The effects of temperature on biogas production rate and purity

Romeica Noe Z. Rimorin, Christian Mark M. Felix, Roger Jay L. De Vela[*]

Camarines Norte State College, Camarines Norte, Philippines

*Corresponding author: rogerjaydevela@gmail.com

Abstract: This study investigated the effects of temperature on the performance of anaerobic digesters for biogas production. Digesters were filled with a 1 : 1 ratio of substrate to water, containing 15 kg of cow dung and 3 kg of crop waste, and maintained at temperatures of 50 ± 2 °C and 30 ± 2 °C, corresponding to the thermophilic and mesophilic biodigesters, respectively. The experiments run for 75 days, and biogas production rate and purity were measured. The thermophilic digester produced 48.4% more biogas and had a slightly higher pH (7.65) than did the mesophilic digester (7.37) by the end of the observation period. However, gas chromatography revealed that the CH_4 and CO_2 contents did not significantly differ between the two treatments. The CH_4 concentration in the mesophilic environment was 42 ± 10%, whereas that in the thermophilic environment was 53.5 ± 10%. The CO_2 composition was 32.5 ± 1% and 35.5 ± 1% for the mesophilic and thermophilic setups, respectively. These were supported by the wavelength (460 nm to 620 nm) of the flame colour, indicating that the biogas from both setups is predominantly composed of methane. In conclusion, thermophilic anaerobic digesters may have a relatively high biogas production rate, but the biogas purity is not significantly different from that of mesophilic digesters.

Keywords: anaerobic digester; biomethane; methane; mesophilic; thermophilic

Methane (CH_4), the second largest contributor to global warming, after carbon dioxide, is emitted into the atmosphere through human activities, including agriculture which is responsible for 40% of total anthropogenic emissions (Food and Agriculture Organisation of the United Nations 2024). Both livestock and crop production activities, including enteric fermentation, manure management, crop cultivation and residue burning, among others, are major contributors (Smith et al. 2021).

One way to reduce CH_4 emissions from the agricultural sector while effectively reducing its other negative environmental impact is to process agricultural waste through anaerobic decomposition. This process produces biogas, which is considered an important renewable energy source, especially for most developing countries whose energy demand is expected to grow in the future (Barz et al. 2019).

In the decomposition process, organic matter is degraded by anaerobic microorganisms or methanogens inside an oxygen-free digester or bioreactor. Biogas is primarily composed of CH_4 (50–75%) and carbon dioxide (CO_2) (25–50%), with trace amounts of hydrogen sulfide (H_2S), hydrogen, mois-

ture and siloxanes (Adebayo et al. 2015; Li et al. 2019). Among these gases, only methane, carbon monoxide and hydrogen are combustible and are therefore desirable in high-purity biogas (Harish Kumar and Indianraj 2022), whereas CO_2, hydrogen sulfide and moisture should ideally be minimised (Kokieva et al. 2020).

Several factors affect the production rate and quality of the biogas produced in an anaerobic digester system. Some of these factors include the type of feedstock, organic loading rate, pH, hydraulic retention time, C/N ratio, type of digester and operating temperature (Adebayo et al. 2015; Yadav and Singh 2018; Yilmaz et al. 2018; Li et al. 2019). This work aims to contribute to understanding the effects of temperature on biogas systems, specifically the biogas production rate and the quality of the biogas in terms of its methane composition. The amount of methane in biogas primarily influences its calorific value and consequently its readiness to be injected into the natural gas grid (Seman et al. 2019); hence, biogas with high methane content is desirable. Therefore, this study contributes to Sustainable Development Goal 7, on affordable and clean energy, and indirectly to Sustainable Development Goal 13, Climate Action. Moreover,

this study also demonstrates an innovative and quick approach to biogas flame characterisation if sophisticated gas chromatograph/mass spectrometer is not available.

MATERIAL AND METHODS

Preparation of the substrate. The substrate used in this study was composed of cow dung and crop residues (mainly rice straw) collected from various small-scale farms in the municipality of Vinzons, Camarines Norte, Philippines. The rice straw was manually cut to a length of 1 cm via a machete.

Before the substrate was placed inside the stainless-steel digester tank, it was mixed with tap water. The ratio of the weight of waste to the weight of water in kilograms was 1 : 1, whereas the ratio of animal waste to crop residues was 5 : 1. Therefore, one digester had 18 kg of waste mixture, where 15 kg was cow dung and 3 kg was rice straw. The weight of the water was 18 kg, resulting in a total mass of 36 kg, which occupied 75% of the digester's 53-liter volume. The remaining 25% (13.25 L) was allocated to the headspace of the produced biogas (Figure 1). Due to budgetary constraints, properties
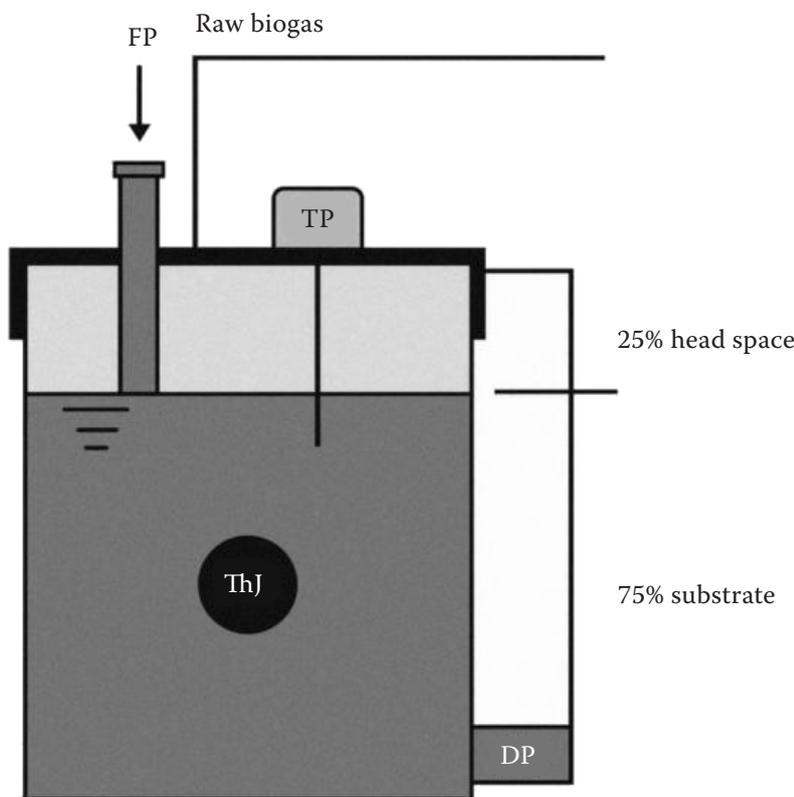

