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Autonomous biogas reactor designed for rural regions

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Abstract - The current energy crisis and the desire to cut greenhouse gas emissions urgently motivate the exploration of new, less polluting energy sources. Using industrial and home waste for biogas generation can reduce carbon dioxide and methane. The goal of this study was to create a prototype small-scale biogas generation system intended for use in rural areas. The low-cost sensors and Arduino Uno (hardware and software) used in this research's biogas production system give an effective and affordable alternative. Because of its adaptability in handling various kinds of organic waste, the prototype is a good fit for small-scale uses, particularly in rural regions. Talk about how the system's functionality is improved by the incorporation of IoT technology, particularly LoRa, which makes remote monitoring and control possible.

Keywords: Arduino-based sensor monitoring system. Biogas generation in remote places.

Reator autônomo para produção de biogás em áreas rurais

Resumo - A atual crise energética e a necessidade de diminuir as emissões de gases causadores de efeito de estufa induzem urgentemente à exploração de fontes alternativas de energia e menos poluentes. A utilização de resíduos industriais e domésticos para a produção de biogás pode reduzir significativamente as emissões de dióxido de carbono e de metano. Este estudo buscou desenvolver um protótipo de biodigestor em pequena escala projetado especificamente para áreas rurais. O sistema de produção de biogás desenvolvido possui sensores acoplados a uma plataforma Arduino Uno para fornecer uma solução eficiente e econômica. O protótipo apresenta versatilidade no processamento de diversos tipos de resíduos orgânicos, tornando-o adequado para aplicações de pequena escala, principalmente em áreas rurais. Se discute a integração da tecnologia IoT, via LoRa, e seu potencial para melhorar sua funcionalidade, facilitando o monitoramento dos processos internos via controle remoto.

Palavras-chave: Monitoramento com sensores na plataforma Arduino Uno. Produção de biogás em regiões remotas.

Reactor autónomo para producir biogás en zonas rurales

Resumen - La actual crisis energética y la necesidad de reducir las emisiones de gases de efecto invernadero alientan urgentemente la exploración de fuentes de energía alternativas y menos contaminantes. El uso de residuos industriales y domésticos para producir biogás puede reducir significativamente las emisiones de dióxido de carbono y metano. Este estudio buscó desarrollar un prototipo de biodigestor de pequeña escala diseñado específicamente para zonas rurales. El sistema de producción de biogás desarrollado cuenta con sensores acoplados a una plataforma Arduino Uno para proporcionar una solución eficiente y económica. El prototipo presenta versatilidad en el procesamiento de diferentes tipos de residuos orgánicos, que lo hacen apto para aplicaciones a pequeña escala, principalmente en zonas rurales. Se discute la integración de la tecnología IoT, vía LoRa, y su potencial para mejorar su funcionalidad, facilitando el seguimiento de los procesos internos vía control remoto.

Palabras clave: Monitoreo com sensores basado em uma plataforma Arduino. Producción de biogás para regiones remotas.

Introduction

Around 30 million people in Brazil rely on firewood for cooking (Gioda et al. 2019). The combustion of wood in this process releases pollutants that exceed the limits established by the WHO, leading to respiratory diseases and cancer (Silva et al. 2009; Silva et al. 2012; Gioda et al. 2019). Therefore, prioritizing the substitution of firewood and other solid fuels with cleaner alternatives is crucial to improve the quality of life among those people.

The National Guidelines for Basic Sanitation – Law 11.445/2007 (Brazil 2007) – establish that service provision must be economically and financially sustainable and meet the requirements to ensure adequate quality. Solid waste management and landfill storage are mandated by Law 12.305/2010 (Brazil 2010), which lays out the country's solid waste policy. Brazil faces the problem of enhancing the treatment of solid waste (Brasil Probiogás 2015). In accordance with Law 11.003/2022, often known as Brazil 2022, the Federal Government supports programs aimed at reducing methane emissions, encouraging the use of biogas and biomethane as renewable energy sources, and helping Brazil fulfill its international obligations.

