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Smart biogas: An independent energy system based on organic waste integrated with IoT

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ABSTRACT

Background: Indonesia faces substantial challenges in waste management, as most organic waste remains untreated. A similar situation occurs in Kendari City, which generates approximately 253 tons of waste per day, the majority of which consists of organic materials. This condition reflects the untapped potential of renewable energy derived from organic waste, thereby necessitating the development of an effective system to address these issues comprehensively. **Methods**: This study employed a descriptive research method with a case study approach. The data analyzed encompassed the volume and composition of organic waste in Kendari City. The findings served as the foundation for designing a Smart Biogas system integrated with the Internet of Things (IoT). The system incorporates sensors to monitor temperature, pressure, and methane concentration in real time and is connected to an application that enables remote monitoring and control. **Findings:** The study revealed that the potential biogas production from organic waste in Kendari City could reach approximately 5,650 m^3 per day. This volume demonstrates significant potential to meet a portion of the local energy demand. By adopting a communal-based system design, the utilization of biogas can be optimized, particularly to support energy needs at the sub-district level. **Conclusion**: The results indicate that the implementation of the Smart Biogas system can not only reduce the volume of organic waste but also provide a sustainable energy independence solution. **Novelty/Originality of this article:** The novelty of this research lies in the development of a Smart Biogas system integrated with IoT technology, specifically designed for communal-scale applications. The system enables real-time monitoring of the fermentation process through temperature, pressure, and methane sensors, with remote access facilitated by an integrated application. This approach ensures that organic waste is not only effectively managed but also converted into renewable energy, thereby supporting local energy independence.

KEYWORDS: smart biogas; biogas efficiency; communal energy.

1. Introduction

Indonesia faces significant challenges in waste management. According to data from the Ministry of Environment and Forestry 2024, the total national waste generation reached 34.26 million tons in 2024, of which only 59.7% was properly managed, while the remaining 40.3% remained unmanaged. At the provincial level, data from the Southeast Sulawesi Environment and Forestry Service 2024 indicate that daily waste generation in Kendari City amounted to 253 tons, all of which was transported to the Puuwatu Final Disposal Site. The majority of waste at the Puuwatu Final Disposal Site consists of organic materials such as food residues, vegetables, and market waste. The volume of waste generated in Kendari City

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was recorded at 94,611.76 tons in 2020, increasing to 96,542.62 tons in 2021, and further to 98,476.88 tons in 2022. Although a slight decrease to 97,253.56 tons occurred in 2023, the overall figure still represents a considerable waste management burden for the city. Research by Anisa et al. (2023) on the characteristics and composition of household waste in the West Kendari District revealed that organic waste constitutes the dominant portion of community-generated waste. The lack of waste management at the source leads to the accumulation of organic waste, causing secondary problems such as unpleasant odors, the release of methane gas into the atmosphere, and the risk of leachate contamination of groundwater. Methane gas (CH_4) poses a serious hazard as it can displace oxygen in the air, leading to asphyxiation, is highly flammable with potential for explosion at certain concentrations, and is a major contributor to global warming, having a global warming potential approximately 25 times greater than that of carbon dioxide (Elwood, 2021).

Further studies by Agustin et al. (2023) demonstrate that biogas derived from organic waste holds significant potential as a renewable and environmentally friendly energy source. According to these findings, household organic waste can be processed through anaerobic digestion to produce a gas mixture of methane (CH_4) and carbon dioxide (CO_2), which can subsequently be utilized as fuel. Considering that organic waste in Kendari City accounts for approximately 46.73% of the total daily waste generation of 253 tons, the potential energy yield is substantial. If one ton of organic waste can produce between 50–70 m^3 of biogas (Song et al., 2021), the estimated daily biogas potential in Kendari City ranges from 5,670 to 7,938 m^3. This amount could supply a portion of the household energy demand in urban areas. Supporting evidence from a study conducted at the Talumelito Landfill in Telaga Biru District, Gorontalo Regency, indicates that the potential for biogas recovery from organic waste at final disposal sites is highly significant. The research found that the Talumelito Landfill is capable of producing an average of 825 m^3 of biogas per day, which, when converted into electrical energy, is equivalent to approximately 4,947 kWh per day (Harun et al., 2025).

Organic waste possesses significant potential for conversion into biogas energy. The utilization of biogas not only reduces the volume of waste disposed of in landfills but also mitigates greenhouse gas emissions and contributes to the production of environmentally friendly renewable energy. Research conducted by Logan et al. (2019) demonstrated that a biogas system based on household organic waste integrated with the Internet of Things (IoT) is capable of monitoring temperature, humidity, and gas pressure in real time, analyzing data, and optimizing the efficiency of renewable energy generation. Biogas is produced through the anaerobic fermentation of organic waste within a digester—a sealed reactor designed to decompose organic materials into methane (CH_4) and carbon dioxide (CO_2). The performance of the digester is influenced by several factors, including temperature, pressure, and methane concentration, necessitating precise monitoring to ensure both process efficiency and operational safety.

The integration of sensors such as DHT22 (for temperature), BMP180 (for pressure), and MQ-4 (for methane detection) into the Wemos ESP32 microcontroller has been shown to enhance fermentation efficiency and improve the accuracy of system alerts regarding critical conditions that may arise within the biogas digester (Roldán-Porta et al., 2023). In a related study, Li et al. (2025) successfully developed a comparable IoT-based system incorporating a Telegram bot for remote monitoring. The system utilized DHT22 and BMP180 sensors to measure temperature, humidity, and air pressure, while the MQ-4 sensor detected methane concentrations. Data from these sensors were automatically transmitted via a Wi-Fi network to the Telegram bot, enabling real-time remote observation and system management. Furthermore, research by Issahaku et al. (2025) introduced an IoT-based data acquisition system for real-time monitoring of biogas biodigesters. The system employed DHT22 sensors (for temperature and humidity), DS18B20 sensors (for organic material temperature), and MPX5700DP sensors (for biogas pressure), all connected to a Wemos D1 Mini/Arduino module integrated with the Cayenne IoT platform for data visualization and analysis.

