Development and Optimization of a Smart Digester for the Production of Biogas from Food Waste

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Abstract

The ever increasing demand for energy could be solved by exploring the prospects of the renewability and availability of the input raw materials; food and animal wastes coupled with the availability of cost-effective materials from local sources for development. This work studies the design, fabrication and performance evaluation of a smart system for the production of biogas. The plant was designed using Autodesk Inventor and fabricated with stainless steel due to its high resistance to biological corrosion. An Arduino Uno Microcontroller was also connected to a pressure, pH and temperature sensors to monitor the process parameters of the developed biogas plant. Optimization of the process parameters was carried out using the central composite design model and response surface methodology. Taking the biogas yield as the response of the designed experiment, the data obtained were statistically analysed to obtain a suitable model for optimization of biogas yield as a function of the process parameters. The results obtained also show the temperature, pressure, pH and organic loading rate are critical factors that influences the yield of biogas production hence the need for proper monitoring. This will complement electricity generation for domestic uses and production of organic fertilizers to boost agricultural productivity.

Keywords: biogas, corrosion, energy, electricity, micro controller

1. Introduction

The ever increasing demand for energy could be solved by exploring the prospects of the renewability and availability of the input raw materials; food and animal wastes coupled with the availability of cost-effective materials for development from local sources. In addition, uncontrolled food and organic waste indiscriminate dumping is no longer acceptable in the economy today and even controlled landfill disposal and incineration of organic wastes are not considered optimal practices, as environmental standards are increasingly become strict while aiming at energy recovery and recycling of nutrients as well as organic matter. Hence, the development of a smart biogas system using food and animal waste will provide a clean method to solve the problem of energy generation in many developing countries. The use of biomass for energy include: the possibility of reduced carbon emissions and meeting climate change commitments; reduction in the consumption of fossil fuel; technological developments because bioenergy could be used to bridge the gap between the current use of fossil fuels technologies and future technologies. In all parts of the world, increasing production and improper management of food and organic waste is a major environmental problem. Also, due to the rising need for alternative sources of energy in order to reduce over dependence on the conventional non-renewable source of energy and the need for waste to energy conversion there is need to explore other viable sources of clean and renewable energy such as biogas. Biogas is a combustible mix of gases produced by the natural fermentation of wet biomass in an anaerobic process (Gerlach *et al.,* 2014; Waybright, 2015). Anaerobic digestion is the controlled degradation of organic waste in the absence of oxygen and in the presence of anaerobic micro-organisms (Ojolo *et al.,* 2009; Curry *et al.,* 2012; Kabouris *et al.,* 2013; Waybright, 2015). It can be done in a mesophilic environment with a corresponding temperature of 32 -42 ° C or a thermophilic one under a temperature range of 50-57 ° C. Under the action of microbial populations, the organic matter undergoes successive transformations until its final transformation into methane CH_4 (Clarkson and Xiao, 2000; Vijay, 2012; Otaraku and Ogedengbe, 2013;). The average human being produces about 1.2 kg of waste each day (Hoornweg and Bhada, 2012). In all parts of the world, increasing production and improper management of organic waste is a major environmental problem (Al Seadi *et al.,* 2008; Wang *et al.,* 2012; Sasse 2014; Weiland, 2015). Even more troubling, according to the World Energy Council (2013), more than 80% of the world's energy need is currently being met from non-renewable energy sources. It is thus imperative on the engineering profession to develop waste-to-energy systems to help meet the energy demands of society. In domestic application, heat energy is required each day for warmth and cooking. According to Ramatsa *et al.* (2014), anaerobic digestion is a four-stage process brought about by the combined action of several species of bacteria. The first stage called hydrolysis where long chain substances like carbohydrates, proteins and fats are broken down into smaller fragments such as simple sugars, glycerol, fatty acids and amino acids (Sharma and Samar, 2016). In the second stage called acidogenesis and acidification, fermentative microorganisms convert these smaller fragments into short chain fatty acids such as acetic acid, propionic acid, and butyric acid (Yavini *et al.,* 2014; Lahlou, 2017). In the third stage of acetic acid formation (acetogenesis), the products of the previous stage are the starting substrates. With these products, lactic acid, alcohols and glycerol, these substances are converted by acetogenic microorganism into acetic acid, hydrogen and CO_2. In the fourth and final stage, methane bacteria act on the acetic acid, hydrogen and CO_2 to produce methane (Lahlou, 2017; Weise and Konig, 2007). With the above process, it becomes evident that biogas production is a fairly complex process. According to Weise and Konig (2007), without instrumentation and proper monitoring, biogas plants are often under-loaded i.e. the biomass feed rate (organic loading rate) are below required levels to make the process cost-effective. Many other researchers have also reported the feasibility of the conversion of animal waste to biogas (Ossai; 2012; Tsavkelova *et al.,* 2012; Mahanty *et al.,* 2014; Eyo 2014; John 2015; Mao *et al.,* 2015). The novelty of this work lies in the introduction of monitoring systems for efficient control and the development of a predictive model for the optimization of the yield of biogas. Thus, the biogas plant is incorporated with a monitoring system consisting of sensors and a microcontroller to continuously monitor the process parameters- pH, temperature and pressure and indicate plant malfunction. This work proposes the development of a waste-to-energy conversion involving a continuous stirred tank with monitoring system using the anaerobic digestion of animal waste and food wastes to produce biogas for cooking, generation of electrical energy and organic fertilizers for households and on farms. Anaerobic digestion is a simple and cost effective process which can be carried out in various environment where food and organic wastes are generated on a regular basis.

