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Design and Implementation of an IoT-based Smart Household Biogas Digester

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Abstract: There has been significant growth in investment and adoption of biogas systems over the past few years. However, biogas plants often do not perform optimally through their expected lifespan due to unconducive conditions affecting the complex microbiological anaerobic digestion process. Remote monitoring of digester conditions can aid users in gaining real-time insight into the state and performance of the digester. This paper outlines the design and implementation of a smart biogas digester for the remote monitoring of critical digester conditions using IoT technologies. It measures pH and temperature at different locations in the digester and the amount of methane gas produced. Data collected from the system is transferred through a Wi-Fi gateway to the cloud for storage and analysis of the digester state and performance using a web application. Preliminary results from system testing using unbuffered water indicate the temporal and spatial variation of temperature and relatively constant and low concentrations of methane gas in the digester, as expected.

Keywords: Biogas, Smart Biogas Digester, IoT, Monitoring System, Methane Gas, Renewable Energy.

1. Introduction

Biogas has been identified as a highly promising source of clean and renewable energy globally, contributing to the well-being of its population, economic development, and environmental protection [1][2][3], especially in Africa. Biogas is produced from anaerobic digestion (AD) of biological waste, typically in an aqueous microbial slurry in the absence of oxygen to produce a gaseous mixture containing 40-80% energy-rich methane, which can be used as a clean-burning fuel for cooking or electricity [4][5].

Urban and peri-urban environments are growing more quickly than rural environments and produce a high proportion of organic waste, largely as food waste. Recent estimates for Accra, Ghana, suggest that the daily mass of waste will double by 2030, with 66% of this urban waste being organic [6]. Over the past few years, there has been significant growth in investment and adoption of small, household-scale biogas systems across Africa [7][8][9][10]. However, biogas plants often do not operate with ideal performance through their expected lifespan [11]. This has been demonstrated in industrial-scale plants to be due to digester “upset”, where the chemical and physical parameters of the feedstock or operations exceed those required for the complex microbiological AD process [4][12] and the biogas plant is unable to produce methane gas [4]. In industrial plants, sophisticated laboratory tests and expensive monitoring equipment can detect and facilitate operators' mitigation of the problem; for small-scale plants this phenomenon can render an entire biogas plant useless and result in abandonment [6][10][13].

Early detection and mitigation of digester upset can be critical measures to significantly increase the functionality and propagation of small-scale digesters in Africa and globally.

This can be achieved through the real-time monitoring and control of critical conditions in a digester, providing owners with a means to track and correct their systems' performance based on insight and relevant data analysis. Observing the heterogeneity of these parameters within small, unmixed digesters will also provide insights into how such digesters may be built and maintained most efficiently. Such a monitoring system can be developed by adapting and integrating Internet of Things (IoT) tools in biogas digesters to make them smart.

This paper outlines the development of a relatively low-cost smart biogas digester that leverages IoT tools to provide status and performance insights to facilitate the early detection and mitigation of digester upset. The solution is also intended for use as a research platform for biogas systems researchers to collect data on an otherwise "black-box" system for the characterization of internal dynamics. In addition, this system does not assume homogeneity of temperature and pH in the digester and therefore attempts to measure these parameters at different spatial locations in the digester.

There have been other research efforts in this area [14][15][16][17], but some track only gas production, while others measure pH and temperature but assume homogeneity by using a unit sensor. In addition, these previous works adopt native mobile applications for monitoring and visualization, posing compatibility issues and motivating the design of the system here.

2. Objectives

The primary objective of the research is to develop a solar-powered and fully remote smart biogas digester. In accordance with smart technology standards [18], the digester must be made smart by equipping it with accurate sensors to measure pH, temperature, and methane gas produced, as well as a communication device to transmit the data to a cloud server. The digester is also expected to resist harsh weather conditions and maintain a gas-tight configuration. The accuracy of methane measurement must be $<\pm1\%$ and with a range of 0 to 90% volume. The pH measurement accuracy must be $<\pm0.3$ and with a range of 4 to 10, and the temperature accuracy must be $<\pm1$ºC and with a range of 0 to 45ºC. The sampling rate must be 30 minutes to an hour, followed by a secured data transmission to the cloud. A user-friendly software application must be provided for collecting, analysing, and generating insight from the data. The application is expected to display time series visualisations of the measured conditions and alert users when any condition exceeds pre-defined critical thresholds. Users must be able to record every digester feeding process and export both sensor and feed data in CSV format for further analysis.

