

## Article

# Performance Monitoring of Greenhouse Biogas Digester

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**Abstract:** The country of South Africa is facing an energy crisis due to heavy reliance on fossil fuels, resulting in continuous load shedding. The use of renewable energy technologies can help resolve the current electricity crisis in the country. Moreover, waste-to-energy conversion has the potential to greatly contribute to economic development and improve public health. One such technology is biomass, which exploits waste-to-energy conversion. Additionally, solar energy can be utilized to maintain appropriate digester temperatures for optimal biogas yield. The study aims to assemble a portable balloon biogas digester in an enclosed greenhouse cavity and feed it with cow dung. Daily monitoring of pH and temperature (ambient, greenhouse, and slurry) was conducted, while biogas yield was monitored using a serial residential diaphragm flow meter. Furthermore, the composition of methane was monitored using the SAZQ biogas analyzer. The study investigated the impact of temperature on biogas production. The results revealed that the gas production rate of biogas fermentation increased within a certain temperature range. Therefore, maximum biogas production was achieved at a pH of 6.84 to 7.03, and the composition of methane exceeded 50%. Consequently, the study concluded by indicating that the digester housed within a greenhouse envelope, as demonstrated in this novel study, maintains the temperature within the optimal mesophilic range necessary for anaerobic digestion.

**Keywords:** biogas digester (greenhouse); waste-to-energy; anaerobic digestion; biogas yield; mesophilic temperature



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## 1. Introduction

Energy is crucial for human life and economic development. However, traditional energy sources produce harmful pollutants that pose risks to both humans and the environment. As a result, there is a global focus on researching and producing alternative renewable clean energy. One such method is the anaerobic digestion of organic waste, which efficiently produces high-energy biogas and helps reduce greenhouse gas emissions. However, if the temperature required or needed for fermentation is too low or fluctuates rapidly, it can decrease the efficiency and methane content of the biogas [1]. Hence, anaerobic digestion is affected by low-temperature conditions. The primary products of this process are biogas, composed mainly of methane, 50–70%, and carbon dioxide, 30–50%, along with small traces of other compounds like hydrogen sulfide, water vapor, and ammonia. Additionally, the byproduct, known as digestate, is an excellent fertilizer [2].

The anaerobic digestion process occurs in an airtight vessel called a biogas digester in the absence of oxygen. Several factors affect biogas quality and yield, including feedstock type, environmental parameters (such as temperature), and operational physiochemical parameters like pH, TS, VS, chemical oxygen demand (COD), OLR, HRT, C/N ratio, and NH<sub>3</sub> levels [3]. The parameters of the design (construction material, digester type, and feeding mechanism) also have a significant impact [4]. Temperature, in particular, plays a crucial role in biogas yield, as demonstrated by kinetic models for biogas production. Moreover, the metabolic activities within the microbial community, which involved methanogenesis, greatly affect the overall stability of the community [5]. Many bio-digesters have been

modified to enhance process stability and efficiency and reduce temperature fluctuations. The optimal temperature ranges for the anaerobic digestion process are as follows: psychrophilic (below 20 °C), mesophilic (20 to 40 °C, with an ideal temperature of 34–37 °C for small-scale digesters), and thermophilic (40 to 60 °C, with an optimal temperature of 55 °C).

During the winter or in cold regions, biogas production is low due to the inactivity of methanogenic bacteria at low temperatures. For biogas fermentation, it is therefore essential to put in place affordable heat preservation and warming techniques. The temperature at which anaerobic digestion occurs affects methanogenesis and can lead to increased operational costs. Maintaining a stable temperature throughout the process requires additional energy. Therefore, providing heating for the bio-digester is crucial, as higher temperatures improve microbial growth, digestion efficiency, and gas yield. [6]

Low temperatures have been linked to low biogas output and uncertain operational performance in anaerobic digestion systems, according to research on microbial enrichment conducted by Aryal et al. [4]. The regulation of microbial intracellular enzyme activity is largely dependent on temperature, and this, in turn, influences the metabolic activity of bacteria and the effectiveness of anaerobic fermentation. Anaerobic digestion system performance is also affected by modifications in microbial metabolism or community dynamics [7]. Mesophilic conditions, ranging from 30 to 40 degrees Celsius, are typically employed for the anaerobic digestion of agricultural organic waste, resulting in high-quality biogas generation [8]. Interestingly, biogas can be heated directly using steam or hot water or indirectly using a heat exchanger and a heating medium that is usually already hot. With the latter approach, heat is produced without blending with the slurry, whereas the slurry can be heated on the floor, in the vessel, on the vessel, and ex vessel to accomplish indirect heating [6].

A numerical investigation conducted by Ashin et al. [9] demonstrated that the floor heating method results in an approximate increase in slurry temperature of 5 °C, the on-vessel method by 5–6 °C, and the in-vessel method by 6–7 °C. Among these methods, the in-vessel method exhibited superior performance due to its ability to distribute heat more uniformly throughout the slurry.

