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Development and Evaluation of a Smart Compact Biogas Fermentation Device Using Food Waste at Universiti Tun Hussein Onn Malaysia (UTHM)

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Abstract

Food waste produced within university campuses may cause environmental issues due to its disposal through standard waste management procedures. This research has proposed and evaluated a smart compact biogas fermentation system for food waste treatment at Universiti Tun Hussein Onn Malaysia (UTHM). A compact 30 L anaerobic digester was fabricated using HDPE tanks, PVC piping, valves, and some other affordable materials. The food waste was gathered, transformed into slurry, and digested under mesophilic conditions during 35 days. Production of biogas was determined with the aid of water displacement method while sensing the gas involved the use of ESP32 microcontroller, MQ-2 gas sensor and Blynk IoT technology. Levels of pH and temperature during the process of anaerobic digestion were measured manually in selected observation days. Level of pH increased from 6.2 on day 1 to 7.4 on day 35 whereas temperature varied slightly from 35.2°C to 36.0°C. The MQ-2 sensor provided relative detection of combustible gases, with the sensor readings transmitted to the Blynk application. The MQ-2 sensor was not used for determining methane levels since it is not a specific sensor for methane gas. The use of low-cost sensors and IoT technology enabled remote monitoring of the system. In general, the system has proven to be a low-cost educational as well as food waste management solution for universities.

1. Introduction

Food waste has become one of the major environmental problems in the world because of rapid urbanization and food production. One of the places where the generation of the huge amount of food waste occurs is universities, where food waste comes from the universities' cafeterias, residence halls, food courts, and university events. The bulk of the organic waste generated in the universities is collected using the conventional waste management system, and it is disposed of in the landfills. Methane gas production occurs due to the anaerobic decomposition process of the organic material found in the landfill area. Methane gas is among the gases that have higher global warming potential than carbon dioxide. Furthermore, disposing of the organic waste at the landfill site means the loss of the valuable organic waste that could be transformed into useful forms, such as renewable energy and organic fertilizer [1]–[4].

The anaerobic digestion (AD) technique is well-known for being efficient and environmentally sustainable for organic waste management along with energy production. This is a biological process during which

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microorganisms degrade biodegradable substrates under the absence of oxygen and produce biogas, consisting mostly of methane and carbon dioxide. The residual product of this process the so called digestate is a nutrient-rich material and can be utilized as organic fertilizer. In contrast with traditional landfills, anaerobic digestion allows decreasing the volume of waste, reducing greenhouse gas emissions, and contributing to the concept of a circular economy through the recovery of energy and nutrients from the organic waste [5]–[8].

Beside the widespread application of anaerobic digestion technology at industrial facilities and livestock farms, its usage at educational organizations is still quite uncommon. The majority of commercially available biogas plants are expensive and have great space requirements. Thus, biogas digesters became an interesting option due to their relatively small size and easier construction and functioning. These facilities are perfect for laboratory studies, student projects, and waste management on the university campus [6], [9], [10].

Latest advancements in the Internet of Things (IoT) have enhanced the efficiency of small-scale biogas plants even further. IoT technology facilitates remote real-time monitoring of critical parameters in the system through the use of sensors, microcontrollers, and cloud-based apps. It reduces the need for constant monitoring manually while offering the user instant information about the system through smartphones and computers. Real-time monitoring is beneficial in terms of increased safety, as any abnormalities can be detected instantly [11]–[13].

In this research, a smart and portable biogas fermentation system was designed and tested by utilizing food wastes collected from selected canteens in Universiti Tun Hussein Onn Malaysia (UTHM). An inexpensive 30 L anaerobic digester was designed and constructed using low-cost materials such as a high-density polythene (HDPE) tank and polyvinyl chloride (PVC) pipes. Biogas was quantified through the displacement method of water while real-time combustible gas detection was monitored using an ESP32 microcontroller equipped with an MQ-2 gas sensor and Blynk Internet of Things (IoT) system. The pH and temperature of the process were manually measured during the whole experimental process to ensure suitable operational conditions. This paper discusses the performance of the designed system for converting food waste into biogas, remote monitoring of combustible-gas sensor reading, and the sustainable management of food waste on the UTHM campus. This research will have potential impacts on the development of low-cost renewable energy systems in educational institutions [10]–[14].