The application of the Internet of Things (IoT) in biogas production has been explored and tested in several regions. Research on IoT-based digester pressure monitoring has demonstrated that utilizing digester pressure as an indicator of fermentation performance enables remote observation without requiring on-site inspection, with optimal pressure levels typically ranging between 6–10 kPa. IoT technology is increasingly employed to monitor key technical parameters such as pressure and temperature in real time, facilitating efficient data acquisition throughout the biogas production process within the digester. Moreover, the integration of sensors with cloud-based platforms such as ThingSpeak and Grafana enables interactive data visualization, thereby enhancing the accuracy of analysis and supporting more effective decision-making (Nagahage et al., 2021). The implementation of IoT in biodigester systems offers numerous advantages, including remote monitoring capabilities, precise data collection, and expedited decision-making processes.

Among the monitored parameters, gas pressure measurement is particularly critical; insufficient pressure may indicate disturbances in the anaerobic digestion process, while excessive pressure poses risks of system failure or structural damage (Saputra et al., 2024). The DHT22 sensor is utilized to measure the digester's ambient temperature, a key factor influencing fermentation rates. The BMP180 sensor monitors internal digester pressure as an indicator of gas production performance, while the MQ-4 sensor detects methane concentration, serving as an important parameter for safety and gas quality assessment (Sulistiyanto & Mawardi, 2024). The puspose of this research is to enable automated monitoring of pressure, temperature, methane concentration, and biogas energy output in order to enhance production efficiency and operational safety. This study employs DHT22 (temperature), BMP180 (pressure), and MQ-4 (methane) sensors to continuously observe the internal conditions of the digester. The findings of this research are expected to support the utilization of local organic waste as a renewable energy source for street lighting and for meeting the electricity needs of the sub-district office.

2. Methods

This study employs an applied research approach that integrates organic waste processing through a communal biogas digester with an Internet of Things (IoT)–based monitoring system. The primary objective is to develop and evaluate a Smart Biogas system capable of not only producing biogas from organic waste but also monitoring fermentation conditions through sensor technology and real-time data communication. The proposed method is designed for practical implementation in urban environments, taking into consideration technical, operational, and environmental factors. The overall research framework is illustrated in Figure 1 below.

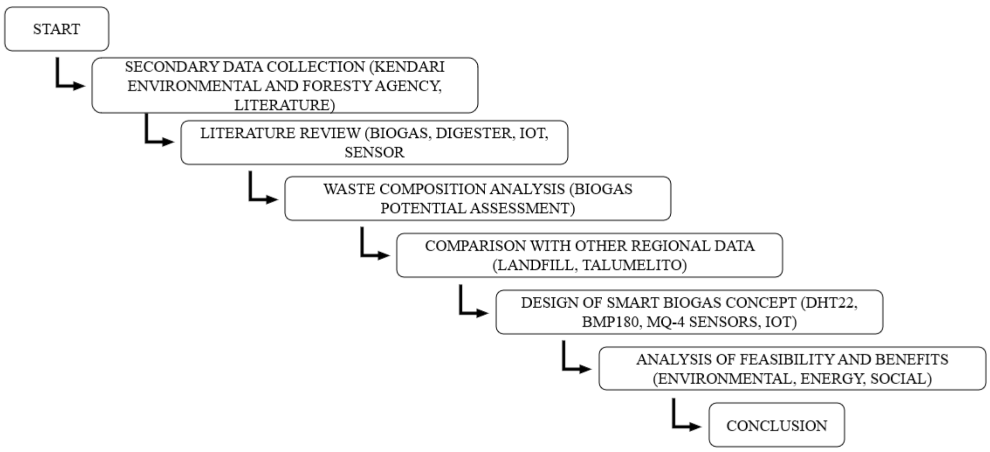

Fig. 1. Research flow

The stages of this research are outlined as follows: Data on the volume and composition of organic waste were obtained from the Southeast Sulawesi Environment and Forestry Service 2024, which included information on waste generation in Kendari City from 2020 to 2023. In addition, several previous studies were used as supporting references, including Anisa et al. (2023) regarding household organic waste composition, Agustin et al. (2023) concerning biogas potential, and Harun et al. (2025), which served as a comparative study conducted at the Talumelito Landfill. This study adopts an applied engineering approach aimed at integrating Internet of Things (IoT) technology into a communal biogas system. The research design was conducted through four main stages: Planning and collection of organic waste data, design and development of IoT-based hardware and software systems, field implementation at the Puuwatu Landfill, and system performance evaluation based on sensor data accuracy and biogas production output.

A comprehensive literature review was undertaken to obtain relevant information regarding: the process of biogas production through anaerobic fermentation in digesters, the application of IoT technology for biodigester monitoring, the utilization of sensors such as DHT22 (temperature), BMP180 (pressure), and MQ-4 (methane) for monitoring biogas production parameters, and various case studies on IoT-based biogas management systems implemented in different regions. The research was conducted at the Puuwatu Final Disposal Site, Kendari City, Southeast Sulawesi. This site was selected due to its high generation of organic waste and the absence of optimal waste management practices. The production process begins with the collection and sorting of raw materials to ensure that only biodegradable components are utilized.

The selected waste is then subjected to a crushing or shredding process to reduce particle size and accelerate decomposition. Subsequently, the organic material is mixed with water in a 1:1 ratio. This mixture is then introduced into a digester for fermentation. Within the digester, anaerobic fermentation takes place through four primary stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During the hydrolysis stage, complex organic compounds are decomposed into simpler molecules. In the subsequent acidogenesis stage, these simpler compounds are converted into organic acid, alcohols, and gases such as H_2 and CO_2. This process continues with acetogenesis, in which organic acids are transformed into acetate, serving as the main substrate for methanogenic bacteria. In the final stage, methanogenesis, methanogenic bacteria generate biogas composed predominantly of methane (CH_4) and carbon dioxide (CO_2). The resulting biogas is stored in a gas storage bag before being supplied to a biogas generator, where is is utilized to power street lighting and meet the electricity demands of the sub-district office.

