Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 8, No. 6, 3872-3885
2024
Publisher: Learning Gate
DOI: 10.55214/25768484.v8i6.2843

Temperature effect of biogas production from a greenhouse biogas digester

Sikho Maxhayi[1], Patrick Mukumba[2], KeChrist Obileke[3]*, Mandilakhe Mzobotshe[4], Ndanduleni Lethole[5]
[1,2,3,4,5]Renewable Energy Research Group, Department of Physics, University of Fort Hare, Alice, South Africa; 201927259@ufh.ac.za (S.M.) KObileke@ufh.ac.za (K.O.).

Abstract: Globally, energy challenges are increasing with population growth. Many countries solely depend on fossil fuels (oil, coal, natural gas, etc.) for energy generation for different processes. Fossil fuels fall under non-renewable energy sources, are polluters of the environment, and get depleted faster, thus making it challenging to sustain a continuous energy supply. Therefore, there is a need for alternative sources of energy to mitigate the hazards associated with the utilization of fossil fuels. The present study aims to monitor the performance of a three-meter cubic (3 m3) greenhouse biogas digester, focusing on the temperature effect in biodegrading cow dung materials for gas generation. The study was conducted under mesophilic temperature conditions, pH, and hydraulic retention time for 30 days. Results revealed that slurry temperatures of about 33.5 ℃ and ambient temperatures of about 35 ℃ resulted in a remarkable peak biogas yield of 0.3 m3 on the 23rd day of the month. After the optimum yield of the biogas, the performance declined and was ascribed to the non-supply of the new feedstock, and the environment in the reactor became acidic, hence hindering the biodegradation process. Ultimately, the total biogas yield obtained from the study was 2.58 m3, equivalent to 15.48 kWh of energy. This amount of bio-generated energy was twofold the average daily electricity consumption of middle-income South African households. It was demonstrated that temperature was a major factor influencing the performance of the assembled biogas digesters and, thus, should be closely monitored for appreciable biogas production. This study is envisaged to pave the way for the future affordable and environmentally friendly biogas production process.

Keywords: *Anaerobic digestion, Cow dung, Mesophilic condition, Methane, Plastics.*

1. Introduction

Recently, energy challenges have increased with increasing population growth. Many countries solely depend on fossil fuels for electricity generation. Fossil fuels fall under non-renewables, which are all polluters of the environment, deplete faster, and are challenging to sustain continuous power generation from them [1]. Hence, decades ago, renewable energy was introduced to mitigate energy demands, control and reduce environmental pollution, and create economic opportunities [2]. Studies conducted by researchers depict that renewables are environmentally friendly, while non-renewables add to the degradation of the environment. Moreover, the desire to reduce global warming has necessitated the adoption of clean energies such as wind, hydropower, solar, biomass, etc. The latter energy has become one of the potential sustainable renewable sources globally to meet the population's energy demands. However, more studies are still required to uncover their fullest potential as the main energy sources [3].

Anaerobic digestion technology has made it possible to utilize biomass to generate energy, which can be used for cooking and lighting. Biogas, produced through the anaerobic digestion of specific biomass types, particularly organic waste, can substitute traditional energy sources, such as firewood, in rural areas. Moreover, biogas technology provides the dual benefits of conserving resources and protecting the environment [4, 5]. Biogas is formed from the breakdown of organic wastes (plant material, animal waste, human waste, and various organic waste) during anaerobic digestion without

* Correspondence: KObileke@ufh.ac.za

oxygen [6]. However, animal waste is commonly used, with a calorific value of 21-24 MJm^{-3} ($6kWm^{-3}$) [7]. Nevertheless, the yield and composition of biogas are influenced by various factors. These include the type of substrate, operational parameters (such as temperature, pH, hydraulic retention time, carbon-to-nitrogen ratio, and organic loading rate), and design parameters (including the construction materials, type of biogas digester, and feeding mechanisms employed) [3].

It is evident from the studies carried out by Ma et al.[8] and Pham et al.[9], among the above-mentioned parameters, that temperature has the most significant impact on biogas production, as demonstrated by their kinetic models. Additionally, according to Rong et al.[10], there are several temperature conditions at which anaerobic digestion takes place; these conditions are psychrophilic at 20℃ below, mesophilic from 25 to 40℃, and thermophilic from 45 to 60℃. Previous studies have shown that anaerobic digestion of organic waste mesophilic conditions (30-40℃) results in effective biogas production [11]. Failing to keep the temperature within the mesophilic range will hinder the growth of methanogens, lengthen the start-up period, and decrease biogas production [12]. Gabhallah et al. [13] emphasizes that temperature fluctuations associated with anaerobic digestion should not surpass (2-3℃) per period. However, maintaining this temperature is hard under natural circumstances. As a result, various heating/warming techniques such as pool heating method, electric heating method, biomass boiler heating, biogas generator waste heat technology, active solar energy heating, hybrid solar heating technology, "pigs a bog a kang" warming method, ground source heat pump (GSHP) heating technology, combined warming technology, solar greenhouse warming technology, etc. are employed to sustain and boost the effectiveness of anaerobic digestion especially in cold climates.

However, the electric heating method's economic cost is higher and consumes electric energy. The "Pigs a bog a kang" warming technology, biomass boiler heating method, pool heating method, and coal boiler heating method have very low thermal energy conversion and fuel combustion causes air pollution. The biogas generator waste heat technology utilizes the thermal energy produced by the biogas engine's cooling system and the exhaust heat to elevate the temperature within the biogas digester. This process can potentially enhance the biogas production rate by approximately fourfold. However, this technology is not universally applicable [14]. Furthermore, there are three main types of biogas digesters: the fixed dome, floating drum (cover), and balloon or tube digesters [15]. However, these designs are hindered by some limitations. Biogas digesters constructed with bricks, types of cement, and sand are subjected to leakages and cracking and are costly, requiring professional, skilled personnel [16]. Metallic biogas digesters are prone to corrosion and have a short life span, while biogas digesters made of plastic are susceptible to physical damage due to exposure and have insufficient low pressure to run the biogas stove for a sustained period to carry out cooking activities. One limitation that hinders all the aforementioned types of digesters is temperature fluctuations. As a result, an alternative biogas digester design is necessary to overcome and minimize these limitations, especially temperature parameters.

Hence, this work aims to assess the performance of the biogas digester system, utilizing a greenhouse for temperature-regulated heating for biogas generation. The greenhouse-based biogas digester tends to provide solutions to previous designs in terms of the ability to trap heat closer to the earth's surface and control the temperature around the surroundings of a biogas digester. The results of this work are anticipated to shed more light on the design of low-cost and environmentally friendly digesters for clean energy production and, thus, commercialization.

