

Innovation in an IoT-Based Smart Biogas Reactor Prototype for Converting Household Organic Waste into Alternative Energy

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Abstract: Biogas is a gas produced by the anaerobic decomposition of organic matter with the aid of microorganisms; it primarily consists of methane (CH₄), which has a high calorific value and holds potential as an alternative energy source. Biogas production is carried out using a biogas reactor as the fermentation medium. The use of household waste as feedstock aims to generate economical and environmentally friendly energy while reducing waste and water pollution caused by leachate. The development of alternative energy is becoming increasingly relevant amid global energy supply instability, including the impact of geopolitical dynamics in the Strait of Hormuz region, which serves as a major global oil distribution route. With technological advancements, innovations in smart biogas reactors based on the Internet of Things (IoT) enable real-time monitoring and control of process parameters to enhance methane gas production efficiency. This study employs an experimental method to evaluate the effectiveness of a biogas reactor design utilizing IoT devices, with a focus on real-time monitoring of temperature, pH, and methane gas concentration parameters. Based on the test results, the methane gas concentration increased from 14.08 ppm on the first day to 16.79 ppm on the ninth day. Fermentation conditions indicated an increase of 19.25%. The developed system design utilizes an ESP32

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microcontroller integrated with DHT11, PH-4502C, and MQ-4 sensors, and employs Blynk and ThingSpeak for data visualization. The selection of sensors was based on considerations of suitability for the application's needs, ease of integration with the microcontroller, market availability, and cost-effectiveness of implementation. Test results indicate that the reactor design and system can consistently transmit and present data within an optimal communication range, thereby contributing to improved efficiency, explosion safety, gas leak prevention, and control over the fermentation process in the constructed reactor. During testing, the results showed that the detected gas leak level was 0% throughout the entire observation period. Thus, the system demonstrated a 100% success rate in leak prevention. The implementation of this reactor design supports the development of a more modern, effective, and sustainable renewable energy processing system.

Keywords: Prototype, Biogas Reactor, Internet of Things (IoT), Real-time Monitoring.

Introduction

Indonesia's annual population growth shows a significant upward trend as one of the developing countries (Kurniawan et al., 2026). This increase has a significant impact on various aspects of life, particularly on energy needs to support activities in the industrial, transportation, household, and other sectors (Permana & Puspitaningsih, 2026). Meanwhile, research conducted by Matondang et al. indicates that as the population grows, the energy needs that must be met also increase. Excessive reliance on fossil fuel energy sources has the potential to trigger an energy crisis. This situation is further influenced by global geopolitical dynamics, such as tensions in the Strait of Hormuz region, which serves as a major global energy distribution route (Mulyadi, 2026). Disruptions in that region could trigger instability in global energy supply and prices (Herunnisa, 2026). Therefore, concrete efforts are needed to reduce dependence on fossil fuel-based energy through the development of more economical and environmentally friendly renewable energy, in line with national policies such as Presidential Regulation No. 5 of 2006 regarding the National Energy Plan 2025. Additionally, population growth contributes to an increase in the volume of waste generated by the community. Waste management practices to date have generally been limited to collection and disposal at landfills or even incineration, which has the potential to cause environmental pollution (Noor et al., 2026). Meanwhile, research conducted by (Kristina et al., 2025) indicates that household waste, particularly organic waste, holds significant potential to be converted into renewable energy, such as biogas, through appropriate processing methods. Meanwhile, research conducted by (Wang et al., 2026) states in their study that the conversion of organic waste into renewable energy can be achieved through various methods, such as anaerobic fermentation to produce gas, composting that generates thermal energy, as well as thermal energy processes like

gasification and pyrolysis. Meanwhile, research conducted by (de Martins et al., 2026) states in their study that the biogas process involves the activity of microorganisms that break down organic material into methane gas, which can be utilized as fuel. Meanwhile, research conducted by (Adekunle & Okolie., 2015) states that the process in a biogas reactor not only produces gas but also generates residues in the form of organic fertilizer that can be reused in the agricultural sector, thereby creating an integrated and sustainable waste treatment system. To fully understand the device to be designed—namely, an IoT-based biogas reactor—an in-depth study of the definition of a biogas reactor using household organic waste as feedstock is required. While there are already numerous specific definitions of biogas reactors using household waste, to identify a research gap, the researcher designed the system using a technological basis that is still very limited in the scientific literature. Therefore, the approach in this study is to outline the concept of the biogas reactor, as well as the effectiveness of the reactor and its technological components from a conceptual perspective, in order to gain a comprehensive understanding of the design and the system that has been built. Thus, a biogas reactor can be defined based on studies conducted by (Hagos et al., 2017) , who state that a biogas reactor is a designed and systematic technology in the form of a closed vessel for processing organic waste that is converted into alternative energy through an anaerobic process (a process without air). Meanwhile, research conducted by (Sitorus & Panjaitan., 2013) involved building a 250-liter reactor for household waste storage; based on design calculations, a reactor filled to capacity with 200 liters of feedstock produces up to 6 m³ of biogas per day. Meanwhile, research conducted by (Abubakar & Ismail., 2012) , and (Pramanik et al., 2019) states in their studies that methane gas production is influenced by several key parameters, such as the carbon-to-nitrogen ratio (C/N), residence time, pH level, temperature, and toxic substance content. Meanwhile, research conducted by (Walker et al., 2009) states that the optimal temperature range in a digester is 5–55 °C with a pH of approximately 7–7.8, which can produce biogas with a methane content of about 77%. Meanwhile, research conducted by (Balussou et al., 2012) states in its study that the biogas requirement for powering lighting is estimated at 0.23 m³/h at a pressure of 45 mmH₂O, while for a gas stove it is 0.30 m³/h at a pressure of 45 mmH₂O. In addition to generating energy, an environmental impact analysis shows that the sludge output from the biogas reactor exhibits a reduction in chemical oxygen demand of up to 90% compared to initial conditions, as well as a biological oxygen demand ratio of 0.37, which is lower than the typical characteristics of liquid waste (Bong et al., 2018) . This indicates that the use of biogas reactors not only contributes to renewable energy production but is also effective in reducing environmental pollution (Arzate et al., 2017) .

