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Advancement of A Lab-Scale Anaerobic Biodigester to Implement Monitoring and Sensing Technologies: A Promising Educational Instrument for Reducing Carbon Emissions and Combating Climate Change

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Abstract

This study showcases a laboratory-scale anaerobic biodigester designed to introduce monitoring and sensing methods for tracking microorganism growth based on various parameters, including redox potential, pH, pressure, and temperature, measured in a near-continuous manner. A microcontroller system (Atmega328—Arduino) was employed for this purpose. The design's foundation lies in flexible and open-source software, hardware, and firmware (Scilab, Arduino, Processing), making it easily adaptable for other relevant research. The biodigester was developed as an educational tool for engineering students to gain a deeper understanding of its operation and to track the system's properties and progression over time. This enables the creation of property curves, which can be correlated for a more comprehensive understanding of biodigester functionality. The study specifically explored the connection between the oxidation-reduction reaction and microbial activity, demonstrating that redox potential can effectively measure microorganism growth in an anaerobic environment. Ultimately, this laboratory-scale biodigester serves as an introduction to the technology typically utilised for controlling carbon footprints, particularly in the wastewater sector, and consequently contributes to climate change mitigation efforts.

Keywords: wastewater; low-carbon; biodigester; laboratory scale; open-source tools
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Introduction

Anaerobic digestion technologies employed in organic wastewater treatment offer effective solutions to environmental issues while simultaneously generating energy. These sustainable, safe, and efficient biotechnologies contribute to carbon footprint reduction through methane capture and fossil fuel replacement [1–7]. While the process of anaerobic digestion has been utilised since ancient times, the focus has been on its final products rather than its underlying processes [3]. The adaptability of anaerobic digestion has made it a valuable technology for addressing key challenges in biotechnological industries [4–7].

In contrast to aerobic processes, where dissolved oxygen can be continuously measured, fermentative processes in anaerobic organisms pose a significant challenge due to the current insufficiency of control process technologies [6–10]. Commonly used pH detection in fermentation processes only reflects proton activity and is not sensitive to subtle changes in intracellular metabolism. Redox potential (ORP), or oxidation-reduction potential, captures electron transfers and reflects intracellular metabolism more accurately [6,11–15]. Recent advances in analytical technologies have facilitated the control and deciphering of complex bioconversion processes, with parameters such as pH, ORP, gas production rate, and flow rates routinely recorded in real-time [16–19].

Given the numerous applications of anaerobic biodigesters, it is crucial to develop strategies for engineering students to understand their operation and governing parameters across different contexts. This can be achieved through hands-on experience with the equipment or student-led experimental designs. The educational approach is grounded in theoretical psychological studies [5,7,8,20–24] highlighting the importance of appropriate teaching environments and the design and construction of equipment to reinforce learning.

In light of the significance of the anaerobic process and the need for continuous control, this study presents the design and fabrication of a laboratory-scale anaerobic batch biodigester, alongside its practical application involving brewer's yeast (Saccharomyces cerevisiae) in a semi-continuous control process. The results are subsequently compared with a previously proposed theoretical model [25–30]. The primary aim of this article is to demonstrate a laboratory-scale experimental design of an anaerobic biodigester and to propose user-friendly, low-cost tools, software, and hardware. These resources will enable engineering students to develop autonomous control elements and transform the collected data into computer-interpretable parameters [31–34]. This research aims to connect the anaerobic digestion process in a sequentially loaded reactor on a laboratory scale, with a known microorganism and lab-prepared substrate, to the profiles of oxidation-reduction potential, pH, temperature, and absolute pressure [35–39].

Materials and Methods

Diagram of the Laboratory Reactor

The devised bioreactor (Figure 2.1) can be categorised into three distinct components: (1) Digestion system—encompassing the digester itself and elements in direct contact with it, such as sensors, heating cable, loading and unloading supplies, etc.; (3-6) Control system, circuits, and voltage source—responsible for receiving data and issuing commands essential for optimal system performance; and (7-8) Computer system, communication interface, and software [40–44].