2. Materials and Method

The part list of the developed small-scale biogas plant is presented in Table 1.

Table 1: Part list

S/N	Description	Quantity	Material	Remarks
1	Digestion tank	1	1 mm sheet metal	Stainless steel
2	Sparkless electric motor	1	Bought-out	0.35 kW
3	Stirrer	1	20 mm ø shaft	Stainless steel
4	Waste grinder	1	1 mm sheet metal for mesh. 125 mm diameter grater.	
5	Valves and fitting	2	Bought-out	½'' ball valve ½'' adapter ¾" socket ¾" X ½" bushing ¼'' gas outlet valve ½" T-fitting ½" PVC pipe
6	Flashband sealing tape	2	Bought-out	Aluminum faced, bitumen backed sealing tape
7	Arduino Uno	1	Bought-out	
8	pH Meter Kit		Bought-out	
9	Pressure transducer sensor	1	Bought-out	
10	Temperature sensor	1	Bought-out	

The Arduino Uno is a microcontroller board that provides a simple and modular way of interfacing the real world with the computer to handle basic processing tasks on a chip while working with hardware sensors. The Arduino Uno uses the ATmega328 chip that supports 14 digital pins that can be configured as either input or output and 6 analog inputs (Goodwin, 2013). Table 2 shows the technical features of the Arduino Uno.

Table 2: Technical specifications of the Arduino Uno

S/N	Item	Value	Remarks
1	Micro-controller	8-bit Atmel ATmega328p	1 mm sheet metal
2	Operational voltage	5V	Input range: 7-12V
3	Digital GPIO	14	6 capable of PWM
4	Analog IO	6	10-bit
5	Program memory	Flash 32kb, EEPROM 1kb	SRAM 2kb
6	Clock speed	16MHz	
7	USB	Type B socket	
8	Programmer	In-system firmware	USB-based
9	Serial communications	SPI, I2C	Software UART
10	Other	RTC, watchdog, interrupts	

The Arduino is programmed using the Arduino IDE with source code written in C.

The pressure transducer measures the pressure of gas with a carbon steel alloy sensor material (Figure 1). It has a working pressure range of 0-1.2 MPa. The normal working temperature range is 0-85°C and the response time is approximately 2 ms. It consists of an elastic material that deforms under the application of pressure and an electrical element which detects the deformation and transmits it as changes in voltage.

Figure 1: Pressure transducer sensor

The pH meter kit is a kit that measures pH of a substance. It is specially designed for the Arduino and has an accuracy of $\pm$ 0.1 pH (at 25°C). The kit has a range of 0 – 14pH. The kit consists of a pH sensor probe, a BNC connector and a pH 2.0 interface. The pH Meter kit is shown in Figure 2.

Figure 2: pH Meter Kit

The temperature sensor employed in shown in Figure 3.