Meanwhile, the components used to implement the IoT system on the reactor include the first component, the ESP32, which is a high-performance integrated microcontroller module equipped with various supporting features; this module is an advancement of the previous microcontroller, the ESP8266, known as a Wi-Fi module. The ESP32 is designed with two processor cores: one handles network connectivity such as Wi-Fi and Bluetooth, while the other runs the main application-. The second component is the MQ-4 sensor, a gas detection sensor that uses the semiconductor material tin dioxide (SnO_2) as its primary sensing element. This sensor operates based on the principle of low conductivity with high resistance values. However, when methane gas is present, the material's conductivity increases as the concentration of the detected gas rises (Ramadhani et al., 2024). The third component is the DHT11 temperature and humidity sensor; this digital temperature sensor uses the 1-wire communication protocol, enabling temperature measurements via a single data line with high accuracy. In addition, the DHT11 is designed to measure ambient air temperature and humidity, so the measurements better represent the air conditions around the reactor compared to direct measurements of the internal temperature of the fermentation substrate. One limitation of this sensor is that the DHT11 has relatively lower temperature measurement accuracy compared to industrial temperature sensors or high-precision digital sensors. Therefore, the data obtained is more suitable for monitoring trends in reactor temperature changes than for thermal analysis requiring a high level of precision. This sensor offers several advantages, including ease of implementation, the ability to be connected in parallel with other sensors on a single communication line, and a wide temperature measurement range spanning from -55°C to $+125^\circ\text{C}$ (Budi & Pramudya., 2017). The fourth component is the PH-4502C pH sensor module, an electronic device designed to measure the acidity (pH) or alkalinity of a solution with high precision (Djaki et al., 2026). However, large-scale implementation still faces various challenges, including limited technical expertise, reactor malfunctions due to leaks or construction errors, and inappropriate temperature and pH levels within the reactor. Therefore, this study aims to design a biogas reactor using IoT technology to monitor gas volume, determine the optimal time required for gas production, identify the effective temperature for optimal gas production, and detect gas leaks in the reactor, followed by testing the effectiveness of the reactor and sensors in the application of IoT within the reactor. Although various studies have been conducted on biogas monitoring systems, most still focus on monitoring specific parameters separately and have not integrated process performance and operational safety aspects into a single platform. Furthermore, the use of expensive instruments and manual monitoring methods remains a barrier to implementation on both laboratory and community scales. Therefore, there is a need to develop an IoT-based biogas monitoring system capable of integrating real-time measurements of temperature, pH, methane

concentration, and gas leak detection at a more affordable cost. The implementation of a biogas reactor integrated with IoT technology is expected to improve the effectiveness of gas production and the management of process residues. The designed system also has the potential to become an appropriate method for waste treatment, thereby providing a solution to environmental issues while supporting increased energy self-reliance for communities amid the energy crisis.

Research Methods

The design, fabrication, assembly, and testing of the reactor and IoT devices were conducted at the Sinar Mas Berau Coal Polytechnic laboratory, spanning from assembly to data collection from December 14, 2025, to January 5, 2026. This study employed an experimental method by designing and constructing a monitoring-based biogas reactor using IoT technology. The main devices used in this study were a 200-liter biogas reactor and electronic components, including a WSP32 microcontroller, a DHT11 temperature sensor, a pH-4502C sensor, and an MQ-4 sensor. One of the limitations of this study is the absence of a control reactor or comparison group in the experimental design. This is because the study focused on the development and functional validation of the IoT-based monitoring system. Therefore, the results emphasize the evaluation of the monitoring system's performance rather than a comparative analysis of fermentation process performance. The design of the biogas reactor prototype in this study is shown in Figure 1.

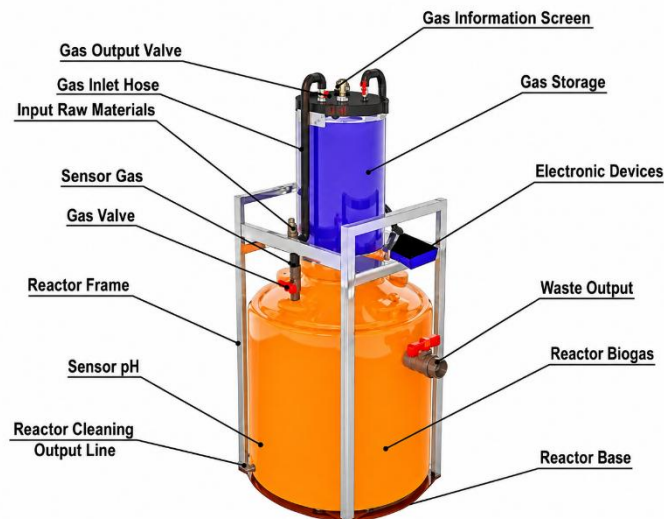


Figure 1 Design of the IoT-Based Biogas Reactor Prototype

The design and system consist of a biogas reactor or fermentation tank, which serves as the site for the decomposition of organic material used as feedstock to produce methane gas. Inside the tank, two sensors are installed: a gas detection sensor and a pH measurement

sensor, both designed to monitor the fermentation process. The pH sensor is used to measure the acidity or alkalinity level in the reactor, ensuring that the fermentation process occurs under optimal conditions. Additionally, a temperature sensor is installed to monitor the temperature inside the reactor, as a stable temperature significantly influences the activity of microorganisms in producing methane gas. There is also a sensor installed on the gas outlet line to detect the methane concentration produced during the fermentation process. The data obtained from all sensors is then processed by the ESP32 microcontroller located inside the system control box and subsequently transmitted wirelessly to a laptop or smartphone via the Blynk app—a low-code IoT platform that allows users to control and monitor the device remotely. Based on research conducted by (Budijono & Felita., 2021) , it is stated that this system enables real-time monitoring of biogas production conditions from different locations via a monitoring system or server. To clarify the research conducted, the research flowchart is shown in Figure 2.

Figure 2 Research Flowchart

The research flowchart shown in Figure 2 illustrates the stages that must be followed in the research, specifically in the context of developing a sensor-based reactor and the IoT. The research process begins with identifying the topic or problem to be studied. This is followed by an observation phase to identify problems or phenomena that require further analysis.

The next phase involves data mapping and determination, where relevant research data is identified, along with mapping the requirements and types of data to be collected. The subsequent phase is data collection and processing, where the previously identified data is gathered and analyzed to obtain the necessary information for system development. The next stage is designing the sensors and the system, where system design begins with designing the sensors to be used, as well as the overall system to be employed in this research. This design includes selecting appropriate sensors and the integration process with the system. The next stage is assembling the sensors and configuring the system; once the design is complete, the next step is to assemble the biogas sensors and configure the system so that it functions properly.