While other heating methods rely on fuel burning and do not convert thermal energy enough, electric heating methods consume electrical energy, which raises economic costs. Using renewable energy sources has negative environmental effects since combustion adds to air pollution [1]. The effects of using plastic as an insulating medium for a methane digester in a solar greenhouse close to Nilgiris, India, were investigated in a study by Kumar et al. [10]. The results showed that the experimental biogas digester's internal temperature and gas output increased to 22.4 °C and 34.6 kg/d, respectively, in comparison to a regular biogas digester. Furthermore, the experimental digester's average annual temperature was observed at 26.3 °C, resulting in the production of gas (39.1 kg/d).

Most direct and indirect heating methods are not economical for rural users and for a small-scale bio-digester. One approach to address the issue of low temperatures in small-scale biogas production is the utilization of a passive solar greenhouse for the comprehensive heating of the digester. Solar thermal energy can guarantee steady biogas production all year round by harnessing ample solar energy and integrating it with the anaerobic digestion process facilitated by the greenhouse effect. The greenhouse construction is straightforward and boasts a cost-effective design, operation, and maintenance [11], making it particularly suitable for rural users. The temperature of the anaerobic reactor using the novel solar greenhouse was 6–8% higher than that of the conventional anaerobic reactor according to the results of [1]. Temperature growth and stability in the solar greenhouse can increase biogas output and guarantee stable gas production. Digging a ring trench and covering the digester are now the main methods used in South Africa to preserve the heat from a biogas digester [11]. The surface of the biogas digester is complete with firewood, materials for preserving heat, a solar greenhouse, and the entire methane fermentation system buried underneath. Another useful insulation tool is the solar green-

house. Regretfully, the majority of small-scale digesters built in underdeveloped nations, such as South Africa, lack a heating system or any other means of preserving a constant temperature inside the digester. As a result, the stability and efficiency of biogas production from these digesters fluctuate with daily temperature changes, decreasing significantly at night and on cold days. The fixed dome, floating, and balloon digesters have undergone various modifications to minimize temperature fluctuations and maintain them within the optimal range anaerobic microorganisms require. The objective of this study is to examine the thermal efficiency of a balloon digester housed in a polyvinyl chloride (PVC) plastic greenhouse, investigate its influence on slurry temperature and biogas output within the Eastern Cape province of South African weather, and offer recommendations to designers for bettering the system (biogas digester).

## 2. Materials and Methods

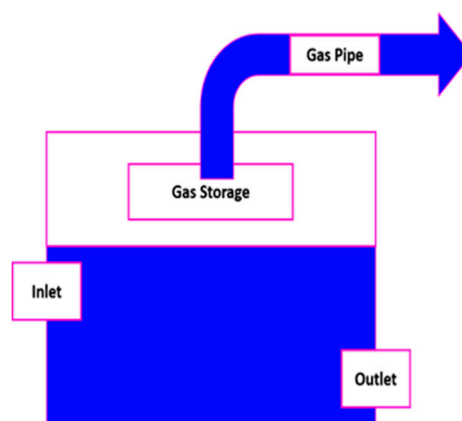
The experimental setup and reactor design comprised the study methodology. Sensors and data loggers were used in experimental procedures to collect the quantitative data. In this work, cow feces were anaerobically digested using a balloon digester housed inside a greenhouse cavity.

### 2.1. Reactor Design

The balloon biogas digester, also known as the reactor, is composed of three main parts: the slurry digester chamber, the inlet, and the outlet chamber. These components are depicted in Figure 1. The enclosure effectively protects the digester from extreme temperature conditions, allowing it to perform optimally. The balloon digester itself is constructed using PVC tarpaulin material, ensuring durability. The dimensions are as follows: height (195 cm), length (156 cm), and width (120 cm). It consists of two sections: the gas storage area with the volume of  $1.3 \text{ m}^3$  and the fermentation chamber with a volume of  $1.7 \text{ m}^3$ , with the volume of the frame of the greenhouse envelope being  $3.4 \text{ m}^3$ . Additionally, the greenhouse enclosure is made from PVC material. Figure 1a,b represent the fabricated biogas digester and its schematic representation respectively.



(a)



(b)

**Figure 1.** (a) diagram of the fabricated biogas digester. (b) Schematic representation of the fabricated biogas digester.

### 2.2. Experimental Design

A continuous mono-digestion feeding technique was employed in the study. From the dairy farm of the University of Fort Hare, cow dung was collected. The substrate was improved by adding fresh dairy cow manure, which naturally contains anaerobic microbes that generate methane. After a few days of feeding, this substrate generated biogas similar to the study conducted by Obileke et al. [12]. Using an AL450 Aqualytic photometer and

a mass balance, the substrate was examined for total solids (TS), volatile solids (VS), pH, ammonia-nitrogen (NH<sub>4</sub>-N), and calorific value (CV) prior to being placed in the digester. The photometer employed several pre-programmed techniques based on tube tests, liquid reagents, and the tried-and-true Aqualytic<sup>®</sup> tablet reagent line.