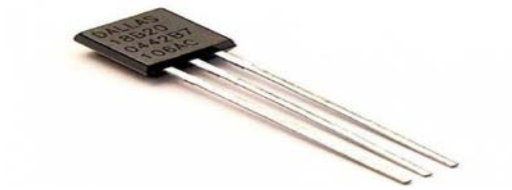

Figure 3: Temperature sensor

2.1 Fabrication of the biogas plant

The volume of digester constructed is 0.06 m^3. A 1 mm thick stainless steel sheet was used in the fabrication of the biogas reactor for the following reasons:

i. It has high resistance to biological corrosion which can arise due to anaerobic digestion process;
ii. It can withstand a wide range of temperatures and pressures.
iii. It also combines good strength with high formability.

In fabricating the small-scale biogas plant, the following stages were undergone:

i. Construction of the cylindrical digester vessel of diameter 350 mm and height 610 mm;
ii. Construction of the grinding unit;
iii. Connection of the plant monitoring system circuit;
iv. Installation of the grinding unit on the digester vessel;
v. Installation of the electric motor;
vi. Installation of piping and fittings;
vii. Installation of plant monitoring circuit on digester vessel.

The biogas plant monitoring system was connected on a breadboard for prototyping using the circuit diagram shown in Figure 4. It shows the connection of the ATmega328 chip on the Arduino Uno with the pH, pressure and temperature sensor

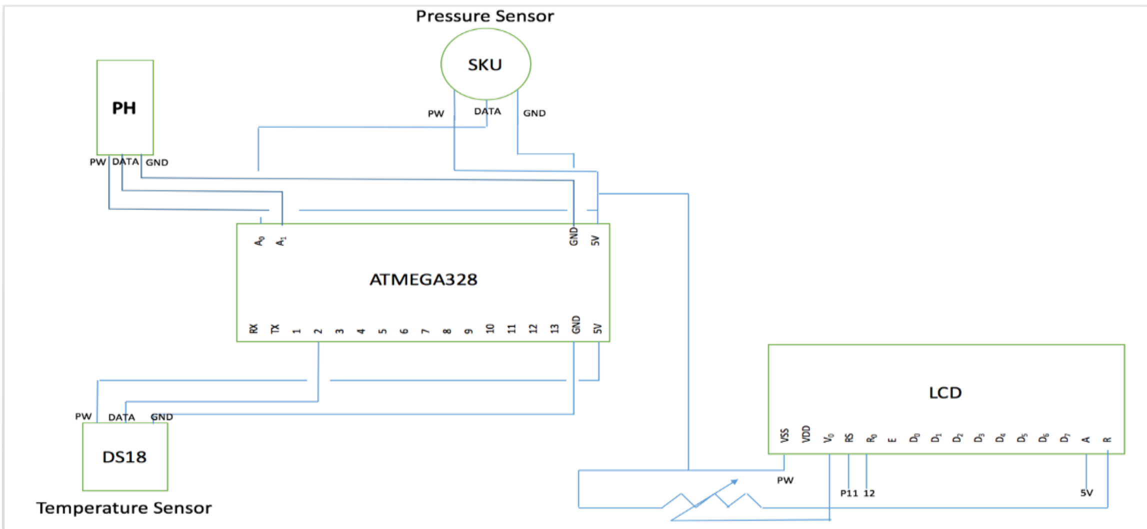

Figure 4: Monitoring system circuit with Arduino Uno microcontroller

2.2 Performance evaluation of the developed biogas reactor

This was done to evaluate the performance of the biogas plant in terms of effectiveness of the continuous monitoring system. Data were obtained from the pressure, pH and temperature sensors to determine their accuracy. The biogas yield is recorded to give daily and total biogas yield. The biogas yield is then evaluated with the pressure, pH and temperature variation per day. The developed biogas plant was fed with 4 kg of food waste (comprising egg shells, cooked rice, pounded yam etc.) and 12 kg of cassava waste water. The total input waste thus is about 16 kg. Samples are shown in Figures 5 and 6.

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Figure 5: Input food waste samples