Biogas can be created artificially in landfills and biogas facilities, or naturally in submerged, anoxic settings like swamps, the bottom of water bodies, and animal intestines (Keller and Hartley 2003; SimGas 2012). It is made up of a variety of gases produced during the anaerobic biological breakdown of organic matter. Biogas has varying densities and energy contents depending on the gas composition; it usually contains methane, carbon dioxide, oxygen, nitrogen, and sulfuric gas in tiny amounts, along with humidity and volatile hydrocarbons (Cavaleiro and Alves 2020).

Long-term trends point to the traditional energy sources' eventual depletion. One could consider biogas and other renewable sources to be the better option (Milanez et al. 2018). Brazil's economy benefits from the sustainable management of organic waste from urban and agro-industrial settings through the production of biogas (ONU 2022). It is clear that biogas production is widely used to produce sustainable energy from energy crops and organic leftovers (Grosser and Neczaj 2018).

Methane traps heat in the atmosphere more than 28 times more effectively than carbon dioxide does (EPA 2023). Therefore, the production of electricity from biogas eliminates its emissions. An equivalent of 12 million tons of carbon may have been prevented from entering the Earth's atmosphere in the first year of energy generation via the recovery and use of biogas.

Accreditation for carbon credits and marketable bonds can be obtained by the carbon sinks, providing landfills that produce biogas with an extra source of income. Moreover, continuous production of biogas distinguishes it from wind and solar energy by allowing for inexpensive compressed gas or raw material storage. Biogas's enhanced purification makes it a highly suitable natural gas replacement in all applications, with a wide range of applications. (Grosser and Neczaj 2018).

In a circular economy, the generation of biomethane has significant advantages for the environment and the producer. According to Noyola et al. (2006) and Freitas et al. (2019), the use of biodigesters facilitates the integration of agricultural operations, increases the value of manure, organizes output, encourages conservation, and supports reverse logistics.Anaerobic parameters, such as feed rate, hydraulics, solids retention time, temperature, alkalinity, pH, and raw material, might effect methane generation. Changes in these variables could negatively impact the process and necessitate corrective measures for recovery (Yang et al. 2022).

Anaerobic digestion of liquid waste from shellfish processing has been used to study the biochemical potential of methane production (BMP), and the results showed a significant BMP capability (Camargo et al. 2022). Monitoring the biomethane production process with sensors coupled to a microprocessor or microcontroller-based board is crucial to the optimization of the process. These gadgets receive and process signals of different intensities. The gases that make up biogas can be measured using a set of sensors, and the system can show the user the results using a graphical monitoring interface.

The goal of this study is to apply reverse logistics to promote sustainable economic, social, and environmental growth. It responds to the following queries: 1. Why is biogas production monitored? 2. What parameters in a biodigester ought to be remotely observed? 3. What program is appropriate for creating the solution? The goal of this effort is to integrate inexpensive MQ sensors into a low-cost continuous methane monitoring system. To further explore the impact of sample pH and environment temperature (oC) on methane production, we also incorporate additional sensors.

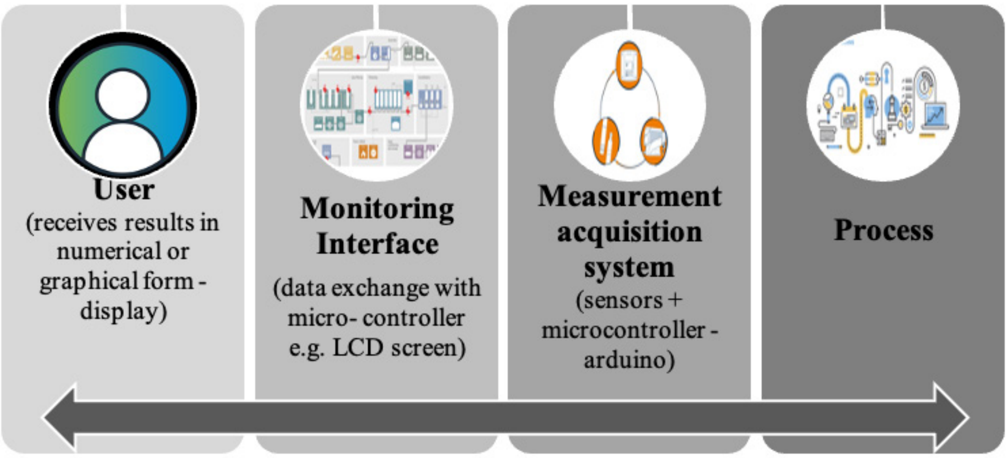
Material and methods

Methane production prototype

In the quest to improve methane production, the first step was to study international biomethane regulations and the fundamental physical and chemical factors that impact the anaerobic digestion (AD) process (Wahid et al. 2019; Omoregbee et al. 2022). AD processes are sensitive to environmental conditions and can be readily influenced by operational parameters.

