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DEVELOPMENT OF A SMART DIGESTER FOR THE PRODUCTION OF BIOGAS

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Abstract

Due to the rising need for alternative sources of energy, as a result of the challenges of fossil fuel, studies must forge on to explore other viable sources of clean and renewable energy like biogas. Biogas is a combustible mixture of bio-methane, carbon (IV) oxide, and other trace gases. It is produced as a result of anaerobic digestion of organic matter. This work develops a small-scale biogas plant with a smart system that was used to enhance the study of biogas production at the Department of Mechanical and Mechatronics Engineering, Afe Babalola University Ado-Ekiti (ABUAD). 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. Results obtained to validate the direct relationship between organic loading rate and biogas production. It also showed the interaction between temperature and pressure, temperature and pH, pH and pressure. 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. For a sample 24-hour period the optimum values of the process parameters for the optimum yield of biogas (23 litres) were found to be: Loading rate (0.75 kgVDM/m^3), temperature (25.34^{o}C), pH (7.04) and pressure (4.84 kPa). The work has been able to lay a foundation for studies on biogas production using sensors and continuous parameter monitoring. It has also laid a foundation for research work by developing a small scale biogas plant for experimental purposes.

Keywords: *anaerobic digestion; biogas; organic matter; smart system; renewable energy.*

1. Introduction

Biogas is a combustible mix of gases produced by the natural fermentation of wet biomass in an anaerobic process [1]. Biogas production technologies are highly beneficial to society as they transform waste into useful energy while reducing environmental pollution. Furthermore, the digestate (decomposed substrate) provides a source of potent fertilizer for improving plant yield. Biogas is a sustainable source of energy and can be explored to end the dependence on energy from fossil fuels.

The average human being produces about 1.2 kg of waste each day [2]. In all parts of the world, increasing production and improper management of organic waste is a major environmental problem [3]. Even more troubling, according to the World Energy Council [4], more than 80% of the world's energy need is currently being met from non-renewable energy sources. It is thus imperative for 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. This energy can be provided in a sustainable manner with the implementation of a waste-to-energy conversion system using anaerobic digestion of organic waste to yield biogas for cooking, space heating and even powering of combined heat and power (CHP) engines, and organic fertilizer for improving plant yield.

This work develops a small-scale biogas plant that converts food waste and animal excreta to biogas via anaerobic digestion. According to Ramatsa *et al.* [5], 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 [6]. 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 [7]. 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 [7-8]. This biogas typically contains 50 -70% of methane [9]. With the above process, it becomes evident that biogas production is a fairly complex process. According to Weise and Konig [9], 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. Thus, the biogas plant will also be 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.

The aim of this work is to develop and optimize a small-scale biogas plant with a smart system for use in small scale applications.

Since conventional biogas plants are not monitored, they are plagued with various challenges including the aforementioned under-loading of organic material (low organic loading rate) and overloading (excessive organic loading rate). Overloading slows down or stops the anaerobic digestion process and may cause a total system breakdown. Another considerable challenge that arises from lack of monitoring is diges-ter instability which arises as a result of unsuitable pH for biogas production. According to Weise and Konig [8], for the first and second stage of biogas production, the best pH is between 4.5 – 6.3. For the third and fourth stages where methane formation is evident, the optimal pH range is specified as 7.0 -7.7.

The anaerobic digestion process, however, self-regulates to achieve such a pH level, but it is common to have biogas plants fed with substrates that will make achieving this range difficult. This greatly increases the time needed for biogas production to commence. Furthermore, another challenge that arises from inadequate or non-existent biogas plant monitoring is poor production due to excessive temperature fluctuations or improper temperature range for various types of methanogenic bacteria. Methanogenic bacteria can either be psychrophilic (operating effectively between 12 to 24°C), mesophilic (operating optimally between 22-40°C) or thermophilic (thriving optimally between 50 – 60°C). All these points to a gap in cost-effective and easily accessible monitoring systems for biogas plants especially in the conventional pilot and small-scale biogas plants. With the recent national economic turbulence and a worldwide slump in oil prices, it has become evident that countries must look inward to renewable sources of wealth and energy that will be economical, socially and environmentally sustainable. According to Davidson [10], 'sustainable energy' is energy for 'sustainable development'. Hence, the development of this system that will minimize improper waste disposal in communities, while creating wealth from waste, reducing landfills and providing a potent organic fertilizer becomes not only attractive but needful. Since waste is generated on a daily basis in academic and industrial areas, the system becomes desirably sustainable to study the anaerobic digestion process continuously. The fertilizer output can then be used on farms to grow crops that will help meet the local nutritional needs of society. Incorporation of the monitoring system also becomes desirable in ensuring that the process is both safe and stable. The sensors can detect anomalies in operation, and warning alarms can be raised to prevent plant instability, accidents, and emergencies before they occur.

This research is limited to development of a small-scale biogas plant for studying biogas production using a variety of organic waste. The small-scale biogas plant is incorporated with a smart monitoring system that is limited to data acquisition and display.

