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IoT-Enabled Monitoring and Methane Energy Forecasting in Tofu Waste Biogas Systems for Electricity Generation

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***Abstract*—**This study presents the development of an Internet of Things based monitoring system and methane energy forecasting for biogas production from tofu wastewater in Somber, Balikpapan. A 1000 L anaerobic biodigester was installed at a home scale tofu industry to process liquid tofu waste through anaerobic fermentation. The monitoring system utilized three ESP32 microcontrollers integrated with MQ-4 methane sensors, DHT11 temperature–humidity sensors, BMP180 pressure sensors, and ultrasonic level sensors. Data were transmitted every 8–10 seconds to Google Spreadsheet via Wi-Fi for real time monitoring. Observations were conducted over a 21-day fermentation period. The results show that methane concentration increased from approximately 4,720–4,810 ppm on day 13 to 5,000–5,050 ppm on day 21. Humidity remained relatively stable between 93.6% and 94.2%, while temperature ranged from 31.5°C to 42.6°C. The average methane quantity was estimated at 1.42×10^7 mol, corresponding to a theoretical energy potential of approximately 3.17×10^6 kWh. These results indicate strong potential for small scale biogas based power generation.

***Keywords*—**Biogas, Internet of Things (IoT), Methane gas, Monitoring fermentation process, Forecasting biogas power

I. Introduction

The management of wastewater generated by tofu industries has increasingly drawn environmental attention due to its high concentration of organic matter, including proteins, fats, carbohydrates, and suspended solids capable of causing significant ecological degradation if improperly disposed of (Marsyea et al., 2025; Zahrina & Yenie, 2022). In recent years, increased attention to renewable energy has highlighted the potential of tofu wastewater as a substrate for anaerobic digestion, a process that converts organic compounds into biogas with methane as the dominant component (Rajagukguk, 2020). Contemporary studies show that tofu wastewater possesses a high Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD), positioning it as a highly favorable feedstock for biogas production (Rindiani, 2023). This bioconversion not only mitigates environmental pollution but also supports localized energy independence, particularly for small- and medium-scale food processing industries (Mufarida & Abidin, 2021; Sally et al., 2019). Despite its potential, the efficiency of anaerobic digestion is strongly influenced by the stability of crucial process parameters such as temperature, humidity, pH, pressure, substrate level, and the concentration of gases produced (Mira et al., 2018). Fluctuations in these conditions can inhibit microbial activity, delay methanogenesis, or reduce methane yield (Kalsum et al., 2024). State-of-the-art research emphasizes that maintaining optimal mesophilic conditions is essential for maximizing methane output and ensuring long-term biodigester performance (Issahaku et al., 2024; Meegoda et al., 2025). To address this need, modern biogas research is increasingly adopting digital monitoring strategies using sensor-based systems that collect and analyze data continuously.

A development of Internet of Things (IoT) technologies has enabled significant advances in real-time monitoring of anaerobic digesters. IoT integration with embedded microcontrollers such as ESP32, Raspberry Pi, and NodeMCU has enabled the deployment of low-cost environmental sensing systems capable of measuring methane concentration, temperature, pressure, humidity, and liquid level (Djohar et al., 2025; Hernández et al., 2025). Although these innovations are promising, many existing systems rely on local servers, offline databases, or complex network configurations that limit scalability and flexibility. In previous research conducted at the Somber Tofu Industry in Balikpapan, an IoT-based monitoring system was successfully developed using ESP32, MQ-4 methane sensors, DHT22 temperature–humidity sensors, and Google Spreadsheet as a cloud-integrated data repository (Oktafiani et al., 2025). This approach uses a lightweight cloud-connected monitoring architecture and removes the need for dedicated servers, making it practical for small-scale industrial applications

Although the system provided reliable real-time data, the previous study had not yet evaluated methane production patterns over a full one-month fermentation period. Recent literature emphasizes the importance of long-term analysis to understand microbial dynamics, including the transitions from acidogenesis to methanogenesis, as well as to optimize biogas output. Furthermore, a previous study highlights the importance of converting biogas into electrical energy using methane calorific value calculations to evaluate its feasibility for small-scale industries (Rindiani, 2023).

