stirring rods underwent a thorough cleaning process using a dry, clean towel. This precaution was taken to avoid any errors that could arise from fingerprints, foreign marks, or chemical residues.
 7. The absorbency of the photometer was calibrated by pressing the "zero" key.
 8. Once the empty vial was taken out, the sample vial was delicately placed into the sample chamber to prevent any sediment from settling at the bottom, which could potentially cause inaccurate results.
 9. The COD result was initially shown in g/L and later converted to mg/L. The Lovibond RS125 reactor can operate at three optional temperature ranges: 100°C, 120°C, and 150°C, depending on the sample being prepared. It also offers three different reaction times: 30, 60, and 120 minutes. After the selected time has elapsed, the device automatically switches off.
- Figure 3.7 shows the oven used to heat the vial.



Figure 3. 7. Lovibond RS125

3.6.5 Determination of pH

The pH scale measures the alkalinity or acidity of a solution and ranges from 1 to 14. Optimal biogas production is typically achieved when the pH level is neutral (Zainudeen et al., 2021). The pH electrode and the temperature sensor were linked to the device and then dipped into the slurry. Subsequently, the device was configured for pH measurement and electrode calibration was performed as required. Subsequently, the pH value measurement of the solution was presented and recorded on the screen. Fig 3.8 depicts the pH meter used in the study.



Figure 3. 8. SD 300 pH

3.6.6 Determination of calorific value

The calorific value is a critical thermal property essential for using biofuels derived from biomass (Christoforou et al., 2014). After the sample was dried and confirmed to be free of moisture, it was ground into a fine powder. The Cal2k bomb calorimeter was then set up following the manufacturer's instructions, which typically involved assembling the bomb, adding oxygen, and connecting it to the calorimeter device. The prepared sample was accurately weighed and placed

into the sample holder of the bomb calorimeter, ensuring even distribution and compaction. The bomb was securely sealed to prevent any leakage during combustion. Inside the bomb, the sample was ignited using an ignition source, resulting in the release of heat and an increase in temperature. The bomb vessel, designed to be airtight and insulated from external temperature fluctuations, used an electrical ignition charge to heat the ignition wire once the temperature inside the vessel had stabilized. This heated wire ignited the firing cotton thread that was attached to it, which then fell onto and ignited the fuel sample. The oxygen-rich environment inside the vessel facilitated the ignition process. However, in the case of a misfire, a notification would be displayed on the LCD, enabling the process to be halted. Figs 3.9 and 3.10 provide illustrations of the internal components and filling station of the bomb calorimeter.

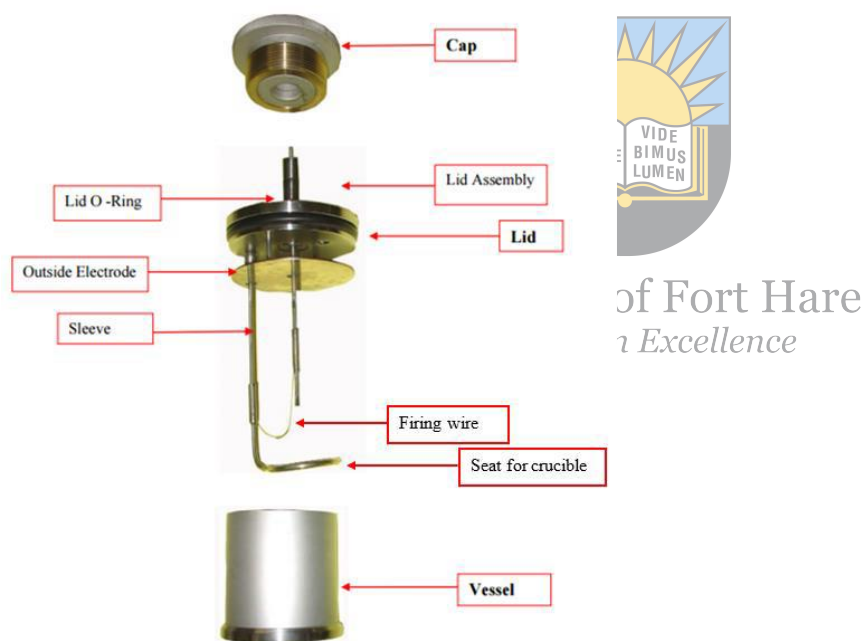


Figure 3. 9. CAL2K vessel and internal components



Figure 3. 10. CAL2K filling station

3.7 Determination of Biogas Production

The biogas flow was measured by installing a flow metre between two valves along the gas pipe. Positive displacement (PD) flow meters were employed in this study. Through an inlet, gas is allowed to enter a chamber with an oscillating diaphragm with a known volume of gas for this sort of metre to function. The chamber's volumetric flow rate is then calculated as it fills and empties during each cycle. The advantages of the PD meter include its extended lifespan, corrosion resistance, and comparatively inexpensive cost. It is ideally suited for pure gas, though, and does need occasional maintenance. The biogas flow meter used to calculate the amount of biogas produced by the balloon digester is shown graphically in Fig 3.11.



Figure 3. 11. Biogas flow meter

3.8 Determination of Biogas Composition

The analyzer can record up to 1200 data entries, connect to a computer via software for data printing, storage, and analysis, and display gas curves. Its gas pump sampling method boasts an accuracy of $\leq \pm 5\%$ F.S. and a response time of ≤ 30 seconds. The gas analyzer is capable of detecting combustible gases such as methane (CH_4), carbon dioxide (CO_2), propane (C_3H_8), and hydrogen (H_2), as well as toxic gases including ammonia (NH_3), nitrogen monoxide (NO), phosphine (PH_3), nitrogen dioxide (NO_2), hydrogen cyanide (HCN), and sulphur dioxide (SO_2) simultaneously. It uses a gas pump sampling method and a high-sensitivity sensor, ensuring high sensitivity and repeatability. The device features a 32-bit built-in MCU for high reliability and adaptability, with comprehensive functions and easy operation. It has a CSTN colourful LCD for a clear, intuitive display and a compact, portable design. Constructed from high-strength engineering plastics and anti-slip rubber, it is waterproof, dustproof, and explosion-proof. The LCD provides real-time display and system status, while LED, audio, and vibration alerts indicate gas leaks, faults, low voltage, and pump operation status. The device operates in environments ranging from -20°C to 50°C with humidity below 95% RH (non-condensing). Powered by a DC3.7V Li-ion battery with a capacity of 3200mAh, it requires 6 to 8 hours for a full charge and can operate continuously for at least 8 hours without alarms. Fig 3.12 displays the SAZQ handheld

biogas analyzer used in the research. This instrument uses the infrared optical principle and the wavelength characteristics of CH₄ and CO₂ gases to measure their concentrations.



Figure 3. 12. Bosean portable biogas analyser

3.9 Determination of Ambient Temperature and Relative Humidity

The temperature/RH smart sensor (S-THB-MOOx) was used to measure the temperature and relative humidity. This sensor has an accuracy of $\pm 0.21^{\circ}\text{C}$ between 0°C and 50°C , measuring temperatures between -40°C and 75°C . The equipment takes five minutes to respond while moving at a speed of one meter per second when detecting air temperature. The sensor's range for measuring relative humidity is 0–100% between -40°C and 75°C . It is noteworthy that exposure to temperatures below -20°C or above 95% relative humidity may cause the maximum relative humidity sensor inaccuracy. The sensor's accuracy ranges from $\pm 2.5\%$ at 10% to $\pm 3.5\%$ at 90% relative humidity, with hysteresis included at 25°C . The accuracy is $\pm 5\%$ for readings that are below 10% and over 90% relative humidity. The ambient and relative humidity sensors utilized in the study are shown in Figure 3.13.



Figure 3. 13. Ambient temperature and relative humidity sensor (S-THB-MOOx).

3.10 Determination of Slurry and Greenhouse Temperature

The temperatures of the slurry, biogas, and cavity of the greenhouse envelope of the balloon digester were measured using a copper pipe thermocouple (CNC50-HD). This thermocouple is suitable for measuring both soil and water temperatures. It has a measuring range of -40°C to 100°C and an accuracy of $\pm 0.25\%$ from 0 to 50°C . The response time in air is typically 2 minutes to reach 90% accuracy when exposed to air moving at a speed of 1m/sec. Fig 3.14 shows the temperature sensor used in the study.