Anaerobic digestion requires a vessel with an enclosed (i.e., air-tight) environment in which diverse microbial consortium which degrade organic material to generate biogas. When organic material including animal manure, agricultural residues, sewage sludge and food waste among others, undergo anaerobic digestion by the action of anaerobic bacteria, biogas is produced. According to Al Seadi *et al.* [3] and Friehe *et al.* [9], this gas mixture called biogas consists primarily of methane (50-75 % vol.) and carbon dioxide (25- 50 % vol.). Biogas also contains small quantities of hydrogen, hydrogen sulphide, ammonia and other trace gases. The composition of the gas is essentially determined by the substrate supplied, the fermentation (digestion) process and the technical design of the plant. According to Friehe *et al.* [9], monitoring biological processes is challenging. Despite this fact, however, a variety of options exist for monitoring of plants ranging from operating logs to fully automated data acquisition and control systems. In the small-scale application, however, complex systems are to be avoided due to cost implication.

According to Weise and Konig [8], to achieve optimal control of the biogas plant, detailed knowledge of key chemical and physical properties including temperature, pH, organic acid and fatty acid concentration, ammonium concentration and acid capacity. The sensors required for monitoring key process parameters including pH, pressure, and temperature will be studied subsequently. The process by which biogas is formed can be divided into four major steps as shown in Figure 1. These individual stages of decomposition (degradation) must be coordinated and harmonized with each other in the best way possible to ensure that the process completes smoothly without impediment or instability [9].

During the first stage, complex compounds of the starting material including carbohydrates, proteins, fats, and oils are broken down into simple organic compounds such as amino acids, sugars and fatty acids/glycerol. The hydrolytic bacteria involved in this stage releases enzymes that decompose the material by biochemical means.

During this acidification phase, the immediate products from hydrolysis are then further broken down by acid-forming (fermentative) bacteria to form lower fatty acids (acetic, propionic and butyric acid) alongside carbon dioxide and hydrogen. Also, small quantities of lactic acid and alcohols are also formed. The nature of products formed during this stage is influenced by the concentration of the intermediate hydrogen content.

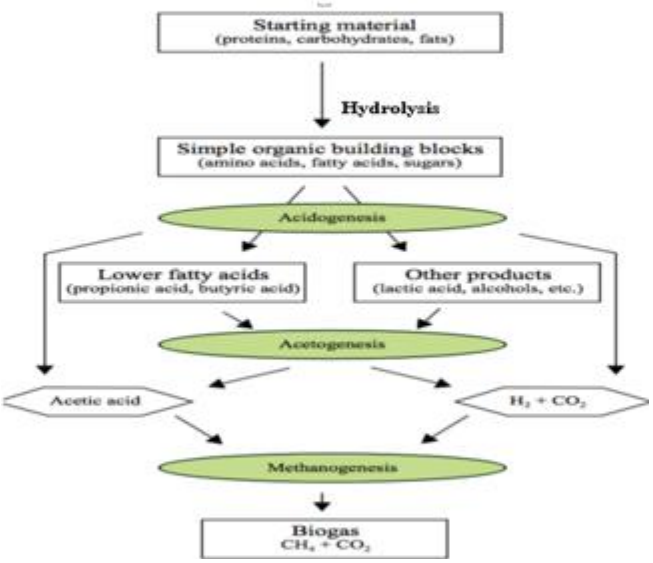

Figure 1. Schematic representation of anaerobic digestion *(Source: Friehe et al.* [9])

In this stage, acetic acid forms. The products of the acidification phase (acidogenesis) are then converted by acetogenic bacteria into precursors of biogas (acetic acid, hydrogen, and carbon dioxide). The partial pressure of hydrogen is particularly important in this connection. Excessive partial pressure of hydrogen can prevent the conversion of the intermediate products of acidogenesis due to energy related reasons.

As a consequence of this excessive partial pressure, organic acids such as propionic acid, isobutyric acid, isovaleric acid and hexanoic acid accumulate and inhibit the formation of methane. For this reason, the hydrogen-forming (acetogenic) bacteria must co-exist in a close biotic community with the hydrogen-consuming methanogenic archaea, which consume hydrogen together with carbon dioxide during the formation of methane, thus ensuring an acceptable environment for the acetogenic bacteria.

This is the final stage of biogas generation. Acetic acid, hydrogen and carbon dioxide are converted into methane by strictly anaerobic methanogenic archaea. The hydrogenotrophic methanogens produce methane from hydrogen and carbon dioxide, whereas the acetoclastic methane-forming bacteria produce methane by acetic acid cleavage. At higher organic loading rates (usually obtainable in agricultural biogas plants), methane is formed primarily via the reaction pathway utilizing hydrogen, while it is only at relatively low organic loading rates that methane is formed via the reaction pathway involving the cleavage of acetic acid [11].

In an anaerobic digester or reactor, these four phases of anaerobic degradation take place simultaneously as a single-stage process. According to Vanek *et al.* [12], anaerobic digesters are open systems which means that diverse types of microbes can come in with the waste streams to circumvent the need to sterilize the inflow streams, and this eventually results in thousands of microbial species being present in a relatively stable consortium. This suggests that within the anaerobic digester, microbes comprise a food web, which means that a product from one microbe is the substrate (food) for another one.

According to Dobre *et al.* [13] and Friehe *et al.* [14], the following key factors affect the production of biogas via anaerobic digestion of organic waste. The hydraulic retention time (HRT) it is the mean range in which the substrate for anaerobic digestion process is retained in the digester, in contact with active bacterial mass. Substrates containing simple compounds are easily decomposed and require short HRT, while substrates containing complex compounds are harder decomposed and require a longer HRT. The retention time of the solids (SRT) is the measure of the biologic system capability to reach certain standards concerning the effluents and/or to maintain a satisfactory rate of pollutants biodegradation. SRT controls the microbial mass in the reactor in order to obtain a degree of waste stabilization.