2. Various Temperature Considerations Around the Biogas Digester

The various heat transfers of temperature (conduction, convection, and radiation) directly and indirectly affect the performance of the biogas digester. That is to say that the pivotal point of this research study lies in the thermodynamic influence of temperature, delineating its effects. Emphasis is directed toward analyzing the biogas digester's internal and external heat transfer phenomena. Notably, the digester undergoes heat transfer at a rate denoted by Q (J/s or W), alongside the internal heat generation within the slurry contained therein due to the greenhouse and the environment. The alteration in internal energy within the digester can be expressed as follows:

ISSN: 2576-8484
Vol. 8, No. 6: 3872-3885, 2024
DOI: 10.55214/25768484.v8i6.2843

$$\Delta U = Q\Delta t + Q_v \Delta t \quad (1)$$

where ΔU is the change in internal energy within the digester, $Q\Delta t$is the heat transferred into the digester, $Q_v\Delta t$ = is the heat generated within the digester. Dividing by $\Delta t,$ the equation (1) becomes:

$$\frac{dU}{dt} = Q + Q_v \quad (2)$$

The heat transfer rate is necessary since temperature is an essential parameter for biogas digester operation.

2.1. Heat Transfer Equation

The heat transfer across the biogas digester chamber can be expressed as:

$$Q = UA\Delta T \quad (3)$$

where Q is the heat transfer per unit time (J S^{-1}), A is the surface area of the bio-digester (m^3), U is the overall coefficient of heat transfer (W m^{-2} K^{-1}), ΔT is the difference in temperature between the inside and outside of the biogas digester (K) [17].

2.1.1. Heat transfer by conduction

This is the heat transfer due to the activities of the slurry particle through the wall of the biogas digester and the ambient or environment. This depends on the material's geometry, the plastic's thickness, the type of plastic used, and the temperature difference. This can be calculated using the equation,

$$\text{Rate of heat transfer (Q)} = \frac{(Area)(Temperature\ differences)}{Thickness} \quad (4)$$

$$Q = kA\frac{(T_1 - T_2)}{\Delta x}$$

where Q is the heat transfer rate, K is the plastic material's thermal conductivity, T_1 and T_2 are the slurries and ambient temperatures, respectively, and A is the cross-sectional area of the bio-digester, and Δx is the thickness of the wall [18].

2.1.2. Heat Transfer by Convection

The heat transferred due to the fluid or random motion of air molecules and the macroscopic scale is determined as:

$$Q = hA(T_1 - T_2) \quad (5)$$

where Q is the heat transfer rate, h is the heat transfer coefficient by convection, and A is the surface area through which heat transfer by convection takes place; and $T_1 and\ T_2$ = Slurry temperature and ambient temperature within the bio-digester [19].

2.1.3. Heat by Radiation

The heat transfer because of the emissivity of the radiating black body material and the atmosphere is given by:

$$Q = e\sigma A(T_1 - T_2)^4 \quad (6)$$

ISSN: 2576-8484
Vol. 8, No. 6: 3872-3885, 2024
DOI: 10.55214/25768484.v8i6.2843

where $e =$ is the emissivity of the radiating material, the black body associated with the color of the constructed bio-digester, $\sigma =$ Stefan Boltzmann constant, A = cross-sectional area of the radiating material, T_1 and T_2 = temperature of the radiating and receiving bodies [20].

2.2. Thermal Insulator of Plastic

Temperature variation depends on temperature, conductivity, thermal absorptivity, specific heat capacity, and diffusivity of the materials. These mentioned properties determine whether any material can be used as an insulator. Fourier's law of the equation governs the general time-dependent of the one-dimensional heat transfer equation.

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{\rho C}{K}\frac{\partial T(x,t)}{\partial t} \tag{7}$$

Equation 7 is applicable when considering the boundary condition of the material surface of both sides of the wall of the biogas digester according to Newton's law and using the initial condition (0, t). The energy balance equation at the material surface can be given as.

$$-K\left(\frac{\partial T(0,t)}{\partial x}\right) = h_e(T_{Tsa} - T_e) \tag{8a}$$
$$-K\left(\frac{\partial T(0,t)}{\partial x}\right) = h_i(T_i - T_{in}) \tag{8b}$$

where h_i & h_e = interior surface of the wall and heat transform coefficient on the exterior, respectively, and T_e & T_i = is the exterior and interior at x = L [21].

The heat transfer equation relating to heat flow through the insulation to the insulation thickness and insulating material or thermal conductivity for cylindrical insulation is given as;

$$Q = \frac{T_1 - T_2}{L/\lambda} \tag{9}$$

where Q is the heat flow (w/m), T_1 is the temperature of the hot surface, T_2 is the temperature of the cold surface, L is the thickness of the insulation in meter, and λ is the conductivity (w $m^{-1}k^{-1}$).

3. Materials and Methods

3.1. Feedstock Characterization

The fresh cow dung sample for biogas digestion was sourced from the University of Fort Hare dairy farm. Before performing the experimental test, various parameters of the sample were determined, including pH, total solids (TS), volatile solids (VS), and calorific value (CV). All these determinations of physiochemical properties of the cow dung sample were carried out at the Chemistry Department of the University of Fort Hare, Alice Campus, according to the standard methods (ALPHA 2005). Therefore, Table 1 presents the physiochemical properties of the slurry samples. The slurry was obtained by diluting solid waste (cow dung) with water in a ratio of 1:1.

3.1.1. Total Solids Determination

Total solids are generally known as the weight of dry material or the dry portion of the substrate after moisture elimination. Digital weighing scales are to be used to weigh different substrates. A heat oven places the weighted samples at 105°C for 24 hours. After that, the heated samples are to be reweighed. Then, the total solids are determined using the following equation.

$$\text{TS (mg L}^{-1}) = \frac{W1 - W2}{W3 - W2} \times 1000000 \tag{10}$$

where W_1 is the weight of the dish and dried residue in (g), W_2 is the dish weight in (g), and W_3 is the weight of the dish and wet sample in (g) [7].

3.1.2. Volatile Solids determination

The total solid is the weighed, dried solid that remains after igniting the substrate at 500-600°C. A muffle furnace at 600°C was used to ignite the residue obtained from total solids determination for a duration of 2 hours. Then, the black mass and the crucible were allowed to cool in air partially before they were completely cooled in a desiccator. After the temperature balance was reached, the sample was weighed. The equation below was used to calculate volatile solids.

$$\text{VS}\ (\text{mgL}^{-1}) = \frac{W1-W2}{W1-W3} \times 10000000 \qquad (11)$$

Where W_1 is the weight of the dish before ignition + the weight of solids at 550°C (g), W_2 is the weight of the dish after ignition + solids at 50°C (g), and W_3 empty dish weight(g) [22, 23].