Therefore, this extended study expands upon prior work by integrating additional sensors such as BMP-180 for pressure measurement and ultrasonic sensors for liquid-level monitoring, enabling more comprehensive biodigester characterization. It further analyzes a one-month dataset to identify methane production trends, conducts forecasting of methane output, and estimates electrical energy potential (kWh). Through this integrated approach, the research provides a detailed assessment of the renewable energy prospects of tofu wastewater at the Somber Balikpapan Tofu Industry and contributes to the advancement of IoT-driven sustainable bioenergy systems.

II. LITERATURE REVIEW

Research on organic industrial waste has increasingly emphasized tofu wastewater as a high-potential feedstock for biogas generation due to its rich organic composition and rapid biodegradability (Sharma et al., 2023). Unlike the introduction section, which highlights general relevance, literature explicitly documents that tofu-processing effluent contains elevated COD, BOD, nitrogenous compounds, and suspended solids, making it particularly suitable for anaerobic digestion. Studies indicate that tofu waste can generate biogas with methane content reaching 50–80%, depending on digester conditions and fermentation duration (Hartini, 2024). This positions tofu effluent as a competitive waste-to-energy substrate compared to livestock manure or municipal organic waste (Budiyono & Syaichurrozi, 2020).

Parallel to advances in waste-to-energy systems, the development of Internet of Things (IoT)–integrated monitoring technology has employed, enabling precise, continuous, and low-cost data acquisition from biodigesters (Saputra et al., 2024; Ibarra-Esparza et al., 2025). Unlike traditional manual monitoring, IoT systems employ sensors such as MQ-4 (methane), DHT-11 (temperature–humidity), BMP-180 (pressure), and ultrasonic level sensors, which together capture the multi-variable dynamics of microbial activity. Current literature emphasizes that such IoT-based monitoring improves the reliability of methane prediction models, enhances safety, and supports automated data logging via cloud platform (Ntaganda et al., 2024). This technological shift makes real-time process optimization feasible not only for large facilities but also for small-scale tofu industries.

Beyond monitoring, methane's primary relevance lies in its energetic value, making it a viable fuel for electricity production. The Lower Heating Value (LHV) of methane, widely used in energy-conversion literature—including in your attached PLTSa Manggar study—serves as the basis for estimating biogas energy potential (Kusuma et al., 2020). Equation (1) calculates the total chemical energy contained in the methane produced during fermentation. The variable n_{CH_4} represents the number of moles of methane, while 802 kJ/mol is the Lower Heating Value (LHV) of methane—indicating how much energy is released when one mole of methane is combusted. This step quantifies the potential energy stored in the biogas before any conversion losses.

$$E_{chemical} = n_{CH_4}\ x\ 802\ J \quad (1)$$

After determining the methane's chemical energy in kilojoules, Equation (2) converts the value into kilowatt-hours (kWh), which is the standard unit for electrical energy. Since 1 kWh = 3,600 kJ, dividing the chemical energy by 3,600 provides an estimate of how much electrical energy could theoretically be generated from the methane produced.

$$E_{kWh} = \frac{E_{chemical}}{3600} \quad (2)$$

Equation (3) estimates the real amount of electricity that a generator can produce by incorporating its efficiency, denoted as η. Because generators typically operate at only 18–30% efficiency, only a fraction of the theoretical energy is converted into usable electricity.

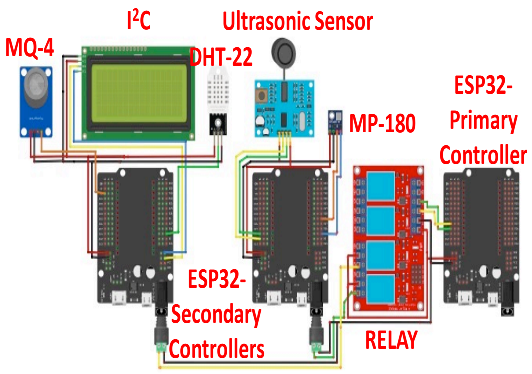
$$E_{electricity} = E_{kWh}\ x\ \eta \quad (3)$$

Multiplying the theoretical energy E_{kWh} by the efficiency value gives the actual electrical output available for practical use.