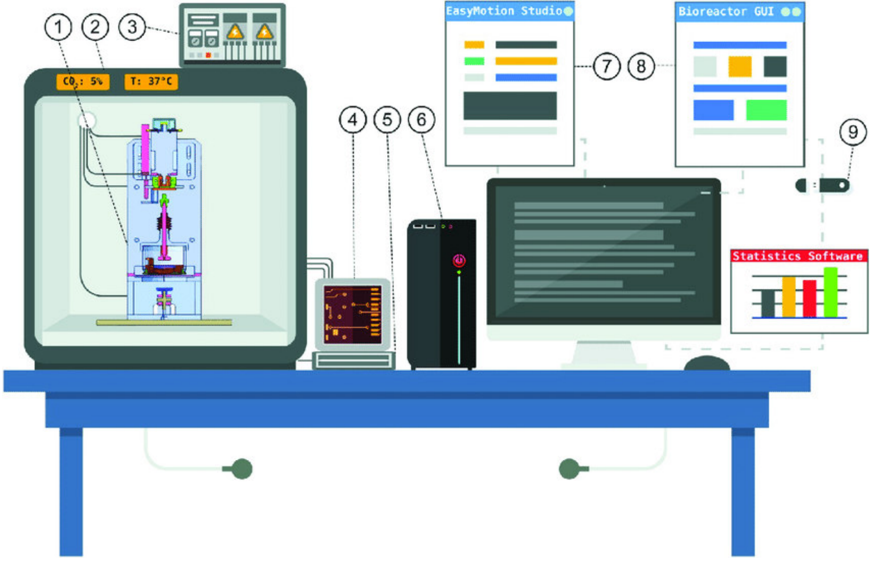


Figure 2.1. Basic diagram of experimental design.

2.1.1 Digestion System

The Digestion System comprises an insulated, hermetically sealed container featuring a feeding and evacuation system designed to ensure thorough mixing during each loading and unloading process. The container's upper section is equipped with an array of sensors, detailed as follows:

1. pH Sensor: A high-quality Scientific Grade Silver/Silver Chloride pH-10 sensor boasting a 95% response speed within one second.
2. ORP (Oxidation-Reduction Potential) Sensor (E): A premium sensor from Atlas Scientific [10,45–48] that utilises an integrated system and a simple serial communication protocol for instant E-value responses.
3. Absolute Pressure Sensor: The Phidgets mod. 1141-0—Gas Pressure Absolute Sensor, ranging from 15 to 115 kPa [49,50], is a high-level analog input sensor whose input is proportional to the ambient pressure.

For the calculation of the temperature from the analogical measurement, considering the resistive values depending on the temperature provided by the manufacturer, and with an algorithm in Scilab, we obtain Equation (2).

$$f(x) = 2.249 \times 10^{-5}x^2 + 0.06872x - 16.03 \quad (2)$$

Table 1. Characteristics of the thermistor NTC, Vishay.

Parameter	**Value**	**Units**
Resistance value at 25 °C	10 K	Ω
Tolerance of R25	± 3	%
B25/85 (Beta)	3678	K
Temperatura range of operation	−5 to 105	°C