3. Technology Description

A high-level architecture of the entire system was developed, guiding system implementation. This defines the primary components of the system: the monitoring device and the web application. The monitoring device consists of the digester and the data acquisition device equipped with the needed sensors. The web application comprises a customised database and a web application interface hosted on a cloud server. Data was transferred from the monitoring device to the web application through a Wi-Fi gateway by making an HTTP request to the cloud server. Figure 1 illustrates the architecture of the smart biogas digester system.

3.1 Digester Design

The Solar CITIES IBC Tank Biodigester [19] inspired the digester design, using a 1040-litre 48x40x46 inch Intermediate Bulk Container (IBC) fitted with a protective metallic frame. Three outlets are fitted on the tank: one at the base for the periodic removal of accumulated solid sludge, one on the side (about 7 inches from the top) for the daily liquid slurry, and one at the top face for gas collection. A 4-inch diameter and 50-inch-long PVC pipe inserted in the tank from the top face serves as a feedstock inlet for feeding the digester. Its bottom end is cut at 40 degrees to create a larger area for the easy flow of feedstock into the digester during feeding. The slurry outlet limits the height of the slurry to <= 31.5 inches, creating a height control mechanism for preventing the slurry from contacting an infrared temperature sensor placed in the tank. Algae growth in the digester is minimized by coating the tank's outer surface with black paint, reducing the amount of light entering the tank. Figure 2 shows the complete build and a model of the internal view of the digester, showing the mounted sensors. The digester was set up outside, 2 meters from the Ashesi University workshop.

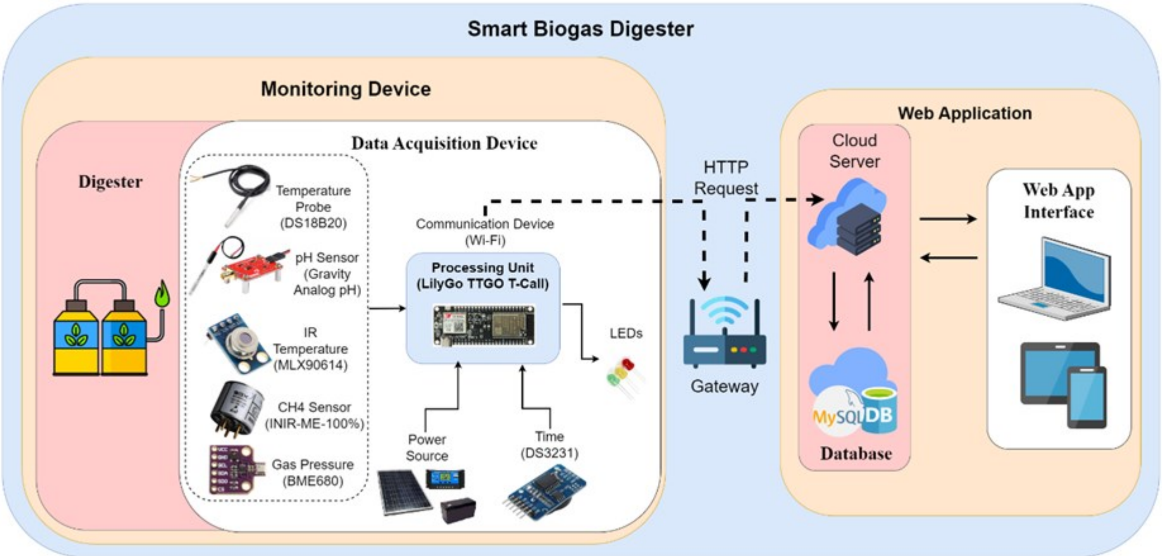

Figure 1: Architecture of the smart biogas digester showing key connections.