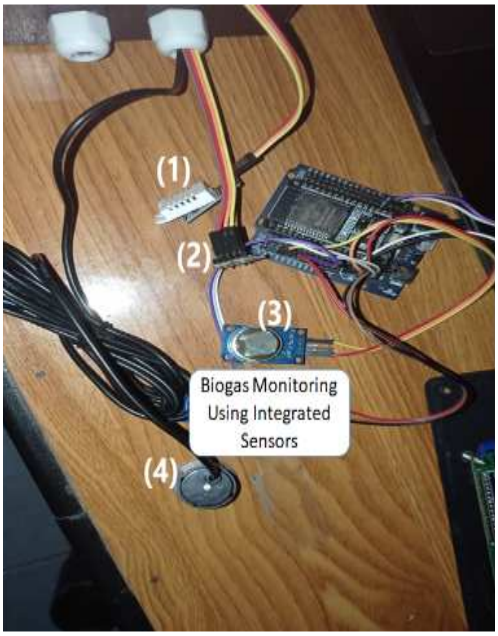
III. METHODS

This study employed an Internet of Things (IoT)–based monitoring system using an ESP32 microcontroller as the central data acquisition and communication unit. Several environmental and gas sensors were integrated into the system to monitor the anaerobic digestion process in real time.

The sensors included the MQ-4 methane sensor, the DHT11 for temperature and humidity, and the BMP180 for atmospheric pressure—were connected through digital and I²C interfaces. The system utilizes three ESP32 microcontrollers, one ESP32 functions as the primary controller responsible for controlling the ON/OFF operation of the other two ESP32 units via a Telegram-based remote control interface. The remaining ESP32 devices operate as secondary controllers and are dedicated to sensor data acquisition and monitoring tasks. An ultrasonic sensor (HC-SR04) was positioned at the upper section of the digester to measure fluid height and indirectly calculate gas volume within the reactor. All modules shared a common ground and power supply consistent with their operational voltage requirements, and the wiring configuration followed the schematic illustrated in Figure 1(a).



(a)



(b)

Figure 1. (a) Wiring diagram of the IoT biogas monitoring system (b) Configuration of the sensors used

The specifications of the sensors used, as shown in Figure 1(b), are presented in Table 1.

Table 1. Sensor descriptions (in Figure 2) and their specifications

No.	Sensor descriptions		
	Sensor Type	Function	Specifications
1	MQ-4	Methane gas concentration measurement	Operating voltage: 5 V DC Dimensions: 20.4 × 32.4 mm
2	DHT22	Temperature and relative humidity measurement	Accuracy resolution:0.1. Humidity range:0-100%RH. Humidity measurement precision:2%RH. - 3-pin package
3	JSN-SR04T K20 Ultrasonic Sensor	Biogas level measurement	Operating voltage: DC 5V, Acoustic emission frequency: 40khz Farthest distance: 4.5m Blind area: under 25cm Dimensions: 41mm x 28.5mm Resolution: about 0.5cm
4	BMP-180	Gas pressure measurement	Pressure range: 300 ~ 1100hPa (elevation of 9000 meters to -500 meters) Power supply voltage: 1,8V ~ 3,6V (VDDA), 1,62V ~ 3,6V (VDDD) Dimensions: 3,6x3,8x0,93CM Low power consumption: 5μA in standard mode High precision: the resolution of 0,06hPa (0,5 meters)

Figure 2 shows the research process flowchart. During operation, the ESP32 collected sensor data at 10-second intervals for a duration of 10 minutes per session.

Data acquisition was conducted three times over a 21-day fermentation period. Each reading included temperature, humidity, pressure, liquid level, and gas concentration values. The microcontroller converted analog readings to ppm and performed corrections for temperature and humidity as necessary. Data were transmitted via Wi-Fi to Google Spreadsheet using an HTTP POST method, ensuring continuous cloud-based storage.