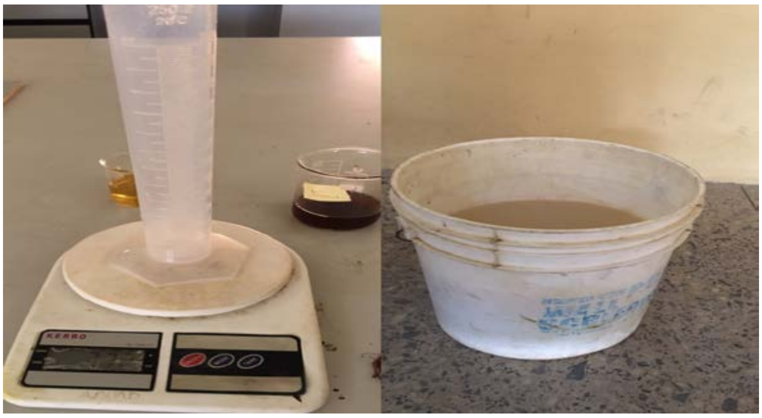

Figure 6: Measurement of the input cassava waste water sample

2.3 Method

The waste materials were gathered from the ABUAD Cafeteria and the cassava waste water from a neighboring village close to the ABUAD community. The waste was prepared by removing foreign or non-organic materials and with water in a ratio 1:1 before being fed into the biogas plant. It was allowed to decompose for 14 days before biogas yield was evaluated. Immediately the waste was fed into the system, the biogas plant monitoring system was initiated to allow for data acquisition.

2.4 Determination of biogas yield

Biogas yield was determined using water-displacement method. A known volume of water is used as a barrier and biogas is collected over it and its volume recorded daily. The correlation, prediction, modelling and optimization of optimum process parameters and yield of biogas produced from food waste was done using the central composite design and response surface methodology.

The software employed was Design-Expert® (version 7) which is used for experiment design. A four-level-four factor central composite design model and response surface methodology was used to study the effect of independent variables such as organic loading rate (kgVDM/m^3), temperature (℃), pH and pressure (kPa) and on the biogas yield. The input process parameters varied and their range include; organic loading rate (0.5-1.0 kgVDM/m^3); reaction temperature (22 – 28℃); pH (6.00-8.00) and pressure (3.00-6.00 kPa). It is also used to investigate the quadratic cross effect of the four input process parameters earlier mentioned on biogas yield. Table 3 shows the input values for process parameters denoted as numeric factors over 4 levels. This generated a runs of 30 experiments and the data obtained was statistically analyzed with the Design-Expert® software to get a suitable model for biogas yield (litres) as a function of the four independent variables.

The performance evaluation of the developed biogas plant was carried by introducing a total input waste of 16 kg. 4.0 kg of food waste material comprising of 46% egg shells and 54% leftovers was sourced from the ABUAD Cafeteria. The food waste comprises of egg shells, cooked rice, pounded yam etc. alongside with 12.5 kg of cassava waste water was also fed into the plant.

3. Results and Discussion

The developed biogas system with its associated expert system is shown in Figure 7.

Figure 7: The developed small-scale biogas plant

The system pressure, pH of substrate and corresponding temperature variation were determined. The biogas yield per day for the given substrate was then obtained via collection over water as shown in Table 3.

Table 3: Methane yield per day

S/N	Time (days)	Weigh of input waste (kg)	Weight of consumed waste (kg)	Volume of methane generated (m^3)	Weight of methane generated (kg)	Methane Yield (%)
1	14	12.5	3.2	2.95	1.33	41.5
2	28	11	3.5	3.02	1.37	39.1
3	42	10.5	3.9	3.14	1.40	35.9
4	56	9.2	4.2	3.40	1.45	34.5
5	80	9.0	4.4	3.84	1.48	33.0
6	94	8.4	4.7	4.25	1.55	32.9

Also Figure 8 shows the methane yield for the input waste consumed as well as the corresponding methane produced. The conversion efficiency of the consumed substrate to methane gas lies between 33-42%. The yield of biogas was observed to decrease with increase in time and the weight of input waste material. This is because the rate of decomposition and conversion of substrate to biogas was rapid at the beginning but decreases overtime. Hence, there is need to constantly increase the loading rate of the input wastes and keep the temperature within the optimum range. Increase in temperature beyond the optimum will kill the bacteria for conversion of the substrates to biogas.