3.1.3. pH of the Slurry

The pH meter electrode tip was immersed in a glass jar containing cow dung substrate to measure its pH. After reaching a steady state, readings were taken, and subsequent samples were similarly assessed using the same procedure. pH is an essential parameter that influences digester stability and performance by regulating the growth of hydrolytic and fermentative bacteria crucial for methane (CH_4) production. Optimal pH ranges for these bacteria, as identified by Rong et al.[10] and Obileke et al.[7], typically fall within 6.8 to 7.2. pH levels indicate the nature of a substance, directly impacting digester stability and biogas production rate. Fluctuations in pH can lead to inconsistency and acid accumulation, consequently, low methane production yields [7]. Table 1 shows the pH results reported in the study.

3.1.4. Calorific value of the substrate

The bomb calorimeter was used to determine or measure the energy value of the cow manure before feeding and after digestion. It is a technique used to determine the heat of combustion, the calorific value of any solid or liquid, and the latent heat of vaporization, as it is linked to the heating value. A CAL2K bomb calorimeter was used in this work. It consisted of the ECO Calorimeter, ECO-KT Calorimeter Installation Kit, CAL2K-3 Filling Station, CAL2K-3-KT Filling Station Kit, CAL2K-4 Vessel and CAL2K-4-KT Vessel Installation Kit. Table 1 shows the value of the Calorific values.

Table 1.
Fresh cow dung properties were used in the study.

Cow dung Properties	Values	Used Test method
pH	6.3-7.4	Hydrogen-electrode
Total solids (TS) [g L^{-1}]	162 348	CR-1000 APHA-2005
Volatile solids (VS) [g L^{-1}]	116 543	CR-1000 APHA-2005
Calorific value [MJg^{-1}]	17.60	Direct method

3.1.5. Construction of the Greenhouse Biogas Digester

The biogas digester was constructed based on temperature maintenance specifications at an optimum mesophilic temperature of 33 ± 0.5 °C. Figure 4 depicts the digester used in this study and its specifications. The digester system was constructed at the University of Fort Hare biogas site. The following materials were used for the construction of the digester: a $3mm$ thick low-density polyethylene (LDPE) hallow sunlight sheet of greenhouse, a galvanized iron metal supporting frame of $l = 1.03m$, $b = 1.03m$, and h = $1.14m$ same as the PVC digester chamber of $2mm$ thickness positioned above ground level, a PVC outlet of pipe of $1m$ connected at the base of the digester chamber, and stainless sink inlet, a gas pipe, and data acquisition system installed during construction as shown in Figure 1. Two type-K thermocouples were securely installed through the plastic wall of the digester and positioned in the space above the plastic vessel within the greenhouse. These placements were intended to monitor the slurry and greenhouse air temperatures.

3.1.6. Low-Density Polyethylene (LDPE) Plastic Used for Greenhouse Construction

To regulate temperature, a greenhouse employs a cover constructed from low-density polyethylene (LDPE) plastic that is both UV-inhibited and IR-absorbing (See Figures 1 and 2). This transparent material is characterized by its affordability, flexibility, the high transmissivity of shortwave radiation (60-80%), permeability to water, and impact resistance [24, 25]. It was designed to facilitate solar radiation transmission and thermal insulation to house the digester chamber [24]. Moreover, various heating methods have been employed to improve the efficiency of biogas systems operating in cold climates. Notably, the solar greenhouse is acknowledged as an effective passive heating technique that harnesses solar radiation without needing active mechanical systems [13]. The greenhouse was constructed to reduce thermal energy losses due to convection, conduction, and infiltration.

Furthermore, the plastic cover of the greenhouse thickness was sufficiently thin to facilitate the effective transfer of thermal energy through its walls [26] to the digester chamber (See Figure 1). Additionally, the fermentation temperature of the biogas digester system is typically between 10-30℃, and subsequently 30-35℃. Moreover, constructing an airtight greenhouse structure range minimized thermal energy loss due to infiltration, facilitated by the greenhouse's mitigation of heat loss, thus optimizing it to 33.5℃.

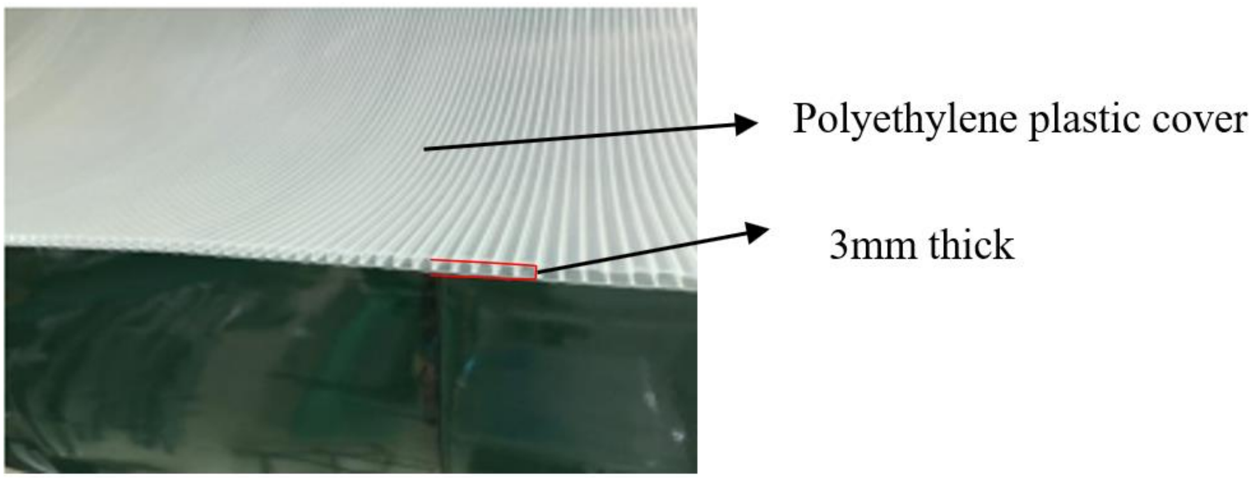

Figure 1.
The low-density polyethylene (LDPE) plastic.

Table 2.
LDPE Hallow sunlight sheet plastic specifications.