2. Methodology

This project was aimed at creating and testing a compact biogas fermentation system which would convert food waste into renewable energy. In order to do that, the project required following four main steps. These were input material preparation, the design of a compact biogas digester, anaerobic digestion and performance testing. Food waste was collected from selected cafeterias of Universiti Tun Hussein Onn Malaysia (UTHM). The collected waste was cleaned through removing the materials which could not be broken down, such as plastics, papers and metals. The food waste was mixed with water to form homogeneous slurry. This was then put into a compact anaerobic digester.

2.1 Development of the Compact Biogas Fermentation Device

An anaerobic digester system having a total volume of about 30 liters was developed through fabrication using locally available and inexpensive materials. The major parts that composed the design included an HDPE storage container, PVC inlet and outlet piping systems, ball valves, gas hoses, gas hose connectors, silicone joint sealant, and a gas holder connected to a water displacement unit for biogas generation. To guarantee safety in operation, all pipe fittings were tightly fitted to avoid any leakages of the gas during the process. The digester was set up in a shaded outdoor location to keep ideal mesophilic operational temperature conditions with sufficient ventilation facilities.

2.2 Feedstock Preparation and Digester Operation

The food waste which was obtained from the UTHM cafeteria was chosen as the substrate for the production of biogas. The collected food waste mainly consisted of cooked rice, vegetables, meat residues, and cooked food residues. The screening of food waste was done manually in order to ensure that no non-biodegradable material such as plastics, metals, and packing materials was present in the food waste. This digestion process was conducted under mesophilic temperatures for about 35 days. During the digestion process, the digester was sealed tightly to maintain anaerobic conditions.

2.3 IoT-Based Monitoring System

The real-time monitoring system used an ESP32 microcontroller together with an MQ-2 gas sensor. The MQ-2 gas sensor was placed near the gas outlet in order to detect any combustible gases produced during anaerobic digestion. Data from the gas sensor were transmitted to the Blynk IoT platform using WiFi, and the sensor

readings and gas-status indicator could be viewed using a smartphone application. The monitoring dashboard provided real-time access to the MQ-2 sensor readings and their variation over time. Figure 1 shows the ESP32 and MQ-2 sensor integrated with Blynk IoT monitoring platform.

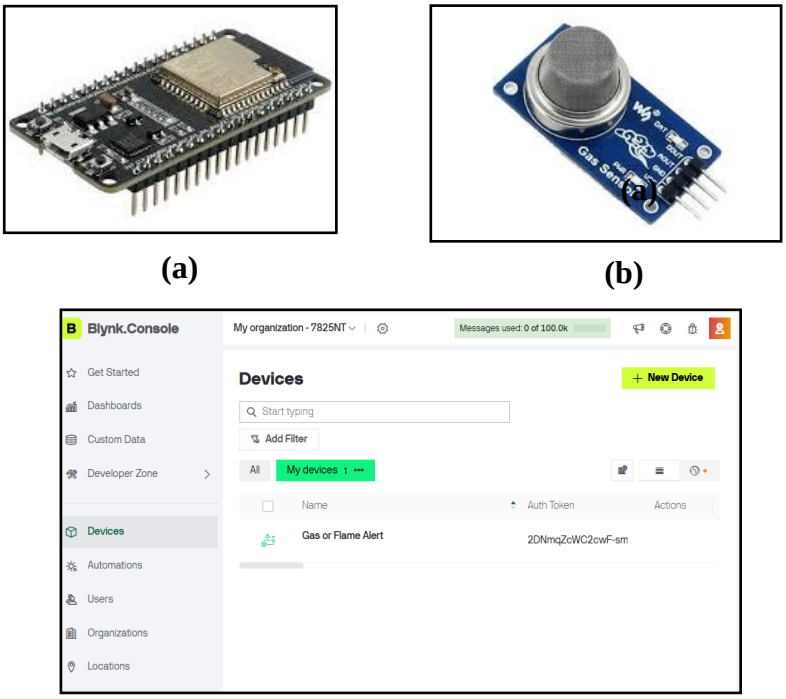


Figure 1: *ESP32 and MQ-2 sensor integrated with the Blynk IoT monitoring platform*

2.4 pH and Temperature Monitoring

The pH and temperature readings were manually taken at chosen observations on alternate days over the entire period of 35 days of digestion. pH readings were taken to ascertain the acidity and alkalinity of the digesting slurry whereas temperature readings were used to check whether the system was in the appropriate mesophilic state. The days of observation chosen were days 1, 7, 14, 21, 28, and 35.