The next step is to test the built system; after assembly and configuration, testing is conducted to ensure that the sensors and system function as expected. If they do not function properly, the process returns to redesigning or repairing the system and sensors; if they function well, the next step is further development. The next step is to integrate the biogas reactor system with the IoT design. In this phase, an IoT-based system design is developed, which includes integrating the sensors with the IoT network so that the generated data can be monitored remotely. The subsequent stage involves testing the integrated system to ensure that the entire system functions properly and meets the intended objectives. If the testing fails, corrections will be made to ensure the system functions as intended; if successful, the research will proceed to the final stage. The final stage involves drawing conclusions and providing recommendations; once all testing is complete and the system has been proven to function properly, conclusions regarding this research are drawn, and recommendations for further development are provided. Overall, this flowchart illustrates the systematic steps in designing, testing, and implementing an IoT-connected sensor-based biogas reactor system, as well as how these steps are carried out iteratively to achieve the desired results.

Results and Discussion


Preparation and Assembly of the IoT-Based Biogas Reactor


In the development of an Internet of Things (IoT)-based biogas reactor, the initial stage involves preparing the tools and materials needed to design and build a biogas reactor system integrated with IoT technology. This process includes selecting the appropriate hardware and software components that will support the system's efficient operation. The design and specifications of the tools and materials used in constructing the reactor are detailed in Table 1, which presents a complete list of components required to support the


reactor's functionality in real-time monitoring and control via the IoT network. Meanwhile, Table 2 presents the specifications of the IoT device tools and materials.


Table 1 Specifications of Tools and Materials in the Biogas Reactor Design

No	Reactor Tools and Materials	Description
1		<p>A biogas reactor is the primary vessel used in the anaerobic fermentation process, which involves the breakdown of organic waste by microorganisms in the absence of oxygen to produce biogas containing methane (CH₄) as an alternative energy source. In this study, the reactor was used to process household organic waste into energy that is more environmentally friendly and has practical value. The material used to construct the reactor is fiberglass or a water tank because it is corrosion-resistant, airtight, lightweight, readily available, and relatively affordable to manufacture. Additionally, this material can withstand gas pressure and temperature fluctuations during the fermentation process, making it suitable for use as a biogas production medium. Reactor components include: 1. Inlet Pipe, 2. Sludge Outlet Pipe, 3. Connecting Valve, 4. Temperature Gauge (Digital Thermo-Hygrometer), 5. Gas Outlet Pipe.</p>
2		<p>The gas storage tank in a biogas system serves as a temporary storage facility for the gas produced by anaerobic fermentation, which is channeled from the reactor before being utilized further. This component plays a crucial role in maintaining a continuous flow of biogas and helps stabilize the gas pressure generated during the fermentation process. The material used for the gas storage tank is a 3 mm thick steel drum. Steel was chosen because it is strong, resistant to gas pressure, and has good resistance to impact and changes in environmental conditions. A thickness of 3 mm was selected to ensure the tank's structure can safely withstand the pressure of the fermented gas without easily deforming or leaking. Steel drums are considered more effective because they offer greater structural integrity compared to plastic or other thin materials. Additionally, steel is easier to weld, resulting in tighter, airtight joints in the gas storage system—a critical factor</p>

No	Reactor Tools and Materials	Description
		<p>in preventing methane leaks. Steel was also chosen because it has a relatively longer service life and can be reused under continuous operational conditions. Observations show that 3 mm thick steel drums maintain gas storage stability and support the overall safety of the biogas production system. Thus, the selection of this material considers not only strength and safety but also operational efficiency and sustainability within an IoT-based biogas reactor system. Components of the gas storage tank include: 1. Drum, 2. Pressure Gauge, 3. Gas Inlet Valve, 4. Gas Outlet Valve.</p>
3		<p>The structural framework of a biogas system serves as the main support structure for all system components, such as the biogas reactor, gas storage tank, piping, and other supporting components. The structural framework is crucial for maintaining the stability and safety of the system during the anaerobic fermentation process. A robust structural framework can withstand the weight of the reactor and the pressure generated during biogas production, thereby reducing the risk of component damage or displacement while the system is in operation. The material used for the framework is 30 mm × 30 mm L-shaped angle iron. L-shaped angle iron was selected because this material offers sufficient strength to support loads, is easy to shape, and has a stable structure suitable for use as a support frame. The L-shaped profile of the material also helps distribute loads more evenly, making the structure more robust. Based on qualitative data, L-shaped angle iron was chosen because the fabrication process is relatively simple—particularly for joining using welding techniques—and it is more economical and readily available on the market. For the reactor base, a 4 mm thick steel plate was used to optimally support the weight of the reactor along with the organic waste and fermentation liquid. This thickness was chosen to ensure the base's strength, preventing it from bending or sustaining damage due to significant loads. Meanwhile, for the gas storage section, a 3 mm thick steel plate was used, tailored to the required strength to withstand the</p>

No	Reactor Tools and Materials	Description
		<p>pressure of the fermentation gas. This thickness is considered sufficiently effective to ensure the safety of the gas storage without excessively increasing the structural load. The selection of construction materials takes into account factors such as strength, durability, safety, ease of fabrication, and cost efficiency. Proper construction can maximize the performance of the biogas system and facilitate the installation of Internet of Things (IoT)-based monitoring devices in a safer and more organized manner, thereby enabling more effective monitoring of reactor conditions and biogas production.</p>
4		<p>A <i>pressure gauge</i> in a biogas system is used to measure the gas pressure inside the storage tank containing the product of anaerobic fermentation. This component plays a crucial role in monitoring system conditions, as gas pressure is a key indicator of successful biogas production. With the pressure gauge, users can directly monitor gas pressure stability, thereby preventing excessive pressure that could potentially cause leaks or damage to the gas storage tank. The materials used in <i>the pressure gauge</i> are stainless steel and glass. Stainless steel was chosen because it offers excellent resistance to corrosion, humidity, and exposure to fermentation gases containing specific compounds. Additionally, stainless steel possesses high mechanical strength, enabling it to protect the internal components of the measuring instrument from impacts and pressure fluctuations during operational processes. Based on qualitative data, stainless steel is considered more durable and requires relatively low maintenance compared to ordinary metals that are prone to rust. Meanwhile, the use of glass for the <i>pressure gauge's</i> cover is intended to facilitate the visual reading of gas pressure values. Glass was chosen because it offers good transparency, allowing the measurement scale to be clearly and accurately visible. Furthermore, glass is resistant to temperature changes and does not easily deform during use. The combination of stainless steel and glass in the pressure gauge provides enhanced safety, durability, and accuracy in supporting the biogas</p>