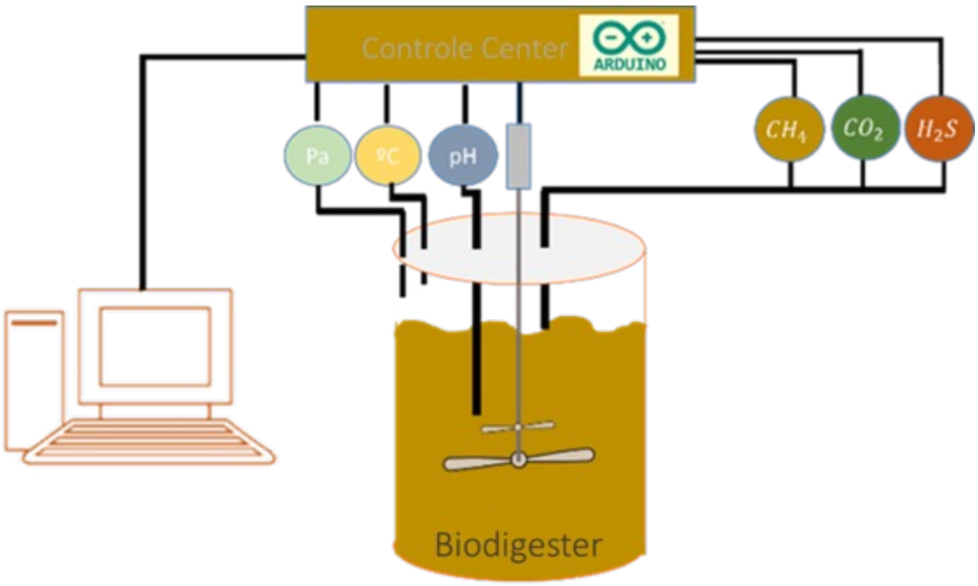
An Arduino platform with a variety of sensors was used to assess methane levels and other pertinent physical-chemical parameters in order to create an ideal and sustainable gas production monitoring system (Figure 1). Following a humidity and H2S trap system, integrated MQ-4 methane, MG-811 carbon dioxide, and MQ-136 hydrogen sulphide sensors were used to maximize methane output and mitigate hydrogen sulphide problems. Additionally, an Arduino-compatible pH sensor module was included inside the reactor. Prior to being incorporated into the system, the sensors underwent testing and calibration.

Figure 1. Platform to monitor the output of biogás.



An Arduino was used to operate a rotary rod that was powered by an engine and placed within the reactor to improve the methane generation process (Figure 2).

Figure 2. Methane production monitoring using a biodigester model.



According to Gonzalez and Calderón (2018), the open-source Arduino Mega 2560 R3 microcontroller has a USB connection port for powering the board and establishing contact with the computer. The system's programming is made easier by its input and output ports and C programming environment.

The purpose of sensors is to convert a physical quantity into a signal that can be sent to an indicator element so that the value of the measured quantity can be shown. The pH sensor electrode was calibrated by submerging it in reference solutions with 4.0, 6.5, and 9.0 values. In order to verify the freshly calibrated reading of 7.0, the electrode was submerged in the reference solution once more after the programming code was reloaded. In the meantime, the temperature sensor was put right inside the reactor, making it possible to measure the humidity and temperature inside the reactor (Figure 3).