### 2.3. Physiochemical Properties of the Cow Dung

#### 2.3.1. Calculation of Total Solids (TS)

TS are the content of solids available in the feedstock after the removal of water in the feedstock. The feedstock was freshly collected from the farm, and thirty grams were put in a known mass dish and weighed by a mass balance before being placed in an oven at 105 °C for 24 h, then later removed and placed in the desiccator to cool at room temperature. It was then weighed again. The total solids were calculated using the standard equation from the APHA [13] method given by Equation (1).

$$(TS \text{ mg/L}) = \frac{A - B}{\text{sample vol}} \times 1000 \quad (1)$$

where  $A$  is the weight dried sample of the feedstock + dish in mg and  $B$  is the weight of the dish.

#### 2.3.2. Calculation of Volatile Solids (VS)

VS represent the organic components within a substrate that are capable of being transformed into gas through anaerobic digestion. The residue from determining the total solids is obtained and placed in a crucible plate and heated to 550 °C for 2 h in the muffle furnace to determine the volatile solids. The sample's residual was weighed, representing the content of the VS, and was calculated using Equation (2), as per the standard APHA method 2023 [13].

$$(VS \text{ mg/L}) = \frac{C - D}{\text{sample vol}} \times 1000 \quad (2)$$

#### 2.3.3. Determination of pH

The determination of pH of the feedstock and of the substrate was performed using a pH meter. Before the feedstock was sent to the digester, a sample was taken, and the electrode of the pH was dipped into the sample and left until a steady reading was displayed on the screen; then, it was recorded. During the retention period, the electrode was completely buried in the slurry, and all changes in pH were recorded and stored by pH meter.

#### 2.3.4. Calculation of Chemical Oxygen Demand (COD)

COD was determined with the help of the Aqualytic AL450 photometry. A Vario test tube with dichromate was mixed with 2 mL of cow manure. The test tube was tightly closed, and its content was mixed by inverting it. The tube was then placed in an oven at 150 °C for 120 min; then, the tube was removed from the oven and left to cool at room temperature. The content of the tube was once again mixed by gently inverting the tube several times while still warm before placing it on the vial chamber, and the COD was displayed on the screen of the photometer.

#### 2.3.5. Determination of Temperature

Four thermocouple temperature sensors were installed in the system to determine the temperature profile for the system. Two were positioned inside the slurry at the opposite end to measure the slurry temperature, one at the inside top of the greenhouse enclosure to measure the temperature inside, and the last outside the greenhouse enclosure to measure the ambient temperature. All four of these temperature sensors were connected to a data logger, which took the reading every 5 min.

### 2.3.6. Calculation of Ammonia-Nitrogen

Ammonia-nitrogen tablet reagents and Aqualytic AL450 photometry were used to determine ammonia-nitrogen. Two ammonia tablets were used with a 0–300 mg/L N range. A tube was filled with a feedstock sample, and the ammonia no. 1 tablet was added to the sample straight from the foil and crushed by a stirring rod, followed by the second ammonia tablet, no. 2, which was taken out from the foil to the sample and crushed by the stirring rod. The tube was then tightly closed and then swirled so that the tablets could be completely dissolved. The tube was placed in a chamber in the photometer, and we pressed the test button and waited 10 min before the reading was displayed.

### 2.3.7. Determination of the Calorific Value

The bomb calorimeter was used to calculate the substrate's thermal energy. Within the stainless-steel bomb calorimeter, a 10 g substrate was filled to a maximum pressure of 300 atm. The oxygen-rich environment allowed the firing wire to glow and ignite the sample when it was pressurised, releasing energy that is measured as temperature. Once the temperature of the bomb vessel stabilized, the firing wire was heated, ignited the sample, and burned the attached firing cotton thread. After ten minutes, the calorific value was shown once the temperature was ascertained using the calorimeter's extremely sensitive temperature sensors. The digester was filled with the slurry to initiate anaerobic digestion in a mesophilic environment. Numerous metrics, such as the digester's internal temperature, pH level, rate of biogas production, and composition, were continuously measured during the whole anaerobic digestion process. A PS-2125 temperature sensor, a PS-2000 Xplorer serial residential diaphragm biogas flow meter, and a SAZQ biogas analyzer were among the specialized instruments used to carry out this monitoring. In addition, data on the composition of hydrogen sulfide ( $\text{H}_2\text{S}$ ), carbon dioxide ( $\text{CO}_2$ ), and methane ( $\text{CH}_4$ ) in the biogas, as well as the biogas yield, was logged using a data logger.

Table 1 illustrates the properties of the cow dung fed into the digester for digestion and performance evaluation.