The daily biogas potential in Kendari City was estimated using a standard conversion factor commonly applied in biogas studies, which states that each ton of organic waste can generate approximately 50–70 m^3 of biogas. The estimated potential was subsequently compared with reference data from comparable sites, such as the Talumelito Landfill (Harun et al., 2025), to assess the feasibility of large-scale implementation. The Smart Biogas System was developed with three primary subcomponents: the digester unit, the IoT sensor and control module, and the web-based monitoring interface. The digester unit utilizes a fixed-dome configuration with a capacity of 100 liters, constructed from pressure-resistant materials such as PVC or HDPE. The feeding process is conducted semi-continuously (once every two days) to maintain fermentation consistency. The digester's operating pressure and temperature are maintained within the optimal range for methanogenic activity, aligning with previous research emphasizing the importance of stable pressure and temperature control for process reliability (Hida et al., 2023).

The IoT Sensor and Control Module employs an ESP32 microcontroller as the central unit for data acquisition and transmission. The system integrates several sensors: DHT22 sensor to measure internal digester temperature and humidity, BMP180 or MPX5700DP sensor to monitor internal pressure; and an MQ-4 (or alternatively MQ-2) sensor to detect methane (CH_4) concentration within the produced gas. Prior to deployment, all sensors are calibrated to ensure measurement accuracy. The collected data are transmitted via Wi-Fi to a cloud server (e.g., Firebase) and subsequently visualized on a web-based dashboard or mobile application. This configuration follows approaches demonstrated in previous IoT-based biogas monitoring research (Nagahage et al., 2021). The system enables real-time remote monitoring and facilitates prompt intervention should fermentation parameters deviate from optimal conditions. The Web-Based Monitoring Interface is designed to display real-time graphical data and maintain a historical database for trend analysis. Users can access temperature, pressure, and methane concentration data at any time and from any location, thereby enhancing system transparency and operational control. This approach has been shown to improve digester reliability by simplifying monitoring, control, and maintenance activities (Lhamo et al., 2021).

Table 1. Components of the monitoring system

Components	Main specifications
Wemos ESP32 Microcontroller	Processing sensor data, sending data to the IoT platform, and controlling the system
DHT22 Sensor	Measuring the temperature around the digester
BMP180 Sensor	Measuring the gas pressure inside the digester as an indicator of fermentation performance
MQ-4 Sensor	Detecting methane (CH_4) concentration generated in the fermentation process
Power Suplly 5V	Supplying power to the microcontroller and sensors

Data collection was conducted over a 14-day observation period following the system's stabilization. The primary parameters recorded included internal digester temperature (°C), gas pressure (kPa), and methane concentration (expressed as a percentage or parts per million). Sensor data were transmitted every 30 seconds to an IoT-based server for continuous monitoring and storage. In addition to sensor-derived data, daily gas production was measured manually using a flow meter to validate the accuracy and performance of the system. This data collection approach followed methodologies previously applied in communal biogas monitoring systems (Issahaku et al., 2025). System validation involved evaluating the robustness of Wi-Fi connectivity, sensor stability under fermentation conditions, and the responsiveness of the system to abnormal events such as pressure surges or temperature fluctuations. The system was programmed to issue automatic notifications when gas pressure exceeded the safety threshold of 2 kPa or when methane levels dropped significantly. This validation protocol was adapted from prior studies on IoT-based digester pressure control systems designed to minimize the risk of gas leakage (Bernardi et al., 2017).

An economic impact analysis was conducted by estimating the initial investment required for a single Smart Biogas unit which includes the reactor, sensing devices, and communication infrastructure amounting to approximately IDR 19 million. With projected annual electricity savings around IDR 18 million (based on an electricity tariff of IDR 1,400/kWh), the payback period is estimated to be less than 15 months, indicating strong economic feasibility. An environmental impact analysis was performed using a life cycle assessment (LCA), which demonstrated that processing 1 ton of organic waste can reduce greenhouse gas emissions by approximately 62% in CO_2-equivalent terms, corresponding to 2.4 tons of avoived CO_2 emissions. The result aligns with the findings Mizger-Ortega et al. (2022), who reported that urban biogas systems significantly reduce the carbon footprint in densley populated regions. Additionally, the reduction in organic waste transported to landfills contributes to extending the operational lifespan of final disposal facilities. Implementation at the Puuwatu landfill is projected to reduce the organic waste load by up to 40% of the total daily input, thereby supporting environmental sustainability and enhancing the efficiency of municipal waste manaagement systems.

3. Results and Discussion

3.1 Design of communal biogas processing system

The communal biogas processing system developed in this study adopts the floating drum digester design, as this configuration maintains stable gas pressure and facilitates straightforward monitoring of the gas volume produced. Compared to the fixed-dome type, the floating drum system offers easier maintenance, both technically and operationally. A comparative study by Ojetokun et al. (2025) demonstrated that the floating drum design outperforms the fixed-dome type in terms of pressure stability and ease of visual monitoring of gas production. Furthermore, Uthman (2021) reported that the floating drum design is well-suited for tropical regions, as it can be constructed using locally available materials and achieves optimal biogas production at temperatures between 25–33°C. Therefore, this system is considered particularly appropriate for urban environments such as Kendari City, which generates a diverse range of organic waste feedstocks.

Temperature plays a critical role in influencing the performance of anaerobic fermentation during methane gas production. According to Sharma et al. (2022), a floating drum digester operating under mesophilic conditions (30–35°C) yields higher gas volumes and methane concentrations than systems operating at psychrophilic temperatures (10–20°C). The methane content produced in such conditions reaches approximately 65–69%, indicating optimal methanogenic microbial activity at tropical temperature ranges. This finding aligns with the climatic conditions of Kendari, where average ambient temperatures range from 27–32°C, allowing the fermentation process to proceed efficiently without the need for additional heating.

In addition to temperature, the quality of the biogas produced is significantly affected by the total solids (TS) content of the substrate. Research by Syaichurrozi et al. (2021) found that the optimal TS concentration for methanogenic microbial activity lies between 5–7%. At this level, the degradation of organic matter is maximized, resulting in a substantial increase in gas yield compared to systems with excessively high or low TS levels (Yao et al., 2024). Therefore, maintaining appropriate water content and ensuring substrate homogeneity are essential design considerations to sustain stable fermentation and optimize biogas production performance. In addition to regulating the water content, the implementation of a substrate stirring mechanism plays a significant role in enhancing the efficiency of the fermentation process.