No	Reactor Tools and Materials	Description
		production monitoring system. In the implementation of Internet of Things (IoT)-based systems, the pressure gauge can also support real-time monitoring through the integration of additional pressure sensors. The pressure data obtained can be used to analyze anaerobic fermentation performance and help maintain the overall efficiency and safety of biogas production.
5		<p>The connecting hose in a biogas system serves as a conduit for gas from the reactor to the gas storage tank and from the gas storage tank to the gas stove for use as fuel. This component plays a crucial role in ensuring the smooth distribution of biogas so that the gas flow remains stable and safe throughout the operational process. In addition to serving as a distribution pathway, the connecting hose also helps maintain controlled gas pressure so that the biogas distribution process can run efficiently. The connecting hose is made of rubber with a thickness of 3 mm and a diameter of 20 mm. Rubber was selected because it is elastic, flexible, and airtight, making it capable of preventing gas leaks during distribution. Additionally, rubber is resistant to gas pressure and does not easily crack with prolonged use. Based on qualitative data, rubber hoses are considered more effective because they are easy to install, easily adaptable to the positions of biogas system components, and have sufficient resistance to temperature changes and environmental conditions. A hose thickness of 3 mm was selected to enhance the hose's wall strength, ensuring it can withstand gas pressure without leaking or bursting easily. Meanwhile, a 20 mm hose diameter is used to ensure smooth biogas flow, enabling optimal gas distribution from the reactor to the storage tank and to the stove. This diameter is also considered appropriate for maintaining a balance between the pressure and flow rate of the gas produced by the anaerobic fermentation process. In an Internet of Things (IoT)-based biogas system, the connecting hose supports the efficiency of the gas distribution system because a stable biogas flow facilitates the monitoring of gas pressure and volume through integrated sensors.</p>


No	Reactor Tools and Materials	Description
		Thus, the selection of the connecting hose's material and size is a critical factor in ensuring the safety, effectiveness, and sustainability of biogas distribution within the system as a whole.
6		Hose clamps in biogas systems serve to secure and hold connecting hoses firmly in place at pipe joints, reactors, and gas storage tanks. These components play a crucial role in maintaining the stability of hose connections, ensuring that biogas flows safely and smoothly. Additionally, the use of hose clamps aims to prevent gas leaks at connection points, which can reduce biogas production efficiency and potentially pose safety risks during operational processes. Hose clamps are typically made of metal, such as stainless steel, because it offers good strength, corrosion resistance, and the ability to provide stable clamping pressure on the hose. Based on qualitative data, the use of stainless steel clamps is considered more effective because they do not rust easily even when used in humid environments and exposed to fermentation gas. Furthermore, this material has a longer service life and maintains its clamping strength over an extended period. The use of hose clamps is particularly critical for connecting rubber hoses that are 3 mm thick and 20 mm in diameter, as the pressure of the flowing gas can cause the hose to shift or loosen if no additional fasteners are used. With hose clamps, the connection becomes tighter and airtight, thereby minimizing gas leaks. This directly supports the efficiency of biogas distribution from the reactor to the gas storage tank or to the gas stove.


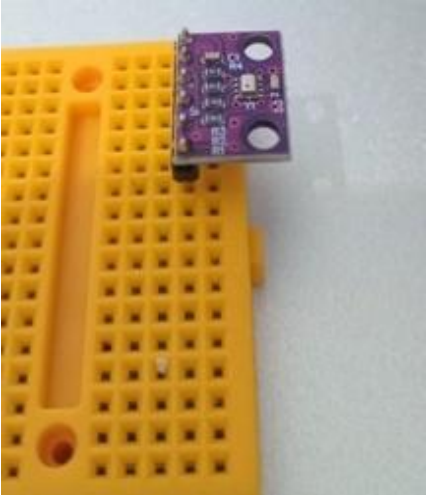
The IoT system in this study was developed to support the automatic, real-time monitoring of biogas reactor conditions during the anaerobic fermentation process. The application of IoT technology aims to improve the effectiveness of monitoring key parameters within the reactor—such as temperature, gas pressure, and biogas production conditions—thereby enabling the fermentation process to proceed more optimally. Additionally, the use of the IoT system is intended to reduce reliance on manual observations, which have limitations regarding the continuity and accuracy of data collection. The integration of IoT devices with

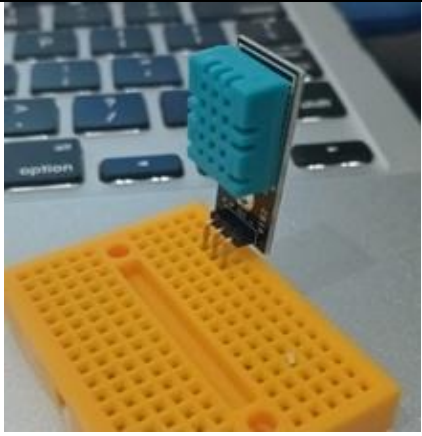


the biogas reactor system enables continuous data collection via sensors installed on various parts of the reactor. The data from sensor readings is then processed using a microcontroller and transmitted via a communication module to the monitoring device. Through this system, users can remotely monitor reactor conditions using digital devices, allowing operational changes to be detected more quickly and corrective actions to be taken immediately if fermentation parameters deviate. Each hardware component used in the IoT system plays a complementary role in the monitoring and control of the biogas system.

Temperature sensors are used to measure temperature stability inside the reactor, as temperature affects the activity of anaerobic microorganisms in biogas production. Pressure sensors are used to monitor gas pressure in the biogas storage tank to ensure that pressure conditions remain safe and controlled. A microcontroller serves as the data processing center for all sensors connected to the system, while the communication module facilitates wireless data transmission, enabling real-time access to monitoring results. In addition to electronic components, supporting materials such as cables, connectors, power supplies, and support structures also play a crucial role in maintaining the stability and sustainability of the monitoring system. Material selection is based on considerations of durability, safety, ease of installation, and long-term efficiency. Therefore, the implementation of an IoT system in a biogas reactor not only improves monitoring effectiveness but also supports biogas production efficiency and overall system operational safety. A more systematic explanation of the IoT system design and its relationship with the tools and materials is provided in Table 2.