**Table 1.** Properties of cow dung.

| Parameters                                        | Values     |
|---------------------------------------------------|------------|
| Calorific value (MJ/g)                            | 25.86      |
| pH                                                | 7.86       |
| Average Slurry Temperature ( $^{\circ}\text{C}$ ) | 31.49      |
| Total solids (mg/L)                               | 167,306.93 |
| Chemical oxygen demand (mg/L)                     | 39,792     |
| Volatile solids (mg/L)                            | 125,178.78 |
| Voaltile solids/total solids (%)                  | 74.82      |

## 3. Results and Discussions

### 3.1. Ambient Temperature Variation

Temperature plays a crucial role in biogas production, with acidifying bacteria performing best in specific temperature ranges: mesophilic ( $32^{\circ}\text{C}$  to  $42^{\circ}\text{C}$ ) and thermophilic ( $48^{\circ}\text{C}$  to  $55^{\circ}\text{C}$ ). Thermophilic conditions yield more biogas, while mesophilic conditions are better for energy production. Anaerobic digestion slows significantly at temperatures as low as  $10^{\circ}\text{C}$ . These temperature variations influence the metabolic processes of microbial groups involved in biogas production.

In spring, moderate temperatures, increased sunlight, and fluctuating humidity affect biogas production. While moderate temperatures are favorable for mesophilic digesters, sudden fluctuations can disrupt microbial activity and reduce efficiency. The longer day-light in spring combined with solar-heated biogas systems can stabilize digester tempera-

tures, improving overall biogas yield. During October and November, which fall in the spring season, ambient temperatures ranged from 10.58 °C to 25.33 °C, with an average of 19.42 °C.

Figure 2 depicts the fluctuation of ambient temperatures below 25 °C in Alice, with a drop into psychrophilic conditions during spring. These temperature changes, resulting from different weather conditions, had an impact on the anaerobic digestion process, as they consistently remained below the optimal range. To address this issue, a greenhouse enclosure was employed to regulate temperatures. This enclosure effectively stabilized the anaerobic digestion process by mitigating the negative effects of seasonal temperature fluctuations.

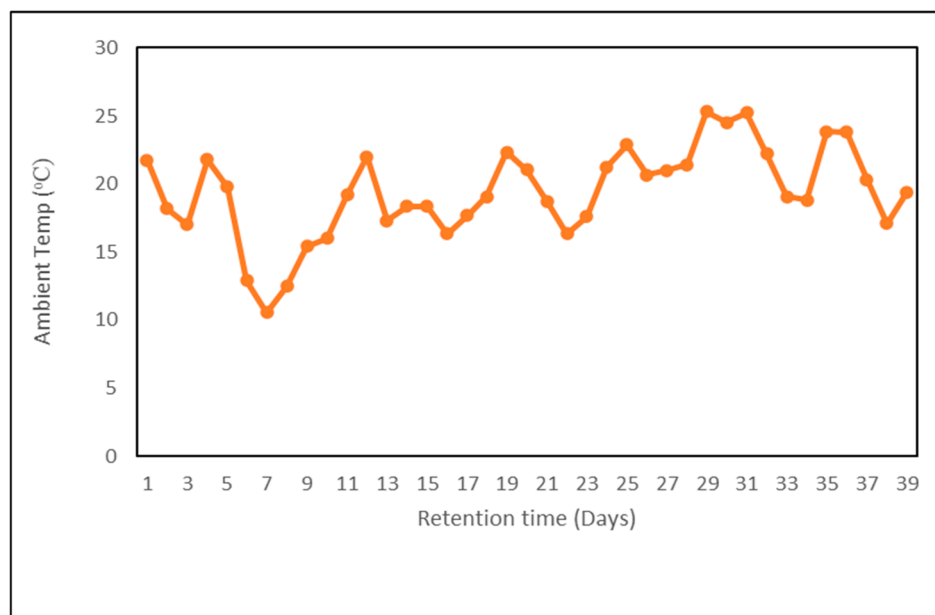


**Figure 2.** The ambient temperature variation throughout the retention period.

### 3.2. Temperature

Temperature plays a vital role in biogas production, as it substantially impacts the efficiency and stability of the anaerobic digestion process. The optimization of temperature conditions are typically within the mesophilic range (approximately 35–40 °C) and thermophilic range (approximately 50–55 °C). In Hu and Shan's [14] study, the enhancement of microbial activity increases methane yield. Therefore, it is imperative to maintain a stable temperature. According to Sudiartha et al. [15], the overall stability of temperature helps to maximize biogas production.

Figure 3 illustrates temperature variations in the greenhouse envelope (Gr), slurry (Sl), and ambient air (Am) during the retention period from 23 October to 30 November 2023. The slurry temperature remained within the mesophilic range, demonstrating the greenhouse's capability to elevate and stabilize the slurry temperature above that of the surrounding air. The average temperatures for the ambient, greenhouse, and slurry were 19.35 °C, 36.0 °C, and 31.49 °C, respectively, all falling within the mesophilic range, which is ideal for anaerobic digestion.