Biogas energy calculations were performed using methane concentration obtained from the MQ-4 sensor. Methane fraction was determined by converting ppm values into molar fraction. The total moles of gas in the digester headspace were estimated using the ideal gas law, and methane moles were obtained by multiplying total moles by methane fraction. Collected data were processed to remove outliers, visualize temporal trends, and compute cumulative methane and energy production. This methodological framework ensured accurate, continuous, and comprehensive monitoring of biogas generation from tofu wastewater.

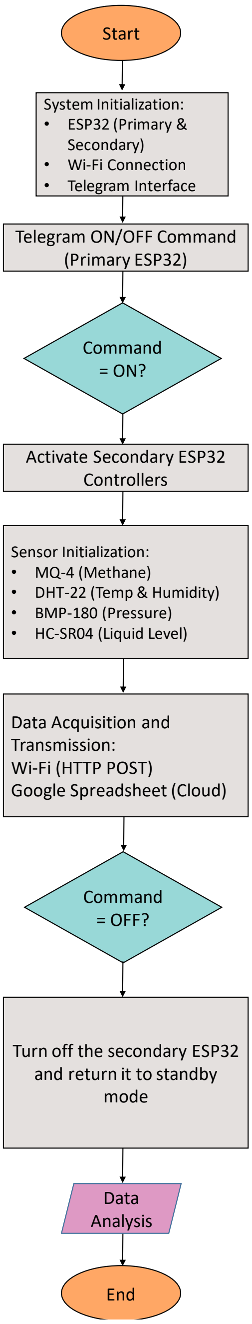


Figure 2. Flowchart of the research process

IV. Results and Discussion

A. *Utilization of tofu wastewater for biogas production using a 1000 L biodigester*

Figure 3(a) shows tofu wastewater collected from home-scale tofu industries in Somber, Balikpapan. In this study, a 1000 L biodigester system was successfully designed and constructed to utilize tofu industrial wastewater for biogas production, as shown in Figure 3(b). The system was developed to collect and process liquid waste generated from tofu production through anaerobic fermentation. The installation consists of several main components. Figure 3(c) and (d) shows the placement of sensors on the biodigester.

The main biodigester (1000 L) serves as an anaerobic reactor where the fermentation of tofu wastewater takes place. Within this reactor, anaerobic microorganisms decompose organic matter to produce methane gas (CH_4) as the primary energy output. In addition to biogas, the process generates liquid organic fertilizer as a by-product, which can be further utilized for agricultural purposes.

(a)

(b)

(c)

(d)

Figure 3. (a) Tofu wastewater storage at tofu industries in Somber, Balikpapan. (b) Installation of a 1000 L biodigester at the tofu wastewater outlet of a home-based tofu industry (c) Sensor probe (d) Integrated sensors on the biodigester. When turned on, the sensors transmit data to Google Spreadsheet, which can be accessed using a mobile phone or a laptop.

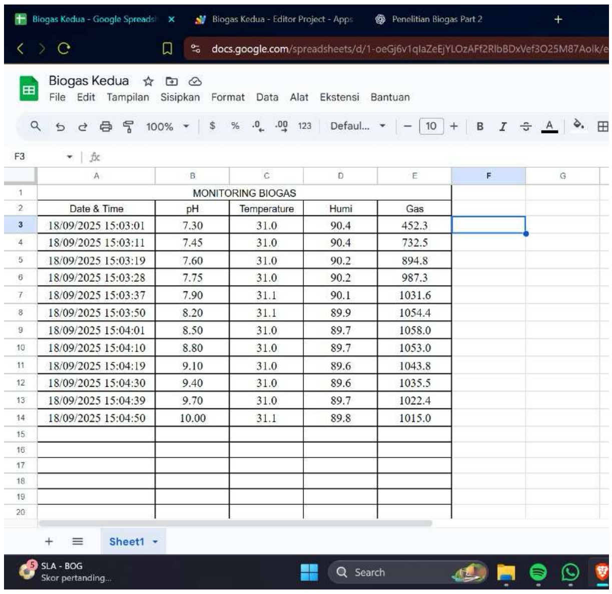
The system is equipped with a distribution piping and flow control unit, constructed using PVC pipes with multiple elbow joints and control valves. Yellow ball valves are installed to facilitate flow regulation, enabling controlled inlet of wastewater into the biodigester as well as pressure management within the gas line.