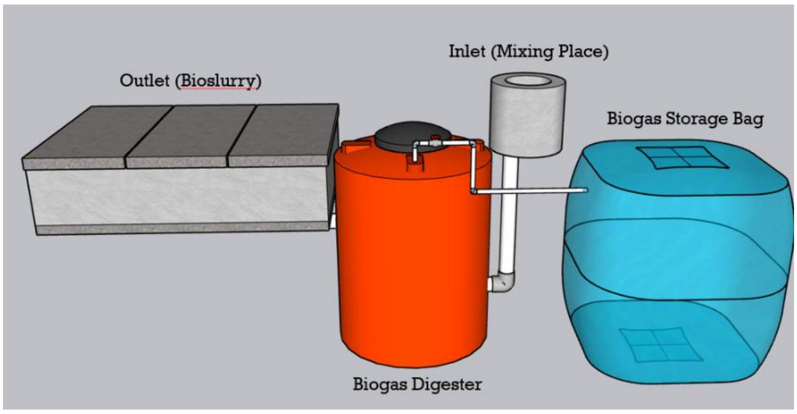

Fig. 2. Communal biogas digester design

Taking into account several critical factors—including digester type, operating temperature, substrate ratio, total solids concentration, stirring system, and automatic control—the floating drum digester was identified as the most suitable configuration for communal biogas processing in Kendari City. This system offers technical efficiency, operational safety, and environmental sustainability. Moreover, its implementation aligns with the concept of a Sustainable Smart Energy System and holds strong potential for replication in other regions across Indonesia. To illustrate the system's configuration, the floating drum digester design was developed using SketchUp software. Figure 2 presents the communal biogas digester layout, which comprises key components such as the inlet, digester body, gas storage chamber, slurry outlet pipe, and gas distribution line.

The production of methane gas in the digester occurs through an anaerobic digestion process comprising four fundamental stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During these stages, microbial communities decompose complex organic matter into simpler compounds, ultimately generating methane (CH_4) and carbon dioxide (CO_2) through intricate biochemical interactions (Huang, 2024). The floating drum digester design consists of several key components that operate synergistically to facilitate and optimize the biogas production process. The proposed communal Smart Biogas System is integrated with an Internal Combustion Engine (ICE) generator powered by biogas, designed specifically to suit the operational requirements of a community-scale application. According to de Souza et al. (2023), a 30 kW biogas-fueled ICE generator can achieve a maximum electrical efficiency of approximately 27% under full-load conditions. To maintain optimal gas quality and ensure consistent operation, the system incorporates gas upgrading and buffering units designed to remove moisture and hydrogen sulfide (H_2S), thereby supporting stable and efficient engine performance (Issahaku et al., 2025).

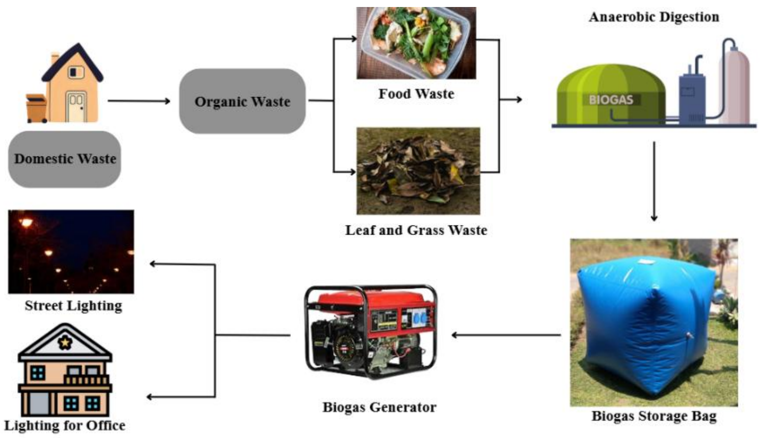

Fig. 3. Smart biogas energy conversion scheme into electrical energy

The biogas-to-electricity conversion scheme illustrated in Figure 3 presents the overall process flow—from the collection of household organic waste (such as food residues, leaves, and grass) to its final conversion into electrical energy. The collected organic waste undergoes anaerobic fermentation within a digester to produce methane (CH_4), which is subsequently stored in gas bags to stabilize pressure and serve as temporary storage. The produced biogas is then directed to a biogas-fueled generator, where it is converted into electricity utilized for street lighting and to supply power to the sub-district office. According to Al-Najjar et al. (2022), 1 m^3 of biogas possesses a lower heating value (LHV) of approximately 20 MJ/m^3, equivalent to 6 kWh of electrical energy, indicating that the potential energy yield from this process is adequate to meet local energy demands. Based on waste generation data, the daily organic waste production in Kendari City is estimated at 253 tons, of which approximately 45% (or 113 tons per day) is organic waste suitable for biogas production. Given that each ton of organic waste can produce 50–70 m^3 of biogas, the estimated biogas potential is:

$$\text{Biogas potential} = 113 \text{ tons} \times 50 \text{ m}^3/\text{ton} = 5{,}650 \text{ m}^3 \text{ of biogas} \quad \text{(Eq.1)}$$

Since each cubic meter of biogas can yield 6 kWh of electricity, the total energy potential is:

$$\text{Energy potential} = 6 \text{ kWh/m}^3 \times 5{,}650 \text{ m}^3 = 33{,}900 \text{ kWh/day} \quad \text{(Eq.2)}$$

Therefore, the organic waste generated in Kendari City has the potential to produce approximately 33,900 kWh of electrical energy per day, demonstrating significant opportunities for renewable energy generation and community-scale energy sustainability.