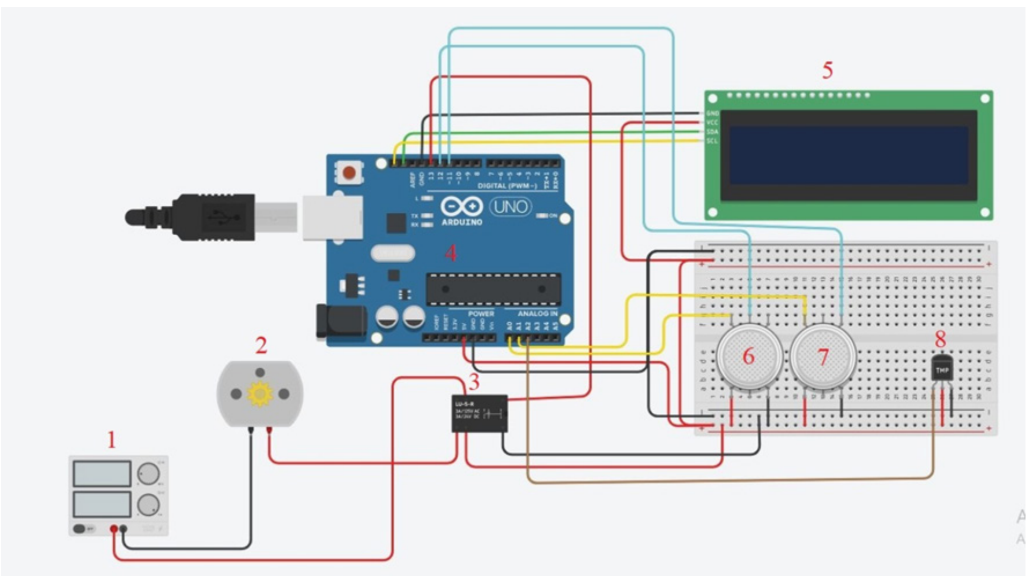
Figure 3. Shows the pH, gas, and temperature sensors as well as the relay module and LCD display.

The Relay Module, which is connected by jumpers, allows the Arduino to activate the loads. This module improves the project's structure and practicality by removing the requirement to assemble boards or circuits for its connection.

Installing sensors and assembling the platform

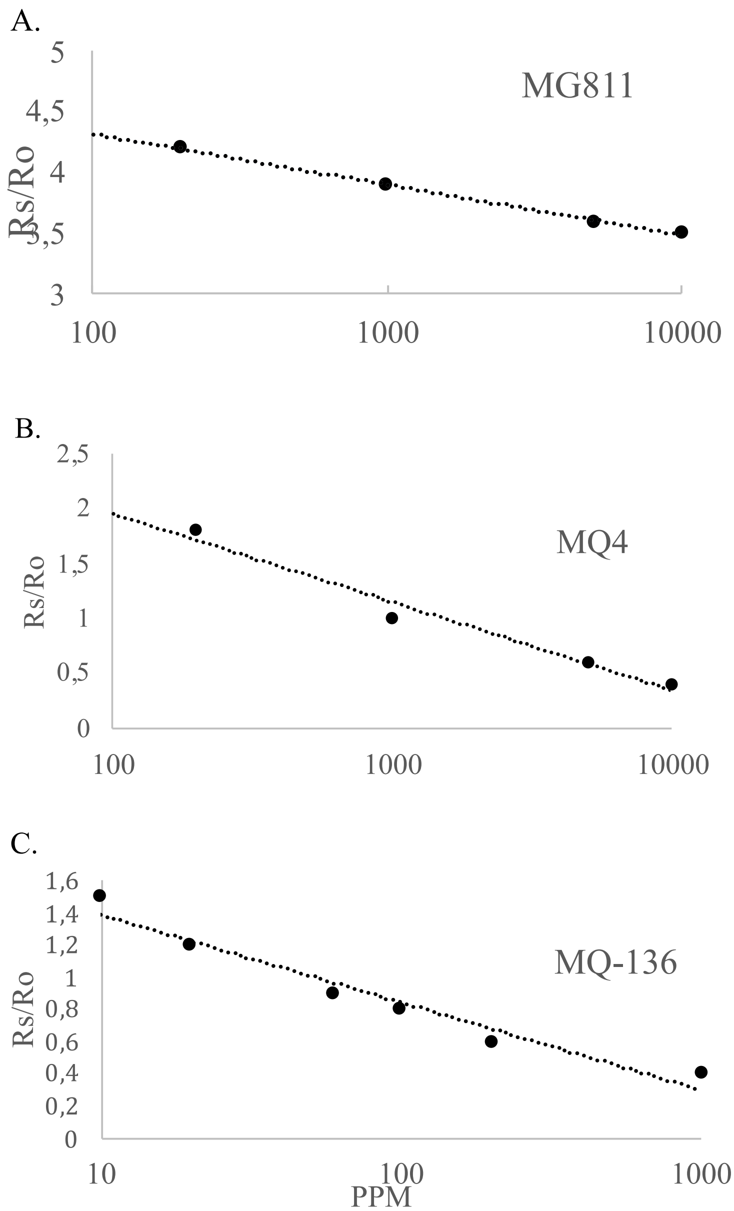
The open-source electronic prototype platform Arduino (https://www.arduino.cc/en/software), which has an intuitive user interface and necessitates the installation of free software on the computer, is used to program the system in the language of C. The installation of each sensor was done in accordance with the guidelines provided in its datasheet. A 5-volt voltage source, a communication line connected to the analog pins of the Arduino platform, and a neutral connection to the GND pin were required in order to meet the energy requirements of the hardware (Figure 4).