Figure 3. 14. Temperature sensor (CNC50-HD)

3.11 Determination of Solar Radiation

As shown in Figure 3.15, the silicon pyranometer smart sensor (S-LIB-M003) was used to monitor the sun's radiation. The plug-in modular connector of this smart sensor makes it simple to integrate it with a weather station data logger. Because the smart sensor stores all calibration parameters internally, it can automatically convey configuration information to the logger without the need for complex human setup, programming, or calibration. The device's spectrum spans from 300 to

1100 nm, with a range of 0 to 1280 W/m². In the sun, its accuracy is usually within ± 10 W/m² or ± 5 W/m², whichever is larger. Furthermore, temperature causes an extra induced inaccuracy of ± 0.38 W/m²/°C from 25°C. Along with an azimuth inaccuracy of less than $\pm 2\%$ at 45 degrees vertical and 360 degrees of rotation, the gadget also features an angular frequency of cosine correction from 0 to 80 degrees from vertical.



Figure 3. 15. Solar radiation (S-LIB-M003)

3.12 Data Recording With UX120 Analogue Data

The Slurry and greenhouse temperature data were recorded using the HOBO 4-channel analogue data logger (UX120-006M) shown in Fig3.16. The HOBO 4-Channel Analog data logger can store up to 1.9 million measurements or events and has a 16-bit resolution. Temperature is one of the sensors that can be used with the four external channels. The logger can also compute minimum, maximum, average, and standard deviation statistics. A built-in LCD screen allows you to inspect the current measurements and keep track of the logging status, battery life, and memory usage between readouts with this simple data logger. The device operates within a range of -20°C to 70°C with a relative humidity of 0 to 95% (non-condensing). It offers logging rates ranging from 1 second to hours, 15 seconds, and 12 minutes. The device is powered by AAA 1.5V alkaline batteries and has an accuracy of ± 0.001 mA.



Figure 3. 16. UX120 four external analogue data logger

3.13 Data Recording With Hobo H21 Mini-Weather Station Data Logger

The HOBO Micro Station is a waterproof data logger designed for multi-channel microclimate monitoring in one or more locations. It can measure ambient temperature, relative humidity, and solar radiation. This battery-powered logger supports up to five plug-and-play smart sensors. Users can easily connect the logger to monitor the status of weather metering sensors, and data can be downloaded using Hoboware Pro for further analysis. The device functions in a temperature range of -20°C to 50°C and offers logging intervals ranging from 1 second to 18 hours. It has a memory capacity of 512 KB for non-volatile flash data storage. Data is recorded every five minutes. The device is powered by four AA 1.5V alkaline batteries and offers a time accuracy of 0 to 2 seconds for the first data point and ± 5 seconds per week at 25°C. Fig3.17 shows the H21 mini-weather station data logger used in this research.



Figure 3. 17. HOBO H21 mini weather station

3.14 Hoboware Pro Software

The HOBOWare software was used to launch, read, and visualize data from HOBO data loggers. In this study, the Hoboware Pro software was used to configure the sensors connected to designated Hobo data loggers and to download and export data for further analysis.

3.15 Development of the Mathematical Models Using Matlab

Standard procedural procedures and MATLAB software version 2021a were used for analytical processing and statistical testing. The target validation data and the validated predicted values derived from mathematical models were compared, as well as the measured volume of biogas yield (target testing data) and the predicted values (model outputs), using the one-way analysis of variance (ANOVA) test to see if there was a significant difference. A multiple linear regression model was established with the input parameters being greenhouse temperature (x_1), ambient temperature (x_2), solar irradiance (x_3), and relative humidity (x_4), and the output being the slurry temperature. Equation 3.3 shows the multiple linear regression model based on the predictors: greenhouse temperature, ambient temperature, solar irradiance, and wind speed.

$$Y = \mu_1 + \mu_2 x_1 + \mu_3 x_2 + \mu_4 x_3 + \mu_5 x_4 \quad [3.3]$$

The impact of input parameters on slurry temperature and the system's thermal efficiency was evaluated by ranking the predictors' contributions using the reliefF method. The model's accuracy for both predictors and the intended target was assessed using the determination coefficient and root mean square error. Hougen's model, which is a nonlinear fitting model, was developed. This includes the dynamics of a nonlinear regression model with three predictors: pH, slurry temperature, and chemical oxygen demand (COD). The aim was the desired response, or biogas volume (Y). The contributions of the COD, slurry temperature, and pH predictors were ranked according to their significance to the output (biogas volume) using the reliefF algorithm. The correctness of the model with respect to the predictions (model outputs) and targets was evaluated using the determination coefficient, mean absolute error, and p-value. Equation 3.4 shows the nonlinear regression model to predict the volume of biogas yield. As predictors, the equation is based on weather, thermal, and physio-chemical parameters.

$$Y = \frac{\beta_1 x_2 - x_3 / \beta_5}{1 + \beta_2 x_1 + \beta_3 x_2 + \beta_4 x_3}$$



[3.4]

3.15.1 Statistical Analysis

The study employed the ANOVA test using p-values to determine the notable distinction between the validation targets. The one-way analysis of variance (ANOVA) test was employed to examine whether there exists a significant difference between the testing data of the targets and the model outputs, as well as the validation data of the targets and the predicted values. This analysis was conducted using the derived mathematical models, namely the multiple linear and non-linear regression models, with their p-values (Tangwe et al., 2022; Faggioli et al., 2021). In the study conducted by Tangwe et al. (2022), the reliefF algorithm was used to assess the predictors' impact on biogas yield and slurry temperature. This involved applying nonlinear multiple regression for biogas yield and multiple linear regression for slurry temperature.

3.16 ReliefF Test Used in Ranking of the Predictors for both slurry temperature and biogas yield.

The number of possible predictors (x) that could affect the result (y) is represented by the variable k , which has a default value of 10. Positive weights indicate that the input parameters were major variables, whereas negative weights assigned to predictors indicated that the input parameters were secondary factors. The weighting ranges from -1 to 1. Higher positive weight values indicate that the parameters significantly impact the desired result.

3.17 Summary

The amount and quality of biogas depend on the type of substrate used, the physiochemical properties, and the digester's capacity to maintain a consistent temperature within a narrow mesophilic range. An experimental method was created to ascertain the physiochemical properties of cow dung, such as TS, VS, COD, pH, and calorific value. Using numerous pre-programmed methods and reagents, the AL450 Aqualytic photometer was used to measure the chemical oxygen demand. Using an oven and the mass balance technique, calculations were made for the total and volatile solids. A mass balance, an oven, and a CAL2K bomb calorimeter were used to determine the calorific value. The copper pipe thermocouple (CNC50-HD) temperature sensor was used to detect the temperature. It was connected to a 4-channel analogue data logger (UX120-006M) so that data could be stored. The temperature/RH smart sensor (S-THB-MOOx) and the silicon pyranometer smart sensor (S-LIB-M003) were used to measure the ambient temperature, relative humidity, and sun irradiance. The HOBO H21 mini-weather station data logger contained all of the data.

CHAPTER 4 – RESULTS AND DISCUSSIONS

4.1 Introduction

The performance of the solar-assisted balloon biogas digester inside a greenhouse envelope is presented in this chapter.

4.2 Substrate Characterisation and Properties

The biogas production performance was monitored daily throughout the retention period to evaluate the solar-assisted digester. Cow dung from dairy farm cattle was used, and certain characterization was conducted to gain valuable insight into the feedstock. Prior to the anaerobic digestion process, the cow dung contained a total solids content of 167306.93 mg/L and a volatile solid content of 125178.78 mg/L. The slurry had an average pH value of 7.11. Prior to the anaerobic process, the COD value averaged 39792 mg/L, while the slurry temperature maintained an average of 31.49°C during the retention period. Table 4.1 showcases the various traits of the parameters discovered in cow dung.