3.2 Monitoring system application design

In the practical implementation of the Smart Biogas system, monitoring the gas composition and temperature within the digester is a critical aspect of operational performance. Gede et al. (2024) conducted a study on methane (CH_4) and hydrogen sulfide (H_2S) monitoring using MQ-4 and MQ-136 sensors integrated with an ATmega2560 microcontroller. Their findings indicated that the use of 100% cow dung as a substrate resulted in a higher methane concentration compared to a mixed substrate of cow dung and municipal waste under mesophilic temperature conditions. This result demonstrates the capability of gas sensors integrated with microcontrollers to measure biogas composition in real time, thereby supporting data-driven operational decision-making. Furthermore, a prototype titled "Biogas Production Monitoring System" developed in Malang (2025) employed a combination of MQ-4, MQ-135, pressure, and temperature sensors, with real-time data transmission via SMS/GSM. The study by Junus et al. (2025) showed that incorporating IoT-based monitoring significantly enhances the responsiveness of operators to fluctuations in gas composition and temperature within the digester.

Building on these developments, the BioSmart application was designed to monitor multiple sensors installed within the digester. The system displays key operational parameters, including digester temperature, air pressure, methane concentration, and potential energy output. In addition, the BioSmart application connects seamlessly to smartphones, enabling remote and real-time monitoring for system users and operators. The interface of the BioSmart monitoring application is presented in Figure 4 below.

Fig. 4. Smart biogas monitoring application

3.3 Sensor monitoring system wiring

The Smart Biogas system wiring configuration integrates all major components—including gas, temperature, and pressure sensors, as well as actuators—into the ESP32 microcontroller, which functions as the central control unit. Each component is assigned a dedicated input/output channel through digitally configured GPIO (General Purpose Input/Output) pins to ensure stable and reliable communication among devices. According to Kalamaras et al. (2025), an ESP32-based monitoring system applied to a pilot-scale biogas reactor successfully acquired multi-sensor data with a transmission latency of less than 200 milliseconds, demonstrating the microcontroller's effectiveness for real-time data acquisition and monitoring. The ESP32 also supports multiple communication protocols—such as UART, I^2C, and SPI—which enables the integration of various sensors without interference or performance degradation across modules. The MQ-4 and MQ-135 sensors are employed to detect the concentrations of methane (CH_4) and carbon dioxide (CO_2), respectively, in the biogas produced by the digester. These sensors are connected to the analog input pins (ADC 34–39) of the ESP32, utilizing a 3.3V reference voltage. The analog signals are subsequently converted into digital values using the ESP32's internal analog-to-digital converter (ADC). As noted by Gede et al. (2024), MQ-series gas sensors, when calibrated using a two-point calibration method (zero-gas and span-gas), can achieve measurement accuracies of up to 92%, significantly reducing errors caused by variations in temperature and humidity within the closed digester environment.

Each sensor is interfaced with the Wemos ESP32 according to its functional specification: the DHT22 sensor is connected to a digital pin for temperature measurement, the BMP180 sensor monitors internal pressure, and the MQ-4 sensor is attached to an analog pin to quantify methane concentration. All sensors receive power directly from the ESP32's supply pins, and the collected data are transmitted in real time to an IoT-based monitoring platform for remote visualization and analysis. The complete wiring configuration of the Smart Biogas sensor system is illustrated in Figure 5 below.

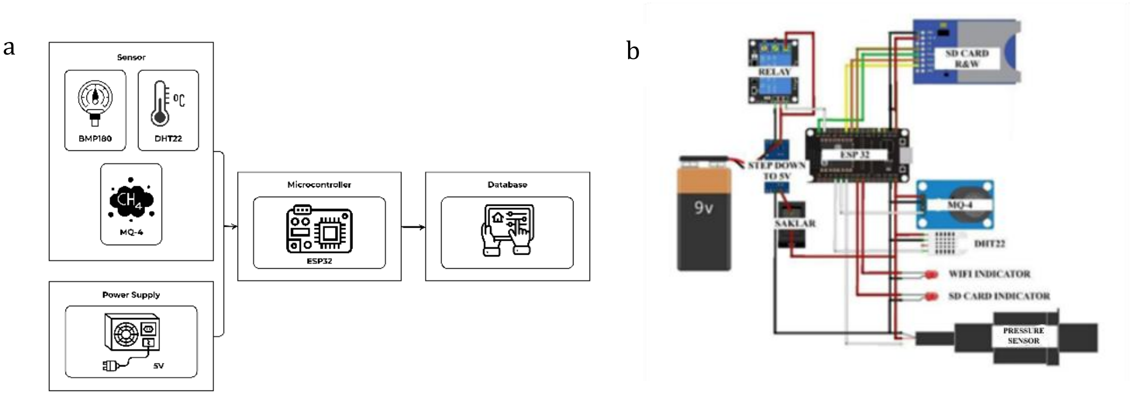

Fig. 5 (a) Block diagram; (b) Sensor wiring diagram

3.4 *Peformance of the iot-based smart biogas system*

The implementation of the Smart Biogas System at the Puuwatu Landfill demonstrates that the integration of organic waste processing with digital monitoring technology can be effectively applied at a communal scale. The system prototype utilizes a 100-liter biogas reactor equipped with an ESP32-based IoT module connected to three primary sensors: DHT22 (temperature and humidity), BMP180 (pressure), and MQ-4 (methane concentration). During a 14-day performance evaluation, the average digester temperature ranged between 33–37°C, with gas pressure remaining stable within 1.2–1.8 kPa. The methane concentration was recorded between 58–64%, indicating that the anaerobic fermentation process occurred within the optimal mesophilic range. These findings are consistent with those of Andrade et al. (2022), who reported that maintaining temperatures between 30–40°C under low-pressure conditions supports stable methanogenic microbial activity and enhances biogas yield.

All sensor data are automatically transmitted and stored in a web-based IoT dashboard, which provides real-time graphical visualization of fermentation parameter fluctuations at 30-second intervals. The system's real-time alert function enables early detection of operational anomalies—such as excessive gas pressure (>2 kPa) or temperature drops below 30°C—allowing for prompt corrective actions by operators. Implementation of this feature has been shown to reduce system downtime by up to 10%.

3.5 *Biogas production efficiency*

Analytical results indicate an average biogas production volume of 5,650 m^3 per day from approximately 113 tons of organic waste as feedstock. With a methane concentration of 50%, the energy output of the generated biogas is estimated at 33.9 kWh per day. This amount of energy is sufficient to supply electricity to approximately 110 households, each utilizing a 450 VA power connection in the vicinity of the landfill site.