Parameters	Value
Thickness (mm)	3.0
Width (m)	2.0
Approximate temperature (℃)	<40.0
Dimensional change rate (%)	<0.1
Thermal coefficient (W/mK)	<0.07
Tear resistance Rally (N)	>40.0
Tear elongation (%)	>200.0
Elongation at break (N)	>80.0
Broken down standard quality (G)	>300.0
Transmittance (%)	>80.0
Anti-aging life (year)	10 years
Anti-wind (Grades)	10.0

ISSN: 2576-8484
Vol. 8, No. 6: 3872-3885, 2024
DOI: 10.55214/25768484.v8i6.2843

Figure 2.
Greenhouse digester designs (a) The front view and (b) the back view.

3.2. Experiment Procedure

The batch-operational mode was employed in the study. The solid waste (cow dung) underwent dilution with water in a 1:1 ratio, ensuring that the total solids value is 10% less to yield slurry. This ratio was adopted in this current study, as it was found by Basumatary et al.[27], to produce a high biogas yield. The biogas digester was fed once with 1176kg of slurry mixed with inoculum sourced from the biogas digesters near the University of Fort Hare to fast-track biodegradation. Subsequently, the gas valve remained open for 72 hours to facilitate air (oxygen) expulsion and closed thereafter. Monitoring of the parameters such as slurry temperature, ambient temperature, slurry pH, and biogas yield occurred for the duration of the stipulated retention time. Type-K thermocouple temperature sensors, in conjunction with the PS-2000 Xplorer, the biogas flow meter, and the SAZQ biogas analyzer, were employed to monitor temperature, pH, and the rate and composition of biogas production as the anaerobic digestion process proceeded respectively. The CR-1000 data logger was connected to a 12V battery, which is changed daily with others for recharging, and the computer system was used to record and determine the data on the Carbon dioxide (CO_2), hydrogen sulfide (H_2S), and methane (CH_4) in the biogas. The characteristics of the cow dung fed into the digester for experiment performance are shown in Table 1. The accumulation of biogas is easily observable through the inflation of the digester chamber, ascending towards the roof of the greenhouse structure.

4. Results and Discussion

The performance of the digester's monitoring was evaluated, focusing specifically on biogas production and the effect of temperature. Various temperature regions were considered in the study, including slurry and ambient conditions. The aim was to determine their influence on methane yield and the compositional profile of the biogas digester. The findings were analyzed, graphically presented, and subsequently discussed and interpreted.

4.1. Performance of the Biogas Digester

4.1.1. The Biogas Yield Profile

The formation of biogas is made possible through the action of anaerobic bacteria in the absence of oxygen. This was the case in the present study. The performance of the greenhouse biogas digester in terms of biogas yield was monitored over a 30-day retention time. A peak biogas of 0.3 m^3 was recorded on day 23, as presented in Figure 3.

ISSN: 2576-8484
Vol. 8, No. 6: 3872-3885, 2024
DOI: 10.55214/25768484.v8i6.2843

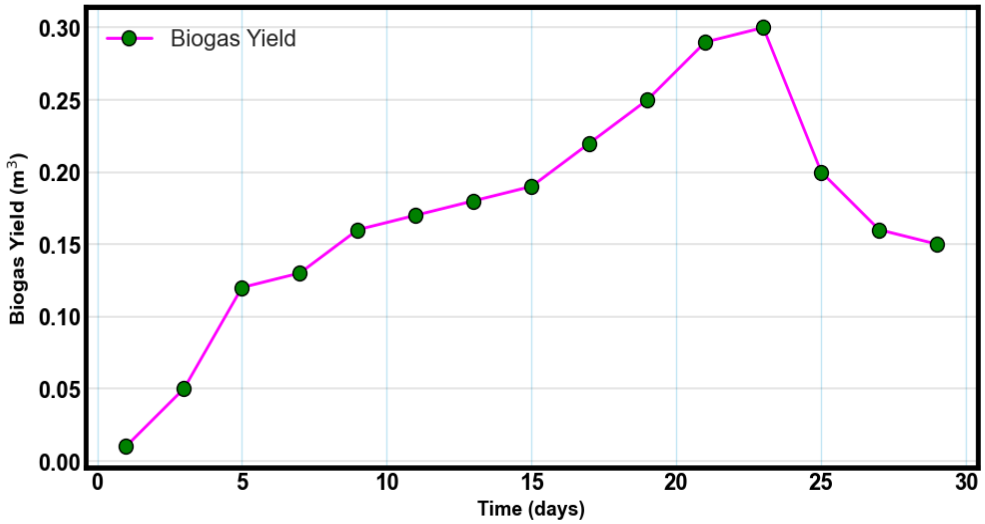

Figure 3.
Biogas yield profile against time.

Figure 3 shows a small trace of biogas yield, approximately 0.01m^3, was recorded. This can be attributed to the lag phase of microbial growth, especially the methane-producing micro-organisms. However, from day 1 to day 21, the biogas yield increased gradually from 0.01m^3 to 0.29m^3; this is due to the inoculum and activity of the anaerobic micro-organisms present in the fresh slurry in response to the temperature and pH, which fluctuated between 7.1 and 7.4 from day 1 to 21. This agrees with the literature, as reported by Patel et al.[28]. According to Hagos et al.[2] and Basumatary et al.[27], several studies report that micro-organisms show better growth in mesophilic compared to psychrophilic conditions, and indeed, for the period of this work, the biogas yield obtained in this study was recorded under mesophilic temperature conditions. As a result, the biogas yield, under this condition, was produced in a steady state as the methane-forming micro-organisms were accumulating with respect to the favorable temperature condition within the digester chamber. Consequently, a peak value of 0.3m^3 on the 23rd day, correlating to with the highest recorded slurry temperature of 33.5℃ was recorded. However, the biogas production declined after day 23 due to a pH drop below 6.8 and reduced methane-producing microorganisms from the slurry, causing instability within the digester, and this was also due to the absence of new material introduction to the digester chamber, as indicated by Mutungwazi et al.[24].

4.2. Effect of Temperature on Biogas Production

Temperature is regarded as an important factor (parameter) in biogas production. Figures 4 and 12 present the variation of ambient and slurry temperatures with the retention time. When addressing the temperature requirements, the acidifying bacteria demonstrate optimal functionality within specific temperature ranges, either mesophilic (32 to 42℃) or thermophilic (48 to 55℃) conditions. Thermophilic conditions promote higher biogas yield. However, mesophilic conditions are more favored due to greater energy production. Furthermore, digestion processes decline at temperatures as low as 10℃. Additionally, Patel et al. [28] stated that the thermophilic temperatures contribute to odor control and diminishing pathogenic presence. The temperature conditions influence the metabolic process within anaerobic digestion, involving diverse microbial groups of organisms, including hydrogenotrophic, acidogenic, acetogenic, and methanogenic organisms. This indicates that fluctuations

ISSN: 2576-8484
Vol. 8, No. 6: 3872-3885, 2024
DOI: 10.55214/25768484.v8i6.2843

in temperature can potentially mitigate or exacerbate imbalances among these metabolic microorganisms and their respective metabolic processes, as noted by Kandhro et al. [29].