During the day, the greenhouse effect raised the temperature inside the greenhouse above that of the slurry, while at night, the slurry retained more heat than the surrounding greenhouse air due to exothermic bacterial activity and its higher heat capacity. However, declines in nighttime greenhouse temperature were attributed to heat losses from infiltration, inadequate insulation, and ineffective heat retention by the concrete slab. The system's ability to maintain the slurry within the mesophilic range demonstrates its effectiveness in supporting anaerobic digestion.

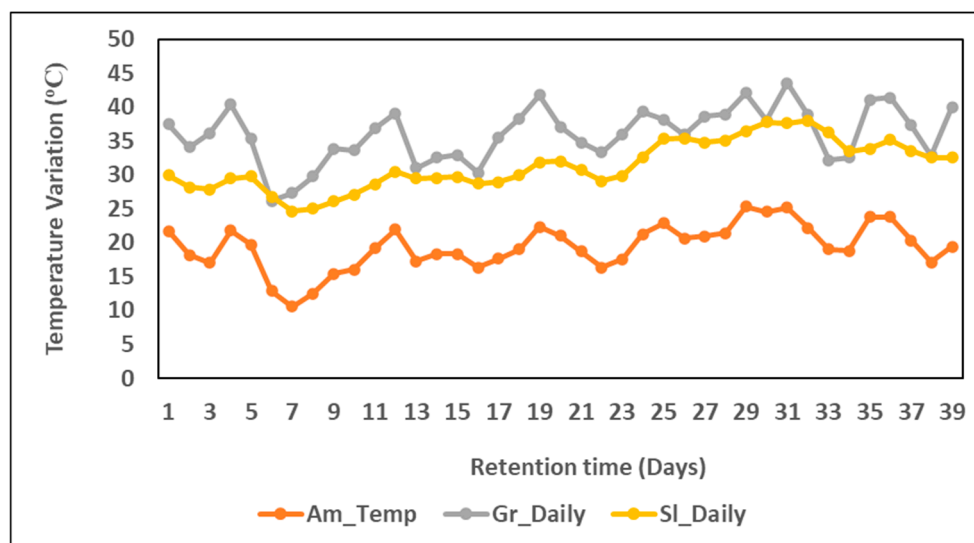


**Figure 3.** Temperature variation of ambient, greenhouse, and slurry temperatures.

Because of the greenhouse effect and insulation against heat loss, the temperature within the greenhouse cavity was continuously higher than the outside temperature ( $T_a > T_{amb}$ ). The slurry temperature is higher than the surrounding air temperature according to a study by Muntugwazi et al. [11]. This is because of the greenhouse effect and bacterial activity, which promotes exothermic reactions in the digesting chamber. In the absence of solar radiation during the night and early morning, the slurry temperature was greater than the temperature of the greenhouse cavity ( $T_s > T_a$ ). The slurry may hold heat longer than the air in the greenhouse because of its larger heat capacity. These outcomes are consistent with the research by Shao et al. [1], which also demonstrated that solar-assisted biogas raises the slurry temperature by more than 6 °C.

### 3.3. Biogas Composition

Biogas composition is key in determining its energy content, quality, and suitability for various applications. Methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ) make up the majority of biogas, with trace amounts of other gases, including water vapor ( $\text{H}_2\text{O}$ ), hydrogen sulfide ( $\text{H}_2\text{S}$ ), and ammonia ( $\text{NH}_3$ ), also present. Biogas is quite combustible since it usually contains between 55% and 80% methane gas in its composition. A greater calorific value of more than 20  $\text{MJ}/\text{m}^3$  is directly correlated with higher concentrations of methane [16,17], which improves biogas's efficiency as a fuel source. The change in the production of  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ , and other gases is depicted in Figure 4.

Based on Figure 4, it is evident that the anaerobic process commenced on day 5. However, the initial methane yield was relatively low for the first 7 days. This can be attributed to the lag phase, as methanogenesis is the last stage of the process, resulting in low microbial growth, particularly among methane-producing microorganisms, at the beginning of the anaerobic cycle. In contrast, between day 5 and day 15, the production of carbon dioxide ( $\text{CO}_2$ ) gas surpassed that of methane ( $\text{CH}_4$ ) gas.

The presence of oxygen during the anaerobic process's early phases and the actions of acid-producing bacteria, which change fatty acids, amino acids, and simple sugars into acetic acid, hydrogen, and carbon dioxide, are responsible for the increased carbon dioxide yield [18]. As seen in Figure 4, carbon dioxide and methane production on day 5 signify the beginning of the sequential acetogenesis, methanogenesis, and hydrolysis processes, albeit with reduced activity among the methane formers. As noted by Obileke et al. [12], the generation of methane gas on day five further supports the idea that the three phases of anaerobic digestion took place simultaneously inside the biogas digester.