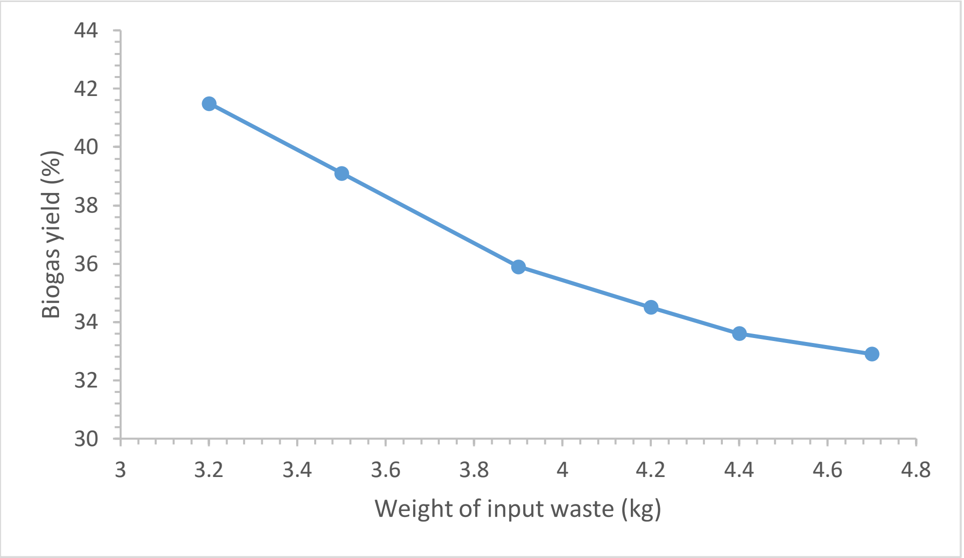

Figure 8: Input waste consumed and methane yield produced

The summary of the designed experiment to predict biogas production in terms of study type using central composite as initial design and a quadratic design model was also given in Table 4.

Table 4: Numeric Factors and Levels

S/N	Factor	Name	Unit	-1 Level	+1 Level	-alpha	+alpha
1.	A	Organic Loading rate	kg/VDM/m^3	0.5	1.0	0.25	1.25
2.	B	Temperature	°C	22	28	19	31
3.	C	pH		6	8	5	9
4.	D	Pressure	kPa	3	6	4	0

The yield of the biogas from food waste was determined using Equation 1.

$$Yield = \frac{Weight\ of\ biogas}{Weight\ of\ input\ waste} \times 100\% \qquad (1)$$

A predictive model for estimating the biogas yield in terms of the process parameters was obtained from Table 4 as given in Equation 2.

$$Yield = 34.93 - 0.14 * A + 0.36 * B - 1.31 * C - 0.85 * D + 0.87 * A * B + 0.43 * A * C - 1.34 * A * D - 0.12 * B * C + 0.46 * B * D + 0.72 * C * D - 0.19A^2 + 0.99B^2 + 0.71C^2 - 0.89D^2 \qquad (2)$$

Where;

A denotes the organic loading rate (kgVDM/m^3); B is the temperature (°C); C is the pH and D is the pressure (kPa).

Figure 9 is a 3D response surface plot of the interaction effect loading rate and temperature when pH and pressure were held constant at 6.32 and 5.65 kPa respectively. The optimum percent yield of biogas was 36. Increase in loading rate increases the temperature and increases the yield of the biogas. Further increase in temperature and loading rate beyond the optimum decreases the yield of biogas. The number of decomposition bacteria may decrease with increase in temperature beyond the optimum resulting in decrease in the yield of biogas.

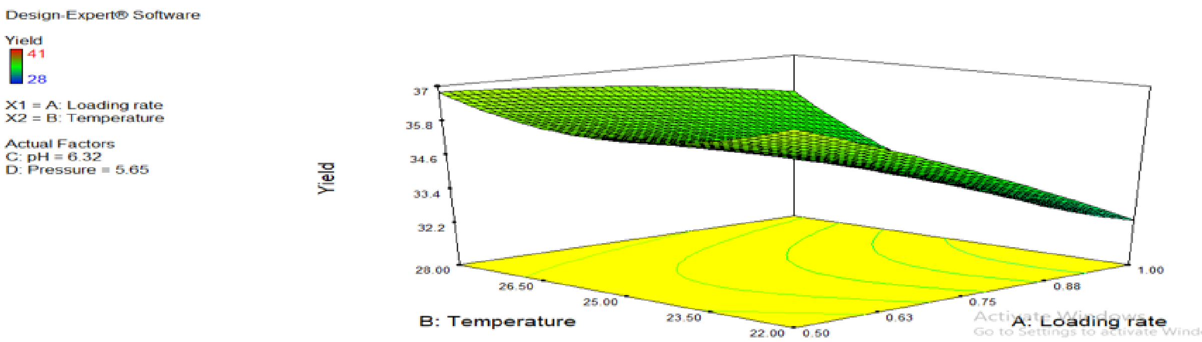

Figure 9: Effect of interaction of loading rate and temperature on biogas yield

Figure 10 studies the interaction effect of loading rate and pH when temperature and pressure are held constant at 23.04^{o}C and 5.65 kPa respectively. The optimum percent yield of biogas was 34.8. Increase in loading rate increases the pH and increases the yield of the biogas up to the optimum yield point after which there is a sharp decrease in the yield with increase in the loading rate and pH. This may be due to the fact that further increase in the volume of substrate beyond the optimum, decreases the rate of decomposition resulting in decreased yield of the biogas.