Table 4. 1. Characterization parameters for cow dung

Parameters	Values
Total solids (mg/l)	167306.93
Volatile solids (mg/l)	125178.78
Volatile solids / Total solids (%)	74.82
Chemical oxygen demand COD (mg/l)	39792
Calorific value (MJ/g)	25.86
Average pH	7.86

4.3 Behaviour of pH Throughout the Retention Period

The pH level plays a pivotal role in the production of biogas, as it directly impacts the microbial activity that drives the anaerobic digestion process. Various groups of microorganisms flourish within specific pH ranges, highlighting the significance of maintaining an appropriate pH level for achieving optimal digestion efficiency and maximizing biogas production. Figure 4.1 illustrates the behaviour of the pH slurry throughout the retention period.

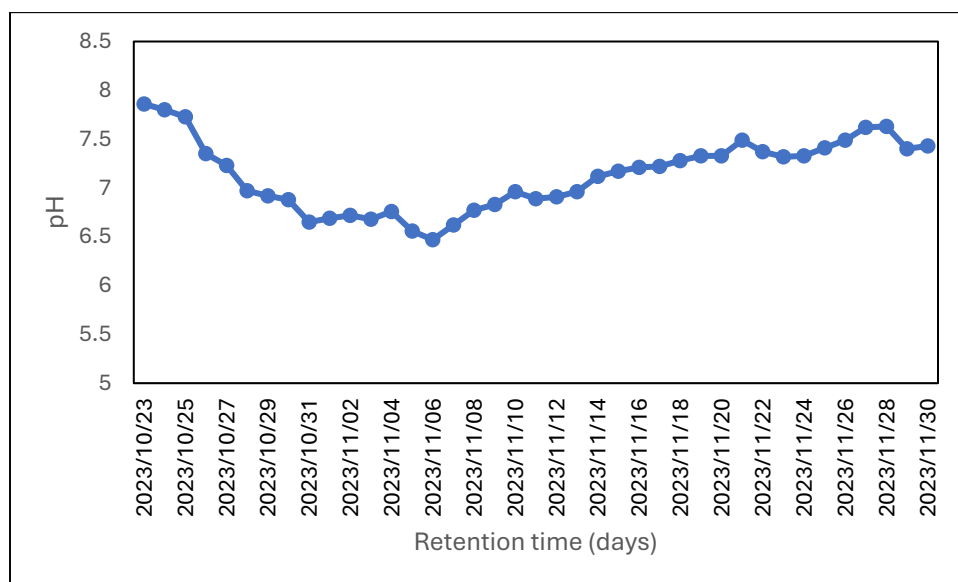


Figure 4. 1. Behaviour of the slurry pH

The initial pH of the slurry was 7.86, which might have caused a delay in microorganism activities as the pH was not yet favourable for the hydrolysis stage, then the pH gradually decreased for the first nine days to 6.65 which can be attributed to the hydrolytic and acidogenic microorganisms as they favour the acidic range (Menzel et al., 2020). The pH fluctuated until the 15th day, reaching a pH of 6.47, further confirming that the hydrolysis stage and acidogenesis are not distinctly separate but rather overlap and occur simultaneously. As hydrolytic enzymes break down complex molecules, acidogenic bacteria immediately begin fermenting the simpler products, creating a continuous and dynamic interplay between these two stages. From day 18, the pH gradually started to increase, suggesting that the acetogenesis stage had started as the pH was 6.83, and the volatile

fatty acids were being converted to acetate, with hydrogen also being produced (Kutz et al., 2019). On the 14th day, the pH was 7.12, which falls within the optimum pH range for methanogenesis and rises until the end of the retention period.

4.4 Relationship Between Biogas Production and pH

Maintaining an optimal pH range is vital for efficient and stable biogas production. Effective pH management ensures that all microbial groups involved in anaerobic digestion can operate at peak efficiency, resulting in maximum biogas yields. Fig4.2 illustrates the impact of pH variation in biogas production as the biogas-forming bacteria feed on the organic content of the feedstock.

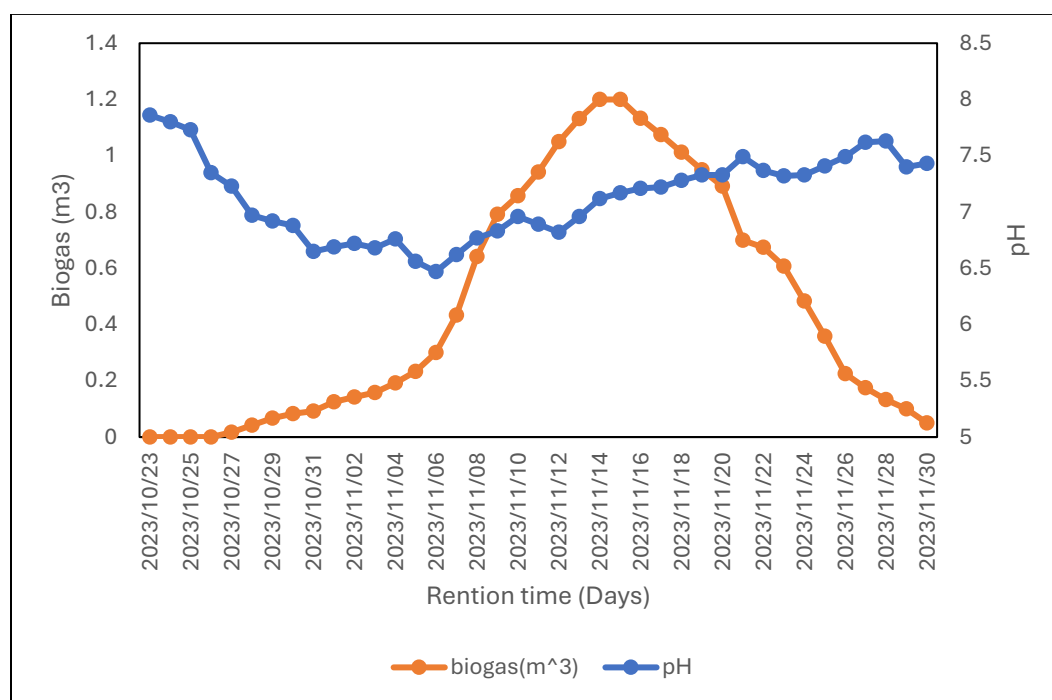


Figure 4. 2. pH and biogas variation with retention period

The pH at the start of the digester was 7.86. Biogas production began on the 5th day, which aligns with the findings of Bahira et al. (2018) regarding the impact of pH variation. This is supported by the high count of viable bacteria suggested by Tangwe et al. (2022), confirming that cow dung contains a significant amount of biodegradable organic matter. The pH decreased from 7.86 on the 1st day to 6.47 on the 15th day. This can be attributed to the high levels of volatile fatty acids,

bicarbonate alkalinity, and carbon dioxide, which are by-products of anaerobic digestion's first and second stages (hydrolysis and acidogenesis). These results are consistent with the findings of Wang et al. (2019). Starting from day 16, the pH gradually increased due to the depletion of volatile fatty acids caused by methanogenic bacteria consumption. The highest biogas yield was observed between days 19 and 29, with an average pH of 7.11. The maximum biogas yield was obtained at pH levels of 7.12 and 7.17. After the 30th day, biogas production gradually decreased as the pH increased, still remaining within the neutral range. This decrease in production can be attributed to the depletion of volatile acids, as noted by Mutungwazi et al. (2020). The total cumulative biogas production during the retention period was 18.269 m³. This study, in line with previous research, suggests that maintaining a neutral pH contributes to increased biogas production, characterized by a higher methane content. The average pH during the retention period in this study was 7.13. Similarly, Bahira et al. (2018) identified an optimal pH of 8.52, resulting in the highest biogas yield compared to pH values of 4.52 and 6.43 under the same temperature conditions.

4.5 COD Destruction Variation with Biogas Production

The COD concentration was 39792 mg/L upon introducing cow dung into the digester, indicating its high degradability organic content. Fig 4.3 illustrates the COD destruction rate with biogas production over the retention period.