On day sixteen, the two gases—methane and carbon dioxide—reached equilibrium. The methane yield increased significantly from day 17 to day 25. This increase can be

explained by the presence of methanogens and easily biodegradable organic materials in cow manure [19]. Furthermore, a high methane output signifies the full activity of the methane formers and the approaching optimum stage of anaerobic digestion for the methanogens [20]. The system ultimately produced 10.585 m<sup>3</sup> of methane (57.94%) and 7.526 m<sup>3</sup> of carbon dioxide (41.2%), showing that methanogenesis had reached its optimal stage, aided by the high biodegradable organic content in cow dung.

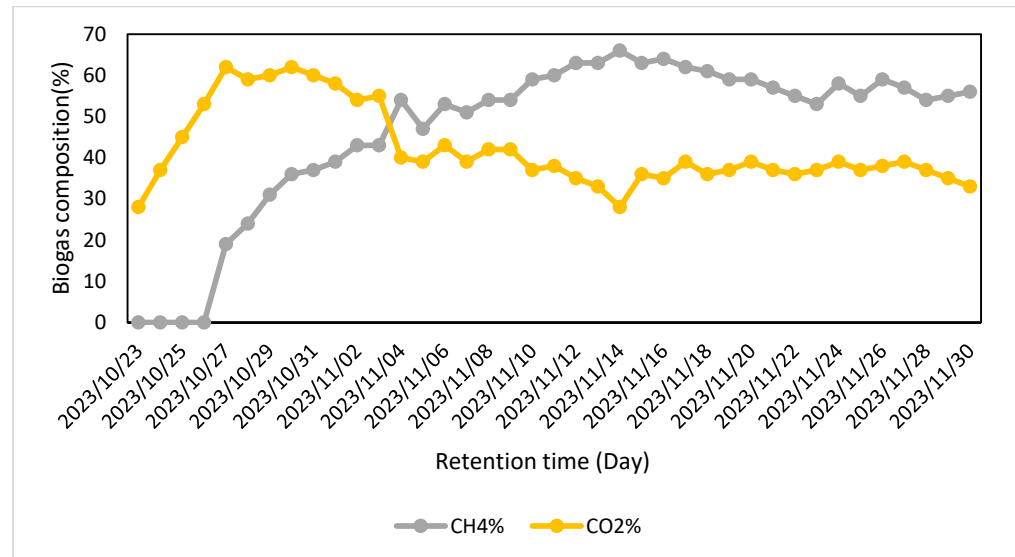


**Figure 4.** Changes in the amounts of CH<sub>4</sub> and CO<sub>2</sub> gases produced.

### 3.4. Variation of pH

The pH is a crucial factor in biogas production because it directly affects microbial activity, which is essential for anaerobic digestion. Different groups of microbes thrive within specific pH ranges, so it is important to maintain the optimal pH level to ensure efficient digestion and maximize biogas output. Figure 5 demonstrates the pH changes in the slurry over the retention period, emphasizing its significance in sustaining effective biogas production.

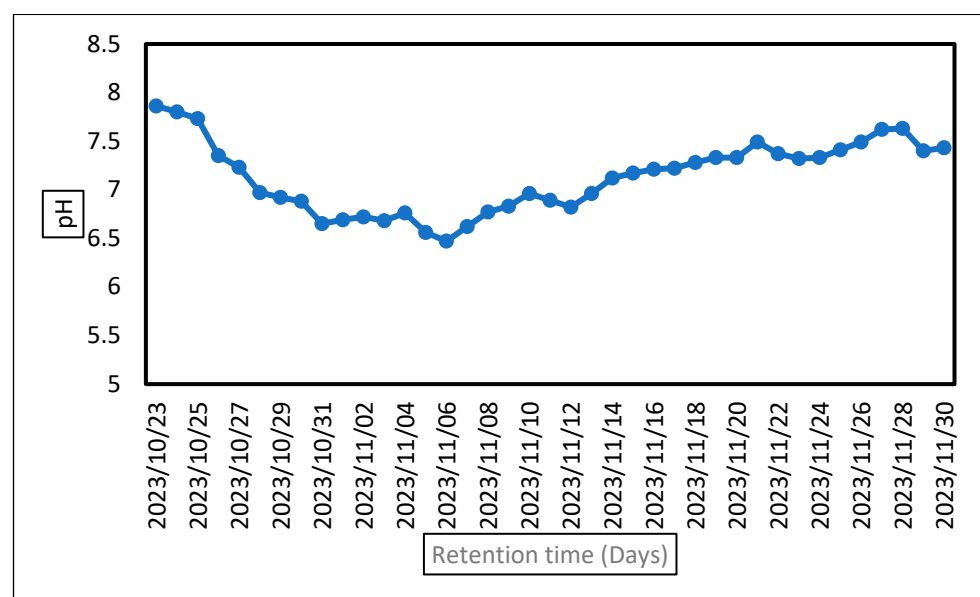


**Figure 5.** The pH variation of the system.

The initial pH of the slurry was 7.86, which was not ideal for the hydrolysis stage and likely caused a delay in microbial activity. However, over the first nine days, the pH dropped to 6.65, indicating the presence of hydrolytic and acidogenic microorganisms that thrive in acidic conditions. The pH continued to fluctuate until day 15, reaching 6.47, which highlighted the simultaneous breakdown and fermentation of complex molecules during the overlap of hydrolysis and acidogenesis.