Table 2. Specifications of Tools and Materials in the IoT Device Design

No	IoT Device Tools and Materials	Description
1		<p>ESP32 DevKit V1 and 16x2 LCD Display. The ESP32 DevKit V1 is a development board designed to simplify the use of the ESP32 microcontroller. This microcontroller features a dual-core processor and wireless connectivity options, including Wi-Fi and Bluetooth, making it an ideal choice for various applications in embedded systems. The ESP32 DevKit V1 makes it easy for developers to access and program the ESP32, as well as connect it to various sensors and external devices in Internet of Things (IoT) projects. This board is equipped with various input/output (I/O) interfaces that enable data communication with sensors, actuators, and other modules, and also supports various development</p>

No	IoT Device Tools and Materials	Description
		platforms such as Arduino, MicroPython, and ESP-IDF.
2		<p>The sensors play a role in acquiring data on critical parameters, such as temperature and gas pressure inside the reactor and biogas storage tank. The data obtained from the sensors is then processed by the microcontroller—which serves as the system’s control center—before being transmitted via a communication module to support <i>real-time</i> monitoring. This integration allows users to obtain information on the reactor’s condition more quickly, accurately, and continuously. The MQ-4 sensor is a device designed to detect the presence of methane gas (CH₄). This sensor operates based on semiconductor principles, where its conductivity changes when exposed to methane gas. This change generates an electrical signal that can be monitored and processed by a microcontroller system. The MQ-4 is frequently used in various fields, such as gas leak monitoring, air quality systems, and sectors involving biogas or natural gas production.</p>
3		<p>pH-4502C sensor: a device designed to accurately measure the pH level of a solution in real time. This sensor is widely used in applications such as hydroponic systems, aquariums, and wastewater treatment. Using electrochemical principles, the pH-4502C sensor detects the concentration of hydrogen ions (H⁺) in a liquid, which is then converted into an analog signal that can be processed by a microcontroller. This module is easy to integrate with microcontroller platforms such as Arduino and Raspberry Pi, making it ideal for IoT-based monitoring applications. Additionally, the pH-4502C features a calibration function to maintain measurement accuracy under various conditions.</p>
4		<p>The DHT11 temperature and humidity sensor is a device designed to measure air temperature and humidity. This sensor can measure temperatures ranging from 0°C to 50°C and humidity from 20% to</p>

No	IoT Device Tools and Materials	Description
		<p>90%. The DHT11 provides digital readings with adequate accuracy, though not as high as other temperature and humidity sensors within certain ranges. This module is widely used in environmental measurement applications, temperature control systems, and Internet of Things-based applications, such as weather monitoring systems and home automation. This sensor can be easily integrated with microcontrollers such as Arduino and Raspberry Pi via digital output signals.</p>
5		<p>Jumper wires are cables used to connect components in electronic circuits, such as sensors, microcontrollers, and other modules. Jumper wires have connectors on both ends, allowing connections between device pins without the need for soldering. Available in various configurations—such as male-to-male, female-to-female, or male-to-female—jumper wires are commonly used in prototyping and the development of electronic systems, particularly in microcontroller-based projects like Arduino and Raspberry Pi. These wires are known for their ease of use and their ability to connect components quickly.</p>
6		<p>The data transfer cable in a biogas reactor IoT system serves as a connection medium for transferring data and programs from the programming device to the microcontroller. This component is used to send instructions or <i>code</i> to the microcontroller so that the device can perform monitoring functions, process sensor data, and control the system in accordance with the pre-designed program. In addition to its role in the initial programming process, the data transfer cable is also used for system updates and device testing during both the development and maintenance phases of the IoT system. Schematically, the data transfer cable connects a computer or laptop to the microcontroller via a communication interface, such as USB (<i>Universal Serial Bus</i>). Through this connection, program data is sent from the programming software</p>

No	IoT Device Tools and Materials	Description
		<p>to the microcontroller's memory to be processed and executed in controlling sensors, communication modules, and other supporting components in an IoT-based biogas system. The data transfer process is conducted digitally, ensuring data communication occurs quickly, stably, and accurately. Data transfer cables typically use copper conductors because they have good electrical conductivity, thereby supporting optimal data transmission. Meanwhile, the cable's protective sheath uses insulating materials such as PVC (<i>Polyvinyl Chloride</i>), which protects the conductors from physical damage and electrical interference. Based on qualitative data, the use of high-quality data transfer cables enhances communication stability between programming devices and microcontrollers while minimizing errors during program transmission. In the implementation of IoT systems in biogas reactors, data transfer cables play a critical role in supporting the configuration and integration of electronic devices. Smooth data transfer allows the microcontroller to run system algorithms optimally for sensor data acquisition, information processing, and <i>real-time</i> monitoring data transmission. Therefore, data transfer cables not only function as a communication medium between devices but also serve as a critical component in supporting the overall performance and success of the IoT system.</p>

Integration of the Reactor Prototype and IoT Devices

The next phase of this research involves integrating IoT devices by assembling and installing these components on the biogas reactor. This process includes configuring and connecting relevant hardware—such as sensors, microcontrollers, and communication modules—to form an IoT system capable of monitoring and controlling reactor conditions in real time. By connecting the biogas reactor to the IoT network, this system is expected to automatically monitor key parameters—such as temperature, pH, and methane gas concentration—and provide data that can be accessed remotely. This integration of the biogas reactor with IoT

also enables continuous data collection for further analysis and optimization of the fermentation process in biogas production. The results of the device installation on the biogas reactor are shown in Figure 3.



Figure 3 IoT-Based Biogas Reactor Prototype

Once all components were assembled, the resulting configuration is shown in Figure 3. In the gas distribution section, the connecting hose and hose clamps play a crucial role in maintaining a stable gas flow from the reactor to the storage tank and the gas stove. A rubber hose with a thickness of 3 mm and a diameter of 20 mm was selected because it maintains a stable gas flow and minimizes leaks. Meanwhile, hose clamps are used to reinforce the connections so that gas pressure does not cause the hoses to detach. Analytically, the stability of gas distribution significantly affects the accuracy of pressure sensor readings and the efficiency of biogas utilization. The biogas frame, constructed using L-shaped angle iron, supports all system components to ensure stability during operation. The use of steel plates for the reactor base and gas storage tank further enhances the system's safety against loads and pressures generated during fermentation. In this IoT-based biogas reactor design, the system is engineered to integrate the anaerobic fermentation process with digital monitoring technology, enabling more effective monitoring and control of biogas production. Analytically, the system schematic consists of several main components: the biogas reactor unit, the gas distribution and storage system, sensors, a microcontroller, a communication module, and monitoring devices.

All these components are interconnected to support real-time data acquisition, information transmission, and control of fermentation conditions. The process begins in the biogas reactor, which serves as the site for the anaerobic fermentation of household organic waste.