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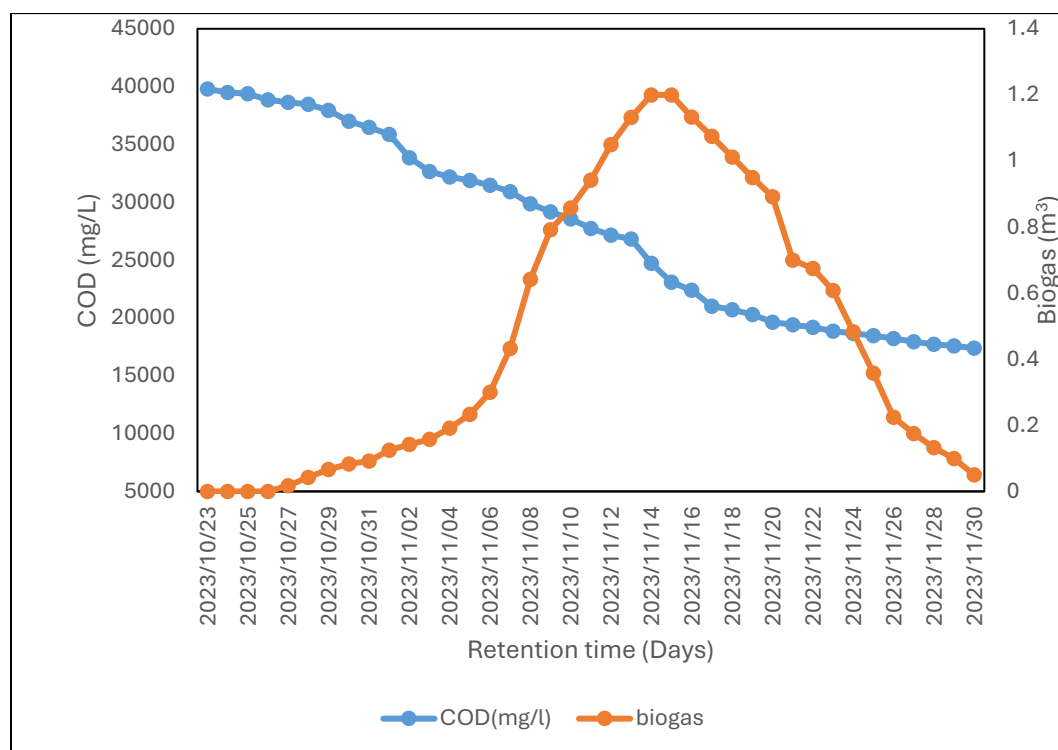


Figure 4. 3. Relationship between COD destruction rate and biogas production

Initially, biogas production was slow within the first 7 days due to a decline in pH, likely caused by fluctuations in COD destruction by acid-forming bacteria. This phenomenon arises because acidogenesis and methanogenesis processes occur concurrently (Mutungwazi et al., 2020). Notably, there were sharp declines in the COD destruction rate observed between November 1st to November 4th and November 13th to November 21st, coinciding with periods of heightened biogas production. The highest biogas yield was recorded on November 14th and 15th, 2023. By the end of the retention period, the COD decreased to 17387 mg/L, resulting in a total COD destruction rate of 56.31% for the system.

4.6 Biogas Composition

Figure 4.3 illustrates the variation in methane CH₄ and carbon dioxide CO₂ production over the retention period.

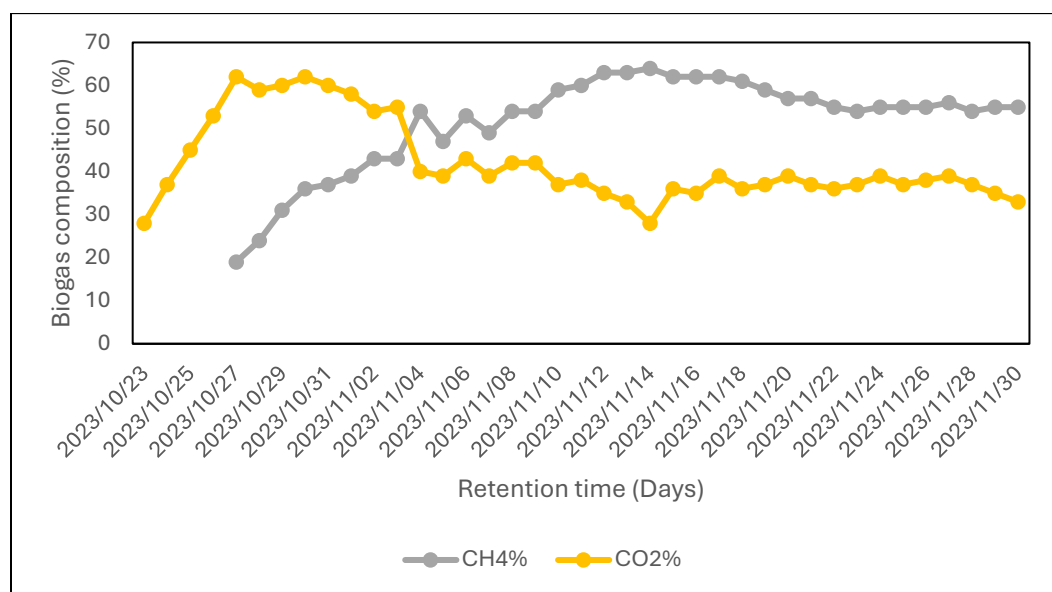


Figure 4. 4. Biogas composition (CH₄ AND CO₂ variation)

The variation of carbon dioxide and methane in the biogas generated is shown in Fig 4.4 Methane exhibited a lag phase compared to carbon dioxide, which can be attributed to microbial activity, specifically the bacteria that generate methane. However, carbon dioxide gas prevailed over methane gas for the first 12 days. This could be due to the activities of acid-forming bacteria that convert fatty acids, amino acids, and simple sugars into acetic acids, hydrogen, and carbon dioxide. Thereafter, from November 4th, carbon dioxide decreased sharply. In terms of methane and carbon dioxide generation, hydrolysis and acidogenesis predominated during the initial phase of anaerobic digestion, as indicated by the high carbon dioxide level. Furthermore, large amounts of carbon dioxide are caused by the presence of anaerobic bacteria the activities of acid-generating bacteria, which aid in converting fatty acids, amino acids, and simple sugars into hydrogen and carbon dioxide. The decline in carbon dioxide is prompted by the conversion of carbon dioxide, hydrogen, and amino acids into methanogenic bacteria and oxygen deprivation. By the end of the retention period, carbon dioxide fluctuated within a narrow range of 30% to 40%. The methane concentration of the gas was measured on the 5th day and gradually increased and stabilized in the 55% to 60% range. The delay in methane generation demonstrates that the first three steps of the anaerobic process occurred simultaneously, as shown in Obileke et al. (2020) and Prasard et al.(2017).The increase in methane production is linked to an increase in slurry temperature, which

promotes the growth of methanogenic bacteria and the conversion of fatty acids, hydrocarbons, and carbon dioxide to methane-forming bacteria (Mutungwazi et al., 2020). On Day 13, methane surpassed carbon dioxide since none of the methanogenic activities are used as reactants, unlike CO₂. Furthermore, the high methane content in the biogas yield is evidence that the methanogenesis process of the anaerobic digestion process is approaching its optimum stage, indicating that cow dung contains a significant amount of biodegradable organic matter. Methane reached equilibrium due to the continuous synthesis of carbon dioxide by methanogenic processes, resulting in an equilibrium point. The system produced a total of 10.585 m³ (57.94%) methane and 7.526 m³ (41.2%) carbon dioxide by the end of the retention period.

