Automatised Bioreactor to Produce Biogas from Biomass: Development and Evaluation

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Brazil's abundant biomass from agricultural and industrial activities offers significant potential for biogas production, aligning with the ONU Sustainable Development Goals. This study aims to explore anaerobic digestion for biogas production from biomass, investigating key factors influencing the process and advancing efficient technologies. A literature review utilizing biogas as a sustainable energy source was conducted, and an Arduino-controlled bioreactor was built to automatically monitor and control crucial variables in anaerobic digestion, ensuring high-quality and efficient biogas production. The developed bioreactor efficiently enabled continuous tracking of pressure, temperature, hydrogen, and methane in the bioreactor, contributing to energy transition and decarbonization.
Keywords: Biogas. Bioreactor. Efficiency. Automation. Sustainability.

Introduction

World energy policies are shifting towards renewable energy sources, and Brazil's energy matrix stands out, with 44.5% sourced from renewables, as reported by EPE [1]. With its rich cultural heritage and agricultural trade, Brazil has abundant biomass resources for energy production. Anaerobic digestion offers an efficient means to convert biomass into biogas. In 2021, the country had 755 operational biogas plants, producing 2.3 billion cubic meters of biogas [2]. A study on biogas as an alternative energy source [3] revealed that 1 mL^3 of biogas equals 0.613 liters of gasoline, 0.579 liters of kerosene, or 0.553 liters of diesel. Brazil's biogas production could replace 1.4 billion liters of gasoline, 1.3 billion liters of kerosene, or 1.27 billion liters of diesel. Research and development of sustainable and environmentally friendly energy sources has become a global priority amid challenges related to climate change and natural resource scarcity. In this context, biogas production through anaerobic digestion from biomass has emerged as a promising and renewable alternative to meet the energy demand. Anaerobic digestion is a biological process that converts organic materials, such as biomass, into biogas, a renewable energy source composed mainly of methane (CH_4) and carbon dioxide (CO_2) [4-6]. This environmentally friendly technology is crucial in waste management and renewable energy production. The anaerobic digestion process involves four key stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In hydrolysis, hydrolytic enzymes break down complex organic matter into simpler compounds, such as lipases and proteases. This stage prepares the biomass for further degradation. During the acidogenesis stage, acid-forming bacteria convert the simpler compounds into volatile fatty acids (VFAs), alcohols, and other intermediate products. In the subsequent acetogenesis stage, acetogenic bacteria metabolize these intermediate products, producing acetic acid, hydrogen (H_2), and carbon dioxide (CO_2). Finally, methanogenic archaea carry out methanogenesis, where methane-producing microorganisms utilize the acetate, H_2, and CO_2 produced in the previous stages to generate methane [5-14]. The overall reactions can be represented as follows:

a. Hydrolysis: Complex organic matter → Simple compounds
b. Acidogenesis: Simple compounds → VFAs, alcohols, and other intermediates
c. Acetogenesis: VFAs, alcohols, and intermediates → Acetic acid, H_2, and CO_2

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d. Methanogenesis: Acetic acid, H_2, and CO_2 → Methane (CH_4) and CO_2 Different types of biomass can be used as feedstock for anaerobic digestion.