Figure 4. Sensors and Arduino Board Connection Diagram: 1. Source, 2. Engine, 3. Relay, 4. Arduino, 5. LCD 16x2, 6. Methane Gas Sensor, 7. Hydrogen Sulfur Gas Sensor, and 8. Temperature Sensor.



The calibration procedure was essential to ensuring the precision and dependability of the sensor readings. Given that MQ sensors have a non-linear connection with analog data, particular equations were developed for each sensor in order to maximize performance. Since the values on the curve were expressed on a logarithmic scale (RS/R0), a separate correction equation for every sensor had to be created. The sensitivity model described in each gas sensor's unique datasheet was the source from which these equations were created (Figure 5).

Figure 5. Gas sensor sensitivity curves: A) MG-811; B) MQ-136; and C) MQ-4 Gas sensors.



Code:

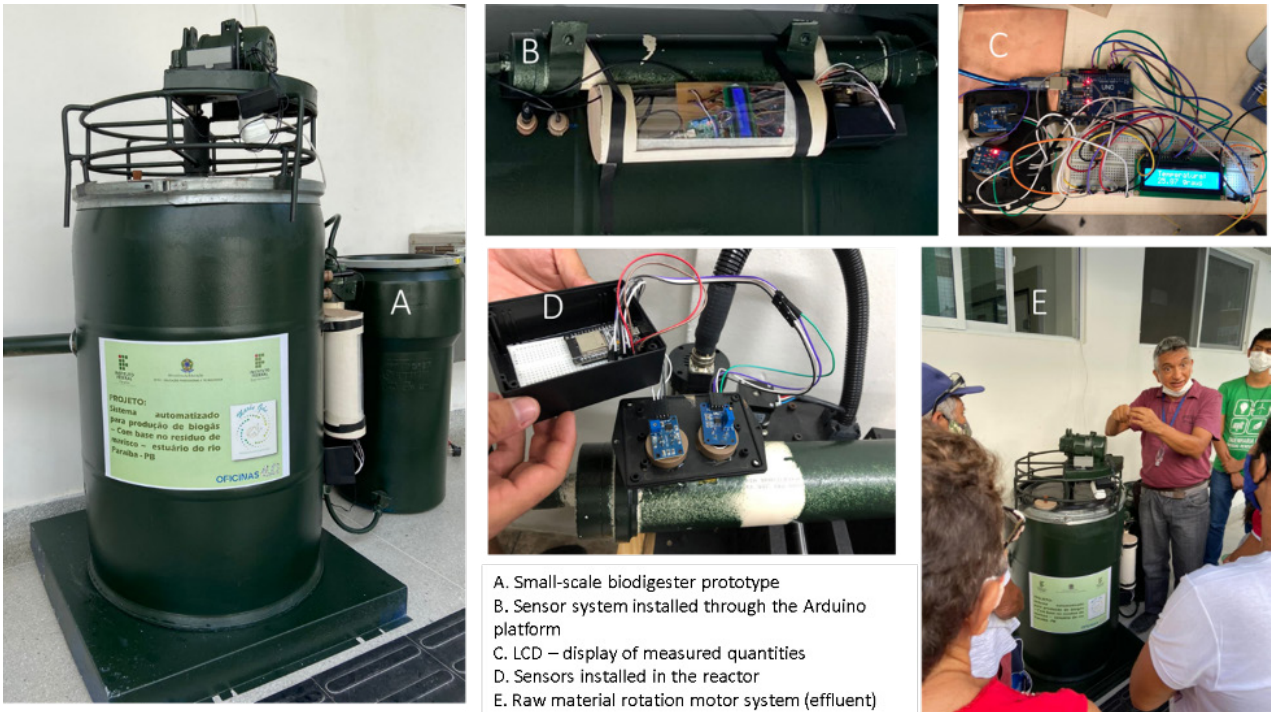
```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 16, 2);
float calibration_value = 21.34; // Calibration factor
int count = 0; // count variable
float sum_tension = 0; // Variable for voltage sum
float average = 0; // Variable that calculates the average
float input_A0; // Variable for reading pin A0
float tension; // Variable to convert to voltage
unsigned long time; // float time
void setup() {
lcd.init(); // Initialize the display
lcd.begin(16, 2); // Initialize all characters
lcd.backlight(); // Initialize the backlight
lcd.setCursor(0, 0); // Position the cursor at the position
lcd.print("USINAINFO"); // Write to serial monitor
lcd.setCursor(0, 1); // Position the cursor at the position
lcd.print("Ph reading"); // Write to serial monitor
delay(2000);
lcd.clear(); // Clear the content of the display
}
 media = voltage sum / 10; // Calculates the average of readings
 float valor_pH = -5.70 * mean + calibration value; // Calculates pH value
 lcd.setCursor(0, 0); // Position the cursor on the display
 lcd.print("Valor pH: "); // Write on the display
 lcd.setCursor(11, 0); // Position the cursor on the display
 lcd.print(valor_pH, 1); // Write pH to one decimal place