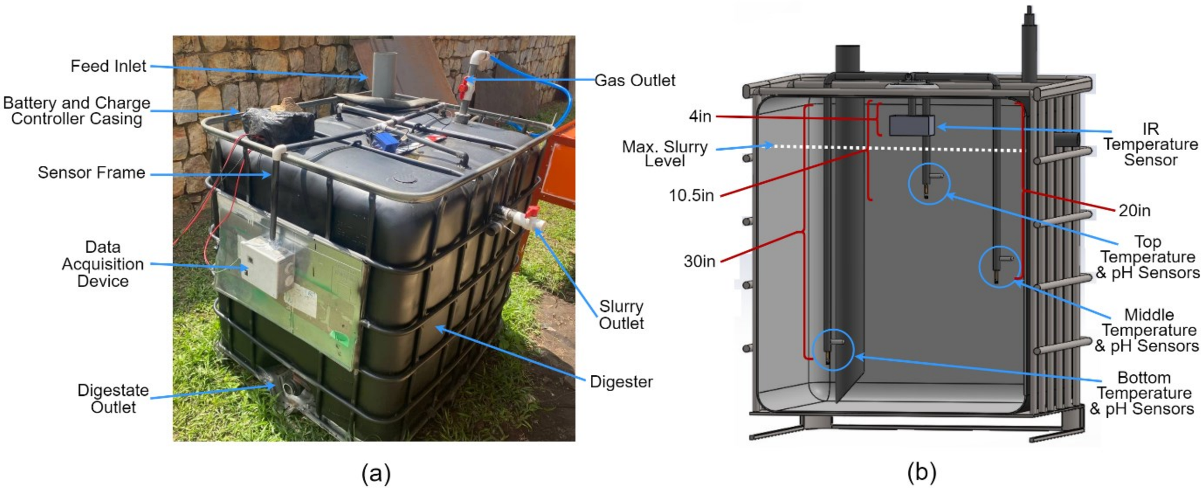

Figure 2: (a) Labelled image of the smart biogas digester. (b) Internal schematic of the smart biogas digester.

3.2 Data Acquisition Device

A data acquisition device was developed and integrated into the biogas digester to enable data collection and monitoring of the conditions in the digester. The data acquisition device interfaces selected sensors to monitor the digestate pH, temperature, methane gas pressure, and concentration. The digestate pH and temperature are known conditions that directly affect bacterial activity in the digester and, inevitably, methane gas production [20][21]. Three Gravity Analog pH and DS18B20 temperature sensors were set up in pairs to measure digestate pH and temperature, respectively, at three different vertical and horizontal positions in the digester, as shown in Figure 2b. These will record conditions in different parts of an unmixed digester and help us understand digester heterogeneity. These sensors were mounted in the digester using PVC pipes as frames for support. An infrared temperature sensor (MLX90614) was mounted in the digester and positioned about 4 inches from the top of the digester, facing the centre of the digestate surface to measure the surface temperature of the slurry. The methane gas concentration and gas pressure were measured using an INIR-ME-100% and BME680, respectively, and positioned in a gas sensor chamber outside the digester. A desiccant chamber containing silica gel was set up between the gas outlet and the gas sensor chamber (as shown in Figure 3) to dehumidify the gas before passing through the sensors for measurements to be taken, preventing the sensors from being damaged by excessive humidity and condensation.

Figure 3: An image showing the desiccant and gas sensor chambers

As shown in Figure 1, all sensors are connected to and controlled by a LilyGO TTGO T-Call ESP32 development board, which comes with Wi-Fi, Bluetooth and GSM communication functionality for data transfer. The system is designed for both off-grid and on-grid power supply by way of a 2.1mm power input jack, which requires 6.5V to 35V and 1A of DC power input. System testing was performed using a 30W solar panel to power the system using a charge controller and a 7Ah lead acid battery.