4.2.1. Ambient Temperature Against Time

Figure 4 shows the graph of ambient temperature against time. The maximum ambient temperature fluctuations were recorded in the autumn season, with a maximum of 35 ℃ and an average of 27.1 ℃.

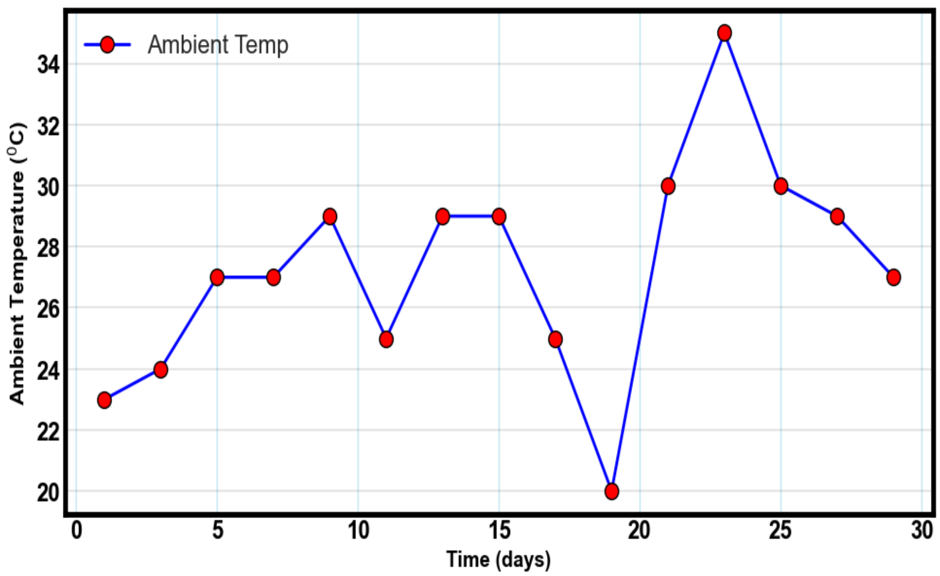

Figure 4.
Ambient temperature against retention time.

In Figure 4, the ambient temperature fluctuates between 20 ℃ and 35 ℃ during the experimental period. This range is similar to that of Jegede et al. [30], which reported ambient temperatures between 20 ℃ and 25 ℃. The fluctuations depicted in Figure 11 are attributed to the varying weather conditions in Alice during the autumn/winter season, which is known to influence anaerobic digestion (AD), particularly at lower temperatures, as noted by Nandi et al. [31]. As the retention time approached the end, the ambient temperature dropped to 27 ℃ . A temperature controller system (greenhouse) was implemented to mitigate temperature gradients caused by seasonal changes, ensuring stability in the anaerobic digestion process. Ambient temperature plays a crucial role in insulating the biogas digester, minimizing fluctuations that could positively affect biogas production rates. Moreover, significant temperature variations can reduce methanogenic bacterial activity, subsequently lowering biogas yield, a finding supported by Nie et al. [32] and Sudiartha et al. [33]. On the 19th day, a significant drop to 20 ℃ was recorded, attributed to the cold and windy weather conditions, on that particular day as noted by Mutungwazi et al. [24] in his study. Conversely, on the 23rd day, the ambient temperature peaked of 35℃, likely due to solar radiation. Overall, the average temperature over the 30-day retention period was 27.1 ℃, which falls within the optimal range for biogas production, as stated by Younus Bhuiyan Sabbir et al. [34], and aligns with the findings in the literature.

4.2.2. Slurry Temperature Against Time

Figure 5 shows the temperature environment obtained from the study. The slurry temperature is a determinant of the ambient temperature. The greenhouse insulation maintained the anaerobic digestion

ISSN: 2576-8484
Vol. 8, No. 6: 3872-3885, 2024
DOI: 10.55214/25768484.v8i6.2843

slurry temperature from 33 - 33.5 ℃ , falling under mesophilic conditions known in the literature as optimum for higher biogas production energy.

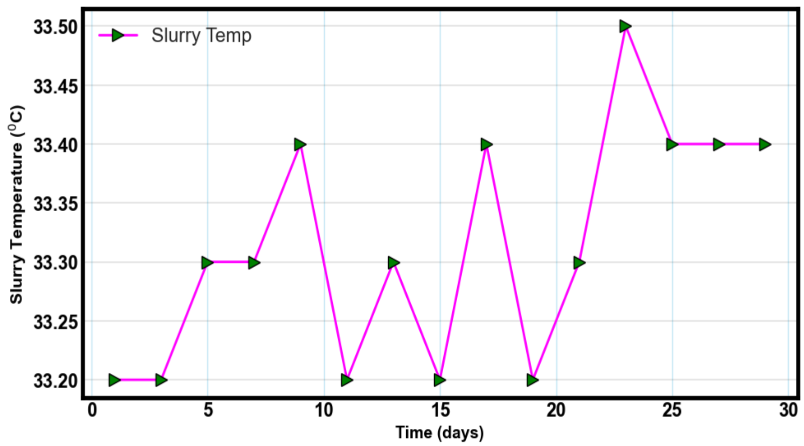

Figure 5.
Slurry temperature profile.

Figure 5 shows that the slurry temperature ranged from 33.2 to 33.5 ℃ , which is within the mesophilic temperature as reported by Patel et al. [28] and Bhajani et al. [35]. The slight variation in the slurry temperature was due to changing ambient weather patterns in Alice; however, the greenhouse insulation prevented major temperature variations inside the digester. The recorded data and the graph show no major slurry temperature fluctuations, similar to a study by Zheng et al. [36]. The results of this work indicate that, during the autumn season, the fluctuation in slurry temperature was not correlated with the changes in ambient temperature. This aligns with the findings of a previous conducted by Younus Bhuiyan Sabbir et al. [34]. In a study conducted by Bai and Kumar, they introduced a heating system utilizing a greenhouse to enhance the slurry temperature within the biogas digester. Their findings indicated an increase in slurry temperature from 26.3 to 29.1 ℃ , leading to significant enhancement in biogas production during winter conditions, making the digester plant employed in this study an exceptional preventer of thermal loss. A ± 0.5 ℃ slurry temperature variation is observed in this current which is the preferred variation as a slurry temperature fluctuation of ± 3 ℃ is an ideal variation for methane-forming micro-organisms since these bacteria are very sensitive to temperature changes, negatively influencing biogas production, as reported by Obileke et al. [7].