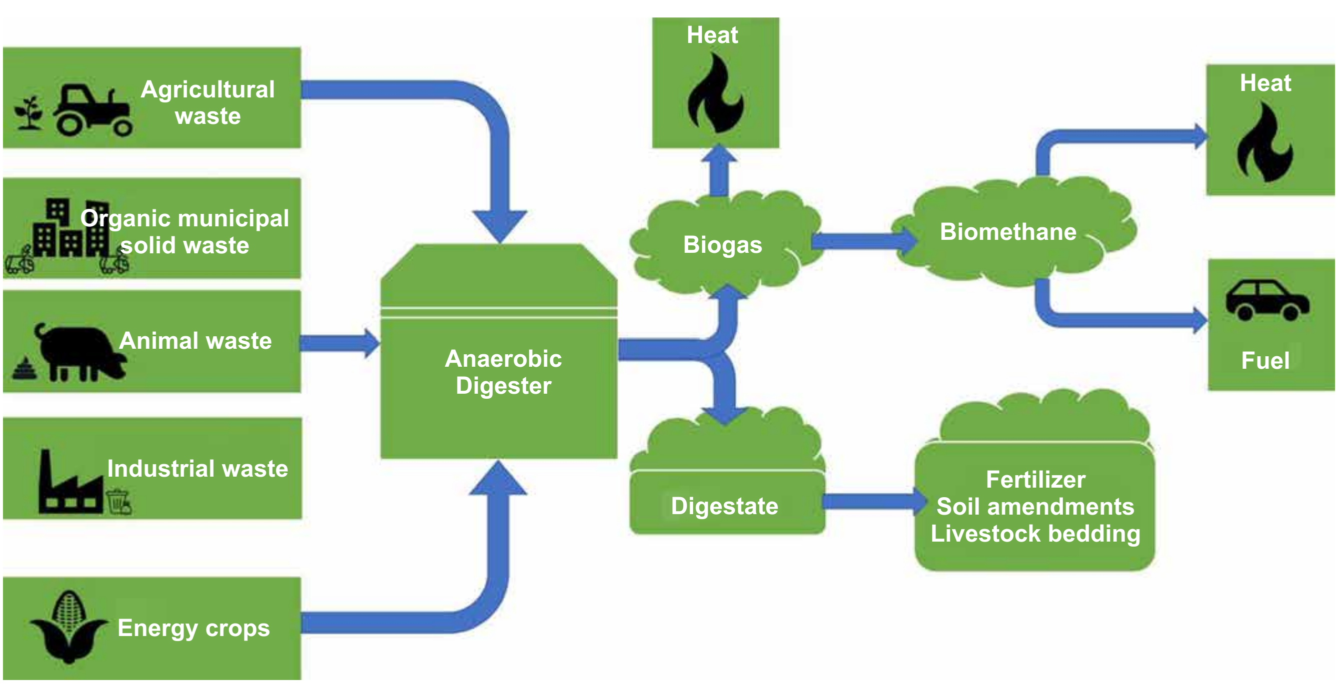
Each type of biomass has its unique composition, which influences the efficiency and performance of the anaerobic digestion process [14]. The most common biomass used are:

1. Agricultural waste: Crop residues, manure, and other agricultural byproducts are commonly used as biomass for biogas production. These materials are readily available and can help recycle waste [10,12].
2. Organic municipal solid waste (MSW): Food waste and green waste from households, restaurants, and food industries are potential biomass sources for anaerobic digestion [6,13].
3. Animal waste: Livestock manure, such as from cattle, pigs, and poultry, is a valuable source of biomass for biogas production. Anaerobic digestion of animal waste generates biogas and helps manage and reduce greenhouse gas emissions.
4. Industrial waste: Organic waste generated by industries, such as breweries, food processing plants, and distilleries, can be utilized as biomass for anaerobic digestion [10].
5. Energy crops: Dedicated energy crops like corn, sugarcane, and switchgrass can also be grown specifically for biogas production, providing a sustainable source of biomass [11].

Proper management and optimization of the anaerobic digestion system, tailored to the specific biomass characteristics, are essential to achieve optimal biogas production. Overall, anaerobic digestion is a versatile and environmentally beneficial technology that can convert various biomasses into biogas, contributing to renewable energy generation and waste management and reducing greenhouse gas emissions (Figure 1).

Brazil is known for its rich biodiversity and abundant biomass from agricultural and industrial activities. The country holds significant potential for biogas production. The efficient utilization of biomass through anaerobic digestion can contribute significantly to the country's sustainable development, aligning with the ONU Sustainable Development Goals. In this context, the present work aims to study and evaluate the anaerobic

Figure 1. Schematic of anaerobic digestion applications.



digestion reaction for biogas production from biomass, seeking to comprehend the key factors influencing the process and develop more efficient technologies for biogas production. Through a comprehensive literature review and analysis of experimental data, valuable insights are expected to be provided for advancing the utilization of biogas as a clean and sustainable energy source.

This work has built an Arduino-controlled bioreactor for automatic monitoring and control of essential variables in the anaerobic digestion of biomass for biogas production to produce high-quality and efficient biogas.

Materials and Methods

Anaerobic digestion is a complex biological process involving a consortium of microorganisms, including archaea methanogens, responsible for producing methane gas. Several key factors, including temperature, pH, and the composition of methanogenic archaea communities, influence the efficiency of methane production in anaerobic digestion. This literature review aimed to provide insights into how these parameters impact methane production in anaerobic digestion processes.

Temperature

Temperature is a critical factor affecting the rate and efficiency of anaerobic digestion. Different groups of methanogenic archaea have distinct temperature optima. According to the literature, anaerobic digestion at around 25-35°C promotes higher methane production due to lower energy requirements and better process stability [15,16].

pH

The pH level of the anaerobic digestion reactor is another critical parameter influencing methane production. Methanogenic archaea are sensitive to pH changes, and their optimal growth typically occurs in the range of 6.5 to 7.5. Acidic conditions ($pH < 6$) can inhibit methanogenic activity, reducing methane production and process instability. On the other hand, overly alkaline conditions ($pH > 8$) can affect the structure and activity of the microbial community, disrupting the overall digestion process [17,18].