3.3 Firmware Design

A firmware was developed to implement the system's functionalities by controlling data collection from the sensors and transmission to the cloud database. The firmware was developed using the Arduino variant of C++ to implement hardware-level control.

On start-up, the firmware imports all third-party libraries required for the system to function. This is followed by the initialization and definition of all system parameters, Wi-Fi connection details and sensor objects. The system checks the local storage and transmits any backlog of data that could not be transmitted due to a failed Internet connection. The system then enters a 60-second wait time to warm up the methane gas sensor. Data acquisition from all the sensors begins immediately after the warm-up time. The collected data is then transmitted to the cloud server or stored locally on the device if transmission fails. Finally, the device enters an hour-long sleep mode to conserve power and wait for the next data collection cycle.

3.4 Web Application

The web application component of the system required the development of an interface for both hardware devices and users and an online database to manage and store system data. These software components were designed to seamlessly interact with each other while ensuring smooth data transfer, retrieval, and modification. The web application is hosted on a cloud-based Apache server to provide remote access to the application from any part of the world through the Internet.

3.4.1 Database

The need to store data for analysis and insight generation made it pertinent to integrate a database into the web application. Due to the structured and relational nature of the data generated by the monitoring system and users, a relational database management system was selected and used to store and manage data. MySQL was used as a Database Management System because of its simplicity and scalability. A database was created for the project with nine tables to manage and organize data. These comprise a table each for storing sensor data, user account information, feed records, feed items, feed units, feed categories, device information, user-defined alert threshold and system default alert thresholds. Each table has a primary key field for the unique identification of all records in that table.

3.4.2 Web Application Interface

The development of the web application interface employs the LAMP web development stack, using HTML, CSS, Bootstrap and JavaScript for the frontend, PHP and JavaScript for the backend, while SQL is used for the database interaction.

A new user must sign up to use the application, while an existing user must log in to access their account and information. A Device ID is requested during sign-up, which serves as a unique identification for a user's smart digester data in the database. Once login or signup is successful, users can access a graphical dashboard (shown in Figure 4) to visualise select parameters from the monitoring hardware over time. The application also allows users to record new digester feeds, add new feed items, add new feed units of measurements, view all recorded feeds, and export feed and sensor data in a CSV file format for further analysis. Figure 4 shows a screenshot of the web application's dashboard interface.

3.5 Sensor Calibration

Factory calibration was maintained for the BME680, MLX90614, and DS18B20 sensors. A three-point calibration was performed for all three pH sensors using the IS5050 buffer calibration kit containing standard pH buffers of pH 4.0, 7.0 and 10.0. During each calibration, the system measured and stored a single stable voltage value (calibration parameter) for each of the three-point pH levels. The stored calibration parameters were applied to compute pH values during sensor measurements using Equation 1.

Where x is the measured voltage value from the sensor, C_{high} is the calibration parameter at pH 10.0, C_{mid} is the calibration parameter at pH 7.0, and C_{low} is the calibration parameter at pH 4.0.