Maintaining a high SRT translates to more stable running, better tolerance to toxic and shock loads and quick recovery after toxicity or instability. HRT is a key factor in the design process anaerobic digestion for digestible and hard complex organic pollutants, while SRT is the control parameter in the design process for readily digestible organic elements.

HRT is determined by the volume of the digester and the amount of substrate loaded per unit of time, according to the equation .1.

$$\mathrm{HRT} = \frac{V_d}{V_s}\ [\mathrm{days}], \qquad (1)$$

where: HRT is the hydraulic retention time [days]; V_d is the digester volume [m^3]; V_s is the amount of substrate loaded per time unit [m^3/s].

A short retention time determines a better flow rate of the raw material, but the low productivity of biogas.

In the production process of biogas, the pressure is of great significance. The experiments have shown that when hydrostatic pressure prevailing on the methanogenic bacteria increases over the range, 400 - 500 mm H_2O [13], biogas production ceases and is resumed when the hydrostatic pressure falls below that range. This is a critical component of the design work as it determines the height of fluid that the digester tank should operate with. For vertical digesters where the height can reach tens of meters, biogas is produced only up to maximum depth 4 – 5 m and the rest of the area occupied by the substrate does not produce biogas, which is why it is necessary to periodically bring to surface the material under the limit of reaction, by the stirring continued. The negative impact of this factor can also be avoided by using a horizontal tank whose height is typically below 3.5 m.

In anaerobic digestion all biological processes are carried out at well-defined values of pH. The pH of the optimal hydrolytic stage is between 5 - 6, and for methane production (methanogenesis) stage, the optimal pH value varies between 6.5 – 8. If the pH value decreases below 6, methane production is strongly inhibited. In the hydrolytic stage, the acidogenic bacteria require a pH in the range 5.5 – 7.0, and in the final stages, methanogenic bacteria require a pH value ranging between 6.5 - 8.0.

A major limitation to the processing of organic substrates through the process of anaerobic digestion in a single phase is a lower value of pH in the reactor due to rapid acidification by the production of volatile fatty acids. This effect hinders and inhibits the activity of methanogenic bacteria. At digesters operating in a single phase with the full mixing of the substrate, the pH must meet the requirements of the populations of micro-organisms that coexist in the digester. The temperature of the reaction medium influences the pH value. While the temperature is increasing, the carbon dioxide solubility decrease; this is why in the case of thermophilic digesters the pH value is higher than in the mesophilic ones where the carbon dioxide will dissolve easier and will produce carbonic acid in reaction with the water, increasing the acidity. During the digestion process, the pH value may increase because of the ammonia presence resulted either by the protein degradation or by its presence in the charging flux. The size of organic particles to be digested affects the rate of anaerobic digestion and thus the overall rate of biogas production. The smaller the particle size, the faster the rate of anaerobic digestion due to increasing in surface area. This smaller particle size increases biogas generation rate and reduces the amount of residue thus reducing digestion time overall. Smaller particles also mean shorter settling time since particles can be suspended in the fluid for greater digestion [15].

To achieve steady and increased biogas production rate, the substrate to be digested and the anaerobic bacteria must have extensive contact. This contact can be achieved by proper mixing of the substrate in the digester tank. If there is insufficient mixing, layers of sediments begin to form in the digester tank, trapping bacteria beyond the reach of the undigested substrate [14]. Due to differences in density, these various substrates form layers with the majority of the bacterial mass settling at the bottom of the tank out of reach of the majority of the substrates to be decomposed.

Solids that can float then form a layer of scum at the top of the slurry making it difficult for gas to escape from lower levels. The result of these factors is a significantly lower biogas production rate. Thus, mixing is essential for proper biogas production. Excessive mixing must, however, be discouraged in biogas plants as the bacteria that help form acetic acid (during acidogenesis) and the archaea responsible for methanogenesis form a close biotic community that can be destroyed by excessive stirring. A compromise thus must be reached between stirring time and stirring intensity.

Other factors that affect biogas production include mixing ratio, inoculums, loading rate, nitrogen inhibition, C/N ratio, agitation, toxicity, solid concentration, seeding, metal cations, additives, etc.

A wide array of research work has been carried out on biogas production in Nigeria and in other parts of the world. Biogas production and science have steadily progressed in the last four decades. However there is much room for innovation and creative thinking. Otaraku and Ogedengbe [16] studied the effect of Sawdust concentration in the co-digestion of sawdust, cow dung, and water hyacinth. This was done over a period of 64 days, and it was observed that about 40% of Sawdust in the total solids yielded optimum biogas production. Increased Sawdust content lowered biogas productivity due to the high lignin content of the sawdust which is difficult to digest.

Yavini *et al.* [17]studied the mesophilic biogas production potential of Groundnut shell, Maize cobs, Rice straw, and Bagasse. It was observed that the inoculation of these agricultural wastes with methanogenic bacteria sources such as cattle dung and poultry droppings had an important role and positive impact on biogas generation quantity. Rajendran *et al.* [18] gave an insightful overview into the various designs and operation of household biogas digesters, noting that moderate mixing is essential in biogas reactors as too much mixing stresses the microorganisms and too little mixing encourages foaming and even formation of scales.