4.7 Ambient Temperature Variation

Temperature is an important factor in biogas production. Acidifying bacteria function optimally within specific temperature ranges: mesophilic (32°C to 42°C) or thermophilic (48°C to 55°C) conditions. Thermophilic conditions result in higher biogas yield, while mesophilic conditions are preferred for greater energy production. Digestion processes decline at temperatures as low as 10°C (Wang et al., 2019). These temperature conditions affect the metabolic process in anaerobic digestion, which involves various microbial groups such as hydrogenotrophic, acidogenic, acetogenic, and methanogenic organisms. Fluctuations in temperature can potentially impact the balance among these microorganisms and their metabolic processes (Kandhro et al., 2024). During the spring, weather conditions can significantly impact biogas production due to temperature, humidity, and sunlight variations. Spring season typically brings moderate temperatures, increased sunlight, and fluctuating humidity levels, which collectively influence the anaerobic digestion process and biogas yield. Spring temperatures are generally moderate, which can benefit biogas production by providing a stable environment for the anaerobic microorganisms. These conditions are conducive to maintaining the optimal temperature range for microbial activity, especially in mesophilic digesters (Miller et al., 2020). However, spring also brings temperature fluctuations, which may challenge the stability of biogas production. Sudden temperature changes can stress the microbial community, potentially reducing the efficiency of the digestion process. The longer daylight hours in spring increase the availability of solar energy. Biogas systems integrated with solar heating can enhance overall efficiency by maintaining a consistent and optimal digester temperature, thus improving biogas yield. Fig 4.5 shows the ambient temperature variations over

time over the retention period of days in October and November, which fall under the spring season. The maximum temperature during this period was 25.33°C, the minimum was 10.58°C, and the average temperature was 19.42°C

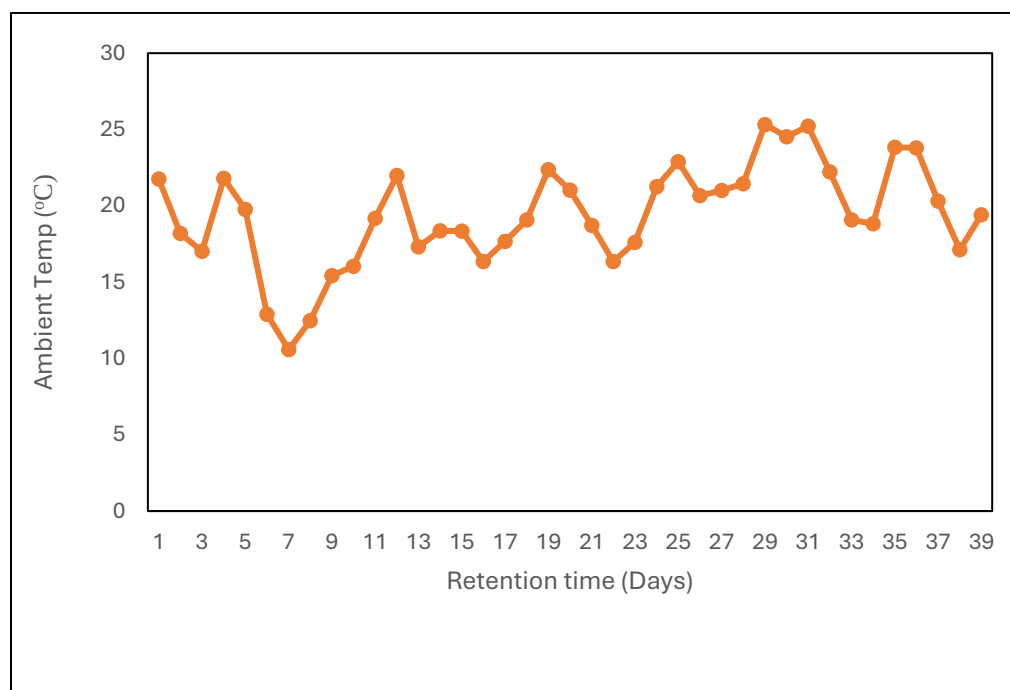


Figure 4. 5. Ambient temperature variation throughout the retention period

As observed in Figure 4.5, the ambient temperature fluctuated under psychrophilic conditions under 25°C. The observed fluctuations are attributable to the diverse weather conditions experienced in Alice during the spring season, which are known to be one factor affecting the anaerobic digestion process. The graph of the ambient temperature clearly shows that the temperature was well below the optimum temperature range. An enclosure known as a greenhouse envelope was utilized to regulate temperatures and mitigate the temperature disparities resulting from seasonal fluctuations. This approach aimed to maintain stability in the process of anaerobic digestion.

4.8 Temperature Variation of the System

Usually, ambient temperature influences the slurry temperature, making it responsible for biogas production (Sabbir et al., 2021). The production of biogas increases as the operational temperature of the slurry increases, specifically within the mesophilic range (Sabbir et al., 2021). Therefore, the estimation of daily biogas production is based on the operational temperature of the slurry. Different temperature ranges correspond to the activities of bacteria. Figure 4.6 displays the temperatures recorded in the study. The temperature of the slurry depends on the ambient temperature and the temperature inside the greenhouse.

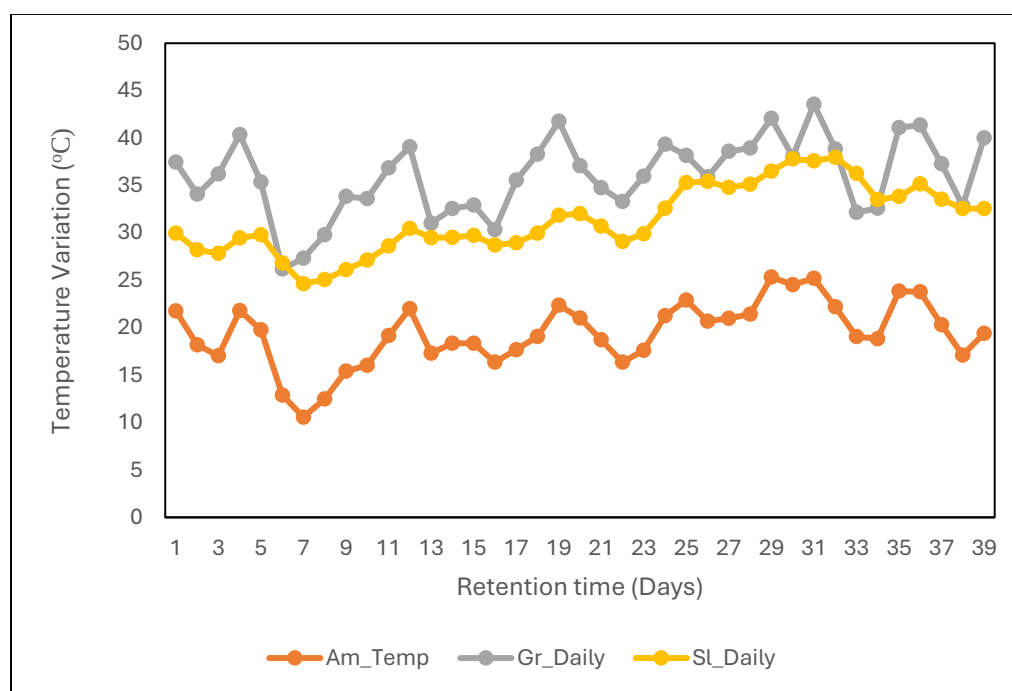


Figure 4. 6. Temperature variation of the system during the retention time

Figure 4.6 illustrates the temperature variation within the greenhouse envelope (Gr), slurry (Sl), and ambient (Am) during the retention period from October 23, 2023, to November 30, 2023. The fact that the slurry temperature stayed within the mesophilic range during the retention time illustrates the greenhouse influence on the slurry temperature in Fig4.6. For the duration of the retention time, the slurry temperature was higher than the surrounding air due to the greenhouse envelope. The ambient, greenhouse, and slurry average temperatures throughout the retention period were 19.35°C, 36.0°C, and 31.49°C, respectively. The slurry, greenhouse, and ambient

temperatures varied within their respective mesophilic ranges. This shows that the system successfully raises the slurry temperature to the ideal mesophilic range, which is beneficial for anaerobic digestion. The greenhouse effect raises the greenhouse temperature over the slurry temperature during the day. At night, the lack of solar radiation, exothermic bacterial activity within the digester, and the slurry's higher heat capacity compared to the greenhouse air result in the slurry being warmer than the greenhouse. The decrease in greenhouse temperature is a result of infiltration and insufficient insulation, including convective and conductive losses. Additionally, the concrete slab is ineffective at retaining heat. Additionally, fluctuations in solar radiation intensity, caused by weather conditions such as cloud cover or rain, can impact the amount of heat entering the greenhouse (Capossio et al., 2022). The final composition percentages of CO₂, CH₄, water vapour, and other gases, as determined by the gas analyser, are shown in Table 4.2. The methane yield obtained was above 55%. This discrepancy can be explained by the fact that the slurry temperature was kept constant throughout the investigation.