Starting from day 18, 8 November, the pH gradually increased, reaching 6.83, which signaled the beginning of the acetogenesis stage. This stage involves the conversion of volatile fatty acids into acetate and hydrogen. By day 14, 4 November, the pH had risen to 7.12, falling within the optimal range for methanogenesis. The pH then continued to increase until the end of the retention period, indicating a favorable environment for methane production.

### 3.5. Correlation Between Biogas and pH

An important factor in the anaerobic digestion process that affects the total amount of biogas produced is the pH level. The pH should be kept between 6.8 and 7.2 to maximize microbial activity, particularly that of methanogens, which are critical for producing methane, as reported by Lima et al. [21]. The correlation between the pH during the retention period and the biogas yield is depicted in Figure 6.

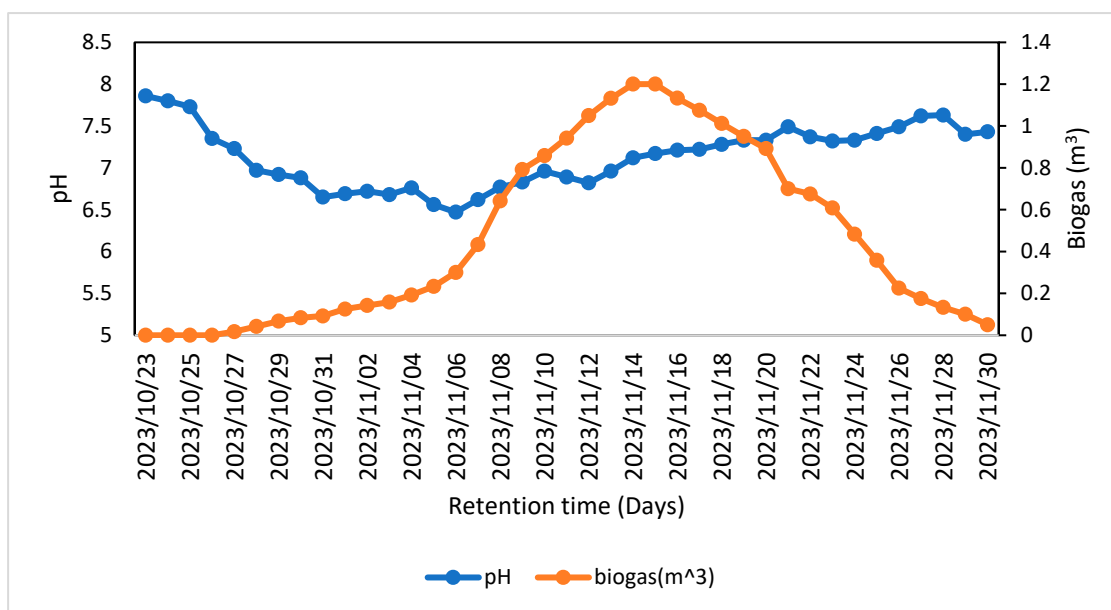


**Figure 6.** The biogas yield and pH for the retention period.

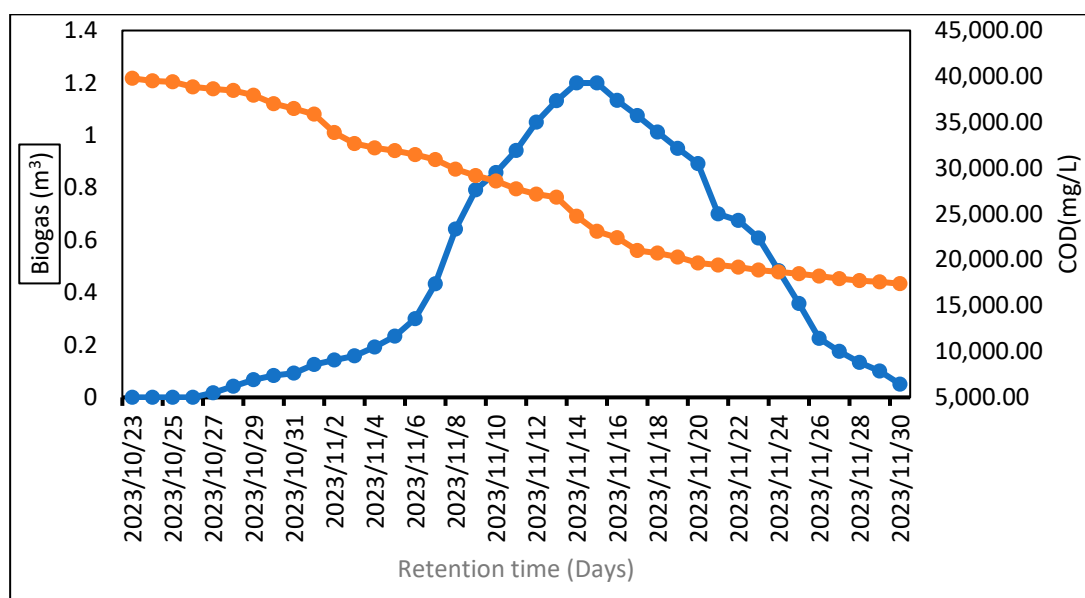
The biogas output and pH fluctuation over a 39-day retention period are shown cumulatively in Figure 6. Because there was not enough inoculum to start the anaerobic process on day 5, the graph clearly shows that 18,269 m<sup>3</sup> of biogas was produced overall during the anaerobic digestion of dairy cow feces. The slurry's high concentration of biodegradable organic matter and ideal pH range are responsible for the steady rise in biogas generation observed between days 5 and 19. On the other hand, as the pH rose over 7.5 in the last seven days of the retention period, the biogas yield decreased, which is in line with the results of [22]. Table 2 presents the composition of biogas from the biogas digester.