Dahunsi and Oranusi [19]worked on co-digestion of food waste and human excreta for biogas production. They provided relevant data on the pH regime in the mesophillic temperature range for co-digestion of food waste and human excreta. The limitation of their research lies in the fact that temperature and pH were not continuously monitored but taken daily and weekly respectively. Ezeokoye and Okeke [20] worked on the design, construction, and performance evaluation of a Plastic Bio-digester and the Storage of Biogas. They Monitored parameters for biogas production from grains during batch digestion, but in their digesters, Practical digesters are mostly continuously fed, temperature monitored daily, pH monitored weekly. Dobre *et al.* [13] studied the overview of Main factors affecting biogas production. They highlighted lack of effective parameter monitoring to be a major cause of poor production and instability. Labatut and Gooch [21] monitored of anaerobic digestion process to optimize performance and prevent system failure. The work highlighted lack of process monitoring and operational management as a major cause of failure in most Biogas plants. They used analytical laboratories for onsite monitoring of large-scale plants which are too expensive for the domestic or small-scale application.

Despite the many benefits of biogas digesters, there are also a number of drawbacks that can make the implementation of this technology difficult. These difficulties include: Methanogens have many specific parameters, such as temperature and pH, this hinders widespread commercialization of anaerobic digesters [22]. The hydraulic retention time (HRT) poses a challenge, HRT which is the average time that the input slurry spends in the digester before it is removed, in tropical countries is 30 to 50 days, whereas in colder climates, it can be as long as 100 days, which requires a larger digester volume and raises costs [23]. While digesters can provide energy savings or even income to small-scale owners at farms—by way of selling electricity produced back to the power company—finding the right economies of scale possess yet another challenge. While biogas digesters do indeed offer a valuable way to reduce food waste and to capture energy that would otherwise be squandered, the actual potential of anaerobic digestion to produce a great deal of electricity is fairly limited. Even if the energy-producing capacity of biogas is small, given the waste-reducing benefits of anaerobic digestion, combined with its ability to slow climate change, pursuing policies to make digesters more common makes a great deal of sense. The main challenge is finding the right scale in order to make biogas digesters more economically feasible.

2. Materials and method

The biogas plant was designed as a continuously stirred reactor type (CSTR) due to its smaller footprint, ease of maintenance and improved gas production over the plug-flow mix type. A fixed-dome configuration was also selected over the floating-dome type due to its stability and relative ease of operation. A grinder was added to the digester vessel to reduce the particle size for improved biogas production. A stirrer system with an electric motor was also added to introduce substrate mixing that would boost biogas yield. The monitoring system was identified as a major improvement based on the limitations of other work and was implemented in the biogas plant.

The methodology employed for the design and construction is elucidated subsequently.

2.1. Materials

The following materials were used for the construction of a biogas plant:

i. Sparkless electric motor (1HP)
ii. Stainless steel type 316
iii. Stirrer

iv. Waste grinder
v. Hopper
vi. Valves and fittings
vii. Flashband sealing tape
viii. Arduino Uno Microcontroller
ix. pH Meter Kit
x. Pressure transducer sensor
xi. Temperature sensor

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	

2.1. Digestion tank

The digestion tank is the main reactor chamber where anaerobic digestion takes place. The material for fabrication is selected as stainless steel due to its ability to combine high strength, good formability and good resistance to biological corrosion [24] that can result from the metabolic activity of anaerobic microorganisms. Painting with a chromium oxide based paint will also improve the surface thermal absorptivity from solar insolation. The following design calculations were evaluated for the overall reactor tank design.

i. The volume of the reaction tank

According to Bachmann [25], to ensure that micro-organisms have a balance between the time needed to breakdown waste substrates and the concentration or quantity of substrates available (to avoid overloading the micro-organisms and hence inhibiting biogas production), two factors must be considered in sizing of biogas plants. These include the organic loading rate (OLR) and the hydraulic retention time (HRT).

The formula for calculating the volume of digester tank is given by equation 2.

$$V_d = \frac{I_w \times DM \times VDM}{OLR} \tag{2}$$

where: V_d is the reactor volume [m^3]; I_w is the substrate input [kg/day]; DM is the dry matter content of the waste or total solids content expressed in %; VDM is the volatile dry matter content of the waste [% DM]; OLR is the theoretical organic loading rate [kgVDM/ m^3day] OLR for a continuously stirred tank can be as high as 4 kgVDM/ m^3day [25]. Assuming maximum substrate input (I_w) is 1.4 kg/day of food waste from home kitchens (small-scale application). DM for food waste can be estimated at 20% and VDM as 85% [3,26]. Thus,

$$V_d = \frac{1.4 \times 0.2 \times 0.85}{4} \qquad V_d \approx 0.06\, m^3$$

ii. Tank dimensions

For minimal footprint and aesthetic consideration we take heuristics:

$h = 1.75d = 3.5r$ (3) but, $V_d = \pi r^2 h = .5\pi r^3$ (4)

Equating equations (3.2) and (3.3) $0.6 = 3.5\pi r^3$

Hence $r \approx 0.175\, m$ and $h \approx 0.61\, m$

According to Moss [27], the thickness of the tank is estimated from equation 5.

$$t = \frac{P.r}{SE - 0.6P} \qquad (5)$$

where: t is the minimum thickness of the cylindrical reactor wall (mm); P is the maximum internal pressure (N/mm^2); r is the internal radius of the reactor tank (mm); S is the maximum allowable working stress of the component (N/mm^2); and E is the joint efficiency.