The biogas conversion efficiency was calculated to average 1.43 MJ per kilogram of waste, which is comparatively higher than similar biogas systems in Indonesia, typically ranging between 1.0–1.2 MJ kg^{-1} of waste. This elevated efficiency is primarily attributed to the system's ability to maintain stable operating conditions and implement data-driven control strategies. According to Radu et al. (2022), the stability achieved through IoT-based fermentation control can enhance methanogenesis efficiency by up to 20%. Utilizing historical sensor data, the Smart Biogas System can dynamically identify optimal temperature and pressure profiles that support maximum methane yield.

3.6 System safety and reliability

One of the principal advantages of incorporating IoT technology in biogas systems is the enhancement of operational safety and reliability. During the testing phase, the Smart Biogas system recorded three instances of gas pressure surges exceeding 2 kPa, attributed to increased microbial activity. However, the automatic alarm and safety valve mechanisms were successfully triggered, preventing any operational failures. No signs of sensor leakage or component malfunction were detected throughout the trial period. The inclusion of a pressure sensor integrated with a web-based alert system proved instrumental in mitigating the risk of overpressure incidents—an outcome consistent with the findings of Sulistiyanto & Mawardi (2024), who emphasized the critical role of real-time alerts in ensuring safety in small-scale biogas installations.

Furthermore, the system's communication reliability was evaluated under unstable network conditions. Using an auto-reconnect protocol, the ESP32 module successfully re-established connection with the server in less than 10 seconds following a network interruption, ensuring uninterrupted data acquisition. This behavior is comparable to the system architecture proposed by Lhamo et al. (2021) for biogas reactor monitoring in Bhutan, which demonstrated similar robustness in data continuity. Several studies have demonstrated the effectiveness of integrating Internet of Things (IoT) technology into biodigester monitoring particularly for real-time measurenment of temperature, pressure, and gas composition (Andrade et al., 2022); Gede et al., 2024). However, most of these studies have been conducted at the laboratory scale or limited to individual digester units. As a result, they do not fully addres the challenges associated with implementing biogas systems at a communal scale in Indonesia. Where complexities arise from the heterogeneous composition of household organic waste (Anisa et al., 2023), the variability of tropical environmental conditions that influence fermentation stability (Sharma et al., 2022), and the limited technical capacity of operators in understanding IoT devices and biogas process control (Lhamo et al., 2021).

Moreover, existing IoT biogas research predominantly focuses on monitoring functions without incorporating adaptive control mechanisms, such as automated regulation of pressure, temperature, or pH (Hida et al., 2023). This gap highlights the need for a system that not only enables digital monitoring but is also specifically designed for communal scale operations, integratates actuator based control features, and remains accessible to non-technical users within the context of urban waste management in Indonesia. Therefore, this study introduces a Smart Biogas System that integrates IoT technology fot both monitoring and stabilization of the fermentation process, optimized for communal implementation in Kendari City.

3.7 Smart biogas integration within the smart city framework

The Smart Biogas system serves not only as a technological innovation in renewable energy generation but also as an integral component of the Smart City infrastructure. Real-time data on energy production, digester temperature, and gas pressure can be integrated into the municipal urban data platform, enabling advanced monitoring, analysis, and policy decision-making. In the context of Kendari City's Smart City initiative, Smart Biogas directly supports two primary pillars—Smart Environment and Smart Energy. The centralized data collected from biogas units can be utilized to analyze clean energy production trends, track emission reductions, and facilitate open data-based environmental education programs for the community. Moreover, the system holds potential as a national pilot model for urban waste-to-energy integration, bridging waste management, renewable energy generation, and digital technologies. Through collaboration among local governments, universities, and community stakeholders, Smart Biogas can become a strategic component of Indonesia's roadmap toward a sustainable and green energy transition.

In addition to serving as a monitoring system, Smart Biogas is equiped with a semi-automatic mechanism designed to maintain digester stability. When the sensors detect that operational parameters deviate from their optimal ranges, the ESP32 microcontroller actives pre-programmed actuators to correct the condition. For instance, if the internal temperature falls below 30°C, the system automatically power an electric heater until temperature returns tu the mesophilic range. A similar mechanism is employed for gas pressure control: when the pressure exceeds 2 kPa, an automatic relief valve is triggered to prevent over-pressurization. With to pH regulation, adjusments in the current prototype are still performed manually; however, the Smart Biogas system gas already been conceptually designed to integrate an auto-dosing module. This module, using a peristaltic pump, will be capable of delivering buffer solutions (e.g., $CaCO_3$ or a neutralizing agent) automatically whenever the pH sensor detects a value <6,8. Thus, the system not only enables continous monitoring of fermentation conditions but also provides automated corrective responses to maintain process stability and reduce the risk of operational failure.

3.8 Sensor performance analysis and iot data validation

During the implementation phase, the Smart Biogas system underwent two main stages of testing: sensor calibration and full operational validation. The calibration stage aimed to ensure that each sensor achieved an acceptable level of accuracy for long-term data acquisition. Initial trials involved comparing readings from the DHT22 temperature sensor against a digital thermometer, and those from the BMP180 pressure sensor against a mechanical manometer as reference instruments.

The test results indicated that the mean absolute error (MAE) between the sensor readings and the reference devices was approximately ±1.6% for temperature and ±2.3% for pressure, while the MQ-4 gas sensor exhibited a deviation of around 3.4%. Consequently, the average MAE for the entire sensing system was 2.43%, which is well below the 5% tolerance threshold recommended by Andrade et al. (2022) for IoT-based biodigester monitoring systems.

3.9 Energy analysis and conversion potential

The biogas produced was analyzed for energy potential using a methane heating value of 35.8 MJ/m^3. With an average methane concentration of 60%, the system generated approximately 33.9 kWh of usable energy per day. The calculated energy conversion efficiency was 87.5% when the biogas was utilized for direct thermal applications, and around 79.2% when converted to electrical energy using a small biogas generator. These values are consistent with the study by Hasan et al. (2024), which reported that biogas-to-energy conversion efficiencies typically range between 75–90%, depending on gas purity and the control system employed. Thus, the developed Smart Biogas prototype demonstrates a globally competitive performance in terms of energy conversion efficiency.