Table 4. 2. Biogas composition after digestion

Gas	Composition (%)
Methane (CH ₄)	58
Carbon dioxide (CO ₂)	41
Other gases	1

4.9 Summary

The average temperatures observed during the retention period were 19.35°C for the ambient temperature, 36°C for the greenhouse temperature, and 31.49°C for the slurry temperature. The ambient, greenhouse, and slurry temperatures all day long stayed within the mesophilic ranges, which was what was expected. This shows that the system successfully reaches the ideal mesophilic range for the slurry temperature, which is necessary for anaerobic digestion. It's important to remember that during the day, the greenhouse temperature rises due to the greenhouse effect. For several reasons, the slurry temperature is higher at night than in the greenhouse. The

slurry's temperature rises as a result of the digester's bacteria's exothermic activity and the lack of sun radiation. Furthermore, the slurry can hold more heat than the air inside the greenhouse shell. The decline in greenhouse temperature can be attributed to infiltration, insufficient insulation, and the concrete slab's inability to retain heat effectively. These factors contribute to convective and conductive losses in the greenhouse



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CHAPTER 5 – MATHEMATICAL MODELLING

5.1 Introduction

The development of a mathematical model is the focus of this chapter. A mathematical model is a computational technique or mathematical equation that forecasts a system's or process's dynamic behaviour (Obileke et al., 2021). It is widely applicable to optimization, control systems, and system performance forecasts in situations where it is impossible to reproduce the real conditions (Tangwe et al., 2022). Three elements make up mathematical models: inputs, models, and outputs. The input, model, and output parts represent predictors, mathematical formulas, and intended answers. It can explain an actual plant or procedure. MATLAB software version 2021a was used to conduct analytical and statistical testing in accordance with conventional protocols (Valentine et al., 2022). ANOVA test was used to determine whether there was an important difference between the target validation data and predicted values, as well as between the target testing data and model outputs, using mathematical models (multiple linear and non-linear regression) based on p-values (Faggioli et al., 2021). According to their significance for the anticipated result (biogas yield), the reliefF approach prioritized the predictors (COD, daily slurry temperature, and pH) (Tangwe et al., 2022).

5.2 Development of a Multiple Linear Regression Model

A multiple linear regression model is a data-driven model that calculates the forcing and scaling constants using the least squares regression method. For this model to produce a simulation, input parameters are needed. In this instance, greenhouse temperature, ambient temperature, and input parameters include solar irradiance and relative humidity parameters in the constructed model to simulate slurry temperature. A number of tests, including determining the coefficient, mean absolute error, and p-value against targets and projected values, were run to evaluate the model's accuracy. Each of the chosen predictors is stated individually and linearly in the multiple linear regression model's mathematical equation.

$$y = \mu_1 + \mu_2 x_1 + \mu_3 x_2 + \mu_4 x_3 + \mu_5 x_4 \quad 5.1$$

Let's consider the variables: x_1 represents the temperature inside the greenhouse, x_2 represents the outside temperature, x_3 represents the sun irradiation, and x_4 represents the relative humidity. The forcing constant is represented by μ_1 , while the scaling parameters are represented by μ_2 , μ_3 , μ_4 , and μ_5 . A mathematical model was created using the least squares method in MATLAB. The factors that influence the slurry temperature include greenhouse temperature, ambient temperature, sun irradiance, and relative humidity. These factors are denoted as X_1 , X_2 , X_3 , and X_4 , while the slurry temperature itself is represented as y . Certain input variables are connected to the scaling constants (μ_1 , μ_2 , μ_3 , μ_4 , and μ_5). A regression analysis was conducted on the developed dataset using specific inputs and output parameters to determine the scaling constants. The input and output parameters were fitted using the regress method, and the MATLAB regression tool was utilised to determine the scaling constants. The input, output, and scaling values generated by the multiple linear models created in MATLAB through the regression function are displayed in Table 5.1. The scaling constant (μ_1) is linked to the lumped parameter, while the scaling attributes (μ_2 , μ_3 , μ_4 , and μ_5) are associated with the input variables X_1 , X_2 , X_3 , and X_4 . In the testing dataset, the correlation coefficient and root mean square error between the predicted and measured slurry temperatures were 0.341 and 0.984, respectively. The multiple linear regression model accurately predicted outputs with minimal variance from the actual targets, as evidenced by the high determination coefficient. After evaluating the root mean square error between the predicted and actual outputs, it was determined that the method of multiple linear regression was appropriate.

Table 5. 1. Input and output parameters of the developed multiple linear regression

Input	Input Symbols	Scaling	Scaling values	Outputs
Constant	μ	μ_1	39.463	Slurry temperature
Greenhouse temperature	X_1	μ_2	-0.17857	$R^2 = 0.986$
Ambient temperature	X_2	μ_3	0.4809	RMSE = 0.341
Solar irradiance	X_3	μ_4	-0.0027898	p-value = 0.903
Relative humidity	X_4	μ_5	-0.14615	

$$y = 39.463 - 0.17857(X_1) + 0.4809(X_2) - 0.0027898(X_3) - 0.14615(X_4)$$

Multiple linear regression is a valuable statistical technique used in various fields for modelling complex relationships, predicting outcomes, identifying significant variables, evaluating models, optimizing processes, and informing decision-making. Its significance lies in its ability to offer valuable insights into variable interactions and assist in studying and analyzing real-world phenomena. They were ordered according to how much they contributed to find which input parameters had a bigger impact. This evaluation assisted in determining the efficacy of the system. ReliefF is the name of the algorithm used to rank the input parameters. When the outcome variable (y) is a multiclass categorical variable, ReliefF establishes the predictor weights. Predictors who give different values to neighbours in the same class are penalised by the technique, whereas predictors who give different values to neighbours in separate classes are rewarded. All predictor weights (W_j) are initially set to zero by ReliefF. Next, for every class, the method iteratively chooses a random observation (x_r), determines which observations are k-nearest to x_r , and modifies the weights of the predictors (F_j) for every nearest neighbour (x_q). The ranking of the contributions from the input parameters is shown in Figure 5.1.

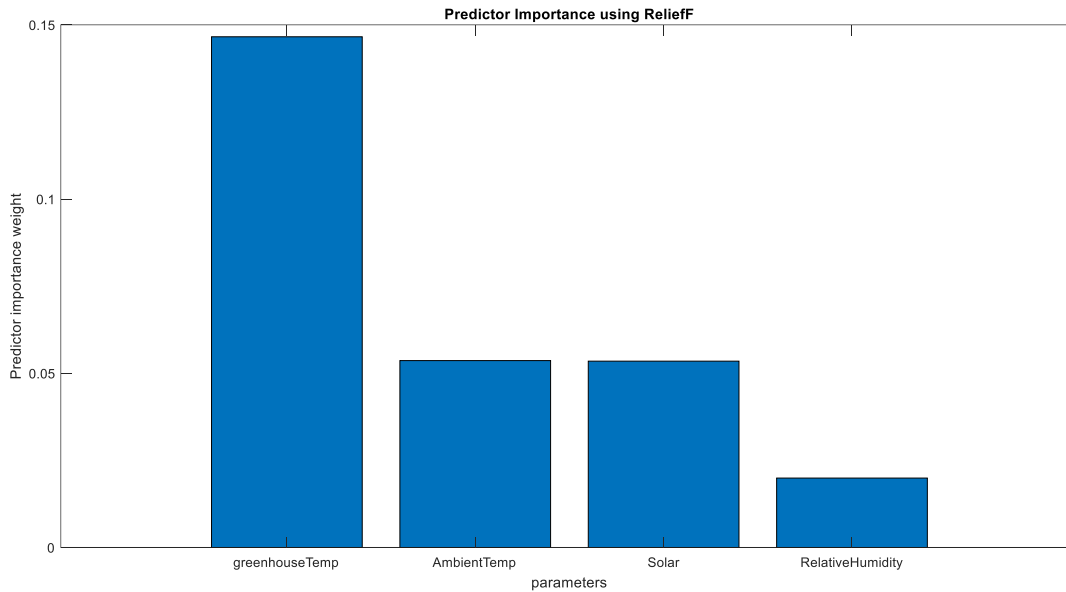


Figure 5. 1. Weight ranking of predictors in accordance with the slurry temperature

From ranking the input parameters, the greenhouse temperature influences the slurry temperature more than other input parameters, meaning that the greenhouse envelope is economical in raising the slurry temperature.