Anaerobic digestion is favored by near-atmospheric pressure condition, and anaerobic bacteria thrive best below 1.2 bar (120 kPa). Consequently, beyond the accepted range above, the anaerobic digestion process stalls and eventually biogas production ceases. Thus, the maximum pressure the tank should withstand should be within a safety limit of 1.2 bar. Using a Factor of Safety of 3, a maximum design pressure P calculated as 3.6 bar (360 kPa) is utilized. The internal radius of the tank, r is 0.175 m assuming a joint efficiency of the weld, E is 0.8. The maximum tensile strength of stainless steel is obtained as 520 MPa [28].

The permissible working stress is calculated as:

$$S = \frac{Maximum\ Tensile\ Strength}{FOS} = \frac{520MPa}{5} = 104\ MPa$$

$$t = \frac{360 \times 10^3 \times 0.175}{(104 \times 10^6 \times 0.8) - 0.6(600 \times 10^3)} = 0.000765\ m\ or\ 0.765\ mm$$

Thus, the thickness of plate was thus selected as 1 mm to the nearest mm.

iii. Baffle design

The digestion reaction tank (reactor tank) is equipped with baffles to prevent swirling and to induce turbulence required for mixing in the tank. According to James [29], the following heuristics apply: 3 to 4 baffles are sufficient for a cylindrical tank, and the geometry is shown in Figure 2.

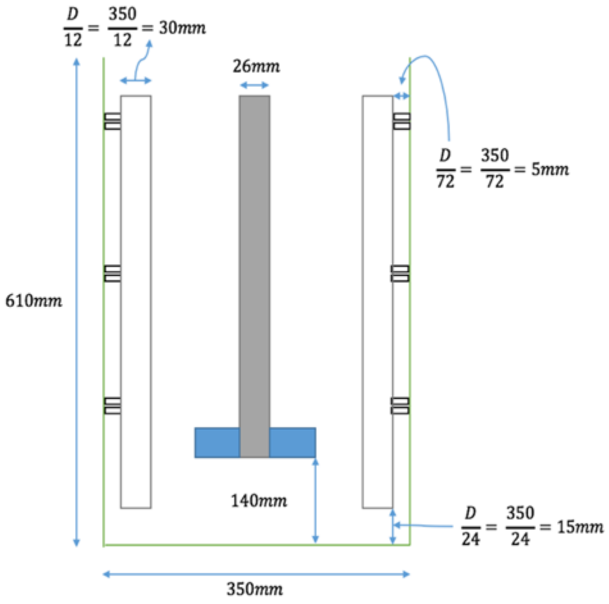

Figure 2. Baffle design for digester tank

The power requirement of the mixer was obtained using equation 6 according to Peters *et al.* [24].

$$P = \emptyset N_r^3 D_a^5 \rho \qquad (6)$$

where: P is the power required for mixing (kW); ∅ is the power function; N_r is the impeller rotation per unit time (rps); D_a is the impeller diameter (m); ρ_s is the density of slurry to be mixed (kg/m^3)

The power function can be estimated from charts using the Reynolds number and impeller characteristics. The Reynolds number for the flow is given by equation 7.

$$Re = \frac{D_a^2 N_r \rho_s}{\mu} \qquad (7)$$

The input waste is food waste of average density; $\rho_{fw} = 360$ kg/ m^3 [2] and water of density ρ_w= 1000kg/ m^3. With a mixture ratio 1:1, $c_{fw} = c_w$, the slurry density is given from equation 8.

$$\rho_s = \frac{\rho_w . \rho_{fw(c_{fw} + c_w)}}{\rho_{fw} c_{fw} + \rho_w c_w} \qquad (8)$$

$$\rho_s = \frac{1000 \times 360\ (2)}{360 + 1000} = 530\ \text{kg}/m^3$$

Slurry viscosity (μ) is approximately 650 cP or 0.65Ns/m^2 [29]. Assuming the impeller speed N_r *is* $600\,rpm\ (10\,rps)$ and the diameter of impeller (D_{athe}) obtained from impeller sizing heuristics according to Peters *et al.* [24] is given as equation 9.

$$D_a = \frac{Tank\ Diameter\ (D_T)}{2.5} \qquad (9)$$

$D_a = \frac{Tank\ Diameter\ (D_T)}{2.5} = \frac{350}{2.5} = 140\ mm$. Therefore, the Reynolds number is calculated from equation 7 as: $Re = \frac{0.14^2 \times 10 \times 530}{0.65} = 160$

Since Froude's number is not a factor (Re < 300), the relation between power function and the Reynolds number for a paddle mixer is shown in Figure A1 from Appendix A. Thus, the power function ∅ *is* 6 as obtained from the chart for Reynolds number Re of 54.

Assuming $N_r = 600\ rpm = \frac{600}{60}\ rps = 10\ rps$, $D_a = 0.14\ m$, and $\rho_s = 530\ kg/m^3$.

Using equation 6, the power required for mixing is calculated as:

$P = 6 \times 10^3 \times 0.14^5 \times 530 = 171\ W$

With loading of 80%, the motor power required will thus be:

$P_m = \frac{171}{0.8} = 250$ W (to the nearest standard). Using a safety factor of 2.5, $P_m = 250 \times 2.5 = 625$ W

Due to availability, a **1 HP** (750 W) motor is selected.