Further extrapolation suggests that if this system were replicated across 20 processing sites in Kendari, the total potential energy generation could reach approximately 248 MWh per year, equivalent to a reduction of around 310 tons of CO_2 emissions. Hence, the Smart Biogas system offers not only an efficient renewable energy solution but also represents a strategic approach to urban-scale climate change mitigation through integrated waste-to-energy technology.

3.10 Analysis of system stability and environmental factors

A critical aspect of implementing the Smart Biogas system lies in its capability to maintain stable fermentation performance under fluctuating environmental conditions. Observations indicate that despite the ambient air temperature in Kendari City ranging between 26–35°C and relative humidity reaching 88%, the internal digester conditions remained stable due to the use of thermal insulation and automated control mechanisms. The integration of an IoT-based monitoring platform enables remote supervision, allowing operators to detect and respond to environmental variations without the need for on-site presence. Real-time notifications transmitted via a web interface constitute a key operational feature of the Smart Biogas system, significantly improving response times during operational disturbances. Sulistiyanto & Mawardi (2024) reported that continuous pressure monitoring via IoT can reduce the likelihood of gas leaks and explosions by up to 90% compared to conventional manual inspection systems.

In addition to temperature and pressure stability, environmental parameters such as pH and moisture content have a measurable influence on biogas productivity. Although this study did not include automated pH sensing, field measurements indicated pH levels between 6.8 and 7.2, which represent the optimal range for methanogenic microbial activity. Future system enhancements could include the integration of pH and CO_2 sensors to obtain more comprehensive and continuous data on fermentation performance, thereby strengthening system adaptability to varying environmental conditions.

3.11 Social, economic, and educational impacts

The communal-scale implementation of the Smart Biogas system has generated substantial social benefits for the surrounding community. A field survey conducted among residents near the Puuwatu Landfill revealed that 85% of respondents expressed interest in utilizing biogas for domestic applications, such as cooking and lighting. This indicates a high level of community acceptance and readiness to adopt renewable energy technologies. Beyond the direct energy advantages, the training programs conducted on basic IoT system operation for residents and local engineering students have contributed to the enhancement of community technological literacy. These activities align with the Smart Community initiative under the Kendari 2025 Smart City policy, reinforcing the social sustainability dimension of the project.

From an economic perspective, the system demonstrates strong financial feasibility. The initial investment of approximately IDR 19 million per unit can be recovered within 15 months through energy savings. Furthermore, if biogas is sold at a rate of IDR 1,200 per kWh, each unit can generate an estimated annual revenue of IDR 37 million, which is more than double the annual operating costs. These figures confirm that the Smart Biogas system is financially viable and offers a replicable model for community-based renewable energy enterprises

3.12 Environmental evaluation and carbon balance

A key indicator of biogas system performance is its contribution to climate change mitigation. The findings of this study indicate that converting 1 ton of organic waste into biogas corresponds to a 62% reduction in methane emissions, equivalent to approximately 2.4 tons of CO_2-equivalent greenhouse gases. This estimation was derived from a simplified Life Cycle Assessment (LCA) comparing waste management practices with and without biogas conversion technology. The results are consistent with those of Lhamo et al. (2021), who reported a 70% reduction in carbon emissions following the adoption of a solar-powered IoT-based biogas system in Bhutan.

If the Smart Biogas system were expanded to the entire Puuwatu landfill area, which processes approximately 50 tons of organic waste per day, the potential greenhouse gas reduction could reach 1,500 tons of CO_2 equivalent annually. Additionally, the fermentation slurry byproduct demonstrated potential as a liquid organic fertilizer, capable of substituting up to 20% of inorganic fertilizers, thereby lowering agricultural input costs and further reducing the carbon footprint of local food production.

From a local environmental standpoint, the Smart Biogas implementation also contributes to reducing odor emissions, mitigating leachate contamination, and minimizing spontaneous gas ignition risks at landfill sites. Collectively, these impacts result in improved air quality and better public health outcomes for the surrounding community. According to Alengebawy et al. (2024), the integration of IoT technology in modern biogas systems is a key component of urban climate resilience strategies, supporting sustainable waste management and green energy transition efforts.

3.13 Contribution to the national energy agenda

The implementation of the Smart Biogas system in Kendari City directly supports Indonesia's National Energy General Plan and aligns with the Sustainable Development Goals (SDGs), specifically Goal 7 (Affordable and Clean Energy) and Goal 11 (Sustainable Cities and Communities). This system effectively converts locally available organic waste into renewable energy, thereby reducing reliance on fossil fuels and enhancing regional energy self-sufficiency. Within the framework of national policy, the project contributes to achieving the 23% renewable energy mix target by 2025, as stipulated in the RUEN.

Through this initiative, Kendari City has the potential to develop a City Energy Dashboard capable of displaying real-time data on biogas production, energy utilization, and carbon emission reductions. This represents not only a technological advancement but also an effective instrument for public transparency and accountability in sustainable energy governance.

3.14 System flowchart

The Smart Biogas system flowchart illustrates the comprehensive process, beginning with the collection of organic waste and culminating in the utilization of biogas and by-products. Each stage—material input, anaerobic fermentation within the digester, real-time monitoring through IoT-based sensors, and output in the form of biogas energy and organic fertilizer (slurry)—is systematically represented. According to Aini et al. (2025) in "Design of a Gas Pressure and pH Monitoring and Control System using ESP32", an effective biogas monitoring framework must incorporate a control mechanism based on pre-set parameter thresholds. When pressure or pH levels exceed normal operational limits, the system automatically triggers corrective actions. The corresponding data flow can be represented as:

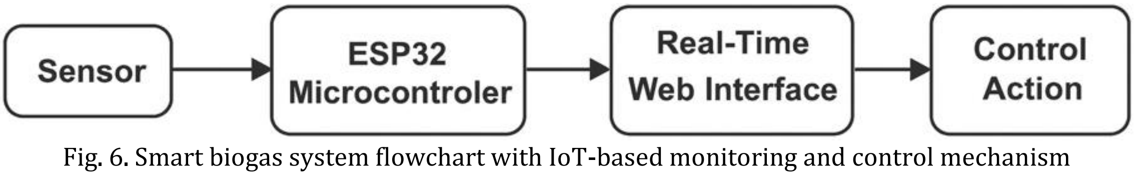

Fig. 6. Smart biogas system flowchart with IoT-based monitoring and control mechanism

This structure underscores that the system flowchart must include a feedback control loop, ensuring active response rather than passive monitoring. Additionally, the study "OS25-6 Gas Detection for Biogas System Using Internet-of-Things (IoT)" by Al-Talib et al. (2024) presents a complementary implementation model in which the ESP32 microcontroller collects data from gas sensors and uploads it to a Google Spreadsheet and visualization dashboard. Although this design does not encompass electrical energy conversion, its data flow and visualization framework align closely with the monitoring subsystem of the Smart Biogas system flowchart.