Inside the reactor, anaerobic microorganisms break down organic matter in the absence of oxygen, producing biogas in the form of methane (CH₄). The stability of conditions within the reactor is a key factor influencing biogas production efficiency; therefore, a monitoring system capable of observing critical parameters throughout the fermentation process is required. In the designed IoT system, a temperature sensor is installed on the reactor to detect temperature changes during fermentation. From an analytical perspective, temperature directly influences the activity of anaerobic bacteria because microorganisms function optimally within a specific temperature range. If the temperature is too low or too high, the decomposition of organic matter can be disrupted, resulting in suboptimal methane production. Therefore, temperature data is used as the primary parameter in fermentation performance analysis. In addition to the temperature sensor, the system is also equipped with a pressure sensor placed in the gas collection tank.

This sensor measures the pressure of the biogas produced during the fermentation process. Gas pressure serves as a quantitative indicator of biogas production levels within the system. An increase in pressure indicates the accumulation of fermentation-derived gas. Conversely, decreasing pressure may indicate a leak, fermentation disruption, or a decline in anaerobic bacterial activity. Thus, the pressure sensor plays a crucial role in ensuring operational safety while supporting the evaluation of biogas production efficiency. The data obtained from the sensors is then sent to the microcontroller, which serves as the system's control center. The microcontroller processes the sensor readings before transmitting them to the communication module. Essentially, the microcontroller functions as an interface between the hardware and the digital monitoring system. Furthermore, communication modules such as Wi-Fi or wireless networks are used to transmit data to the monitoring platform, allowing users to access real-time information on the reactor's condition via digital devices. In an IoT system, structural stability is crucial because sensors and electronic devices require secure mounting positions with minimal interference to ensure the accuracy of the data obtained. Overall, the IoT-based biogas reactor system demonstrates that the integration of sensor technology, microcontrollers, and communication systems provides more effective monitoring capabilities compared to conventional systems. This system enables continuous data collection, improves the accuracy of fermentation condition analysis, and supports biogas production optimization through real-time monitoring of operational parameters. Thus, the application of IoT in biogas reactors not only enhances the efficiency of renewable energy management but also supports the safety and sustainability of biogas system operations in a scientific and measurable manner.

Test Results

Testing was conducted to evaluate the device's performance and functionality, as well as to determine the biogas reactor's operational capacity. This testing process aims to ensure the device functions according to expected specifications and to obtain accurate data regarding the biogas production capacity the reactor can achieve. The results of these tests will provide important information on the extent to which the reactor can operate effectively under different conditions, as well as help identify potential improvements or system optimizations to maximize biogas production efficiency. Thus, these tests are a crucial step in determining the feasibility and performance of the biogas reactor in real-world applications. MQ-4 sensor testing was conducted to effectively monitor gas production activity, as presented in Table 3. This process aims to ensure that the sensor can accurately detect and measure gas concentrations, thereby enabling more precise monitoring of the gas production process.

The results of this testing will provide the data needed to evaluate the performance of the MQ-4 sensor in detecting changes in gas concentration during the biogas fermentation process. Methane concentration validation in this study was performed by comparing the response of the MQ-4 sensor with that of its predecessor, the MQ-2, which served as a reference sensor to ensure consistency in detecting the presence of gas produced during the fermentation process. However, the researchers chose to use the MQ-4 sensor because it has higher sensitivity to methane than its predecessor, the MQ-2, and was therefore used as the primary sensor in the monitoring system. Thus, the validation conducted in this study was intended more to validate the concentration response of the sensor and the system's ability to detect relative changes in gas concentration rather than to determine absolute values of methane concentration with laboratory-grade accuracy. Since many previous studies have used the MQ-2 sensor, it was used as the reference sensor in this study.

Table 3 Calibration Testing of the MQ-4 Sensor and the MQ-2 Sensor as a Reference

No	Calibration of the MQ-4 Gas Pressure Sensor	MQ-2 Sensor (Reference)	Difference
1	13.81	13.43	0.38
2	13.84	13.46	0.38
3	13.87	13.49	0.38
4	13.89	13.51	0.38
5	13.93	13.55	0.38

The table presented shows the comparison results between the MQ-4 Gas Pressure sensor calibration and the MQ-2 Reference sensor. Each row in the table includes two columns: the MQ-4 Gas Pressure sensor calibration value and the value measured by the MQ-2 Reference sensor. The difference between these two values is calculated to determine the

accuracy of the two sensors. From the table, it can be seen that for each measurement (row), the difference between the MQ-4 sensor's calibration value and the MQ-2 reference sensor's value is constant, specifically 0.38. This indicates that the difference in measurement results between the two sensors is quite consistent at every test point, with the MQ-4 sensor's calibration consistently being 0.38 units higher than that of the MQ-2 reference sensor.

Although there is a difference between the two sensors, the consistent value difference indicates that the MQ-4 sensor exhibits predictable characteristics in terms of accuracy relative to the reference sensor, which is important for further evaluation of the sensor's performance in various applications. The next step is to test the accuracy of the DHT11 temperature and humidity sensor against the DS18B20 reference sensor, as presented in Table 4, using tap water. This test was conducted to evaluate the DHT11 sensor's accuracy in measuring air temperature and humidity by comparing its measurements to a reference device (a thermometer using the DS18B20 sensor) tested in two different media: tap water and ice water. Meanwhile, Table 5 presents the accuracy of the DHT11 temperature and humidity sensor compared to the DS18B20 reference sensor in ice water.

Table 4 Calibration Testing of the DHT11 Temperature and Humidity Sensor and the DS18B20 Sensor in Tap Water

No	DHT11 Temperature and Humidity (°C)	DS18B20 Reference Sensor (°C)	Difference
1	28.0	27.8	0.2
2	28.3	28.1	0.2
3	28.4	28.3	0.1
4	28.4	27.8	0.6
5	28.3	28.1	0.2

The table presented shows a comparison of the temperatures measured by the DHT11 sensor with those measured by the DS18B20 reference sensor at five measurement points. Each row in the table includes the temperature values recorded by the DHT11 sensor and the DS18B20 sensor, followed by the difference between the two measurement results. From the table, it can be seen that the difference between the temperatures measured by the DHT11 sensor and the DS18B20 reference sensor varies, with generally small difference values, indicating that both sensors provide relatively accurate and consistent results. The smallest difference is 0.1°C in the third measurement, while the largest difference is 0.6°C in the fourth measurement. Overall, the difference between the two sensors ranges from 0.1°C to 0.6°C, indicating that although there is a slight difference, the DHT11 sensor can provide temperature measurements that are quite close to those of the DS18B20 reference

sensor. This difference may be caused by factors such as sensor calibration, environmental conditions, or the tolerance limits of each sensor.