2.5 Performance Evaluation

Performance of the system was assessed through the measurement of biogas production, stability of the operation process and monitoring capabilities. Measurement of the biogas production was carried out using the water displacement method. The production of biogas was done using the water displacement technique within the 35-day experimental period. Biogas production was noted at specific intervals during the digestion process. Nevertheless, there were no recorded measurements of gas volume on every single day. Hence, the results of biogas were analyzed based on observations alone and not by gas volume measurement per day.

Moreover, regular manual measurement of the pH level and temperature was done to assure that the process is carried out under favourable working conditions for the anaerobic microorganisms. The pH was measured using the digital pH meter and ambient temperature was recorded using the thermometer during the whole period of the experiment. The data obtained from the ESP32-based monitoring system were analyzed to evaluate the functionality of the real-time monitoring system. All the data were further analyzed using descriptive statistical and graphical methods. Table 1 shows the components of the developed smart compact biogas fermentation system.

Table 1: *Main components of the developed smart compact biogas fermentation system.*

Components	Specification	Function
HDPE Tank	30 L	Anaerobic digestion chamber
PVC Pipes	20 mm	Slurry inlet and outlet
Ball Valve	PVC	Flow control
Gas Hose	Flexible PVC	Biogas transfer

MQ-2 Sensor	Gas sensor	Detect combustible gases
ESP32	Wi-Fi microcontroller	Data acquisition and transmission
Blynk IoT Platform	Mobile application	Real-time monitoring
Water Displacement Bottle	Graduated container	Biogas volume measurement

The methodology used in this research has facilitated an organized method of assessing the viability of generating renewable energy from food waste using an anaerobic digester system that uses IoT technology.

3. Result and Discussion

The developed compact biogas fermentation reactor performed well over the 35 days of digestion period at mesophilic temperature range. No obvious gas leakage was observed during the experimental period, indicating that the connections remained adequately sealed during operation. Production of biogas was started within a few days after feeding, implying that the process of microbial activity commenced successfully. During the digestion process, gas formation was observed at different stages of the process, indicating that anaerobic microbial activity occurred within the digester. This pattern corresponds to the usual stages of anaerobic digestion as reported in previous studies [3]-[13]. These researchers explained that in the first stage of the digestion, hydrolysis and acidogenesis happen, followed by methanogenesis stage, when there is an increase in the activity of methane-forming microbes. In addition, this phenomenon was observed by [8], who indicated that in small-scale digesters, several days are needed to stabilize the gas production.

3.1 Biogas Production

Biogas production was determined through the water displacement technique during the digestion process for the 35 days. The displacement of water was a simple measure of the volume of gas generated from the digesters. Biogas formation was observed after the feeding process, indicating that anaerobic microbial activity had commenced within the digester. Nevertheless, there were no numeric measurements of biogas volumes on each individual day within the experiments. Consequently, it was not possible to plot the complete graph of biogas production per day from Day 1 up to Day 35 based on the experimental data. The discussion of the biogas production performance was done based on the observations made in the experiment and biogas development in the system. Thus, the water displacement method provided a simple means of confirming biogas formation during the digestion period. However, numerical gas-volume measurements were not recorded for every individual day. Therefore, daily production rate, cumulative biogas volume, and specific biogas yield could not be calculated reliably from the available experimental data. The present study therefore focuses on demonstrating the functionality and feasibility of the compact digestion system rather than providing a complete quantitative biogas-yield profile. Future experiments should incorporate daily or automated gas-volume measurements to obtain a complete 35-day production curve.

3.2 pH Variation

The values of pH measured at various stages during 35 days of digestion are shown in Figure 2. pH was seen to gradually increase from 6.2 to 7.4 during the digestion period, starting from Day 1 to Day 35. In the initial stage of digestion, the slightly lower value of pH was due to the presence of acids generated from the decomposition of organic matter. The pH values measured after Day 14 fell in the normal range required for the process of anaerobic digestion. The final pH value of 7.4 suggested that the digestion process had progressed towards a more stable condition. This was a normal progression as per the anaerobic digestion process, where acids are produced in the early stage followed by methanogenesis.