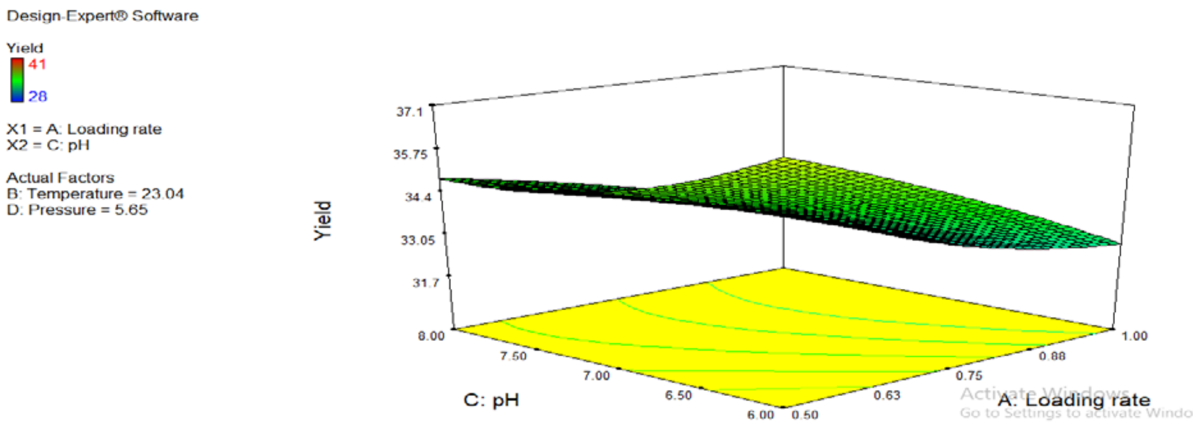

Figure 10: Effect of interaction of loading rate and pH on biogas yield

Figure 11 is a 3D response surface plot of the interaction effect of the loading rate and pressure keeping temperature and pH constant at 23.04^{o}C and 6.32 respectively. Increase in loading rate increases the pressure resulting in an optimum yield of biogas. Beyond the optimum percent yield of 35.7, the yield of the biogas decreases with increase in loading rate and pressure.