2.2. Stirrer

The stirrer consists of paddle-type impeller blades with a vertical shaft subjected to twisting moment only.

i. The diameter of impeller (D_a)

According to Peters *et al.* [24] (2003), the diameter of imthe peller is obtained from impeller sizing heuristics as 140 mm by recalling equation 9.

$$D_a = \frac{Tank\ Diameter\ (D_T)}{2.5} \qquad (Recall\ equation\ 9)$$

ii. Diameter of shaft

As the weight of the shaft is negligible and as the shaft is vertically oriented for mixing, it is subjected majorly to twisting moment. From Khurmi and Gupta [30], shafts may be designed on the basis of rigidity and strength. When subjected to twisting moment only, the following relation holds true:

$$\frac{T}{J} = \frac{\tau}{r} \qquad (10)$$

with little mathematical consideration it can be shown that:

$$d^3 = \frac{16T}{\pi\tau} \qquad (11)$$

where: T is the torque or twisting moment (Nm); τ is the allowable or permissible torsional shear stress (N/mm^2); J is the Polar moment of the shaft about its axis of rotation (mm^4); r is the radius of the shaft (mm); and d is the diameter of the shaft (mm).
The twisting moment T is calculated from equation 11 as

$$T = \frac{P}{2\pi N_r} \qquad (12)$$

$$T = \frac{750}{2\pi \times 10} = 11.94\ Nm$$

The allowable shear stress for stainless steel can be obtained as $\tau = 0.18\sigma_u$ (13)
where: σ_u is the ultimate tensile strength given as 520 MPa [28].

$$\tau = 0.18 \times 520 = 93.6\ MPa$$

Thus, the diameter of shaft the the for the mixer is calculated as:

$$d^3 = \frac{16 \times 11.94}{\pi \times 93.6 \times 10^6} \qquad d = \mathbf{10\ mm}\ (nearest\ standard\ size)$$

Using a safety factor of 2, $d = \mathbf{20\ mm}\ (nearest\ standard\ size)$

2.3. Water crusher

Since food waste is to be used as a substrate, provision is made for the easy crushing of food remains including cooked food and spoiled fruits. The waste crusher will also aid in the particle size reduction of various grains and nuts that will be fed to the biogas reactor. The crusher consists of a roller with a shaft for power transmission. The power required to actuate the crusher depends on the torque needed to rotate the roller cylinder when loaded to maximum. As the digester will be loaded daily in batches of 1.4 kg; the force F on the crusher is given by equation 14.

$$F = m.g \qquad (14)$$

$$F = 1.4 \times 9.81 = 13.74\ N$$

The torque T required is calculated from equation 15.

$$T = F.r \qquad (15)$$

$$T = 13.74 \times 0.1 = 1.374\ Nm$$

Assuming a moderate speed of 40 rpm, hence the minimum power requirement for the crusher can be obtained as:

$$P = \frac{2\pi NT}{60} \qquad (Recall\ equation\ 12)$$

$$P = \frac{2\pi \times 40 \times 1.374}{60} = 5.8\ W$$

Hence, hand grinding was evaluated as an ecoeconomicaltion and thus selected.

2.4. Valves

Two ball valves are utilized for fluid control in the system. One ¾″ valve serves as the drain or flush valve for emptying the contents of the tank after the design HRT is exceeded. A ¼″ gas outlet valve serves for the feeding of gas to the plant outlet.

2.5. Flashband sealing tape

This is a self-adhesive, aluminum faced bitumen backed sealing tape. It is a quick, efficient and cost effective method of flashing, sealing and repair that produces lasting protection in all climates. It provides a watertight seal that improves over time [31].

2.6. Arduino Uno microcontroller

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 [32]. 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.

2.7. Pressure transducer sensor

This measures the pressure of the gas with a carbon steel alloy sensor material. 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.

2.8. pH Meter Kit

This 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.

2.9. Temperature sensor

This takes temperature readings for the plant to aid process insights. It has a temperature range of -40°C - 80°C.

2.10. Construction 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 constructing 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. The 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.

2.10.1. Construction of cylindrical vessel

The following steps are taken to construct the cylindrical biogas digester vessel:

i. The 1 mm stainless steel metal sheet was cut to size (1100 X 610 mm) using the Guillotine machine.
ii. The 1100 X 610 mm stainless steel sheet was rolled to shape using the metal rolling machine.

iii. The metal sheet was welded to form the cylindrical shape of the body plate.
iv. A separate stainless steel sheet was cut and welded into a conical shape for the bottom of the tank.
v. The circular metal plate of diameter 350 mm was marked out and cut as the top plate of the cylindrical vessel.
vi. Three stainless steel plates of dimension 94.5 X 580 mm were cut. These were rolled and welded into cylindrical baffles for the tank.
vii. The three cylindrical baffles were welded to the internal surface of the tank. Baffles at 90°, 180° and 270° relative to the circular top plate.
viii. The conical bottom plate was then welded to the cylindrical body plate.
ix. The stainless steel shaft was turned to 20 mm external diameter.
x. Two 140mm paddle impellers were welded to the stainless steel shaft.
xi. The mild steel square pipe was cut into three sections of length 300 mm These sections were then welded onto the cylinder as the vessel legs.
xii. A 20 mm bore was machined in the circular top plate for the stainless steel shaft.
xiii. The circular top plate was welded onto the cylindrical vessel and installation of a bearing assembly for the machined shaft.