Figure 1. Schematic diagram of the digester showing the volume occupied by the substrate and the headspace

DP – digestate port; FP – feeding port; ThJ – thermal jacket; TP – temperature & pH

of the rice straws and cow dung were not measured analytically in this research. However, from various literature, Table 1 shows the composition of both rice straws and cow dung, making them a desirable substrate in the experiments.

Operation of the digester and data collection. The digester temperature was set and maintained at 50 ± 2 °C (thermophilic setup) and 30 ± 2 °C (mesophilic setup), with the use of a thermal jacket consisting of a silicone drum heater band with a thermostat. Each digester type has two replicates. The substrate inside the digester underwent anaerobic digestion by ensuring that the digester was sealed and free from leaks. The substrate was batch-fed and unstirred to avoid opening the digester's cover, thus preventing air entry. The pH and temperature of the substrate were monitored daily via a pH and temperature probe (Smart Sensor PH 328; Fuzhou Hedao Trade Co., Ltd., Fuzhou, P.R. China). A 2.7-L balloon was connected to the T-connection through plastic tubing to collect samples. During collection, the downstream side of the T-connection was blocked so that the biogas would directly enter the balloon. The production rate was calculated via the following equation:

Biogas flame testing. The collected biogas was transferred from the balloon to a 500-mL Tedlar bag to avoid contamination. A 500-mL plastic syringe was consequently used to collect 500 mL of biogas inside the Tedlar bag. The biogas was then discharged from the syringe to create a flame through a burning candle. An image was captured to describe the flame's characteristics. All images were captured via the video feature of the Samsung Galaxy A52s 5G (Samsung, Philippines), with the same black background. The resulting images were analysed via Colour Picker, a mobile phone application that analyses the wavelength of colours in an image. The application supports advanced camera settings for more accurate colour identification. Users can identify colours in images, work with saved colours, search the database, and browse colours (Gribanov 2016).

The wavelength corresponding to the colour of the biogas flame provided information on its thermal characteristics, particularly its energy value. The wavelength corresponding to the blue flame indicates that methane is dominant in the biogas; otherwise, its flame would be reddish or orange. Hence, the bluer the flame is, the more methane

$$\text{Production rate of biogas} = \frac{\text{Total volume of the balloon}\,(\text{L})}{\text{Time to fully inflate the balloon}\,(\text{h})} \tag{1}$$

Table 1. Properties of rice straw and cow dung as obtained from the literature

Property	Rice straw	Cow dung
Total solids (%)	91.31 ± 3.74	19.56 ± 6.45
Volatile solids (%)	79.03 ± 6.67	72.94 ± 5.12
Carbon (%)	40.78 ± 5.57	39.17 ± 6.97
Nitrogen (%)	0.75 ± 0.25	1.69 ± 0.30
C : N ratio	57.71 ± 18.68	23.82 ± 6.15
Hemicellulose (%)	26.33 ± 4.32	13.16 ± 9.43
Cellulose (%)	33.47 ± 4.62	19.5 ± 12.81
Lignin (%)	9.35 ± 5.78	21.9 ± 10.04
Lignin to cellulose ratio	0.28 ± 0.19	0.56 ± 0.01
References	Chen et al. (2014); Narula and Wati (2014); Dai et al. (2017); Mustafa et al. (2017); Ghatak and Mahanata (2018); Haryanto et al. (2018b); Kim et al. (2018); Luo et al. (2020); Luo et al. (2021); Xu et al. (2021); Sivakumar et al. (2025)	Narula and Wati (2014); Ghatak and Mahanata (2018); Haryanto et al. (2018b); Pathak et al. (1985); Saravanan and Thiyagarajan (2025); Yusuf et al. (2025)

and the less CO_2 it contains (Ilminnafik et al. 2017; Ilminnafik et al. 2019). Only the middle and tail parts of the flame were analysed to minimise the influence of the candle flame on the colour readings, and their values were consequently averaged. This is the first time that this Colour Picker application developed by Gribanov (2016) is used for biogas research. However, this has been used in other applications like in the control of pigment dosing in an auto-paint colour mixer (Sutono et al. 2022) and in detecting low urinary glucose concentrations using commercially available dipstick glucose sensors (Sahare et al. 2025). These studies have demonstrated that smartphone-enabled colorimetric analysis through the Colour Picker application can be effectively and efficiently used specially when conventional laboratory equipment are unavailable, and was therefore used in this present work on biogas.