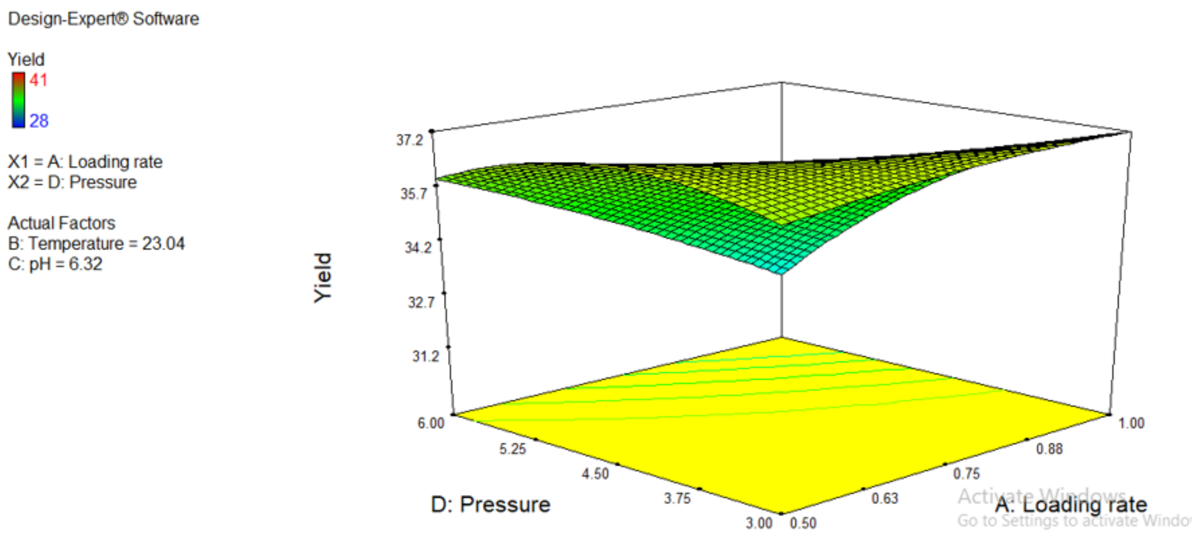

Figure 11: Effect of interaction of loading rate and pressure on biogas yield

Figure 12 is a 3D response surface plot of the interaction effect of temperature and pH when loading rate and pressure were held constant at 0.82 and 5.65 kPa respectively. The value of pH is likely to be unaffected with increase in temperature. Further increase in temperature beyond the optimum may kill the decomposition anaerobic bacteria which will in turn slow down the rate of decomposition resulting in decrease in the yield of the biogas. The optimum percent yield of biogas was found to be 35.9.

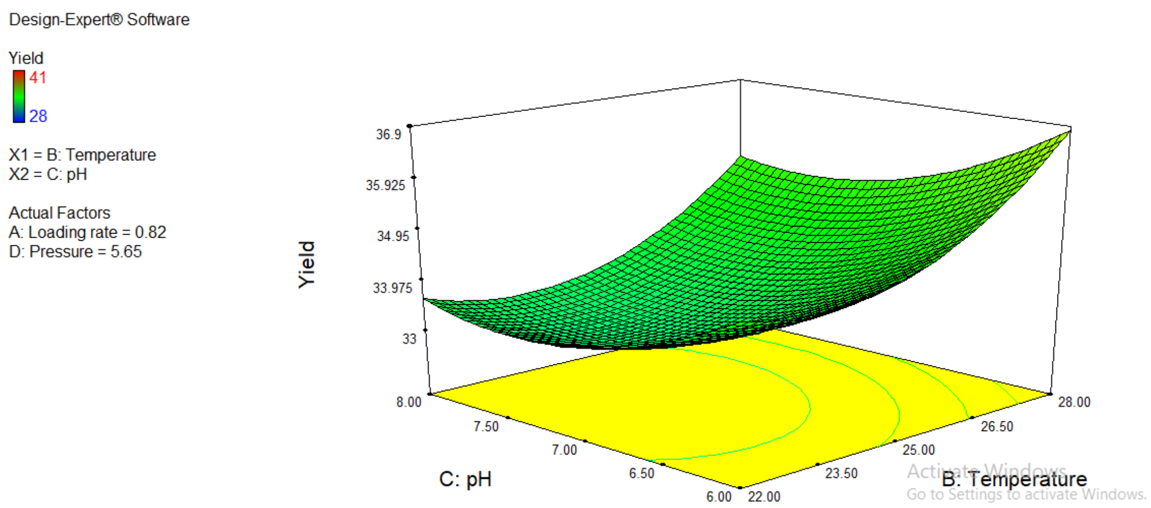

Figure 12: Effect of interaction of temperature and pH on biogas yield

Figure 13 is a 3D response surface plot of the interaction effect temperature and pressure on the yield of biogas when the loading rate and pH were held constant at 0.82 and 6.32 respectively. The interaction between the temperature and pressure was observed to be inversely proportional as increase in temperature reduces the pressure and vice versa. The optimum percent yield of biogas was found to be 37.