4.2.3. Effect of Slurry Temperature on Biogas Yield

The results presented in Figure 6 show a relationship between the biogas production with respect to the slurry temperature. A peak biogas production of 0.3 m^3 was recorded on the 23rd at an optimum temperature of 33.5 ℃. These results emphasize that the slurry temperature plays a vital role in biogas production.

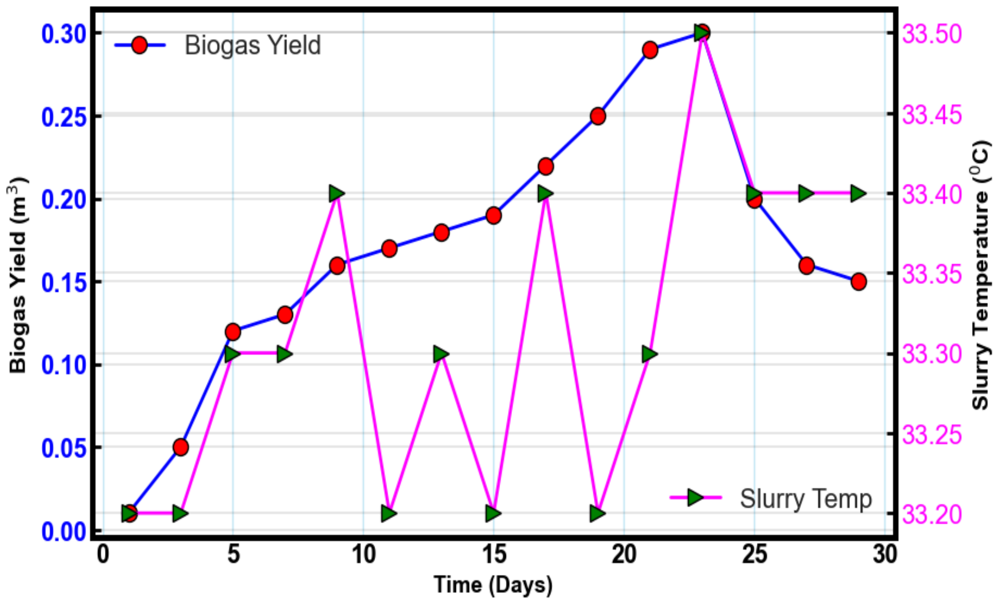

Figure 6.
Biogas yield and temperature profile.

In Figure 6, the slurry temperature on day 1 was recorded at 33.2 ℃, within the mesophilic range (30 – 40 ℃), facilitating methane formation due to the inoculum used to initiate biodegradation. Throughout the mesophilic conditions, a temperature gradient resulted in gradual improvements in the biogas digester, allowing methanogenic bacteria to optimize biogas production, as noted by Patel et al. [28]. These bacteria demonstrate a high degree of conversion of organic matter and thrive best in mesophilic conditions. Furthermore, the availability of readily biodegradable organic matter in the substrate positively affected the rise in biogas production from 0.1 m^3 to 0.12 m^3 at a slurry temperature of 33.3℃, coinciding with a high presence of methanogenic bacteria in slurry, as supported by Nwankwo et al. [37]. The biogas yield continued to increase until reaching an optimum value of 0.3m^3 on day 23, at the highest recorded slurry temperature of 33.5 ℃. The observation aligns with the findings by Wang et al. [38], which indicate that the methanogenic stage can achieve high methane production efficiency while maintaining over 50% methane content within the temperature range of 25 to 35 ℃. From day 24, where a biogas yield of 0.23 m^3 was observed at a temperature of 33.4 ℃, to day 30, where the yield decreased to 0.15 m^3 at 33.35 ℃, there was a notable drop in temperature that inhibited methanogenic activity, resulting in reduced biogas yield. The slurry temperature showed a minor decline from 33.5 to 33.4 ℃, resulting in a slight decrease in biogas yield, as depicted in Figure 6. The study conducted Wang et al. [38], showed that this was due to the activity of methanogenic bacteria, which were more sensitive to temperature disturbances.

4.2.4. Ambient Temperature Against Slurry Temperature

Usually, ambient temperature influences the slurry temperature, making it responsible for biogas production. Figure 7 presents the relationship profile of the ambient and slurry temperature. The results may be good for microbes producing methane as they depict a small temperature variation of 33 ± 0.5 ℃.

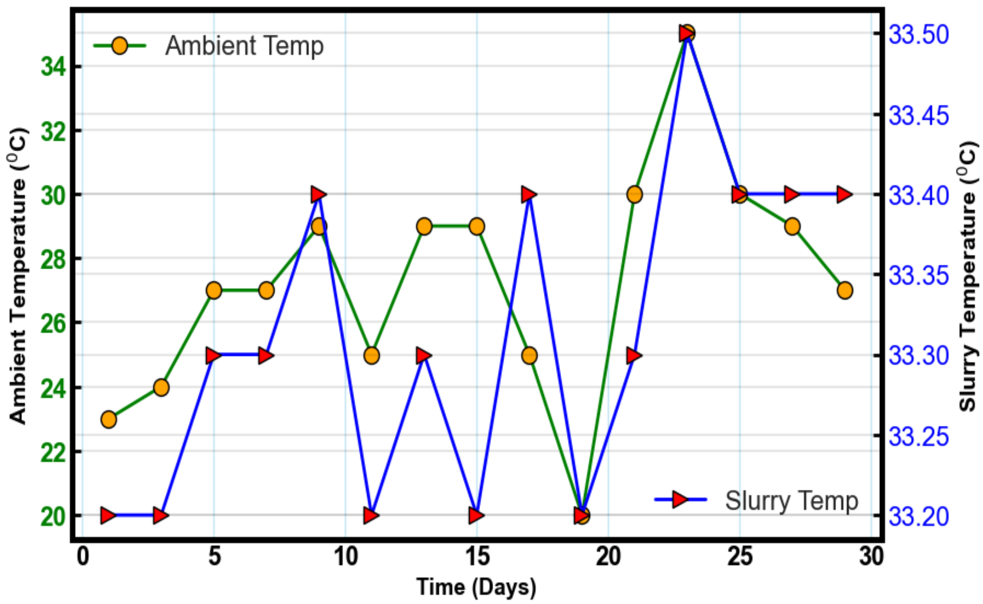

Figure 7.
Ambient temperature and slurry temperature profile.