An IoT-based monitoring system is integrated into the main biodigester to observe critical operational parameters, including temperature, pH, methane gas concentration (ppm), biogas level, and pressure. Sensor data are transmitted in real time to a cloud-based server, allowing operators to remotely monitor biodigester performance and fermentation stability.

Based on the installation results, the system was properly assembled, including the pre-conditioning tank, main biodigester, and distribution piping. All sensors were successfully installed and are functioning to monitor the fermentation process.

This study employed three ESP32 microcontrollers, consisting of one primary controller and two secondary nodes. The primary ESP32 was connected to a relay module to remotely activate and deactivate the secondary ESP32 nodes via Telegram. The first secondary node was equipped with an MQ-4 gas sensor and a DHT11 temperature–humidity sensor, while the second node integrated an ultrasonic sensor and a BMP180 pressure sensor. The secondary ESP32 nodes can be selectively powered on or off individually or simultaneously through Telegram. Figure 4(a) shows the Telegram application interface, and Figure 4(b) displays the monitoring data recorded in Google Spreadsheet and converted to .xlsx.

(a)



MONITORING BIOGAS

Date & Time	pH	Temperature	Humi	Gas
18/09/2025 15:03:01	7.30	31.0	90.4	452.3
18/09/2025 15:03:11	7.45	31.0	90.4	732.5
18/09/2025 15:03:19	7.60	31.0	90.2	894.8
18/09/2025 15:03:28	7.75	31.0	90.2	987.3
18/09/2025 15:03:37	7.90	31.1	90.1	1031.6
18/09/2025 15:03:50	8.20	31.1	89.9	1054.4
18/09/2025 15:04:01	8.50	31.0	89.7	1058.0
18/09/2025 15:04:10	8.80	31.0	89.7	1053.0
18/09/2025 15:04:19	9.10	31.0	89.6	1043.8
18/09/2025 15:04:30	9.40	31.0	89.6	1035.5
18/09/2025 15:04:39	9.70	31.0	89.7	1022.4
18/09/2025 15:04:50	10.00	31.1	89.8	1015.0

(b)

Figure 4. (a) Telegram was utilized as the control interface for activating and deactivating the secondary ESP32 nodes (b) The Google Spreadsheet interface

B. Monitoring results of methane concentration, temperature, and humidity

The MQ-4 gas sensor calibration commonly utilizes the relationship between output voltage and gas concentration (ppm) because the sensor provides an analog voltage output that directly corresponds to changes in sensor resistance due to methane exposure. Since microcontrollers acquire sensor data in the form of voltage, this approach simplifies data acquisition and processing.

Although the MQ-4 datasheet defines the sensor response based on the R_s/R_0–ppm relationship, converting it into a voltage–ppm model is more practical for embedded system implementation. In the absence of standard methane calibration gases, this method provides an estimated concentration that is sufficient for monitoring and trend analysis in biogas applications, rather than precise quantitative measurement. Figure 5 shows the characterization results of the MQ-4 sensor as a function of methane concentration (ppm) and output voltage (V).

The regression analysis of the MQ-4 sensor characterization demonstrates a strong linear relationship between methane concentration and the output voltage. The obtained regression model is expressed as Equation 4.

$$y = 0.30492 + 6.60104\ x\ 10^{-4} x \quad (4)$$

x denotes methane concentration in ppm. The intercept value of 0.30492 V indicates the baseline sensor voltage in the absence of methane, while the slope reflects the sensor sensitivity to changes in gas concentration. Statistical evaluation shows a high Pearson correlation coefficient of 0.99684 and an adjusted coefficient of determination (Adjusted R^2) of 0.99344, indicating that the regression model explains more than 99% of the data variance. The low residual sum of squares confirms that the deviation between measured and modeled values is minimal. These results suggest that the MQ-4 sensor provides stable and consistent voltage responses within the tested concentration range, and that the measurement error of the sensor does not significantly affect the linearity of the calibration curve.