**Table 2.** CH<sub>4</sub>, CO<sub>2</sub>, and H<sub>2</sub>O and other gas composition in biogas.

| Biogas Composition Under Investigation   | Composition (%) |
|------------------------------------------|-----------------|
| Methane (CH <sub>4</sub> )               | 55–60           |
| Carbon dioxide (CO <sub>2</sub> )        | 30–40           |
| Water (H <sub>2</sub> O) and other gases | 0–10            |

### 3.6. COD Destruction Variation with Biogas Production

The initial concentration of the chemical oxygen demand (COD) was 39,792 mg/L, which shows that the cow dung introduced into the digester had a high organic content and degradability. Figure 7 clearly shows the connection between the reduction in the COD and the increase in biogas production over the retention period. This indicates that as biogas generation increased, the organic matter was progressively degraded. The initial chemical oxygen demand (COD) concentration was 39,792 mg/L, reflecting the high organic content and degradability of the cow dung introduced into the digester. Figure 7 illustrates the relationship between COD reduction and biogas production throughout the retention period, demonstrating the progressive degradation of organic matter as biogas generation increases.

**Figure 7.** Relationship between COD destruction rate and biogas production.

Biogas production was initially slow during the first seven days, possibly because the pH declined due to fluctuations in COD destruction by acid-forming bacteria. This may be attributed to the simultaneous occurrence of acidogenesis and methanogenesis. Significant declines in COD destruction were observed between November 1st and 4th as well as November 13th and 21st, which coincided with increased biogas production. The highest biogas yields were recorded on 14 November and 15 November 2023. By the end of the retention period, the COD decreased to 17,387 mg/L, resulting in a total COD destruction rate of 56.31%.

## 4. Recommendation and Further Study

The methane yield and digestion efficiency are increased when biogas is produced by anaerobic digestion in a greenhouse biogas digester. Employing a greenhouse biogas digester significantly lessens the main issue of insufficient temperature control, which results in low methane production. With a methane yield from dairy cow dung of 55–60%,

the greenhouse biogas digester becomes a more attractive option because it is portable, is relatively easy to install in any location (rural, urban, multi-story, and rocky terrains), and can operate at a higher optimum temperature of 35 °C because of the heating effect of the green technology. This methane yield is comparable to the 50% found in the literature for other digester designs, such as the fixed dome with sawdust insulation. It also has the advantage of being inexpensive to build and having locally sourced parts. An attractive remedy for the issue of insufficient temperature control in small digester operations is the installation of a greenhouse. Solar radiation is transmitted through the greenhouse cover within a greenhouse structure, including a digester. A portion of this radiation is absorbed by the digester and delivered into the substrate slurry as thermal energy, increasing the temperature of the slurry. The remainder is released back into the greenhouse as heat radiation. Since thermal radiation has a longer wavelength and a lower frequency than solar radiation, the greenhouse cover is unable to reflect it into space. As a result, the greenhouse's thermal energy increases.

## 5. Conclusions

To determine how much it would cost to heat a greenhouse biogas digester with solar energy as opposed to more traditional options like electrical heating, a feasibility study should be carried out. This analysis should be conducted at the suggested scale to evaluate the greenhouse biogas digester's applicability and cost-effectiveness. Dairy cow manure from the University of Fort Hare dairy farm was used to assess the digester's performance. It is advised, therefore, to evaluate the greenhouse biogas digester's efficacy through the digestion of various substrate types, including co-digestion, pig dung, vegetable and household wastes, and kitchen wastes. Additionally, semi-continuous digester feeding and the use of various inoculum types during digester startup should be used to assess the digester's performance further. This is significant because the batch digestion mode was the only experimental strategy used in this study. Moreover, the development of a mathematical model for this digester design is recommended. The ideal biogas production characteristics under different feeding and operational situations can be found using this model.

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