Methanogenic Archaea

The composition and diversity of methanogenic archaea communities significantly impact methane production. Various species of methanogens have different substrate preferences and tolerances to environmental conditions. Understanding the dynamics of methanogenic archaea can help optimize anaerobic digestion processes to enhance methane production. Advanced molecular techniques, such as high-throughput sequencing and quantitative polymerase chain reaction (qPCR), have enabled researchers to identify and quantify methanogenic archaea and their abundance in different anaerobic digesters [19,20].

The construction of the bioreactor was developed following the following steps:

Materials Selection

1 Arduino uno R3, 1 digital pressure sensor module 0- 40kpa, 1 hydrogen gas sensor mq-8, 1 methane gas sensor MQ-4, 1 temperature sensor ds18b20 waterproof, 1 relay module 4 channels 5v with optocoupler, 1 2l glass bottle with hermetic lid, 2 tire valves, 2 20mm pvc tee, 20mm PVC tube and 2 gas pressure valves.

Arduino System Selection

Arduino is an open-source single-board electronics prototyping platform designed with a microcontroller and uses a user-friendly standard programming language. This system was chosen for this work because it is an efficient and low-cost process. With the built control platform, it was possible to monitor the reaction temperature in real-time through the DS18B20 Waterproof

Temperature Sensor, the pressure through the Digital Pressure Sensor Module (0-40 kPa), and quantify the production of methane (CH_4) with the Methane Gas Sensor MQ-4 and hydrogen (H_2) with the Hydrogen Gas Sensor MQ-8.

Excel program for Monitoring

The chosen Temperature Sensor (DS18B20) is digital and performs measurements in the range of -55 ° to 125 °C, in a dry, humid, or submerged environment. The digital pressure sensor (0-40 KPa) allows measuring the pressure of dry and non-corrosive gases between 0 kPa and 40 kPa. The MQ-8 sensor detects hydrogen gas concentrations in the air in the 100-10,000 ppm range, and the MQ-4 sensor detects methane in the 300-10,000 ppm concentration range. The set also has a relay module that activates an electrical resistance if the temperature of the bioreactor reaches values below the established value (T=35 °C) or activates a cold-water pump to decrease the temperature of the bioreactor when the sensor identifies temperatures above 35 °C. An Excel program was developed (Figure 2) that allows data collection every second, storing the data in a spreadsheet for later analysis. Additionally, an interface was created in Excel that allows a real-time visualization of the bioreactor's operational conditions.

Results and Discussion

According to the literature review studied in this work, anaerobic digestion for biogas production is a promising and sustainable process with great potential to contribute to renewable energy generation and reduce the environmental impact of organic waste. Understanding the main reaction parameters, such as organic load, C/N ratio, temperature, pH, and hydraulic retention time (HRT), is essential to optimize the process and maximize biogas production. Furthermore, using various biomass provides flexibility and economic viability, making this process attractive for transitioning to a more sustainable and clean energy matrix [15-20]. Table 1 shows the most critical parameters to optimize the anaerobic digestion reactions for biogas production.

Figure 2. Excel program developed.