2.2 Preparation and Testing

2.2.1 Preparation of the Substrate

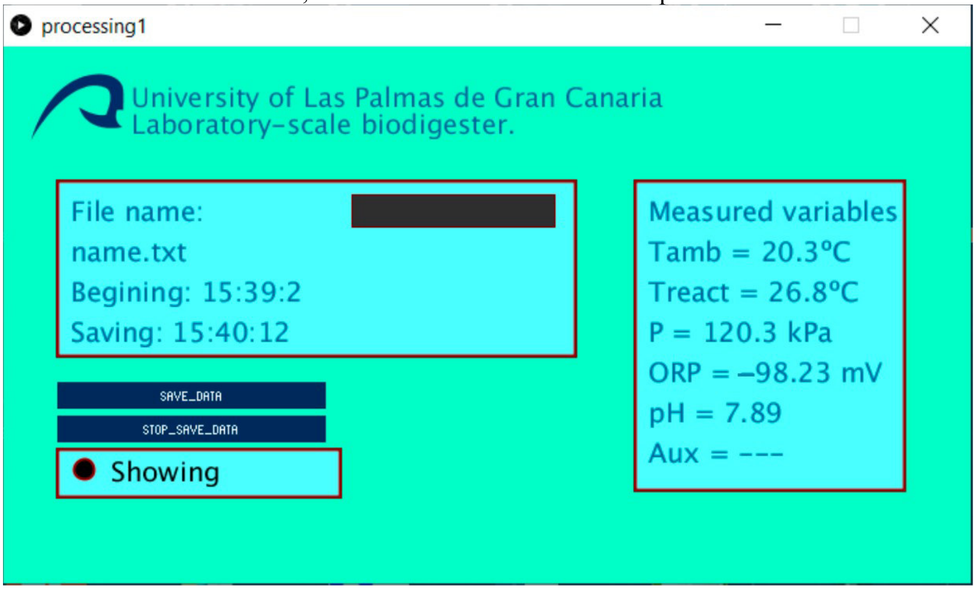
For the preparation of the substrate, the procedure described in bibliography was followed [4]. (1) The substrate was prepared, and its suitability checked. (2) The Brix level was measured and verified to be between 17 and 20 degrees. (3) Once this process was finished, 200 mL of the must was taken, and the yeast was added to it (approximately 2–4 g/L). Although an activation temperature of 37 °C is normally required, it was left at room temperature, as it has been previously proven that the inoculum is active under these conditions for working yeast.

2.2.2 Microbial Inoculum

Brewer's yeast was used whose species includes Saccharomyces cerevisiae with a yield of 0.25–0.33 kg of dry cell weight per kg of substrate.

2.2.3 Control and Saving Data

Through the Arduino (AppendixBshows the Arduino source code), the temperature was controlled and the signals from the pH, ORP, absolute pressure, and temperature sensors (inside the digester and outside the environment) were read. Data were sent to the computer where they were stored by means of the use of Processing tool. Shown in AppendixCis the Processing source code, and Figure6displays the interface. Once all the information was entered, it was saved in a file on the computer's hard disk.



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Laboratory-scale biodigester.

File name: [redacted]
name.txt
Begining: 15:39:2
Saving: 15:40:12

Measured variables
Tamb = 20.3°C
Treact = 26.8°C
P = 120.3 kPa
ORP = –98.23 mV
pH = 7.89
Aux = ---

Figure 2.2. Processing PC interface data logger.

3.Results

a. Digestion Model

Dynamic simulation between reality and model is a very important way for research, as it enables to provide strategies for the An average representation of the tests, carried out in the biodigester over 5 weeks, is shown in Table2. The data was processed using a computerised tool from Scilab. Scilab is a software for numerical analysis, with a high-level programming language for scientific calculation. With the obtained data, a series of graphs were elaborated and the most relevant ones are presented in Figures8–10.

Table 2. Laboratory-scale biodigester; performance periods, operating volume, and Brix measures.

Stage	Date	Feeding/Evacuation (mL)	Brix Grades 1st Lecture	2nd Lecture	Average	Remarks
1	13 June	300	20.30		20.30	
2	18 June	75	20.31	20.29	20.30	
3	23 June	50	20.33	20.24	20.26	Addition NaOH (↑alkalinity)