Table 5 Calibration Testing of the DHT11 Temperature and Humidity Sensor and the DS18B20 Sensor in Ice Water

No	DHT11 Temperature and Humidity (°C)	DS18B20 Reference Sensor (°C)	Difference
1	3.1	3.1	0.0
2	3.4	3.3	0.1
3	3.5	3.5	0.0
4	3.3	3.3	0.0
5	3.3	3.4	-0.1

The table presented shows the comparison results between the temperature measured by the DHT11 sensor and the temperature measured by the DS18B20 reference sensor at five measurement points. Each row in the table includes the temperature values recorded by both sensors, followed by the difference between the measurement results of the two sensors. From the table, it can be seen that the difference between the temperatures measured by the DHT11 sensor and the DS18B20 reference sensor varies, with most of the difference values being very small. In the first, third, and fourth measurements, the difference was 0.0°C, indicating that both sensors provided identical results at those points. In the second measurement, the difference was 0.1°C, indicating a small discrepancy between the two sensors. However, in the fifth measurement, the difference became -0.1°C, where the temperature measured by the DHT11 sensor was slightly lower than that of the DS18B20 reference sensor. Overall, these results show that the DHT11 sensor provides fairly consistent temperature measurements that closely match those of the DS18B20 reference sensor, with relatively small differences. Although there are some discrepancies, they fall within reasonable measurement tolerance limits, indicating that the DHT11 sensor can be effectively used in temperature measurement applications with adequate accuracy. The next test involved the pH-4502C sensor, as presented in Table 6. The test was conducted by comparing the sensor's readings against the pH values obtained from standard buffer solutions. The pH-4502C sensor was alternately immersed in buffer solutions with different pH values, specifically pH 4, pH 7, and pH 10. At each stage, the pH value read by the sensor was recorded and compared with the known pH value from the standard solution. This procedure aims to evaluate the sensor's accuracy and to perform calibration if discrepancies are found between the sensor's readings and the reference pH values. The procedure for calibrating the sensor prior to testing was as follows: the pH-4502C sensor was first calibrated using standard buffer solutions with pH values of 4, 7, and 10. The calibration process was performed by comparing the readings from the pH-4502C sensor with those

from a reference sensor under the same measurement conditions. The calibration results show that the pH-4502C sensor produced the values listed in Table 6. These very small differences indicate that the pH-4502C sensor exhibits a high level of agreement with the reference sensor and meets the requirements for use in monitoring anaerobic fermentation conditions. Thus, the sensor is deemed capable of providing reliable pH data to support real-time monitoring of biogas reactors.

Table 6 Calibration Testing of Water pH

pH Buffer	pH-4502C	Reference Sensor	Difference
pH 4	3.53	3.52	0.01
pH 7	6.40	6.40	0.00
pH 10	8.44	8.43	0.01

The table presented shows the test results of the pH-4502C sensor compared to the reference pH values measured using standard buffer solutions at three different pH points: pH 4, pH 7, and pH 10. Each measurement records the pH values read by the pH-4502C sensor and the reference sensor, as well as the difference between the two values. From the table, it can be seen that the difference between the readings of the pH-4502C sensor and the reference sensor is very small. At pH 4, the difference is only 0.01, indicating that the pH-4502C sensor's reading is nearly identical to the reference value. At pH 7, there is no difference at all (difference of 0.00), indicating that the pH-4502C sensor provides a highly accurate reading. Meanwhile, at pH 10, the difference is again 0.01, indicating a very small difference but still within the measurement tolerance range. Overall, these test results demonstrate that the pH-4502C sensor exhibits excellent accuracy, with a very small discrepancy between sensor readings and reference values across various pH levels. This confirms that the pH-4502C sensor can be relied upon with a high degree of accuracy in applications requiring pH measurement. Meanwhile, Table 7 presents the data from the biogas reactor monitoring

Table 6 Data on Biogas Reactor Monitoring Results and Composition of Household-Scale Organic Waste Feedstock

No	Raw Material	Day								
		1	2	3	4	5	6	7	8	9
1	Dissolved organic matter	20 kg	10 kg	10 kg	5 kg	15 kg	15 kg	20 kg	10 kg	5 kg
2	Water	40 liters	20 liters	20 liters	20 liters	30 liters	20 liters	25 liters	20 liters	20 liters

3	EM4	1 liter		0.5 liters		0.5 liters		0.5 liters		0.5 liters		0.5 liters		0.5 liters		0.5 liters		1 liter			
		L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D		
Temperature (°C)		33.8	25.2	31.4	29.2	32.4	29.3	31.2	28.5	32.2	24.5	31.2	21.3	30.3	20.8	33.9	26.1	32.4	23.1		
		Gas Pressure (ppm)		14.08		15.03		15.07		15.20		3:44		3:71 PM		4:12 PM		4:52 PM		16.79	
		pH		6.4		6.7		6.8		6.8		6.9		7.0		7.1		7.2		7.1	
		Gas Leak Detector		0%		0%		0%		0%		0%		0%		0%		0%		0%	

The table presents data on the composition of raw materials and the results of parameter monitoring during the biogas fermentation process, which lasted nine days. The nine-day fermentation period was chosen with the primary objective of the study in mind—namely, to develop and evaluate the performance of an IoT-based biogas monitoring system—rather than to optimize biogas production or determine maximum biogas yield. This timeframe was deemed sufficient to observe changes in key fermentation parameters, such as temperature, pH, methane concentration, and potential gas leaks, as well as to verify the system's ability to acquire, transmit, and visualize data in real time. The set fermentation duration of nine days was deemed sufficient to evaluate the performance of the developed monitoring system; however, it was not entirely sufficient to comprehensively evaluate the overall biogas production performance. Biogas production is a biological process that occurs through several stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In many anaerobic digester systems, particularly those using complex organic materials—in this study, household organic waste—biogas and methane production can continue to increase for several weeks before reaching a stable state.