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5.3 Development of Non-Linear regression Response Surface Model

Non-linear regression dynamics were used in the development of a non-linear fitting model. Three predictors were used in this model: pH (X_3), daily slurry temperature (X_2), and COD (X_1). The biogas yield (Y) was the desired response of interest. A number of indicators, such as the p-value, mean absolute error, and determination coefficient, were used to evaluate the model's accuracy. As shown in Germec et al. (2021) study, these parameters were compared to the experimental and anticipated biogas yields.

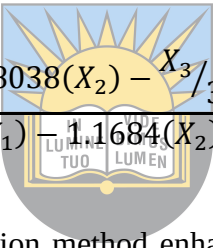
$$Y = \frac{\beta_1 X_2 - X_3 / \beta_5}{1 + \beta_2 X_1 + \beta_3 X_2 + \beta_4 X_3} \quad 5.2$$

Where Y is the biogas yield, X_1 is the COD, X_2 is the daily slurry temperature, X_3 is the pH, and the scaling factors are β_1 , β_2 , β_3 , β_4 , and β_5 . The modeled equation served as the optimization

function for creating the mathematical model in MATLAB. The biogas yield, or intended response, was represented by the symbol Y , while the predictors, or daily slurry temperature, pH, and COD, were represented by the symbols X_1 , X_2 , and X_3 . Scaling parameters β_1 , β_2 , β_3 , β_4 , and β_5 were allocated to particular input variables. Using the modelled equation and the trained (testing) dataset, which came from experimental data, the scaling parameters were found by non-linear function optimisation. Choosing starting values for input and output parameters and applying the optimization function iteratively using these values comprised the optimization algorithm. Iteration proceeded until the scaling parameters were determined with accuracy and the predicted biogas yield (y_o) nearly matched the actual experimental biogas yield (Y). The input and output parameters and the scaling values obtained from the created nonlinear regression model are shown in Table 5.2. One scaling property (β_2) is connected with X_1 , two scaling parameters (β_1 and β_3) are related to X_2 , and two scaling parameters (β_4 and β_5) are associated with X_3 . Between the actual biogas yield (Y) and the anticipated biogas yield (y_o) based on the testing dataset, the determination coefficient, mean absolute error, and p-value were, respectively, 0.985, 0.0239 and 0.8825. In the created non-linear regression model, a determination coefficient value approaching 1 denotes good agreement between the expected outputs (y_o) and the actual experimental biogas yield (Y). With a 95% confidence level, the derived p-value (0.8825), which is more than the 0.05 threshold, indicates that there is no significant difference between the actual experimental biogas yield (Y) and the predicted biogas yield (y_o). Furthermore, the real target's lowest value was greater than the mean absolute error between the projected outputs and the actual objectives. The created non-linear regression model can be used with acceptable justification thanks to this favourable determination coefficient and mean absolute error values.

Table 5. 2. Input and output parameters of the developed non-linear multiple regression

Input	Input symbols	Scaling	Scaling values	Output
Constant			1	
Slurry temperature	X_1	β_2	-0,1096	$R^2 = 0.985$
pH	X_2	β_1 B_3	0,18038 -1,1684	Root mean square error = 0.0239
COD	X_3	B_4 B_5	$-2,40 \times 10^{-6}$ $3,5 \times 10^7$	p-value = 0.8825



$$Y = \frac{0.18038(X_2) - X_3 / 3,5 \times 10^7}{1 - 0.1096(X_1) - 1,1684(X_2) - 2.4 \times 10^{-6}(X_3)}$$

The Hougen-Watson non-linear regression method enhances our understanding of biochemical processes by enabling accurate kinetic models, parameter estimation, model validation, process optimization, and scale-up in fields such as biotechnology, biochemistry, and anaerobic processes. The weighting scale ranged from -1 to 1, with negative weights indicating that certain predictors were secondary factors, while positive weights suggested that they were primary factors contributing to the outcome. Higher positive weight values indicated a greater contribution to the desired output. Fig 5.4 illustrates the importance of predictor weights (slurry temperature, COD, and pH) to the desired output (biogas). It shows that slurry temperature was the primary factor, while COD and pH were secondary factors.

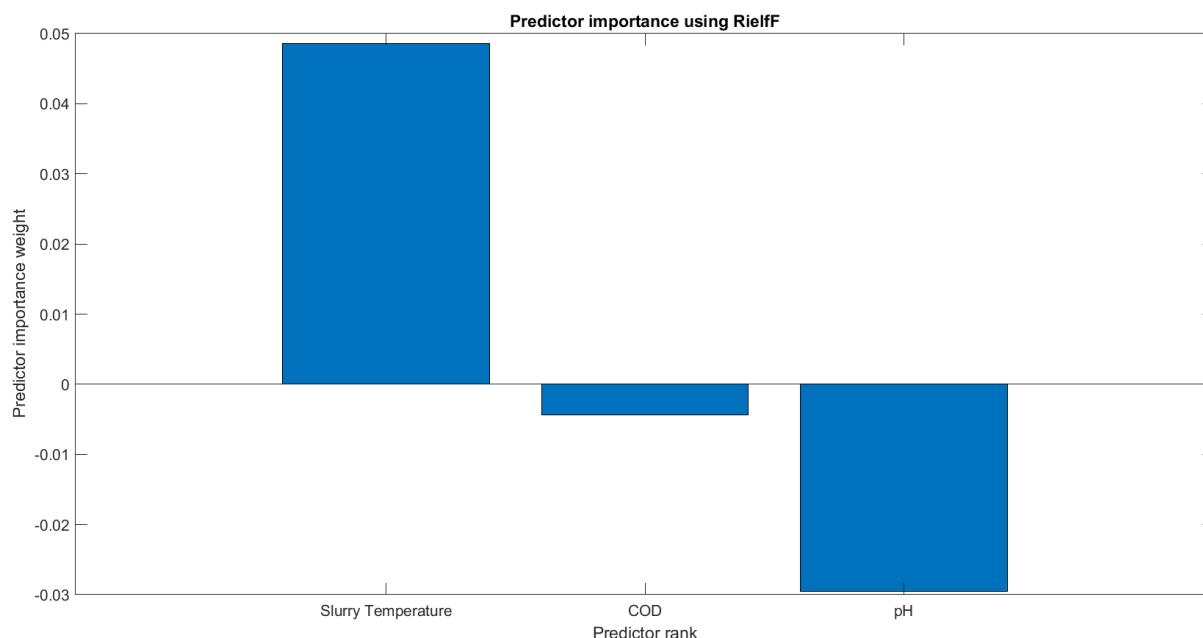


Figure 5. 2. Weight ranking of predictors in accordance with the volume of biogas yield



5.4 Summary

MATLAB software was used to develop the two model equations for the cow manure in a batch system. Temperature had positive values in both equations, suggesting that a rise in digester temperature would raise methane yield proportionately. The greenhouse temperature and slurry were found to be the key determinants, and the reliefF test was used to evaluate the predictors' relevance based on their weights. The biogas yield on the test samples was accurately predicted using the multiple linear and non-linear regression models. The linear regression model estimated coefficient, mean absolute error, and p-value were 0.985, 0.0239, and 0.8825, respectively. When forecasting slurry temperature, the multiple linear regression model yielded consistent values of 0.986, 0.341, and 0.903.

CHAPTER 6 – FINDINGS, CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter presents a summary of the findings from the experiments on solar-assisted digester. It delves into the possibilities of harnessing the greenhouse effect to regulate the temperature of a biogas digester. The text explores the mathematical models utilized in forecasting biogas production and evaluating the efficiency of a biogas digester controlled by greenhouse temperatures. The conclusions and recommendations are drawn from the analysis of these findings.