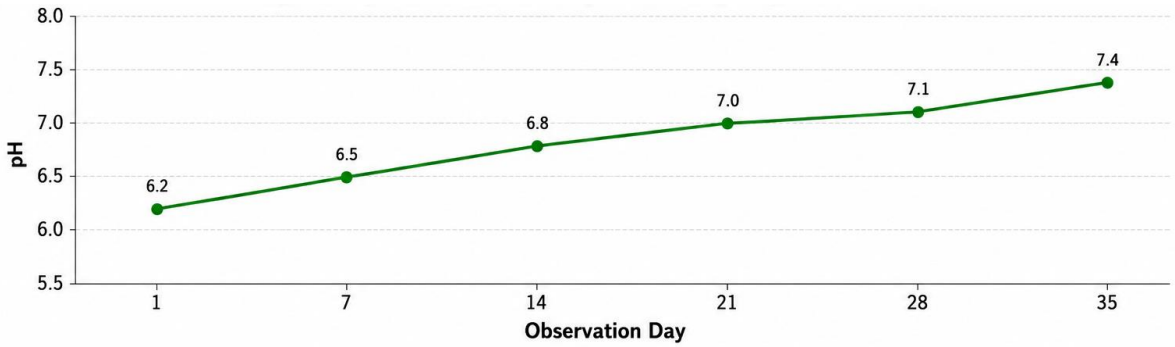


Figure 2: *pH variation during the 35-Day digestion period*

3.3 Temperature Variation

Temperature readings throughout the experimental period were quite steady, ranging from 35.2 °C to 36.0 °C. The highest temperature reading was 36.0°C, recorded on Day 14, while the lowest temperature reading of 35.2°C was taken on Day 1. The variation in temperatures was quite low, being only about 0.8°C. This demonstrated that there was not much fluctuation in the temperatures during the experiment, showing that the relatively small temperature variation indicated that the experimental environment remained thermally stable during the observation period. The recorded ambient temperatures were within the mesophilic temperature range, indicating that the surrounding conditions were generally suitable for the digestion process. Temperature readings are shown in Figure 3 below.

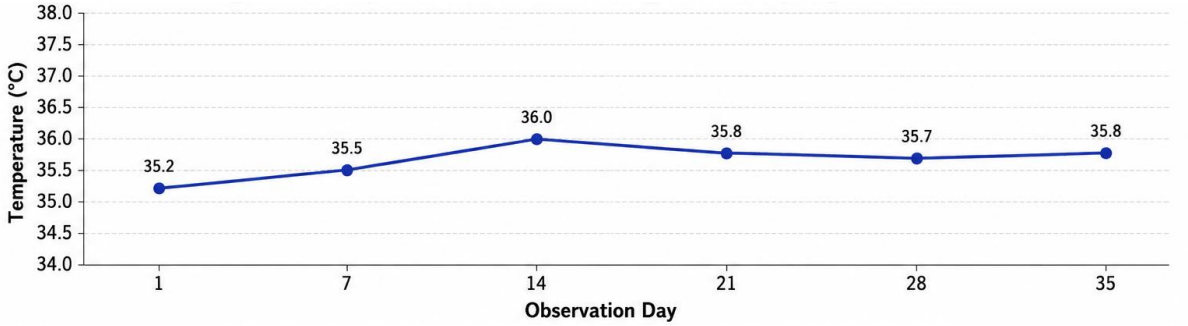


Figure 3: *Temperature variation during the 35-Day digestion period*

3.4 IoT-Based Gas Monitoring

The ESP32 microcontroller and MQ-2 combustible gas sensor were able to detect any changes in the presence of combustible gases in the experiment. Sensor values were sent via Wi-Fi to the Blynk IoT system, making it possible for users to access the values of sensors using their smartphone. The Blynk dashboard was a convenient tool for observing changes in sensor values and gas status values. Nevertheless, these readings were therefore interpreted as relative indicators of combustible-gas presence rather than direct measurements of biogas volume or methane concentration.

Moreover, the monitoring biogas systems using IoT technologies has also been suggested by [4] - [9]. According to these authors, sensors make it possible to monitor biogas systems easily and detect abnormal operation. Also, the World Biogas Association [12] pointed out that digital monitoring helps in improving the safety and operational efficiency of modern biogas systems. The IoT monitoring setup is presented in Figure 4.