Biogas purity testing. To determine the biogas purity in terms of the percentage composition of methane, samples were analysed via a Shimadzu gas chromatograph-14B instrument equipped with a thermal conductivity detector and Porapak-Q column at the Philippine Institute of Pure and Applied Chemistry (PIPAC) at Ateneo de Manila University, Quezon City, Philippines. The temperature settings for both the injector and detector were 100 °C, and the column temperature was set at 60 °C. To determine the differences in the production rates and purities of the biogas produced from the two datasets, the data were analysed via the *t* test ($\alpha = 0.05$) feature of Microsoft Excel (Microsoft, 2019).

RESULTS AND DISCUSSION

Biogas production rate. The biogas digesters were continuously operated for 75 days. In the thermophilic setup, the production rate started at its lowest value of 0.07 ± 0.01 L·h^{-1} on day 1 (Figure 2). The production rate slowly increased until day 11, when there was a sudden increase in the production rate from 0.31 L·h^{-1} to 0.64 L·h^{-1}. The highest peak biogas production rate in the thermophilic setup occurred on day 18 at 0.72 ± 0.04 L·h^{-1}. After this peak, the rate decreased slowly until the end of the study. On the last day of observation, day 75, the production rate was 0.25 ± 0.01 L·h^{-1}, which was still higher than the initial rate and the lowest peak in the graph. This significant production of biogas observed around the 2nd week of HRT (hydraulic retention time) is closely related to the findings of other studies. In the study of Sunada et al. (2012) involving a digester where the solid fraction was not separated from the liquid effluent, the highest biogas production occurred on day 7. Moreover, biogas production from the study of Okonkwo et al. (2018) using domestic wastes and weeds began on day 7 and peaked on day 18. In the study of Ranade et al. (1987), which used market waste, the highest biogas production rate occurred on day 20.

In the study of Ghatak and Mahanata (2018), under thermophilic conditions, a 1-L batch-type digester consisting of the same substrate of cow dung and rice straw produced an average of 0.0007 L·h^{-1} to 0.002 L·h^{-1}. In the study of Uzodinma et al. (2007), a 1-L batch-type micro digester with cow
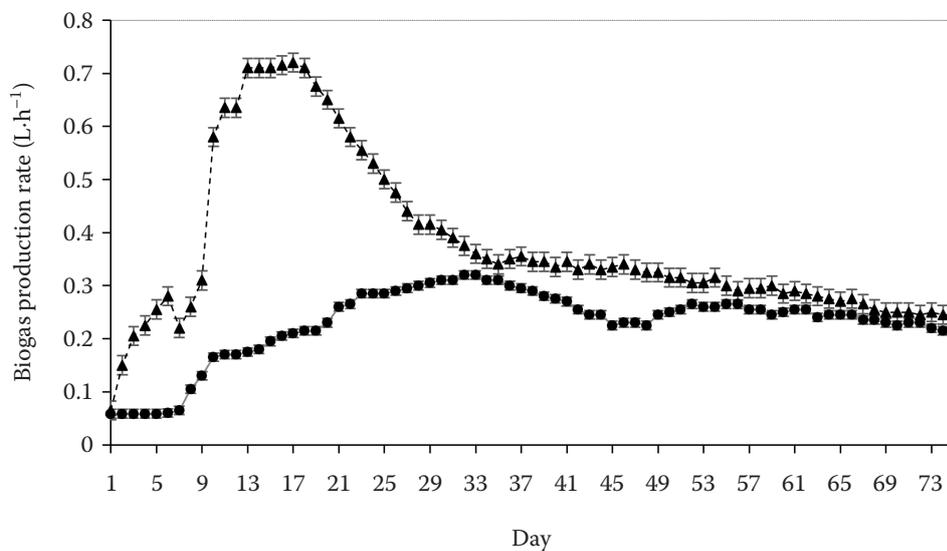

Figure 2. The average biogas production rates of thermophilic (▲) and mesophilic (■) digesters

dung and brewery-spent grain as the substrate produced 0.007 L·h^{-1}. Salam et al. (2011) used a 1-L batch-type glass conical flask with cow manure as the substrate and produced 0.003 L·h^{-1}.

Normalising the data in the present work, 1 L of substrate would produce an average of 0.01 L·h^{-1}, which is higher than the previous works mentioned in the preceding paragraph (Uzodinma et al. 2007; Salam et al. 2011; Ghatak and Mahanata 2018). On the other hand, comparing the present work with that of Castrillón et al. (2011), which used a 2-L batch-type jacketed stirred glass reactor with cow manure and crude glycerine as the substrate and produced 0.008 L·h^{-1} to 0.04 L·h^{-1}, the biogas production rate in this work was lower, as it was only 0.02 L·h^{-1} for 2 L of substrate. The stirring process in the work of Castrillón et al. (2011) may have increased biogas production.

For the mesophilic setup, the initial production rate was the lowest at 0.06 ± 0.01 L·h^{-1}. Unlike the thermophilic setup, the mesophilic setup production rate gradually increased, and there was no spike in its graph (Figure 2). It slowly increased until it peaked on day 32 and day 33, with an average production rate of 0.32 ± 0.01 L·h^{-1}. Following its peak, the rate gradually decreased until the study's conclusion was reached. The production rate was measured to be 0.21 ± 0.01 L·h^{-1} on day 75, the last day of observation, and the value was still higher than the initial and lowest production rates. These production rates were compared with those reported in the literature. For example, in the study of Haryanto et al. (2018a), a 220-L batch-type digester under mesophilic conditions

with cow manure and elephant grass as substrates had production rates ranging from 0.21 L·h^{-1} to 0.32 L·h^{-1}. Similarly, in the study of Huang et al. (2016), a 0.5-L batch-type borosilicate glass digester was used with cow manure and rice hull or rice straw as substrates, and the production rates ranged from 0.002 L·h^{-1} to 0.003 L·h^{-1}.