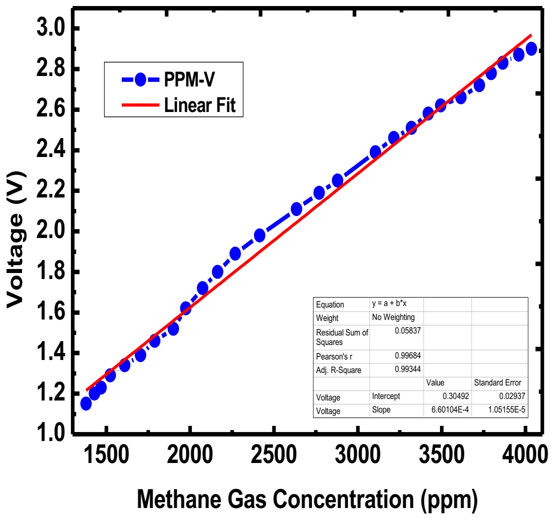


Figure 5. Linearity curve of methane gas concentration versus voltage

Table 2 presents the monitoring results of methane concentration, humidity, and temperature measured on Day 13, Day 17, and Day 21 of the biogas fermentation process. The monitoring data were continuously recorded using Google Spreadsheet with a sampling interval of approximately 8–10 seconds over a period of 10 minutes for each observation day. Due to the large volume of recorded data, only ten representative data points are displayed in Table 2 to provide a concise overview of the measurement trends without compromising data clarity.

The humidity values show a relatively stable pattern, consistently remaining within the range of approximately 93.6% to 94.2% across all observation days. This stability indicates that the moisture conditions inside the digester were well maintained during the monitoring period. Such stable humidity levels are essential for supporting anaerobic microbial activity, as microorganisms involved in biogas production require a moist environment to sustain metabolic processes. During the second and third weeks of fermentation, this stable humidity suggests that the digestion process had reached a relatively steady operational state, allowing microbial consortia to function effectively.

A gradual increase in methane concentration is observed over time, with higher values recorded on Day 21 compared to Day 13 and Day 17. This trend reflects the progression of the anaerobic digestion process, as methane-producing bacteria become more dominant and active as fermentation advances, particularly following the stabilization of microbial consortia during the later stages of digestion. In contrast, temperature variations exhibit a different pattern and appear to be more strongly influenced by ambient weather conditions and surrounding environmental temperature rather than by metabolic heat generated within the digester. These fluctuations indicate that temperature was not solely governed by internal biochemical reactions. Overall, the results demonstrate that methane production increases with fermentation maturity, humidity remains relatively stable and supportive of microbial activity, and temperature is largely affected by external environmental factors, highlighting the importance of environmental control for consistent biogas performance (Akash et al., 2025).

In this context, the strategic implementation of anaerobic digestion can markedly improve energy yield and sustainability, as optimized operational conditions, supported by focused policies and advanced technological practices, enable more efficient biogas utilization. Furthermore, insights from large-scale applications in regions such as China and Europe provide valuable references for enhancing environmental performance and guiding the development of sustainable biogas systems in similar settings (Alengebawy et al., 2024).

Table 2. Results of methane concentration, temperature, and humidity

C. Monitoring results of biogas production

No.	Day-	Measurement Parameters		
		Methane (ppm)	Humadity (%)	Temperature (°C)
1	13rd	4720	94.2	31.5
		4755	94.1	31.5
		4780	94.1	31.6
		4790	94.1	31.6
		4800	94.1	31.6
		4810	94.0	31.6
		4780	94.0	31.7
		4780	94.0	31.7
		4755	94.1	31.7
		4730	94.1	31.7
2	17th	4800	94.2	36.2
		4815	94.2	36.2
		4820	94.2	36.2
		4855	94.1	36.3
		4845	94.1	36.3
		4830	94.2	36.3
		4845	94.2	36.3
		4850	94.1	36.3
		4865	94.1	36.3
		4860	94.0	36.3
3	21st	5000	93.9	42.5
		5015	93.8	42.5
		5000	93.8	42.5
		5005	93.8	42.5
		5000	93.8	42.5
		5005	93.8	42.5
		5035	93.8	42.5
		5050	93.8	42.5
		5050	93.7	42.6
		5045	93.6	42.6