 delay(1000); // Wait for next reading
}
void loop() {
sum_tension = 0; // Start sum_voltage at 0
count = 0; // Start counting at 0
while (count < 10) { // Execute while count less than 10
time = millis(); // Set the time in microseconds
input_A0 = analogRead(A0); // Read the analog input
voltage = (input_A0 * 5.0) / 1024.0; // Convert the value read into voltage
sum_tension = (sum_tension + voltage); // Adds the previous voltage to the current one
count++; // Add 1 to the count variable
delay(100); // Wait for next reading
```

Results and discussion

For the biogas value chain to advance, it is imperative to embrace a circular economy marked by creativity and new business prospects (ONU 2022). The carefully engineered biological reactor, intended for the production and observation of biogas, stands out for its effectiveness, dependability, ecological sustainability, robust engineering, and financial feasibility. It offers a compelling option to address small-scale demands, especially in rural regions, with an affordable price tag of 165 USD.

With minimal chemical reagent usage and comparatively low energy consumption, the reactor runs smoothly at room temperature and atmospheric pressure. The production system is versatile enough to utilize many forms of organic waste, such as leftover fruits and vegetables and organic effluents, and the sensor programming and calibration processes are easy to use (Figure 6).

Figure 6. Prototype of a biodigester designed to monitor biogas output using sensors and a microcontroller system.



Although the overall energy consumption of the prototype is still low, improvements would be required to make it suitable for use in rural regions given its dependency on energy sources such heat exchange, solar panels, or batteries (Oliveira et al., 2023). The prototype offers advantages with its affordability, ease of signal quantification, and compact size when compared to alternative detection methods such as gas chromatography and infrared spectrometry (Kohler et al. 1999; Yea et al. 1999; Littlewood, 2013; Zheng et al. 2023).