The raw materials used consisted of organic waste, water, and the EM4 microbial activator, with varying amounts added each day. The amount of organic waste used ranged from 5 kg to 20 kg, while the water volume ranged from 20 to 40 liters. EM4 was added in relatively constant amounts, approximately 0.5 to 1 liter, to accelerate the decomposition process by microorganisms. Temperature parameters were measured under two time conditions—daytime and nighttime—revealing temperature fluctuations during the fermentation process. Daytime temperatures tended to be higher than nighttime temperatures, ranging from approximately 30–33.9°C during the day and 20.8–29.2°C at night. This indicates the influence of environmental conditions on temperature stability within the reactor. The gas pressure generated during the fermentation process showed an increasing trend day by day,

rising from 14.08 ppm to 16.79 ppm on the 9th day. This increase indicates that microbial activity in gas production—particularly methane—becomes increasingly optimal as the fermentation period progresses. The pH value also increased gradually, from 6.4 on the first day to reaching a neutral range, approximately 7.1–7.2, in the following days. This pH condition, approaching neutrality, indicates an environment that is increasingly conducive to the growth of methanogenic bacteria. Additionally, monitoring results from the gas leak detector showed a value of 0% on all observation days, indicating no gas leaks during the process. Overall, these data indicate that the fermentation process is proceeding well, marked by increased gas production, pH stability, and the absence of leaks in the reactor system.

Methane Gas Monitoring Dashboard

Monitoring of sensor measurement data is conducted via a web-based interface accessible via a smartphone or laptop/PC. As shown in Figure 4, this web system displays monitoring data in real time, allowing users to monitor measured parameters without needing to be at the biogas reactor site.

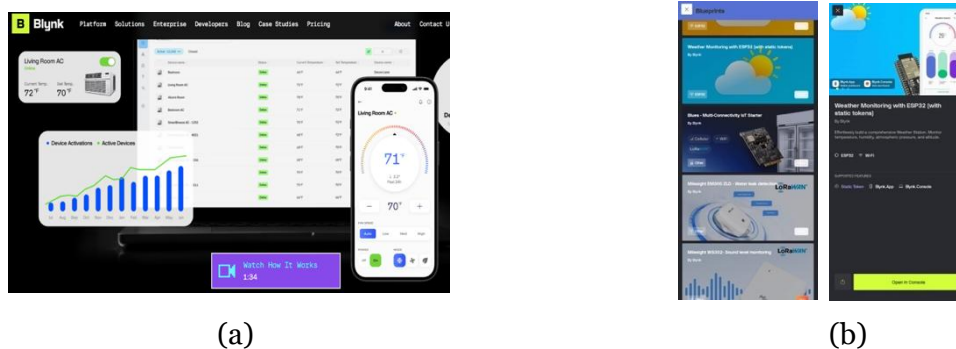


Figure 4 (a) Blynk app display on a laptop/PC, (b) Blynk app display on a smartphone

The Blynk application interface displayed on laptops/PCs and smartphones, as shown in Figure 4, serves as a platform for real-time monitoring and controlling the IoT-based biogas reactor system. The Blynk platform is used to display data from sensors connected to the microcontroller, allowing the operational conditions of the biogas reactor to be monitored directly via digital devices. The use of this application makes it easier for users to monitor the system because data can be accessed flexibly without having to be physically present at the reactor site. Operationally, the Blynk interface displays several key parameters related to the anaerobic fermentation process, such as reactor temperature, gas pressure, and biogas production status. The temperature parameter is used to assess temperature stability inside the reactor, as temperature affects the activity of anaerobic microorganisms in the methane gas formation process. Meanwhile, the gas pressure parameter is used to monitor the amount of gas produced and stored in the biogas storage tank. This information serves

as a key indicator for evaluating fermentation performance and biogas production efficiency. The data obtained from monitoring via laptop/PC and smartphone interfaces is visualized in the form of numerical displays, graphs, and status indicators, making it easier for users to understand system conditions more quickly and accurately. Real-time data presentation allows changes in operational parameters to be detected immediately. For example, unstable temperature changes or a significant increase in gas pressure can be identified early, enabling prompt adjustments to maintain the stability of the fermentation process. In addition to supporting data visualization, the Blynk platform also provides remote monitoring capabilities via the internet.

The integration of sensors, microcontrollers, and the Blynk app enables data to be automatically sent to the user's device, allowing reactor conditions to be monitored at any time and from different locations. This remote access capability enhances monitoring efficiency because system oversight no longer relies on direct on-site observation at the research location. The Blynk app also supports user interaction with the monitoring system through specific notification and control features. When parameter changes occur outside normal conditions, the system can automatically alert the user, allowing potential disruptions to the fermentation process to be addressed promptly. Thus, the Blynk interface functions not only as a data display medium but also as a decision-making support tool for operating the IoT-based biogas reactor. Overall, the use of the Blynk application interface significantly contributes to improving the effectiveness of biogas system monitoring and control. Real-time monitoring features, informative data visualization, remote access, and user interaction capabilities help improve the accuracy of monitoring the anaerobic fermentation process. This contributes to the optimization of biogas production, enhanced operational safety, and the overall efficiency of managing IoT-based biogas reactor systems.

Conclusion

Testing of the IoT-based reactor design, which integrates an ESP32 microcontroller, demonstrates that the system is capable of optimally monitoring key fermentation process parameters. The DHT11 temperature and humidity sensor, the pH-4502C pH sensor module, and the MQ-4 gas sensor have proven capable of measuring temperature and pH, as well as detecting gas leaks and methane concentrations, stably, with high accuracy, and in real time. Test results indicate that the fermentation temperature ranges from 28°C to 33°C, which falls within the mesophilic zone, thereby optimally supporting the activity of methane-producing microorganisms. The pH value increased from a slightly acidic condition toward a neutral condition (approximately 6.4 to 7.2), indicating that the reactor environment is becoming increasingly conducive to the anaerobic fermentation process.

Additionally, the gas concentration increased gradually from 14.08 ppm to 16.79 ppm, indicating that biogas production is occurring progressively over the course of fermentation. The absence of leaks in the biogas reactor (0%) during testing also demonstrates that the reactor system operates safely and reliably. Meanwhile, based on sensor calibration results, all sensors exhibited relatively small error margins, indicating that the monitoring system possesses good accuracy and reliability. Consequently, this system is effective in supporting real-time and remote monitoring of the biogas production process. For future research and development, several aspects can be improved, including integrating the system with a cloud-based platform and performing data analysis using artificial intelligence (AI) to predict biogas production patterns and automatically optimize fermentation conditions. The development of an automatic control system (closed-loop control) can also be explored in future research, such as automatically regulating temperature and pH to maintain optimal conditions within the reactor. Future research could focus on larger-scale applications and the use of various organic waste feedstocks to enhance the efficiency and production capacity of biogas as a sustainable renewable energy source. The level of reliability regarding the increase in methane production in this study is at the inductive or trend-based evidence level and is not intended as an absolute verification of gas composition. Further research should involve analyzing biogas composition using standard methods, such as gas chromatography or calibrated NDIR sensors, to validate methane content more accurately and strengthen the scientific rigor of the results obtained.

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