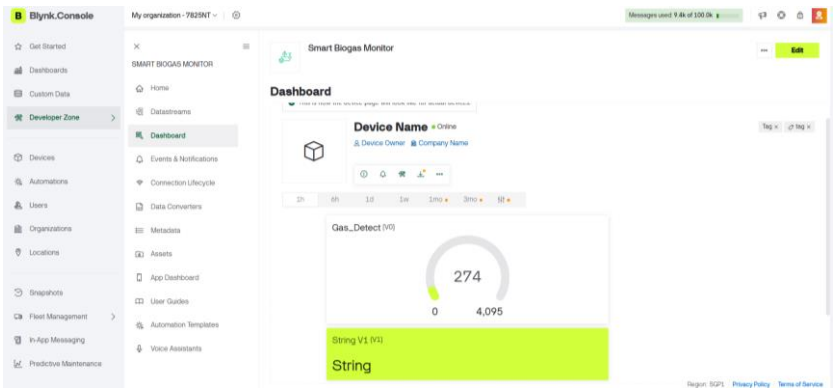


Figure 4: *Real-time monitoring dashboard developed using the Blynk IoT Platform*

3.5 Process Stability

During the course of digestion, pH and temperature were maintained at appropriate levels, thus favoring anaerobic digestion. Operating under stable conditions helped sustain the constant biological action and biogas formation. Upon completion of the digestion process, it was noted that the color of the digestate became dark brown, and the foul smell had disappeared. These visual observations provided a preliminary indication that

decomposition had occurred. However, the suitability of the digestate as an agricultural fertilizer would require further nutrient and pathogen analysis. The digestate may have potential for use as an organic fertilizer; however, nutrient and pathogen analyses were not conducted in this study. This is in line with the findings of [2], who state that the maintenance of appropriate pH level will ensure the stability of biological actions in anaerobic digestion. Similarly, [1] stated that it was crucial to maintain the appropriate environmental conditions for the maximal methane production. Another indicator of the quality of digestate pointed to its potential for being used as an organic fertilizer. This is confirmed by UNEP [10].

3.6 Discussion

Generally, the fabricated compact smart biogas fermentation unit has been able to meet all the objectives of this study by transforming food waste to renewable energy while incorporating an affordable Internet of Things (IoT) monitoring system. The design of the compact unit was simple to manufacture using locally sourced materials and therefore appropriate for use in educational establishments and laboratory settings. As opposed to traditional methods of monitoring, the ESP32, MQ-2 sensor and the Blynk technology enabled real-time monitoring of combustible-gas sensor readings and improved access to the monitoring data through smartphones. This has also been observed in [2], where the authors found that compact anaerobic digesters with smart monitoring systems are practical means of dealing with food waste in institutions. Although the MQ-2 sensor was used to detect combustible gases, it was not capable of selectively measuring methane concentration. Therefore, the sensor readings were treated as relative indicators of combustible-gas presence rather than quantitative methane measurements. In future, methane sensors, digital pH sensors, temperature sensors, and automatic gas flow meter will be incorporated in the system to increase the precision of monitoring. This approach has been recommended in previous studies [1]-[12].

4. Conclusion

This study demonstrated the feasibility of implementing a smart compact biogas fermentation system that was able to show the feasibility of converting UTHM's food waste during the 35-day digestion period into renewable energy and digestate using a low-cost anaerobic digester. The 30 L digester worked successfully using mesophilic conditions, and biogas formation was observed during the 35-day digestion period using the water displacement method. At the same time, monitoring the system in real time using the ESP32 microcontroller, MQ-2 gas sensor, and Blynk IoT provided convenient real-time access to combustible-gas sensor readings through a smartphone. The incorporation of IoT technology improved access to the monitoring data through a smartphone. However, the MQ-2 sensor provided only a relative indication of combustible-gas presence and could not determine the actual methane concentration or biogas volume. Therefore, the study demonstrated the feasibility and functionality of the compact system rather than providing a complete quantitative methane-yield assessment. Besides, the pH increased from 6.2 on Day 1 to 7.4 on Day 35, while the recorded temperature remained within 35.2–36.0 °C, indicating relatively stable operating conditions during the selected observation periods. In general, the result showed that this system has been proven to be able to help sustainably manage the food waste within the campus environment while providing renewable energy and environmental education. The developed system shows potential for educational applications and small-scale food-waste management. Further improvement can be made by adding automated gas-volume measurement, a methane-specific sensor, and continuous pH and temperature monitoring to improve quantitative evaluation of the system.

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