Compared to the studies of Haryanto et al. (2018a) and Huang et al. (2016), the current study had higher results. Normalising the conditions in the current study resulted to 1.4 L·h^{-1} which is greater than 0.21–0.32 L·h^{-1} of Haryanto et al. (2018a) and 0.005 L·h^{-1} which is greater than 0.002–0.003 L·h^{-1} of Huang et al. (2016). Moreover, in the study of Li et al. (2015), which used 2.5-L batch-type digesters that were manually mixed twice a day and utilised cow manure and rice straw as the substrate, production rates ranging from 0.03 L·h^{-1} to 0.06 L·h^{-1} were observed. For the same amount of substrate, the production rate in the present study was 0.02 L·h^{-1}, which was lower than that reported in the study of Li et al. (2015). This superior performance of the Li et al. (2015) digesters may be due to the mixing process they incorporated into the operation. The mixing process aids in increasing biogas quantity and quality through a uniform distribution of nutrients and microorganisms, which can enhance the synergistic effects of pure and mixed substrates. Another important feature of mixing is that it reduces solid accumulation, prevents settling, scum, and floating layers, and releases the gas bubbles trapped within the substrate (Singh et al. 2020). These support the general observation that continuously stirred tank reactor (CSTR) systems
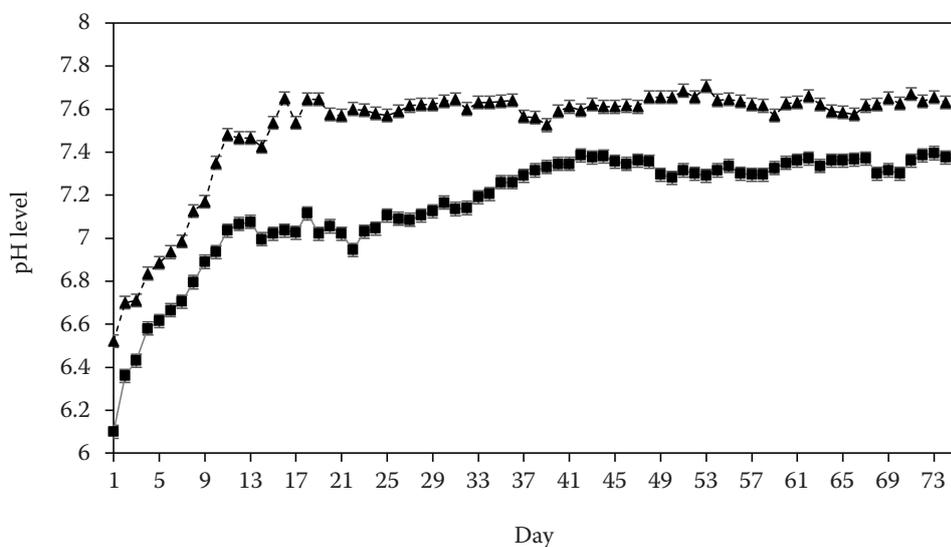

Figure 3. The average pH level in thermophilic (▲) and mesophilic (■) biogas digesters

ensure homogeneity and uniformity of the substrate and prevent settling. This mixing provides better substrate–microorganism contact, thereby enhancing hydrolysis and methanogenesis efficiency (Varol and Ugurlu 2016). As a result, continuous mixed systems generally achieve higher methane yields and more stable operation compared to batch-fed systems. However, although continuous-fed systems with mixing may seem a better setup, there are drawbacks when organic loading rates (OLRs) exceed optimum levels. Excessive loading can cause solids build-up in the bioreactor, mixing limitations, and nutrient deficiencies. These conditions often lead to lower biodegradability performance due to decreased pH and increased volatile fatty acid (VFA) accumulation, which can inhibit methanogenic activity (Ünyay et al. 2022). Thus, while a continuous system offers higher productivity, it requires careful control of OLRs for optimisation and to avoid process instability (Bhajani and Pal 2022).

In terms of household anaerobic digesters which small farmers in developing countries may setup, Jegede et al. (2019) highlights the balance between simplicity and performance. Household designs typically lack internal mixing devices, relying instead on natural mixing via pressure changes from gas production, feeding, and gas usage. This simplicity reduces construction and maintenance costs and makes operation feasible in rural or low-resource settings. However, because mixing is limited, these digesters must operate at low organic loading rates and long hydraulic retention times to maintain stability, which results in relatively low volumetric biogas production and suboptimal substrate degradation compared to forced-mix, engineered digesters. In contrast, forced-mix digesters with internal mixing or recirculation generally achieve higher biogas yields and better waste conversion efficiency due to more uniform substrate distribution and microbial activity, but at the cost of added mechanical complexity, energy consumption, and maintenance needs.