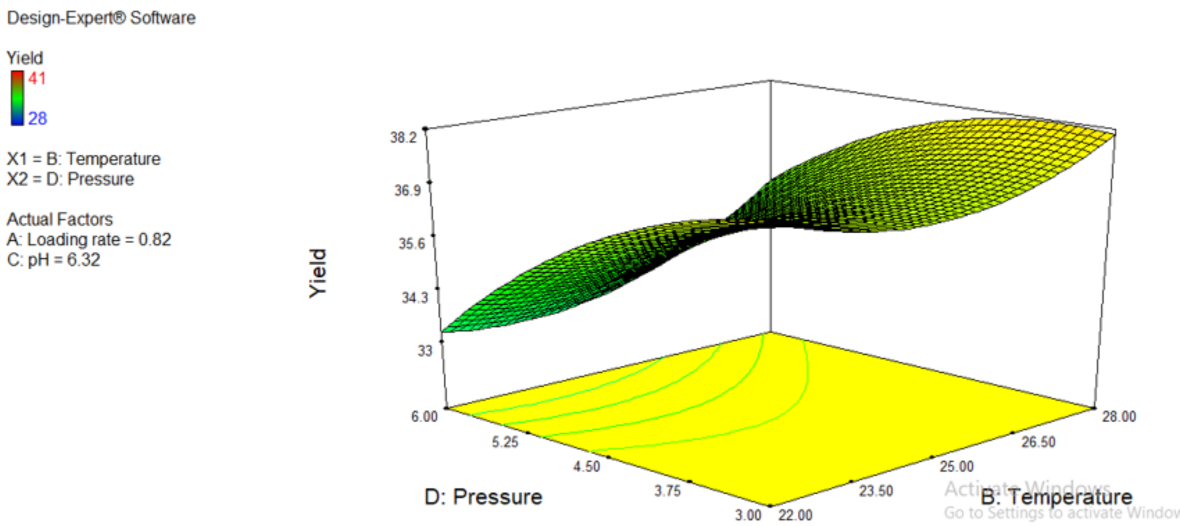

Figure 13: Effect of interaction of temperature and pressure on biogas yield

Figure 14 is a 3D response surface plot of the interaction effect of pH and pressure on the yield of biogas. The variation in pH is unlikely to affect the pressure variation. Hence the percent optimum yield of biogas was found to be 36.

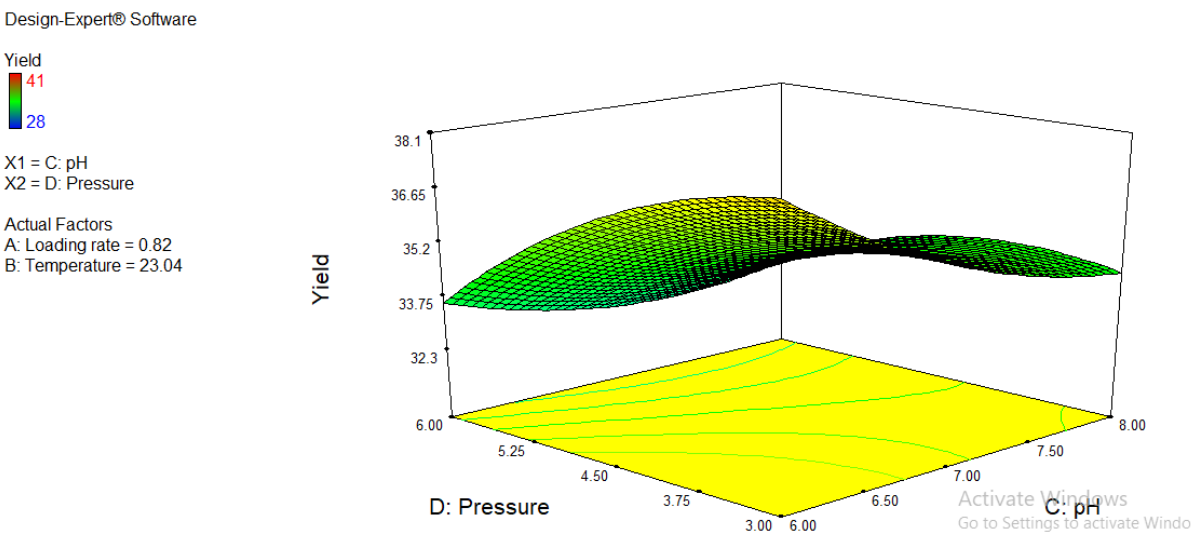

Figure 14: Effect of interaction of pH and pressure on biogas yield

From Figures 9-14, the optimum values of the process parameters for the optimum percent yield of biodiesel (37) was found to be: loading rate (0.82 kgVDM/m^3), temperature (28^{o}C), pH (6.32) and pressure (5.80 kPa).

4. Conclusion

The successful completion of this work featured the design a biogas plant for use in ABUAD for studying biogas production, fabrication of the designed biogas plant, incorporation of a relatively low-cost continuous parameter monitoring system for the small-scale biogas plant and evaluation and optimization of the developed biogas plant. The optimum conversion of substrate to methane gas was 41.5% within 84 days. The percent conversion of the substrate to methane gas was observed to decrease with the increase in the number of days and the weight of input waste. Hence, for optimum substrate conversion, there is need for periodic loading in between the time interval for conversion.

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