Figure 7 illustrates that methanogens are significantly influenced by temperature. During the anaerobic digestion, the slurry temperature fluctuated between 33 ℃ to 33.5 ℃, while the ambient temperature varied from 20℃ to 35℃. The observed difference between the ambient and slurry temperatures is approximately ± 11 ℃, indicating that the slurry temperature depends on the ambient temperature. However, in this study, the slurry temperature is found to be slightly independent of the ambient temperatures, consistent with the findings of Younus Bhuiyan Sabbir et al. [34], likely due to the presence of a greenhouse. On day 1, the slurry temperature was recorded at 33.2 ℃, while the ambient temperature was 20 ℃. The elevated slurry temperature on the first day resulted from the heat being retained by the greenhouse. Consequently, on day 2, the slurry temperature increased slightly to 33.3 ℃, demonstrating the greenhouse effectiveness in retaining heat, even though the ambient temperature dropped to 25 ℃ due to changing weather conditions in Alice. Throughout the experiment, it is evident that these two parameters fluctuated over time. Figure 7 further highlights that when the slurry temperature exceeds the ambient temperature, it is due to heat trapped by the greenhouse, making a favorable environment for methane achieved, as less heat was lost to the environment through the walls of the digester, given that no insulating material can provide 100% insulation as stated by Mutungwazi et al. [24].

5. Conclusion

This study examined the critical role of temperature management in optimizing biogas production efficiency. Using a greenhouse envelope to house the biogas digester effectively minimizes temperature fluctuations and enhances thermal insulation. The LPDE plastic used in the greenhouse construction facilitated solar radiation transmission while preventing heat loss through convection, conduction, and infiltration. The greenhouse utilizes the greenhouse effect, where solar radiation (short wave radiation) enters the transparent polyethylene material. This radiation was absorbed by the slurry inside the digester and converted into heat (infrared radiation). Moreover, this design contributed to maintaining the slurry temperature of 33 ± 0.5 ℃ biogas digester is within the desired range despite the large ambient temperature variations. As a result, the total biogas yield from the study totals 2.58m^3 over the monitoring period, highlighting the potential of anaerobic digestion as a viable renewable energy source. The yield was equivalent to 15.48 kWh of energy, which could substantially supplement household energy needs such as lighting, cooking, etc., particularly in rural areas where access to conventional energy sources is limited.

Author Contributions:

S.M.: Conceptualization, writing, original draft preparation, reviewing, and editing. P.M.: supervision and investigation. K.O.: writing, reviewing, and editing. M.M.: writing, editing, and methodology. N.L.: supervision and editing. All authors have read and agreed to the published version of the manuscript.

Acknowledgments:

The authors greatly appreciate the financial support of the Govan Mbeki Research and Development Centre (GMRDC), Research Niche Area (RNA), and Renewable Energy Wind at the University of Fort Hare.

References

[1] O. J. Akintande, O. E. Olubusoye, A. F. Adenikinju, and B. T. Olanrewaju, "Modeling the determinants of renewable energy consumption: Evidence from the five most populous nations in Africa," *Energy*, vol. 206, p. 117992, 2020/09/01/ 2020, doi: https://doi.org/10.1016/j.energy.2020.117992.

[2] K. Hagos, J. Zong, D. Li, C. Liu, and X. Lu, "Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives," *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 1485-1496, 2017/09/01/ 2017, doi: https://doi.org/10.1016/j.rser.2016.11.184.

[3] K. Obileke, S. Mamphweli, E. L. Meyer, G. Makaka, N. Nwokolo, and H. Onyeaka, "Comparative Study on the Performance of Aboveground and Underground Fixed-Dome Biogas Digesters," *Chemical Engineering & Technology*, vol. 43, no. 1, pp. 68-74, 2020.

[4] M. Balat and H. Balat, "Biogas as a renewable energy source—a review," *Energy Sources, Part A*, vol. 31, no. 14, pp. 1280-1293, 2009.

[5] N. S. Nethengwe, S. E. Uhunamure, and D. Tinarwo, "Potentials of biogas as a source of renewable energy: A case study of South Africa," *Int. J. Renew. Energy Res*, vol. 8, pp. 1112-1123, 2018.

[6] R. F. T. Tagne, X. Dong, S. G. Anagho, S. Kaiser, and S. Ulgiati, "Technologies, challenges and perspectives of biogas production within an agricultural context. The case of China and Africa," *Environment, Development and Sustainability*, vol. 23, pp. 14799-14826, 2021.

[7] K. Obileke, S. Mamphweli, E. L. Meyer, G. Makaka, and N. Nwokolo, "Design and fabrication of a plastic biogas digester for the production of biogas from cow dung," *Journal of Engineering*, vol. 2020, no. 1, p. 1848714, 2020.

[8] C. Pham, C. Vu, S. G. Sommer, and S. Bruun, "Factors affecting process temperature and biogas production in small-scale rural biogas digesters in winter in northern Vietnam," *Asian-Australasian journal of animal sciences*, vol. 27, no. 7, p. 1050, 2014.

[9] J. Ma, L. Yu, C. Frear, Q. Zhao, X. Li, and S. Chen, "Kinetics of psychrophilic anaerobic sequencing batch reactor treating flushed dairy manure," *Bioresource Technology*, vol. 131, pp. 6-12, 2013/03/01/ 2013, doi: https://doi.org/10.1016/j.biortech.2012.11.147.

[10] K. R. Chew *et al.*, "Effects of anaerobic digestion of food waste on biogas production and environmental impacts: a review," *Environmental Chemistry Letters*, vol. 19, no. 4, pp. 2921-2939, 2021.

[11] S. Khan, "Effect Of Hydrothermal Pre-Treatment On Methane Production During Anaerobic Digestion Of Thickened Waste Activated Sludge," Toronto Metropolitan University.

[12] B. Dhungana, S. P. Lohani, and M. Marsolek, "Anaerobic Co-Digestion of Food Waste with Livestock Manure at Ambient Temperature: A Biogas Based Circular Economy and Sustainable Development Goals," *Sustainability*, vol. 14, no. 6, doi: 10.3390/su14063307.

[13] E. S. Gaballah, Q. Yuan, and T. K. Abdelkader, "Improving Biogas Production by Integrated Solar Greenhouse Technique: A Pilot Study Using Semi-buried Tubular Digester in Cold Climate Regions," *Waste and Biomass Valorization*, vol. 15, no. 3, pp. 1355-1367, 2024/03/01 2024, doi: 10.1007/s12649-023-02206-4.

[14] X. Shao, X. Su, S. Tian, and J. Cai, "The effect of biogas fermentation assisted by simple solar greenhouse," in *E3S Web of Conferences*, 2021, vol. 246: EDP Sciences, p. 03001.

[15] S. Cheng, Z. Li, H.-P. Mang, and E.-M. Huba, "A review of prefabricated biogas digesters in China," *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 738-748, 2013/12/01/ 2013, doi: https://doi.org/10.1016/j.rser.2013.08.030.