Furthermore, a comparison of the average production rates of the two treatments revealed that the thermophilic setup (0.72 ± 0.04 L·h^{-1}) resulted in a production rate that was 125% higher than that of the mesophilic setup (0.32 ± 0.01 L·h^{-1}). Consequently, the cumulative biogas production throughout the 75-day period was 675.48 ± 49.72 L and 412.26 ± 19.77 L for the thermophilic and mesophilic setups, respectively, resulting in a dif-ference of approximately 40%. The average daily biogas production rates were 0.38 ± 0.15 L·h^{-1} and 0.23 ± 0.07 L·h^{-1} for the thermophilic and mesophilic setups, respectively. A *t* test ($\alpha = 0.05$) revealed that there was a significant difference between the daily production rates of the two groups (*P*-value = 1.20×10^{-11}). Compared with its mesophilic counterpart, the thermophilic digester had a higher biogas production rate. This is because maintaining thermophilic conditions enhances metabolic processes and accelerates the growth of thermophiles, which are known for producing high-quality and large quantities of biogas (Chen et al. 2008; McVoitte and Grant Clark 2019). Additionally, elevated temperatures help eliminate pathogens such as *E. coli*, which are significant contributors to carbon dioxide production during fermentation, while promoting the activity of methanogens (Zinder et al. 1984; Merlin et al. 2003; Budde et al. 2014). As a result, biochemical processes occur more quickly, reducing the substrate retention time and ensuring stable biogas output (Gebreeyessus and Jenicek 2016).

pH level. The pH of the substrate inside the digester was also monitored daily throughout the study. The initial pH of the whole mixture before being put inside the digesters was 6.04, which is within the optimal range of 6.0–8.0 (Garcia et al. 2000). For the thermophilic setup, the pH reached 6.52 ± 0.57 after day 1 of the experiment and then gradually increased to 7.54 ± 0.04 over the next 15 days. After day 18, it almost stabilised at a pH of 7.65 ± 0.01. The highest pH was 7.71 ± 0.06, which occurred on day 53, with a stable production rate of 0.31 ± 0.01 L·h^{-1} maintained for five days. After 15 days, the pH increased from 6.04 to 7.54. From day 1 to the end of the experiment on day 75, the pH ranged from 6.52 to 7.65, which was within the optimal pH range (Garcia et al. 2000).

Moreover, for the mesophilic digester, the pH reached 6.1 ± 0.06 on the first day of operation. Unlike the thermophilic setup, the mesophilic setup demonstrated a slow and steady increase in pH every day. The highest pH reached in the mesophilic setup was 7.4 ± 0.01 on day 73. A comparison of the average pH of the two treatments revealed that the mesophilic setup had a lower pH of 7.15 ± 0.27, whereas the thermophilic setup had an average pH of 7.52 ± 0.26. A *t* test ($\alpha = 0.05$) revealed that there was a significant difference in the pH values of the two groups (*P*-value = 9.32×10^{-15}). Compared with lower

temperatures, higher temperatures cause the pH values to increase (Babaei and Shayegan 2020). The pH inside the digester fluctuates depending on the volatile fatty acids (VFAs) that accumulate during the acidogenesis phase. In the studies of Ge et al. (2011) and Li et al. (2015), the acidogenesis phase limits the anaerobic process, wherein an increase in temperature of 10 °C also increases methane production. Owing to the higher temperature in thermophilic environments, the acidogenesis phase is more rapid than it is in mesophilic environments, as organic material degradation is faster, which leads to its conversion to VFAs (Bhajani and Pal 2022).

Biogas purity. The composition of the biogas was analysed at the Philippine Institute of Pure and Applied Chemistry (PIPAC) at Ateneo De Manila University, Quezon City, Philippines. Owing to the lack of Tedlar bags, the gas samples were collected 16 days after their peak production rate. The thermophilic samples were collected on day 33, whereas the mesophilic samples were collected on day 49. Although both treatments started on the same date, their biogas production rates differed, potentially because of the microorganisms (methanogens) that convert volatile fatty acids (VFAs) into combustible gas.

Using a previously calibrated and tested protocol with a gas chromatography-thermal conductivity detector, the CH_4 and CO_2 concentrations of the biogas samples were measured. The methane content, typically ranging from 40–70%, was 42 ± 10% in the biogas produced by the mesophilic setup and 53.5 ± 10% in the thermophilic setup (Figure 4).

Compared with the methane content, which makes biogas flammable, the biogas from the thermophilic setup was found to have an 11.5% higher methane content than that from the mesophilic setup. However, at α = 0.05, there was no significant difference between the methane content of biogas from the thermophilic and mesophilic setups ($P = 0.19$). Although there was a difference in the average percentage of methane content, the difference was not significant enough to consider that increasing the temperature increased the methane content of biogas. In the study of Cavinato et al. (2013), although the thermophilic digester produced a significantly better biogas yield and volatile solids removal than did the mesophilic digester, there was no significant difference in the methane content between the two temperature ranges.

In terms of carbon dioxide, slightly more biogas from the thermophilic setup than from the me-

sophilic setup. The average carbon dioxide content was 32.5 ± 1% for the mesophilic setup and 35.5 ± 1% for the thermophilic setup (Figure 4). However, a *t* test revealed that there was no significant difference in the CO_2 content of the biogas between the two groups.

Quality of flame. A flame test was conducted to evaluate the quality of the biogas flame, which provides information on its thermal characteristics (i.e. energy content). A 500-mL syringe was used to collect biogas samples, which were later fired to a candle flame, thereby creating a flame that was eventually photographed against a uniform black background. The images were analysed via Colour Picker, a mobile phone application that provides information on the corresponding wavelength of the flame colour.

Visible light ranges from 400 to 700 nanometres. However, the application only has a range from 450–620 nm. As the wavelength approaches the blue flame, the wavelength becomes shorter. The shortest wavelength but with the highest frequency is violet, which ranges from 400–430 nm, followed by blue at 430–480 nm, green at 480–560 nm, yellow at 560–590 nm, orange at 590–620 nm, and red, which has the longest wavelength but shortest frequency at 620–700 nm (Zwinkels 2016). The bluer the flame is, the higher the energy content. The blue flame produced from biogas indicates that methane is its predominant component (Ilminnafik et al. 2017). Photos of the biogas flame were taken every two days, and the middle and tail points of the flame were analysed via colour picking.