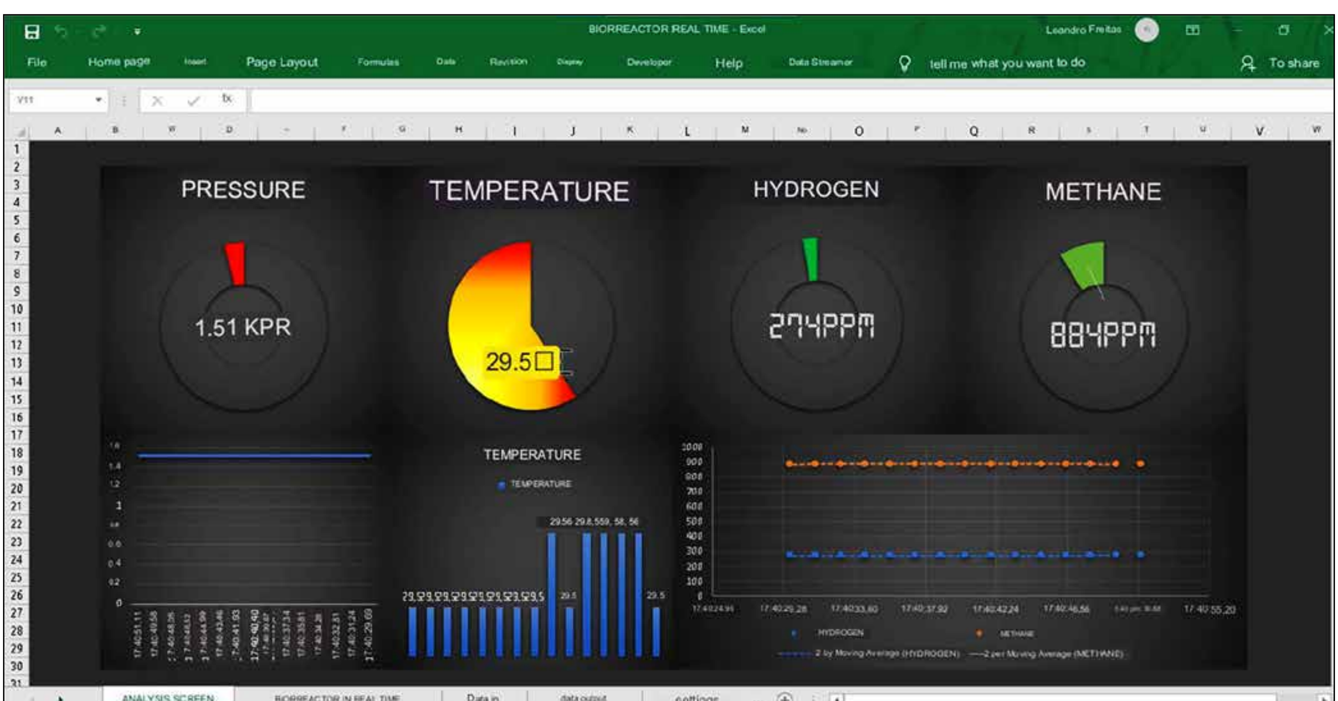


Table 1. Main reaction parameters of anaerobic digestion [15-20]

Organic Load (Feeding Rate)	The organic load is a critical parameter that determines the amount of biomass added to the anaerobic reactor within a specific period. An appropriate balance between the organic load and the microorganisms' capacity to degrade the biomass is essential to avoid process inhibition.
Carbon/Nitrogen Ratio (C/N)	The ratio of carbon to nitrogen in biomass is significant for microbial activity. An ideal C/N ratio typically ranges from 20:1 to 30:1. When the ratio is too high, toxic ammonia accumulation may occur in the reactor, affecting the efficiency of anaerobic digestion.
Temperature	Anaerobic digestion is temperature-sensitive and can be classified into three ranges: mesophilic (30-40°C), thermophilic (50-60°C), and hyper mesophilic (above 60°C). Temperature directly affects the activity of microorganisms and, consequently, the biogas production rate. Temperature control is crucial for maximizing process performance.
pH (Hydrogen Ion Potential)	pH is crucial for the functioning of microorganisms involved in anaerobic digestion. The optimal pH range is generally between 6.5 and 7.5, varying depending on the type of biomass and the dominant group of microorganisms in the reactor. hydraulic
Retention Time (HRT)	HRT is the average period that biomass remains in the reactor, determined by the total reactor volume and the biomass feeding rate. An appropriate HRT is essential to provide microorganisms with sufficient time to degrade organic matter.

The experiments used fermented beans as inoculum and sugar as a substrate. The Excel program satisfactorily identified the formed products (H_2 with 274 ppm and CH_4 with 884 ppm), as well as the temperature and pressure (respectively 1.51 KPa and the reaction temperature without activating the heater was 29.5 °C) (Figure 3). The Excel program was developed to accurately and continuously monitor the internal pressure of the bioreactor, temperature, and the precise amount of hydrogen and methane produced (3 hours).

Conclusion

In conclusion, temperature, pH, and the composition of methanogenic archaea communities are critical parameters that significantly influence methane production in anaerobic digestion processes. Understanding and optimizing these parameters are essential for achieving higher biogas yields, increased process stability, and overall efficiency in sustainable biogas production. Further research in this area can lead to advancements in biogas technology and contribute to developing environmentally friendly renewable energy sources. The realization of this work proved to be positive since the expected objectives were achieved; the prototype of the bioreactor fulfilled its function of helping researchers to identify changes in real-time and thus know what measures to take so that the reactions occur more efficiently, with the controlled temperature monitoring made it possible to keep the most suitable organisms active for the process. The prototype is efficient and can be improved by including

Figure 3. Bioreactor.

other sensors, such as pH and CO_2 concentration, and adding more automatic control functions.

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