The amount of biogas produced was determined by integrating measurements from an ultrasonic sensor and a pressure–temperature sensor (BMP180), the results were shown in Table 3. The ultrasonic sensor was employed to measure the distance between the sensor and the liquid surface inside the biogas storage tank. By subtracting this distance from the known total height of the tank, the liquid level was obtained. The liquid level was then converted into liquid volume based on the geometric proportion of the cylindrical tank, while the gas volume was calculated as the remaining volume inside the tank. To improve measurement reliability, multiple ultrasonic readings were acquired and averaged, with invalid readings filtered to reduce noise and reflection errors. Pressure and temperature data were measured using the BMP180 sensor, which operates based on piezoresistive pressure sensing and an integrated temperature sensor.

Similar to the ultrasonic measurements, pressure and temperature readings were averaged over several samples to obtain stable values. The measured temperature was converted from degrees Celsius to Kelvin for thermodynamic calculations.

The number of moles of gas was calculated using the ideal gas law, with the measured pressure, calculated gas volume, and absolute temperature used as input parameters. This approach enables indirect estimation of the gas quantity without direct gas flow measurement.

Table 3. Results of biogas production

No.	Day-	Measurement Parameters: Waste tofu liquid level (cm)	Total Gas Volume (mol)	STP Volume (L)
1	13rd	94.74	14,658,342	330.94
		94.73	14,660,645	330.99
		94.75	14,655,020	330.86
		94.74	14,658,109	330.93
		94.73	14,660,674	330.99
		94.98	14,594,360	329.49
		94.89	14,617,914	330.03
		94.99	14,591,215	329.42
		94.81	14,639,279	330.51
		94.70	14,668,108	331.16
2	17th	94.76	14,457,396	324.03
		94.84	14,437,984	323.59
		94.87	14,439,442	323.63
		94.86	14,442,517	323.70
		94.58	14,514,420	325.31
		94.68	14,490,373	324.77
		94.35	14,575,891	326.69
		94.67	14,493,104	324.83
		94.67	14,492,500	324.82
		94.66	14,491,269	324.79
3	21st	93.86	14,167,166	317.52
		93.87	14,197,776	318.21
		93.83	14,226,740	318.86
		93.86	14,237,340	319.10
		93.83	14,258,619	319.57
		93.86	14,258,657	319.58
		93.81	14,284,284	320.15
		93.87	14,279,804	320.05
		93.87	14,284,029	320.14
		93.88	14,289,158	320.26

Additionally, the calculated gas amount was converted into an equivalent volume at standard temperature and pressure (STP) to allow comparison with conventional biogas data. Overall, the combined use of ultrasonic level sensing and pressure–temperature measurement provides a practical and continuous method for estimating biogas quantity in real-time monitoring applications.

The experimental results indicate that during the second and third weeks of operation, the total amount of gas, expressed in moles, remained relatively constant, while the methane concentration (ppm) exhibited a noticeable increase. This phenomenon suggests that the biogas production process had reached a stable phase in terms of total gas volume, whereas the gas composition continued to evolve. The calculated molar quantity represents the total gas mixture within the reactor, whereas the ppm value obtained from the MQ-4 sensor reflects the methane fraction. As anaerobic digestion progressed into the methanogenesis stage, the conversion of intermediate compounds led to a reduction of non-methane gases such as CO_2 and H_2, while methane production became dominant. Consequently, the proportion of methane increased without significantly altering the total number of gas moles. This behavior indicates an improvement in biogas quality rather than quantity. The observed trend confirms that the fermentation process was approaching steady-state conditions, which is favorable for energy recovery applications. A higher methane concentration enhances the calorific value of biogas, making it more suitable for power generation systems, even when the overall gas volume remains stable.