A comparison of the average middle and tail point measurements from mesophilic and thermophilic biogas flame samples revealed a longer wavelength (orange flame range) in the first week of opera-
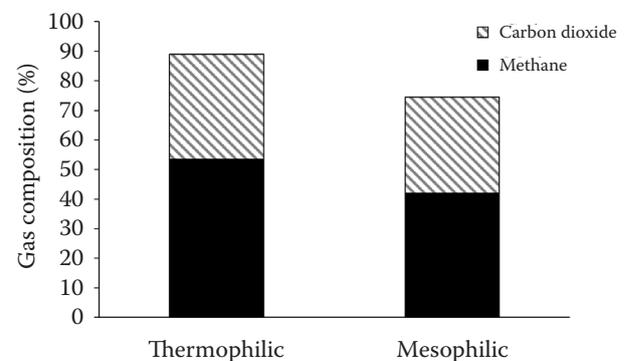

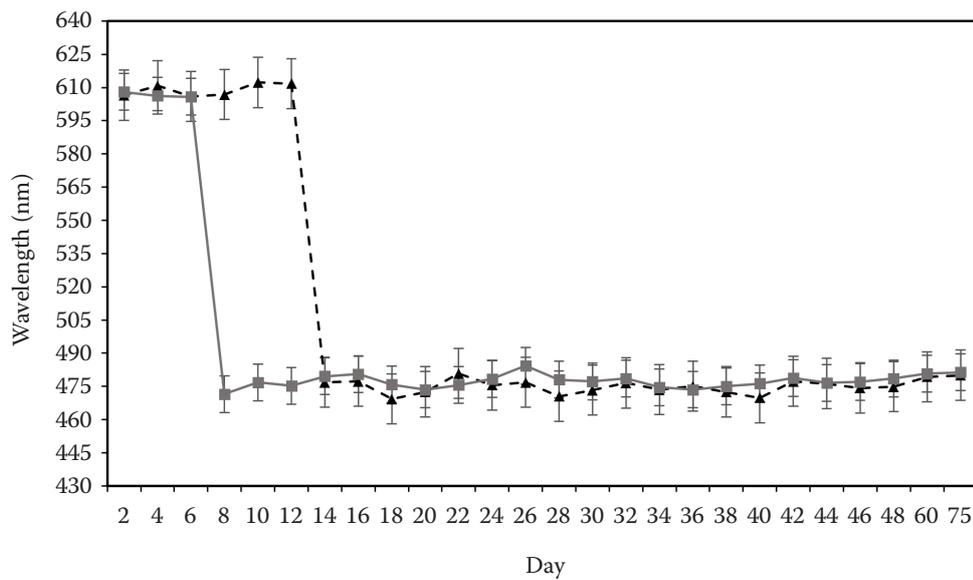Figure 4. Composition of biogas from thermophilic and mesophilic digesters

Figure 5. Average wavelength of the biogas flame from thermophilic (▲) and mesophilic (■) biogas digesters

tion. The mesophilic setup started producing a blue flame on day 8, whereas the thermophilic setup started producing a blue flame on the 12th day. On day 14, both treatments produced blue flames in the range of 474–480 nm (Figure 5). The blue flame from the thermophilic setup was discovered to have a shorter average wavelength at the middle and tail points of the flame. A shorter wavelength corresponds to a bluer colour and higher energy content, which agrees with the results of gas chromatography shown in Figure 4.

However, a *t* test ($\alpha = 0.05$) revealed that there was no significant difference between the thermophilic and mesophilic setups in terms of flame colour. Therefore, in terms of purity and, consequently, the energy content of the biogas, it can be deduced that the biogas from the two setups have more or less the same values.

CONCLUSION AND RECOMMENDATIONS

This study successfully showed the effects of the temperature of the digester on the biogas production rate and purity. Over the course of the study, the pH starts at acidic levels and ends at slightly alkaline levels. The higher pH in the thermophilic setup caused more successful substrate degradation, hence a higher production rate than that in the mesophilic setup. In conclusion, a relatively high temperature of the digester contributes to increased biogas production.

In terms of biogas purity, the methane content of the biogas from the thermophilic setup was greater than that from the mesophilic setup, but the difference was not statistically significant. Hence, it is not conclusive whether increasing the temperature of the digester can improve the purity of the resulting biogas. This was supported by the results of the analysis of photographs from the flame tests. Although the mesophilic setup produced blue-flamed biogas earlier than the thermophilic setup did, the corresponding wavelengths of the flame colours were not significantly different.

For future studies, a continuous type of digester is recommended to further understand how temperature affects biogas production and quality. Continuous gas sampling will also provide more data for comparing biogas purity in thermophilic and mesophilic setups and will enable temporal studies on biogas purity. For a more accurate characterisation of biogas from the experiments, gas chromatograph/mass spectrometer shall be used.

REFERENCES

Adebayo A.O., Jekayinfa S.O., Linke B. (2015): Effects of organic loading rate on biogas yield in a continuously stirred tank reactor experiment at mesophilic temperature. British Journal of Applied Science & Technology, 11: 1–9.

Babaei A., Shayegan J. (2020): Effects of temperature and mixing modes on the performance of municipal solid waste anaerobic slurry digester. Journal of Environmental Health Science and Engineering, 17: 1077–1084.

Barz M., Delivand M.K., Dinkler K. (2019): Agricultural wastes – A promising source for biogas production in developing countries of the tropical and subtropical regions. Revista Forestal Mesoamericana Kurú, 16: 2–12.