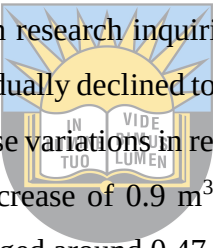
6.2 Summary of Findings

Biogas production is influenced by various factors such as slurry temperature, pH levels, and chemical oxygen demand. These factors play a crucial role in the process of anaerobic digestion. Some types of small-scale digester designs, such as fixed dome, Bio-bag, and Floating dome digesters, can face challenges when it comes to temperature control. This can lead to lower biogas production and methane yields. To tackle this problem, using a greenhouse to control the temperature in small-scale digesters offers an attractive solution. Inside a greenhouse structure, solar radiation can pass through the cover, reaching the digester. The digester absorbs a portion of the radiation, resulting in the transfer of thermal energy to the substrate slurry and subsequently increasing its temperature. A further amount of the radiation is released back into the greenhouse space as thermal radiation. This type of radiation has longer wavelengths and lower frequency than solar radiation, resulting in a reduced likelihood of it escaping into the surrounding air through the greenhouse cover. As a result, heat builds up inside the greenhouse, leading to the warming of the slurry. Nevertheless, some of the thermal energy from the greenhouse manages to escape into the atmosphere through various channels. These include conduction across the cover, convection within the air and the cover, air circulation, and infiltration through openings in the greenhouse walls.

Regarding the second and third research questions, the average daily temperatures recorded for the ambient, greenhouse, and slurry throughout the retention period are 19.35°C, 36.0°C, and 31.49°C, respectively. The temperatures in the environment, greenhouse, and slurry varied within the

optimal ranges for growth. This shows that the system can raise the slurry temperature to the ideal mesophilic range, which is advantageous for anaerobic digestion. The greenhouse effect temperature inside the greenhouse compared to the slurry temperature during daylight hours. During the night, the temperature of the slurry is higher than that of the greenhouse because there is no solar radiation. The temperature inside the digester is influenced by the heat generated by bacterial activity and the slurry's higher heat capacity compared to the greenhouse air.

Heat is essential in digester technology to ensure a stable and efficient process. The heat dissipation observed in anaerobic digester tanks mainly occurs due to gas storage losses through infiltration and inadequate insulation, specifically convective and conductive losses. In addition, the digester's concrete slab, flooring, and walls do not effectively retain heat. Having shade and moisture from nearby structures and vegetation can effectively lower the temperature in the area surrounding the digester. Concerning the first and fourth research inquiries, the production of biogas reached its highest point of 1.2m³ on Day 23 but gradually declined to 0.05m³ by Day 39. The dynamic activity of anaerobic microorganisms caused these variations in response to temperature and pH variations. During Days 28 to 39, a significant decrease of 0.9 m³ was caused by the exhaustion of fresh substrate. Daily biogas production averaged around 0.47 m³.


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The biogas generated consisted of carbon dioxide (CO₂) and methane (CH₄). Aerobic bacteria initially generate carbon dioxide (CO₂) through the breakdown of carbohydrates. Subsequently, acidogenic bacteria contributed to the production of CH₄ and CO₂ by decomposing fatty acids. The CH₄ content reached a final concentration of 58%. The high methane content is likely a result of the initial chemical oxygen demand and the system's ability to regulate the pH levels carefully. In addition, the temperature fell within the mesophilic range, which is ideal for COD destruction.

6.3 Conclusion

During the retention period of anaerobic digestion, two distinct temperature ranges were observed in the daily slurry and greenhouse: psychrophilic in the evening and mesophilic during the day. The analysis of cow manure before anaerobic digestion confirmed sufficient biodegradable matter, as indicated by the percentages of total solids and volatile solids levels in the balloon digester. The study emphasized the significance of daily slurry temperature, pH, and chemical oxygen demand (COD) as predictors of biogas volume yield, with slurry temperature having the greatest impact. Over the hydraulic retention time of anaerobic digestion, a total biogas volume of 18.269m³ was produced, with methane and carbon dioxide comprising 58% and 41%, respectively. Multiple linear and non-linear regression models were developed to predict the daily slurry temperature and biogas yield using a selected set of input parameters in the solar-assisted balloon digester. These models demonstrated acceptable accuracy, as evidenced by determination coefficients, mean absolute errors, and p-values falling within acceptable ranges for both testing and validation datasets. The study aimed to understand the thermal behaviour of a small-scale anaerobic digester under psychrophilic and mesophilic conditions and its impact on biogas production. The research also aimed to explore how the utilization of a greenhouse could alleviate temperature variations, which are known to affect quality and biogas output. Additionally, the study sought to develop a multiple linear regression model to predict slurry temperature and a non-linear response surface model to predict biogas yield.

This study demonstrates that small-scale on-site biogas digesters offer a practical and environmentally sustainable solution for rural farmers and off-grid households to generate renewable energy from animal waste, particularly cattle. It addresses issues such as wastewater contamination, renewable energy generation, and global warming. The overarching objective of this research was to advance digestion technology by. Obtaining comprehensive insights into the performance of these systems across various conditions. Enhancing digestion efficiency by implementing temperature control methods using greenhouse enclosures. Developing mathematical models to understand better and predict the behaviour of these systems, optimizing

processes and systems by identifying optimal conditions or configurations that lead to desired outcomes, and being more cost-effective than conducting real-world experiments or trials.

The findings of this research can be utilized to offer rural households an economical biogas system that requires minimal upkeep and yields biogas containing approximately 58% methane. This system eliminates the need for collecting firewood, reducing reliance on fossil fuels and combating climate change. It also opens up economic opportunities by enabling the sale of digestate as fertilizer while simultaneously mitigating environmental degradation, fire risks, respiratory issues, and air pollution.

The positive coefficients for temperature in both models confirmed that increasing digester temperature proportionally enhances methane production, reinforcing the importance of maintaining optimal thermal conditions in biogas systems.

Key determinants identified included greenhouse temperature and slurry temperature, both of which were evaluated for their predictive relevance using the reliefF test. This analysis demonstrated their substantial influence on biogas yield, underscoring the necessity of effective thermal regulation in digesters. The study further demonstrated that the biogas yield for test samples was accurately predicted using both multiple linear and non-linear regression models. The linear regression model delivered reliable outputs, with an estimated coefficient of 0.985, a mean absolute error of 0.0239, and a p-value of 0.8825. Similarly, the multiple linear regression model for forecasting slurry temperature showed consistent and accurate results, achieving values of 0.986, 0.341, and 0.903 for the coefficient, mean absolute error, and p-value, respectively. These findings are significant in the broader context of biogas production and renewable energy. They not only validate the effectiveness of regression models in predicting biogas yield and slurry temperature but also highlight the critical role of temperature control in optimizing anaerobic digestion processes. By identifying key predictors and demonstrating the accuracy of the models, this research contributes to the development of more efficient and reliable biogas systems, particularly in low-resource or rural settings where energy demands are growing. The outcomes provide a foundation for integrating advanced monitoring and control mechanisms, such as solar-

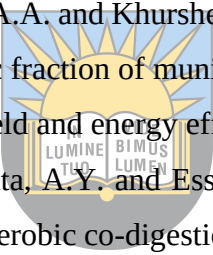
assisted heating or automated temperature regulation, further enhancing the sustainability and scalability of biogas production as a renewable energy solution.

6.4 Recommendations

Based on the findings, several recommendations have been outlined to enhance the performance and monitoring of small-scale anaerobic digesters. In the short term, it is recommended to address the limitation of insufficient temperature monitoring by incorporating at least ten temperature sensors equipped with data loggers within the digester. This will allow for a detailed understanding of heat flux and thermal phenomena, leading to potential performance improvements. Additionally, selecting an appropriate site for the biogas system is crucial; the site should lack shading and have an adequate water table to ensure optimal operational efficiency, as ambient temperature plays a critical role in system performance. Installing a biogas-specific meter with a data logger at the gas outlet is also essential for accurately correlating temperature fluctuations with biogas production, thereby improving monitoring precision.

In the long term, the evaluation of the digester should be expanded to include additional substrate types such as household waste, crop residues, and other forms of manure to assess the system's versatility and efficiency. Testing co-digestion with different feedstocks is also recommended to provide insights into biogas composition and yield optimization. Furthermore, transitioning from batch digestion to semi-continuous feeding would offer a more comprehensive understanding of the system's performance under practical, real-world conditions. Finally, conducting additional experiments to validate the accuracy of the proposed model is essential for ensuring reliability and guiding future research efforts. These recommendations aim to improve the technical and operational aspects of small-scale digesters, contributing to their long-term sustainability and effectiveness.

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