2.10.2. Construction of the grinding unit

The following steps are taken to construct the grinding unit:

i. The side plates of the hopper were marked out with dimensions 70 X 65 mm for the square component and 130 X 70 X 110 mm for the trapezium component.
ii. The marked out shape was cut to specifications.
iii. The face plates of the hopper were marked out and cut with dimensions 90 X 65 mm for the square component and 175 X 90 X 110 mm for the trapezium component.
iv. The side plates were drilled to create a 25 mm bore for the shaft and cylindrical grinder mesh.
v. The cylindrical grinder mesh was developed with recommended 1.5 mm mesh basic size and 3mm clearance.
vi. The cylindrical mesh, shaft, and handle were assembled.
vii. The four plates (two side plates and two face plates) were welded together to obtain the hopper unit.

2.10.3. The connection of the biogas plant monitoring system circuit

The biogas plant monitoring system was connected on a breadboard for prototyping using the circuit diagram shown in Figure 3. Figure 3 show the connection of the ATmega328 chip on the Arduino Uno with the pH, pressure and temperature sensor.

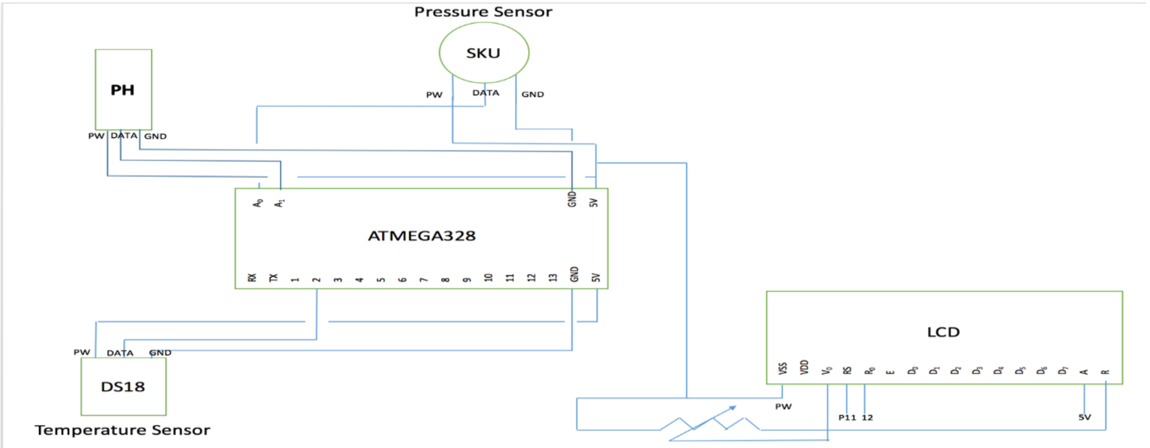

Figure 3. Monitoring system circuit with Arduino Uno microcontroller

2.11. 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.

2.12. Leak and integrity testing

After the electric motor, grinding unit and monitoring system are installed, the biogas plant is subjected to a leak and integrity test using the following steps:

i. Close all valves were closed and tighten all fitting joints.
ii. Introduce compressed air at a regulated pressure and inspect all fittings, valves, and joints for leakage.
iii. Mark out leaks if any.
iv. Tighten all joints and carry out final inspection on the entire plant.

2.13. Input Waste

The developed biogas plant was fed with 3.55 kg of food waste (comprising egg shells, cooked rice, pounded yam, etc.) and 11.45 kg of cassava waste water. The total input waste thus is about 15 kg.

2.14. Method

The waste material was gathered from the ABUAD Cafeteria 1 and the cassava waste water from a neighboring village close to the ABUAD community. The waste was prepared by removing foreign/non-organic materials and fed into the biogas plant and fed

The food waste material was fed by mixing with water in a ratio 1:1. The waste material is allowed to decompose for 7-14 days before biogas yield is evaluated. Immediately the waste was fed into the system, the biogas plant monitoring system was initiated to allow for data acquisition.

2.15. Determination of biogas yield

Biogas yield is determined using the water-displacement method. A known volume of water is used as a barrier and biogas is collected over it, and its volume is 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 were 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 includes; organic loading rate (0.6-0.9 kgVDM/m^3); reaction temperature (24.27 – 26.42℃); pH (6.81-7.28) and pressure (4.20-5.48 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 run of 30 experiments and the data obtained were 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 15 kg. 3.55 kg of food waste material composing of 54% egg shells and 46% leftovers were sourced from the ABUAD Cafeteria. The food waste comprises egg shells, cooked rice, pounded yam, etc. 11.45 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 4.

Figure 4. Developed small-scale biogas plant

The system pressure, pH of the 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)	Amount of electricity generated (kWh)	Methane yield (%)
1	14	15	2.5	1.95	1.28	4.17	51.2
2	28	15	2.6	2.01	1.32	4.30	50.7
3	42	16	2.8	2.18	1.43	4.67	51.0
4	56	18	3.2	2.60	1.70	5.57	53.3
5	80	16	2.7	2.14	1.40	4.58	52.0
6	94	18	3.0	2.45	1.60	5.24	54.0

The volume of methane generated and the amount of electricity produced from 14-84 days is shown in Figure 5. High pressure favours the conversion of the substrate to methane gas. An optimum amount of 5.24 kWh of electricity was generated within 84 days which is sufficient for domestic applications.