The existence of sulfate-reducing bacteria, which produce the very poisonous hydrogen sulfide (H_2S), is a major obstacle to using biogas (Kronos, 2014). Sulfur oxides (SO_x) and sulfuric acid (H_2SO_4) are produced during the burning of biogas, which damages combustion equipment and adds to air pollution. For biogas to be used safely and effectively, H2S must be effectively removed (Miao et al. 2018). This study's technological strategy for biogas desulfurization uses a steel sponge filter to facilitate chemical absorption following the biodigestion process. Steel wool coated with rust is used in the procedure to create the reaction bed. Steel wool's comparatively tiny surface area, however, limits its ability to bind sulfur dioxide. Iron oxide-impregnated wood chips can be used as an economical and effective reaction bed to address this (Ryckebosch et al. 2011).

Gas detection is a typical application for semiconductor metal oxide-based sensors, like the MQ4 and MQ136, which are inexpensive. Tests using these, however, showed concentrations as high as 10,000 ppm and 200 ppm, respectively (pers. Obs.). In order to assess high gas concentrations, Fakra et al. (2020) proposed a solution that involved diluting the gas under investigation in a predefined air volume utilizing an adjustable capsule for MQ sensors. As the TGS 2611 metal-oxide-semiconductor (MOS)-type sensor from Figaro Engineering Inc., Osaka, Japan, provided accurate methane gas readings beyond its detection range, Nagahage et al. (2021) advocate replacing the MQ4.

In order to upgrade this project, the LoRa32 WiFi must be included in order to satisfy one of the core IoT requirements: giving biodigester sensors internet access. With the use of this technology, data may be transmitted over long distances at low energy costs via radio waves. Essentially, LoRa-enabled biodigester sensors can send data to distant stations via an Internet service provider (ISP). Consequently, the electric motor that stirs the raw material in the biodigester may be remotely controlled and sensor readings can be accessed via an internet-connected application.

LoRa is a low-power, long-range radio transmission technology that can be used with battery-operated or photovoltaic systems. It is energy-efficient and allows wireless communication over long distances (up to several kilometers) in remote areas. Due to its use of license-free sub-gigahertz frequencies (below 1 GHz), such as 433 MHz and 868 MHz, it is especially well-suited for Internet of Things (IoT) applications. Emphasizing the importance of the Internet of Things (IoT), it allows for the easy integration of devices located in remote locations via a gateway that has internet connectivity via other technologies like LoRa.

This gateway effectively addresses issues related to internet connectivity by serving as a central hub that connects data sent over long-range radio and guarantees interference resistance. Thus, the deployment of an Internet of Things system establishes a comprehensive framework for both control and monitoring, simplifying the biodigester's biochemical process optimization.

IoT makes it possible to remotely control sensors and actuators, while also producing value for operations and promoting well-informed decision-making. One other advantage of LoRa technology is its capacity to create an LPWAN (Low-Power Wide Area Network), which allows two pieces of equipment or a small group of devices to communicate with each other without the need for the internet. As a result, whether linked to the internet or running on its own, a pilot system of biodigesters equipped with LoRa makes system monitoring possible in a variety of remote places.

In conclusion, this study tackles important problems with energy use, environmental sustainability, and public health, taking into account biogas as a renewable energy source that shows promise in lowering pollution. The study demonstrates how biogas can reduce carbon emissions significantly, supporting Brazil's efforts to meet global environmental targets.

Low-cost sensors and the Arduino platform (hardware and software) were used in this research's biogas production system as a practical and affordable alternative. The prototype is adaptable enough to handle a range of organic waste kinds, which makes it ideal for small-scale uses, especially in rural locations. The system's capabilities are further enhanced by integrating IoT technology, particularly LoRa, which allows for remote monitoring and control.

The paper also discusses issues with hydrogen sulfide, which is a problem in the generation of biogas, and stresses the significance of desulfurization for safe and effective use. The technological path that involves chemical absorption that has been suggested offers a workable option.

Thus, by investigating novel methods for monitoring and regulating biodigestion, this research helps to maximize the generation of biogas. The results have consequences for Brazil's use of renewable energy sources, circular economy principles, and sustainable development. On the basis of this foundation, further research might investigate new technological developments, broaden the use of biogas in other contexts, and quantify the energy output of biodigesters.

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Conflict of Interests: The authors declare that there is no conflict of interest.

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