Bhajani S., Pal S. (2022): Review: Factors affecting biogas production. International Journal for Research in Applied Science & Engineering Technology, 10: 79–88.

Budde J., Heiermann M., Quiñones T.S., Plöchl M. (2014): Effects of thermobarical pretreatment of cattle waste as feedstock for anaerobic digestion. Waste Management, 34: 522–529.

Castrillón L., Fernández-Nava Y., Ormaechea P., Marañón E. (2011): Optimization of biogas production from cattle manure by pre-treatment with ultrasound and co-digestion with crude glycerin. Bioresource Technology, 102: 7845–7849.

Cavinato C., Bolzonella D., Pavan P., Fatone F., Cecchi F. (2013): Mesophilic and thermophilic anaerobic co-digestion of waste activated sludge and source sorted biowaste in pilot- and full-scale reactors. Renewable Energy, 55: 260–265.

Chen Y., Cheng J.J., Creamer K.S. (2008): Inhibition of anaerobic digestion process: A review. Bioresource Technology, 99: 4044–4064.

Chen X., Zhang Y., Gu Y., Liu Z., Shen Z., Chu H., Zhou X. (2014): Enhancing methane production from rice straw by extrusion pretreatment. Applied Energy, 122: 34–41.

Dai B., Guo X., Yuan D., Xu J. (2017): Comparison of different pretreatments of rice straw substrate to improve biogas production. Waste and Biomass Valorization, 9: 1503–1512.

Food and Agriculture Organisation of the United Nations (2024): Livestock and Enteric Methane. Available at https://www.fao.org/in-action/enteric-methane/en

Garcia J.-L., Patel B.K.C., Ollivier B. (2000): Taxonomic, phylogenetic, and ecological diversity of methanogenic Archaea. Anaerobe, 6: 205–226.

Ge H., Jensen P.D., Batstone D.J. (2011): Relative kinetics of anaerobic digestion under thermophilic and mesophilic conditions. Water Science & Technology, 64: 848–853.

Gebreeyessus G.D., Jenicek P. (2016): Thermophilic versus mesophilic anaerobic digestion of sewage sludge: A comparative review. Bioengineering, 3: 15.

Ghatak M.D., Mahanata P. (2018): Effect of temperature on biogas production from rice straw and rice husk. IOP Conference Series: Materials Science and Engineering, 377: 012146.

Gribanov M. (2016): Colour Picker (Version 7.7) [Mobile application software]. Available at https://play.google.com/store/apps/details?id=gmikhail.colorpicker&hl=en&gl=US

Harish Kumar D.K., Indianraj N. (2022): Biogas production and its uses in agriculture. EPRA International Journal of Agriculture and Rural Economic Research, 10: 45–48.

Haryanto A., Hasanudin U., Afrian C., Zulkarnaen I. (2018a): Biogas production from anaerobic codigestion of cowdung and elephant grass (*Pennisetum purpureum*) using batch digester. IOP Conference Series: Earth and Environmental Science, 141: 012011.

Haryanto A., Sugara B.P., Telaumbanua M., Rosadi R.A.B. (2018b): Anaerobic co-digestion of cow dung and rice straw to produce biogas using semi-continuous flow digester: Effect of urea addition. IOP Conference Series, 147: 012032.

Huang X., Yun S., Zhu J., Du T., Zhang C., Li X. (2016): Mesophilic anaerobic co-digestion of aloe peel waste with dairy manure in the batch digester: Focusing on mixing ratios and digestate stability. Bioresource Technology, 218: 62–68.

Ilminnafik N., Listyadi D.S., Sutjahjono H. (2017): Thermal characteristic of flame as quality parameter of biogas of market waste. International Journal of Applied Environmental Sciences, 12: 1379–1385.

Ilminnafik N., Setiyawan D.L., Sutjahjono H., Rofiq A., Hadi A.S. (2019): Flame characteristics of biogas from coffee waste materials. Journal of Physics: Conference Series, 1175: 012273.

Jegede A.O., Zeeman G., Bruning H. (2019): A review of mixing, design and loading conditions in household anaerobic digesters. Critical Reviews in Environmental Science and Technology, 49: 1–37.

Kim M., Kim B.-C., Nam K., Choi Y. (2018): Effect of pretreatment solutions and conditions on decomposition and anaerobic digestion of lignocellulosic biomass in rice straw. Biochemical Engineering Journal, 140: 108–114.

Kokieva G.E., Protodiakonova G.P., Dondokov U.Z., Shalbuev D.V., Voinash S.A. (2020): Production of biogas using method of agricultural waste fermentation. IOP Conference Series: Materials Science and Engineering, 941: 012019.

Li D., Liu S., Mi L., Li Z., Yuan Y., Yan Z., Liu X. (2015): Effects of feedstock ratio and organic loading rate on the anaerobic mesophilic co-digestion of rice straw and cow manure. Bioresource Technology, 189: 319–326.

Li Y., Alaimo C.P., Kim M., Kado N.Y., Peppers J., Xue J., Wan C., Green P.G., Zhang R., Jenkins B.M., Vogel C.F.A., Wuertz S., Young TM, Kleeman M.J. (2019): Composition and toxicity of biogas produced from different feedstocks in California. Environmental Science & Technology, 53: 11569–11579.

Luo J., Li J., Zhang L., Li N., Wachemo A.C., Liu C., Yuan H., Li X. (2020): Effects of different potassium and nitrogen pretreatment strategies on anaerobic digestion performance of rice straw. RSC Advances, 10: 25547–25556.

Luo L., Qu Y., Gong W., Qin L., Li W., Sun Y. (2021): Effect of particle size on the aerobic and anaerobic digestion characteristics of whole rice straw. Energies, 14: 3960.