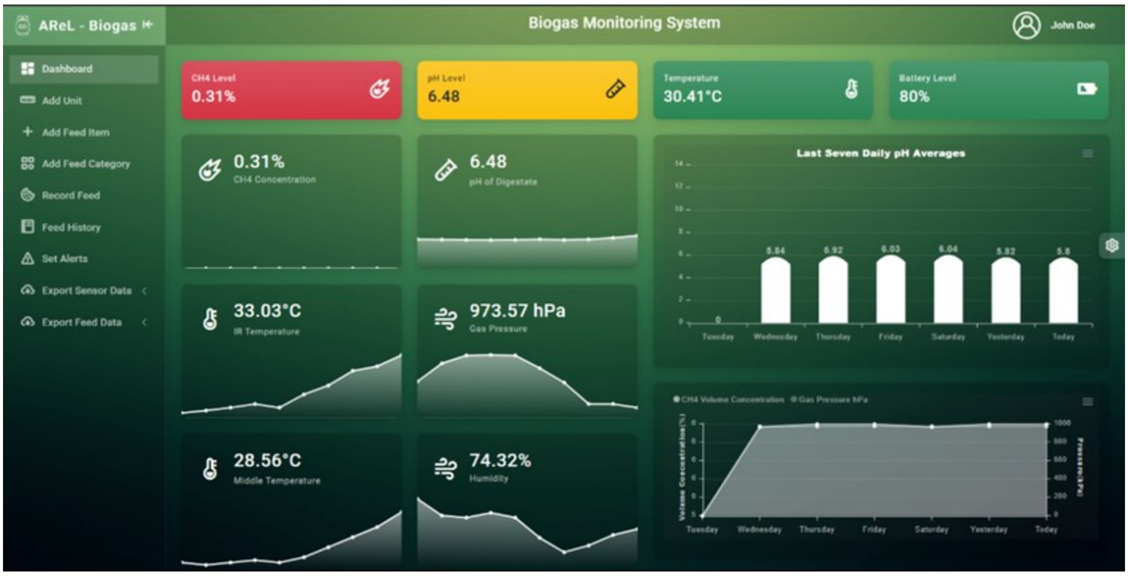

Figure 4: Web application dashboard showing visualisations of real-time data from the smart digester.

$$f(x) = \begin{cases} 7 - \frac{3}{C_{low} - C_{mid}} \times (x - C_{mid}),\ for\ x > C_{mid} \\ 7 - \frac{3}{C_{mid} - C_{high}} \times (x - C_{mid}),\ for\ x \leq C_{mid} \end{cases} \quad (1)$$

A calibration function was developed using a GFM 426 Gas Analyzer as a standard instrument to calibrate the methane gas sensor. The GFM 426 Gas Analyzer and the INIR-ME-100% methane sensor were subjected to incremental concentrations of methane gas from an underground biogas digester. Each sensor's methane concentration reading was recorded during each test. The calibration graph in Figure 5a was generated, showing the relation between both sensors using linear and polynomial regressions to fit the data.

Comparing both regressions using RSME analysis, the linear regression had an RMSE of 0.078896, while the polynomial regression had a slightly better RMSE of 0.045632. Therefore, the polynomial regression was selected as the calibration function for the methane sensor. Equation 2 represents the polynomial regression, where x is the methane concentration from the INIR-ME-100% sensor.

$$f(x) = 0.0030183x^2 + 0.93876x + 0.13579 \quad (2)$$

4. Results

The system was tested using unbuffered water in lieu of organic waste as a first step to validate the ability of the monitoring system to measure and record the parameters of interest accurately. Approximately 14 consecutive days of hourly data collected in October 2023 were sampled from the system and analysed.

4.1 Methane Gas Measurement

The methane gas concentration was expected to be close to 0% volume concentration and relatively constant. This is primarily because the digester is enclosed, with no expectation of methane gas production. Figure 5b corroborates this expectation as the methane gas concentration over the 14 days remains relatively constant at around 0.3% volume concentration. The recorded methane concentrations also show no association with temperature changes in the digester, with a Pearson correlation coefficient (r) of -0.0424.

4.2 Temperature Measurement

Digestate temperature oscillates from low to high and high to low from morning to afternoon and afternoon to night, respectively (Figure 5b). The spatial variation and