[16] A. Mutungwazi, P. Mukumba, and G. Makaka, "Biogas digester types installed in South Africa: A review," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 172-180, 2018/01/01/ 2018, doi: https://doi.org/10.1016/j.rser.2017.07.051.

[17] A. Nazari, M. Soltani, M. Hosseinpour, W. Alharbi, and K. Raahemifar, "Integrated anaerobic co-digestion of municipal organic waste to biogas using geothermal and CHP plants: A comprehensive analysis," *Renewable and Sustainable Energy Reviews*, vol. 152, p. 111709, 2021/12/01/ 2021, doi: https://doi.org/10.1016/j.rser.2021.111709.

[18] G. Caposciutti, A. Baccioli, L. Ferrari, and U. Desideri, "Impact of ambient temperature on the effectiveness of inlet air cooling in a co-digestion biogas plant equipped with a mGT," *Energy Conversion and Management*, vol. 216, p. 112874, 2020/07/15/ 2020, doi: https://doi.org/10.1016/j.enconman.2020.112874.

[19] F. Makamure, P. Mukumba, and G. Makaka, "An analysis of bio-digester substrate heating methods: A review," *Renewable and Sustainable Energy Reviews*, vol. 137, p. 110432, 2021/03/01/ 2021, doi: https://doi.org/10.1016/j.rser.2020.110432.

[20] D. H. Bacon, *Basic heat transfer*. Elsevier, 2013.

[21] C. Edet, P. Ushie, and C. Ekpo, "Effect of additives on the thermal conductivity of loamy soil in cross river university of technology (crutech) farm, Calabar, Nigeria," *Asian Journal of Physical and Chemical Sciences*, vol. 3, no. 4, pp. 1-8, 2017.

[22] P. Mukumba, G. Makaka, and S. Mamphweli, "Anaerobic digestion of donkey dung for biogas production," *South African Journal of Science*, vol. 112, no. 7-8, pp. 1-4, 2016.

[23] E. K. Orhorhoro, P. O. Ebunilo, and G. E. Sadjere, "Experimental determination of effect of total solid (TS) and volatile solid (VS) on biogas yield," *Am. J. Mod. Energy*, vol. 3, no. 6, pp. 131-135, 2017.

[24] A. Mutungwazi, P. Nyamukamba, P. Mukumba, and G. Makaka, "Use of a portable greenhouse for temperature control in a small-scale biogas production unit," *Int. J. Renew. Energy Res*, vol. 10, no. 3, pp. 1236-1244, 2020.

[25] C. Maraveas, "Environmental Sustainability of Greenhouse Covering Materials," *Sustainability*, vol. 11, no. 21, doi: 10.3390/su11216129.

[26] H.-K. Kim, S.-Y. Lee, J.-K. Kwon, and Y.-H. Kim, "Evaluating the Effect of Cover Materials on Greenhouse Microclimates and Thermal Performance," *Agronomy*, vol. 12, no. 1, doi: 10.3390/agronomy12010143.

[27] S. Basumatary, S. Das, P. Goswami, and P. Kalita, "Investigation of the effect of slurry mixing ratio and temperature on biogas production from cattle dung in a field-scale anaerobic digestion plant," *International Journal of Ambient Energy*, vol. 45, no. 1, p. 2267573, 2024/12/31 2024, doi: 10.1080/01430750.2023.2267573.

[28] M. Patel, D. Patel, N. Patel, V. Shah, and P. Prajapati, "Production of biogas and the associated factors: A guide for successful implementation of a biogas digester," *AIP Conference Proceedings*, vol. 2960, no. 1, 2024, doi: 10.1063/5.0184736.

[29] B. Kandhro *et al.*, "Seasonal variation in biogas production in reinforced concrete dome biogas plants with buffalo dung in Pakistan," *Biomass Conversion and Biorefinery*, vol. 14, no. 4, pp. 5171-5185, 2024/02/01 2024, doi: 10.1007/s13399-022-02654-3.

[30] A. O. Jegede, G. Zeeman, and H. Bruning, "A review of mixing, design and loading conditions in household anaerobic digesters," *Critical Reviews in Environmental Science and Technology*, vol. 49, no. 22, pp. 2117-2153, 2019/11/17 2019, doi: 10.1080/10643389.2019.1607441.

[31] R. Nandi, C. K. Saha, S. Sarker, M. S. Huda, and M. M. Alam, "Optimization of Reactor Temperature for Continuous Anaerobic Digestion of Cow Manure: Bangladesh Perspective," *Sustainability*, vol. 12, no. 21, doi: 10.3390/su12218772.

[32] E. Nie, P. He, H. Zhang, L. Hao, L. Shao, and F. Lü, "How does temperature regulate anaerobic digestion?," *Renewable and Sustainable Energy Reviews*, vol. 150, p. 111453, 2021/10/01/ 2021, doi: https://doi.org/10.1016/j.rser.2021.111453.

[33] G. A. Sudiartha, T. Imai, and Y.-T. Hung, "Effects of Stepwise Temperature Shifts in Anaerobic Digestion for Treating Municipal Wastewater Sludge: A Genomic Study," *International Journal of Environmental Research and Public Health*, vol. 19, no. 9, doi: 10.3390/ijerph19095728.

[34] A. S. M. Y. B. Sabbir, C. K. Saha, R. Nandi, M. F. Zaman, M. M. Alam, and S. Sarker, "Effects of Seasonal Temperature Variation on Slurry Temperature and Biogas Composition of a Commercial Fixed-Dome Anaerobic Digester Used in Bangladesh," *Sustainability*, vol. 13, no. 19, doi: 10.3390/su131911096.

[35] S. S. Bhajani and S. Pal, "Review: Factors affecting biogas production," *Int. J. Res. Appl. Sci. Eng. Technol*, vol. 10, pp. 79-85, 2022.

[36] L. Zheng *et al.*, "What Could China Give to and Take from Other Countries in Terms of the Development of the Biogas Industry?," *Sustainability*, vol. 12, no. 4, doi: 10.3390/su12041490.

[37] C. Nwankwo, J. Eze, and C. Okoyeuzu, "Design and fabrication of 3.60 m3 household plastic bio digester loaded with kitchen waste and cow dung for biogas generation," *Scientific Research and Essays*, vol. 12, no. 14, pp. 130-141, 2017.

[38] S. Wang, F. Ma, W. Ma, P. Wang, G. Zhao, and X. Lu, "Influence of Temperature on Biogas Production Efficiency and Microbial Community in a Two-Phase Anaerobic Digestion System," *Water*, vol. 11, no. 1, doi: 10.3390/w11010133.