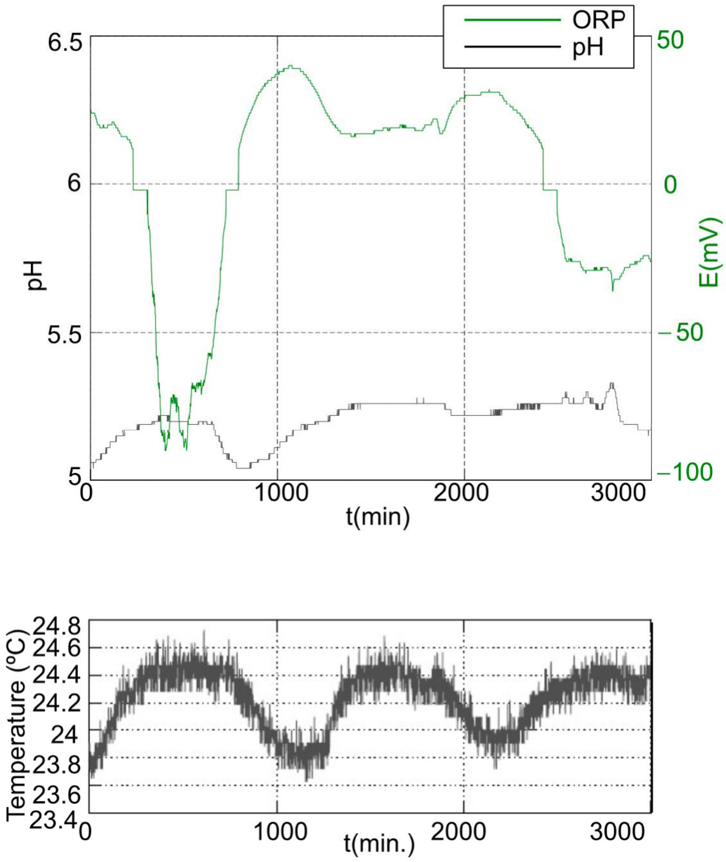

Figure 3.1 ORP, pH, and temperature in the second period.

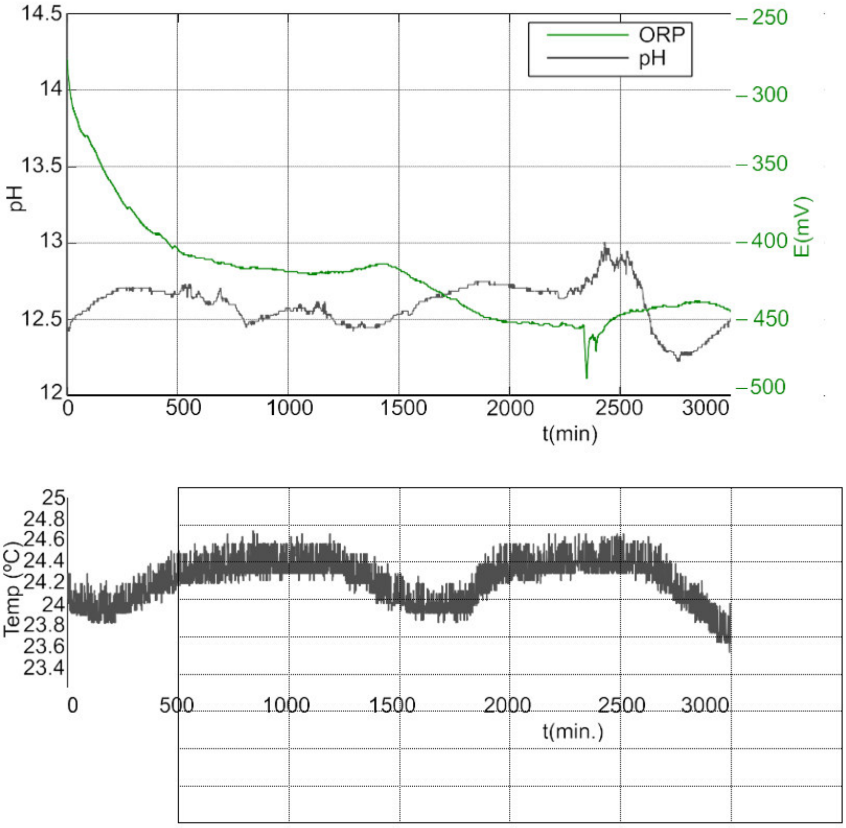

Figure 3.2. ORP, pH, and temperature in the third period.