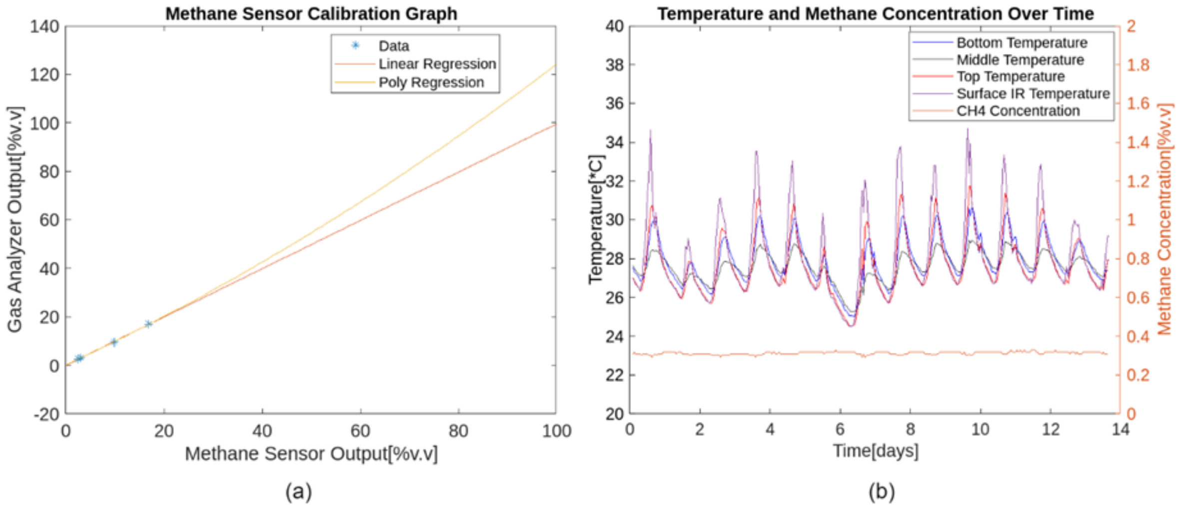

Figure 5: (a) Methane sensor calibration graph. (b) Graph of all four temperature sensors and methane sensor values sampled once every hour over the 14 days.

stratification of digestate temperature were recorded, as different temperatures are recorded at different vertical levels of the digestate. From Figure 5b, the daily highest and lowest temperatures often occur at the top of the digester. Diurnal variation in each region of the digester is 4-6 degrees. Additionally, it can be seen that temperature changes more rapidly at the top of the digester as compared to the middle and bottom. Interestingly, the bottom temperature is often higher than the middle, especially during the day.

4.3 pH Measurement

pH measurement was still in development as of the time of documenting this paper. The polylactic acid or polylactide (PLA) 3D printed cases for the electronics proved insufficiently robust for use in field conditions, where relatively high temperatures were experienced over an extended period of time and resulted in irregular readings. Once a more robust casing is developed, the pH results will be communicated in subsequent publications.

5. Business Benefits

The target users of the smart household biogas digester consist of homeowners, biogas researchers, food vendors and business owners. The system enables its users to contribute to reducing environmental pollution and greenhouse gas emissions, while cutting down cost on cooking fuel. Additionally, the smart biogas digester enables its users to control the performance of the digester, ensuring better yield overtime and a longer lifespan as compared to traditional digesters. This offers value to users and presents a business opportunity for income generation for both producers and users of the smart biogas digester.

Further system trials are required to validate the performance of the system. This includes testing the system with organic waste for about 6 months, detecting digester upsets and analysing system performance. Overall, it will take about one year to complete trials and develop a market ready product.

The estimated cost of producing a unit of the smart biogas digester is approximately \$800. However, this cost could be reduced by up to 40% through economies of scale and adopting more locally sourced materials and equipment.

6. Conclusion

To fully utilise the many advantages of biogas in Africa, there is a need to develop systems to mitigate the problems that often cripple existing biogas plants. This paper presents an IoT-based monitoring approach to collecting real-time data from a biogas digester for insight into digester status and performance. This solution will serve as a platform for biogas digester research. Results from unbuffered water show spatial variation of temperature in the digester as higher temperatures are recorded at the top and bottom of the digestate during the day and lower at night. Methane sensor testing also shows expected results of relatively constant and very low concentrations. pH measurements are under development, and preliminary tests revealed the need for highly robust casing materials that can withstand field conditions. It was also learned from this research that condensation can be significant in biogas digesters, leading to sensor malfunction or damage. Hence, waterproofing such sensors or placing them outside the digester proves beneficial. The next steps include feeding the smart digester with different organic waste materials and monitoring their influence on the average and spatial pH of the digestate. Further research will also be conducted on the effect of the average and spatial pH and temperature on methane gas production to guide improved digester design and feeding patterns.

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