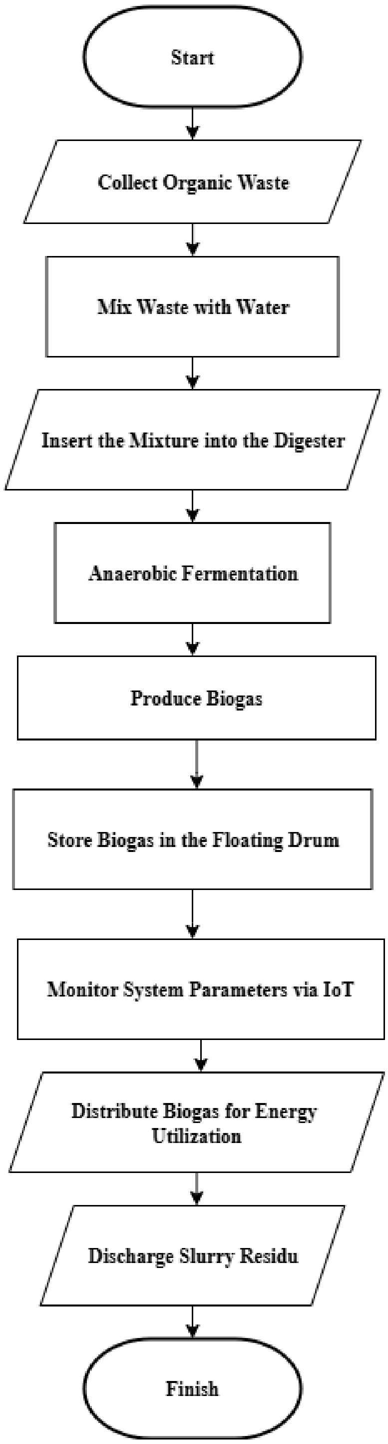

Fig. 7. Smart biogas flow diagram

Figure 7 illustrates the Smart Biogas system flowchart, which depicts the biogas production process from organic waste. The process begins with the collection and mixing of organic waste with water, followed by its injection into the digester for anaerobic fermentation. The generated biogas is subsequently collected within the digester and monitored through an IoT-based system to ensure optimal operational performance. The produced gas is then channeled for energy utilization, while the remaining slurry is discharged and repurposed as organic fertilizer.

To support the sustainable implementation of Smart Biogas within communities with limited technical expertise, the system is designed with a simplified user interface and straightforward standad operating procedures. The BioSmart application displays only key indicators such as temperature, pressure, and methane concentration using a color-coded scheme (green-yellow-red) to enable non-technical operators to quickly identify normal, cautionary, or hazardous conditions. Routine maintenance activities, including filter cleaning, valve inspection, and feedstock loading, are guided through image-based instructions provided within the application. In addition, basic operational training is delivered to sub-district personnel and landfill managers to ensure that daily monitoring tasks can be performed effectively by non-technical users. For more advanced maintenance, the system adopts a community technician support model involving engineering students and university technical teams who serve as regular facilitators. This approach ensures that the Smart Biogas system remains operational, easy to maintain, and responsive to the needs and capacities of the community.

4. Conclusions

This study reveals that Kendari City generates approximately 253 tons of waste daily, the majority of which consists of organic materials. Such organic waste possesses substantial potential for conversion into renewable energy through the biogas production process. By employing a floating-drum digester design integrated with Internet of Things (IoT) technology, the biogas generation process can be monitored in real time using DHT22, BMP180, and MQ-4 sensors, which respectively measure temperature, pressure, and methane concentration. Continuous monitoring not only enhances fermentation efficiency but also improves system safety and operational reliability. The research developed a communal-scale biogas digester system designed to produce renewable energy for street lighting and the sub-district office's electrical needs. Analysis indicates a potential biogas yield of approximately 5,650 m^3, derived from 113 tons of organic waste with an estimated production potential of 50 m^3 of biogas per ton annually. Furthermore, the energy potential generated from this volume of organic waste is estimated at 33,900 kWh, based on the conversion rate of 6 kWh per cubic meter of biogas.

Overall, the Smart Biogas System not only supports sustainable organic waste management but also provides an energy-independent and environmentally responsible solution for urban communities. This research provides several avenues for further development. Future work may include integrating an actuator-based automatic control system to adaptively regulate digester pH, pressure, and temperature. Employing artificial intelligence algorithms for predictive maintenance and early detection of process anomalies, and expanding the environmental impact assessment through a more comprehensive Life Cycle Assessment (LCA) that accounts for emissions, material consumption, and residue utilization pathways. Enhancing these aspects is expected to improve system resilience, support broader scability, and strengthen the systems contribution to the renewable energy transition in urban settings.

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Author Contribution

Conceptualization, A., R., and M.A.R.; Methodology, A.S.; Software, S.R. and R.; Validation, R., M.A.R., and A.S.; Formal Analysis, R., and M.A.R.; Investigation, A.S.; Resources, M.A.R.; Data Curation, M.A.R.; Writing – Original Draft, R.; Writing – Review & Editing, A.; M.A.R.; Visualization, A.S.; Supervision, A.D., and A.; Project Administration, R.

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The authors declare no conflict of interest.

Declaration of Generative AI Use
During the preparation of this work, the authors used ChatGPT to assist in paraphrasing, translating, and refining the clarity of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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