4. Conclusions

The developed anaerobic biodigester monitoring system demonstrates effective performance for small-scale testing, serving as a valuable resource for research and education. It facilitates the development of new research projects while supporting engineering students' learning. The continuous data collection by ORP, pH, temperature, and pressure sensors allows for easy determination of factors influencing anaerobic microorganism growth. Subsequent data processing enables the creation of graphs that can be compared with a previously proposed theoretical model and relevant governing equations (e.g., Nernst equation). A notable advantage of this design is its reliance on flexible, easily accessible, and open-source software, which allows students to adapt the experimental design to specific cases. The results indicate that the experimental setup is viable for controlling and collecting data on growth-related magnitudes of anaerobic bacteria within a digester. In conclusion, the economically feasible design and construction of a laboratory-scale biodigester is a readily available tool for engineering students to enhance their knowledge and learning experience.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A SCILAB Source Code

```
clear; clc; mu_max=.1/3600;
k_s=100; k_d=.00001; k_x=.00000150; V_1=.01; V_2=3.99; V_T=V_1+V_2;
S_min=k_d*k_s/(mu_max-k_d);     S_in=130;     dt=100;     time=200*24*3600;     Delta_t=.05*24*3600;
q=round(Delta_t/dt);
t=0:dt:time;
X=zeros(1,length(t)); S=zeros(1,length(t)); X(1)=.1; S(1)=0; S_in=S_in; X_in=.1;
e=1; f=0; g=0;
for k=2:length(t)
f=f+1;
if f>=q //Impulse input
S(k-1)=(V_2*S(k-1)+V_1*S_in)/V_T; X(k-1)=(V_2*X(k-1)+V_1*X_in)/V_T; f=0;
end
//Prediction step.
X(k)=(1+(mu_max*S(k-1)/(k_s+S(k-1))-k_d)*dt)*X(k-1);
S(k)=(1-k_x*X(k-1)/(k_s+S(k-1))*dt)*S(k-1);

//Initialization and recursive correction steps. While (e>=.01)
x=X(k);
s=S(k);
X(k)=X(k-1)+dt/2*((mu_max*S(k-1)/(k_s+S(k-1))-k_d)*X(k-1)+
+(mu_max*S(k)/(k_s+S(k))-k_d)*X(k));
S(k)=S(k-1)-k_x*dt/2*(S(k-1)/(k_s+S(k-1))*X(k-1)+S(k)/(k_s+S(k))*X(k)); e=sqrt((x-X(k))ˆ2+(s-S(k))ˆ2);
end
end
```

Appendix B Microcontroller Source Code (Arduino)

```
// *****Digital inputs for pH y ORP****
#include <SoftwareSerial.h> //add the soft serial libray #define rxph 4 //set theRX pin to pin 2
#define txph 5 //set the TX pin to pin 3 #define rxorp 2#define txorp 3
// ****pH data***
SoftwareSerial phserial(rxph, txph); //enable the soft serial port
String inputstringph = ""; // string to hold incoming data from the PC
String sensorstringph = ""; //a string to hold the data from the Atlas Scientific product boolean
input_stringcompleteph = false;//have we received all the data from the PC boolean sensor_stringcompleteph =
false; //have we received all the data from the Atlas Scientific product
// ****ORP data***
SoftwareSerial orpserial(rxorp, txorp);
String inputstringorp = ""; //a string to hold incoming data from the PC
String sensorstringorp = ""; //a string to hold the data from the Atlas Scientific product boolean
input_stringcompleteorp = false; //have we received all the data from the PC boolean sensor_stringcompleteorp
= false;//have we received all the data from the Atlas Scientific product
// ****Analog inputs***
String sensorpresion=““;//presion
```

```
float ntcbiodig=0; //termistor NTC lectura sistema de control float ntcext=0; //termistor NTC lectura entorno
int analogPin1 = A1; //definimos los pines de entrada para la temperatura entorno int analogPin2 =
A2;//definimos los pines de entrada para la temperatura sistema
// **** SETUP ****
void setup(){ //set up the hardware

Serial.begin(9600);
phserial.begin(9600); //set baud rate for software serial port to 38400 orpserial.begin(9600);
phserial.print(“r\r”);
orpserial.print(“r\r”); phserial.print(“r\r”); orpserial.print(“r\r”);
inputstringph.reserve(5); //set aside some bytes for receiving data from the PC

sensorstringph.reserve(30); //set aside some bytes for receiving data from Atlas Scientific product

inputstringorp.reserve(5);//set aside some bytes for receiving data from the PC sensorstringorp.reserve(30);
pinMode(analogPin1, INPUT); //def de los pines de entrada

}
archivo.flush(); // Writes the remaining data to the file archivo.close(); // Finishes the file
nom_archivo=“name.txt”;
}
```

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