The energy potential of methane produced in the biogas system was evaluated based on the average amount of methane measured by the sensor at each sampling interval, using the equations 1, 2, and 3. From the monitoring data (Table 3), the average methane quantity was calculated to be approximately 1.42×10^7 mol per interval. This averaging approach was adopted because the sensor continuously recorded methane levels at short time intervals, and the averaged value represents a stable operating condition of the biogas system rather than cumulative production.

Using the lower heating value (LHV) of methane, which is 802 kJ/mol, the average chemical energy content of the produced methane was estimated. The calculated chemical energy corresponds to approximately 1.14×10^{10} kJ. This value reflects the theoretical energy stored in the methane under the observed operating conditions. To express the energy potential in terms relevant to electrical applications, the chemical energy was converted into kilowatt-hours (kWh), resulting in an estimated theoretical electrical energy equivalent of approximately 3.17×10^6 kWh.

Although this value represents a theoretical maximum, it demonstrates that the methane generated by the biogas process possesses a substantial energy content. When practical conversion efficiencies of biogas generators, typically ranging from 18% to 30%, are considered, a significant portion of this energy can still be converted into usable electrical power. These results indicate that the biogas system has promising potential for power applications, particularly for small- to medium-scale electricity generation. Overall, the findings highlight the feasibility of utilizing methane from anaerobic digestion as a renewable energy source, supporting its application in sustainable power generation systems.

Recent literature further supports the development of biogas energy systems through advances in anaerobic digestion from technological, microbial, and policy perspectives. Updated studies emphasize the importance of key operational parameters, including substrate composition, temperature, pH, and substrate-to-inoculum ratio, in improving methane yield and process stability. The integration of co-digestion strategies, pretreatment methods, metagenomic analysis, and machine learning-based modelling has enhanced system efficiency and predictability. In addition, recent policy frameworks and economic incentives, particularly in the European Union and emerging economies, play a crucial role in accelerating the large-scale deployment of sustainable biogas energy systems (DelaVega-Quintero et al., 2025)

V. Conclusion

The results of this study confirm that tofu wastewater can be effectively converted into biogas using a 1000 L anaerobic biodigester equipped with an IoT based monitoring system. The developed system, consisting of three ESP32 microcontrollers and multiple sensors, successfully performed real time monitoring of methane concentration, temperature, humidity, pressure, and biogas level, with data transmission intervals of approximately 8–10 seconds over a 21-day fermentation period.

Monitoring results show a consistent increase in methane concentration from an average of 4,750 ppm on day 13 to more than 5,000 ppm on day 21, indicating the progression of anaerobic digestion toward the methanogenesis phase. Humidity values remained stable within the range of 93.6%–94.2%, supporting favorable microbial activity, while temperature varied between 31.5°C and 42.6°C, largely influenced by ambient environmental conditions. The calculated total gas quantity remained relatively constant, with an average methane amount of approximately 1.42×10^{7} mol per monitoring interval, demonstrating that biogas quality improved mainly through increased methane composition rather than total gas volume.

Based on the lower heating value of methane (802 kJ/mol), the theoretical chemical energy potential was estimated at approximately 1.14×10^{10} kJ or 3.17×10^{6} kWh. Considering generator efficiencies of 18%–30%, the system shows promising feasibility for small to medium scale electrical power generation, supporting sustainable waste-to-energy applications in tofu industries.

Future studies should focus on extending the monitoring period to cover a full fermentation cycle of 30–45 days in order to capture complete microbial dynamics and long-term methane stability. The integration of additional gas sensors, such as CO_2, H_2S, and H_2, is recommended to improve biogas quality assessment and safety analysis. Implementing automatic control mechanisms for temperature and pH could further optimize methane yield under varying environmental conditions. Moreover, experimental validation using a biogas generator or microturbine is suggested to evaluate real electrical output and conversion efficiency, thereby strengthening the practical feasibility of small-scale biogas power applications

VI. Acknowledgment

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