McVoitte W.P.A., Grant Clark O. (2019): The effects of temperature and duration of thermal pretreatment on the

solid-state anaerobic digestion of dairy cow manure. Heliyon, 5: e02140.

Merlin C., Masters M., McAteer S., Coulson A. (2003): Why is carbonic anhydrase essential to Escherichia coli? Journal of Bacteriology, 185: 6415–6424.

Mustafa A.M., Poulsen T.G., Xia Y., Sheng K. (2017): Combinations of fungal and milling pretreatments for enhancing rice straw biogas production during solid-state anaerobic digestion. Bioresource Technology, 224: 174–182.

Narula A., Wati L. (2014): Paddy straw supplementation to cattle dung for enhanced biogas production and enrichment of effluent slurry. Journal of Pure and Applied Microbiology, 8: 3269–3272.

Okonkwo U.C., Onokpite E., Onokwai A.O. (2018): Comparative study of the optimal ratio of biogas production from various organic wastes and weeds for digester/restarted digester. Journal of King Saud University – Engineering Sciences, 30: 123–129.

Pathak B.S., Jain A.K., Dev D.S. (1985): Biogasification of cattle dung and cattle dung–rice straw mixture at different solid concentrations. Agricultural Wastes, 13: 251–259.

Ranade D.R., Yeole T.Y., Godbole S.H. (1987): Production of biogas from market waste. Biomass, 13: 147–153.

Sahare T., Rana S., Sahoo B.N., Khanda M., Joshi A. (2025): Smartphone-based colorimetric detection of urinary glucose using a novel green and red/green approach. Biosensors and Bioelectronics: X, 26: 100650.

Salam B., Biswas S., Das T.K. (2011): Biogas from thermophilic anaerobic digestion of cow dung. In: The International Conference on Mechanical Engineering 2011, Dhaka, Bangladesh.

Saravanan G., Thiyagarajan P. (2025): Optimizing biogas production from food waste and cow dung: Impact of mixing ratios. Periodica Polytechnica Chemical Engineering, 69: 302–312.

Seman S.Z.A., Idris I., Abdullah A., Shamsudin I.K., Othman M.R. (2019): Optimizing purity and recovery of biogas methane enrichment process in a closed landfill. Renewable Energy, 131: 1117–1127.

Singh B., Szamosi Z., Siménfalvi Z. (2020): Impact of mixing intensity and duration on biogas production in an anaerobic digester: A review. Critical Reviews in Biotechnology, 40: 508–521.

Sivakumar P., Saravanane R., Mohan S., Sankar B. (2025): Biochar as a catalyst for methane enhancement in anaerobic digestor containing cow dung, food waste, and rice straw: An experimental and statistical study. Cleaner Waste Systems, 12: 100388.

Smith P., Reay D., Smith J. (2021): Agricultural methane emissions and the potential for mitigation. Philosophical Transactions of the Royal Society A, 379: 20200451.

Sunada N.D.S., Orrico A.C.A., Orrico Júnior M.A.P., Miranda de Vargas Junior F., Garcia R.G., Fernandes A.R.M. (2012): Potential of biogas and methane production from anaerobic digestion of poultry slaughterhouse effluent. Revista Brasileira de Zootecnia, 41: 2379–2383.

Sutono, Ginting S.L.B., Ginting Y.R., Udiata K.W. (2022): Automatic paint color mixer using Mikhail Gribanov color picker application and Bluegiga WT11 bluetooth. In: Proceedings of the 5th International Conference on Informatics Engineering, Science & Technology (INCITEST) 2022, Bandung, Indonesia: 040042.

Ünyay H., Yılmaz F., Başar İ.A., Perendeci N.A., Çoban I., Şahinkaya E. (2022): Effects of organic loading rate on methane production from switchgrass in batch and semi-continuous stirred tank reactor system. Biomass and Bioenergy, 156: 106306.

Uzodinma E.O.U., Ofoefule A.U., Eze J.I., Onwuka N.D. (2007): Optimum mesophilic temperature of biogas production from blends of agro-based wastes. Trends in Applied Sciences Research, 2: 39–44.

Varol A., Ugurlu A. (2016): Comparative evaluation of biogas production from dairy manure and co-digestion with maize silage by CSTR and new anaerobic hybrid reactor. Engineering in Life Sciences, 17: 402–412.

Xu Z., Yuan H., Li X. (2021): Anaerobic bioconversion efficiency of rice straw in continuously stirred tank reactor systems applying longer hydraulic retention time and higher load: One-stage vs. two-stage. Bioresource Technology, 321: 124206.

Yadav N.K., Singh A.K. (2018): Factors affecting biogas production during anaerobic digestion – A review. International Journal of Creative Research Thoughts, 6: 1276–1282.

Yilmaz A., Ünvar S., Kocer A., Aygun B. (2018): Factors affecting the production of biogas. International Journal of Scientific and Engineering Research, 9: 59–62.

Yusuf S.S., Ismail M., Jibrin A., Ahmed A., Salim S.A., Hassan M. (2025): Synergistic co-digestion of invasive typha latifolia (cattail) and cattle dung: Biogas enhancement, process stability, and modified gompertz kinetics. SSRN Electronic Journal: 1–25.

Zinder S.H., Anguish T., Cardwell S.C. (1984): Effects of temperature on methanogenesis in a thermophilic (58 degrees C) anaerobic digestor. Applied and Environmental Microbiology, 47: 808–813.

Zwinkels J.C. (2016): Light, electromagnetic spectrum. In: Luo R. (ed): Encyclopedia of Color Science and Technology. New York: Springer Reference: 1–8.