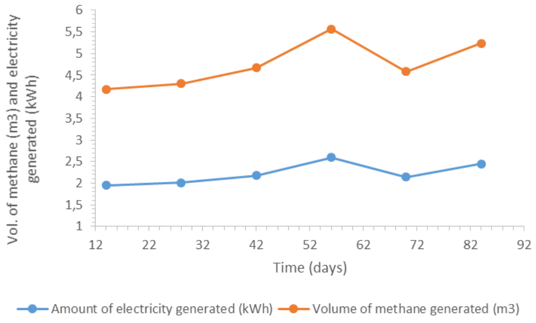

Figure 5. Volume of methane generated and amount of electricity produced

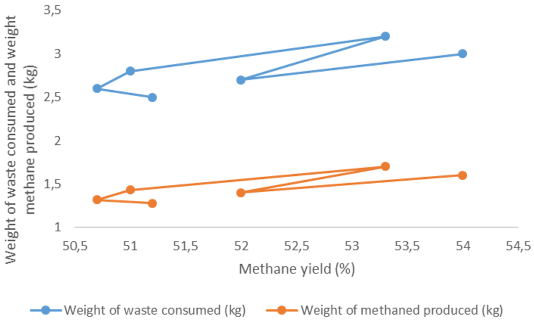

Figure 6. Methane yield for waste consumed and methane produced

Also, Figure 6 show 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 50-54%. This agrees with the findings of Banks [32] while evaluating the potential of anaerobic digestion to provide energy and soil amendment.

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	-alpha	+alpha
1.	A	Organic loading rate	kg/VDM/m^3	0.6	0.9	0.45	1.05
2.	B	Temperature	℃	24.27	26.42	23.195	27.495
3.	C	pH		6.81	7.28	6.575	7.515
4.	D	Pressure	kPa	4.20	5.48	3.56	6.12

The yield of the biogas from food waste was determined using equation 16.

$$Yield = \frac{Weight\ of\ biogas}{Weight\ of\ input\ waste} \times 100\% \qquad (16)$$

A predictive model for estimating the biogas yield in terms of the process parameters was obtained from Table 4 as given in equation 17.

$$Yield = 18.27 + 0.000 * A + 0.28 * B + 0.50 * C + 0.000 * D - 0.81 * A * B + 1.19 * A * C + 0.69 * A * D + 0.44 * B * C - 3.06 * B * D - 0.063 * C * D \qquad (17)$$

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

Figure 7 was a 3D response surface plot of the interaction effect loading rate and temperature when pH and pressure were held constant at 7.04 and 4.84 kPa respectively. The optimum yield of biogas was 23 litres. Increase in loading rate increases the temperature and increases the yield of the biogas.

7

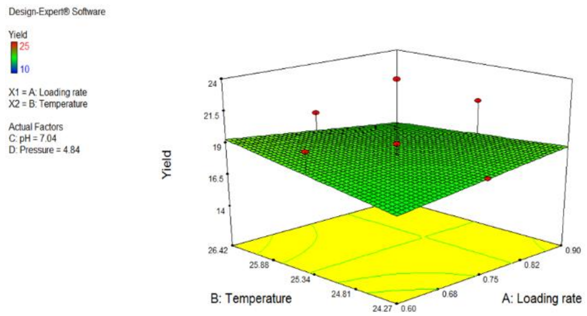

Figure 7. Effect of interaction of loading rate and temperature on biogas yield

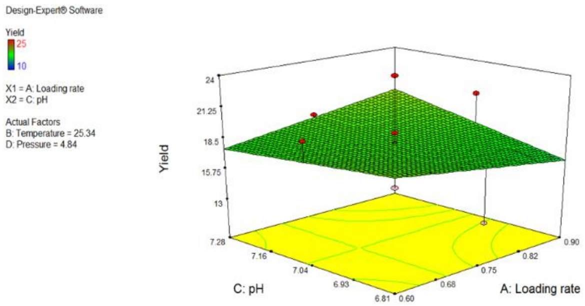

Figure 8. Effect of interaction of loading rate and pH on biogas yield

Figure 8 studies the interaction effect of loading rate and pH when temperature and pressure are held constant at 25.34°C and 4.84 kPa respectively. The optimum yield of biogas was 23 litres. 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 an increase in the loading rate and pH. This may be due to the fact that when the biogas is loaded beyond the optimum, the rate of decomposition decreases resulting in a decreased yield of the biogas.

Figure 9 is a 3D response surface plot of the interaction effect of the loading rate and pressure keeping temperature and pH constant at 25.34°C and 7.04 respectively. Increase in loading rate increases the pressure resulting in an optimum yield of biogas. Beyond the optimum yield of 23 litres, the yield of the biogas decreases with increase in loading rate and pressure.

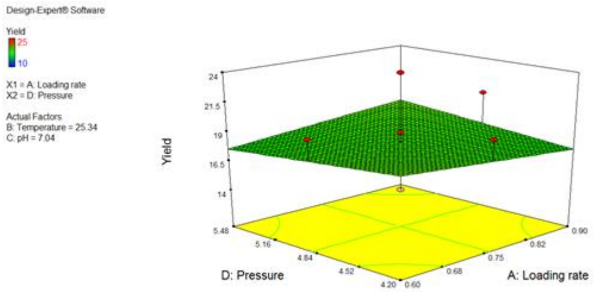

Figure 9. Effect of interaction of loading rate and pressure on biogas yield

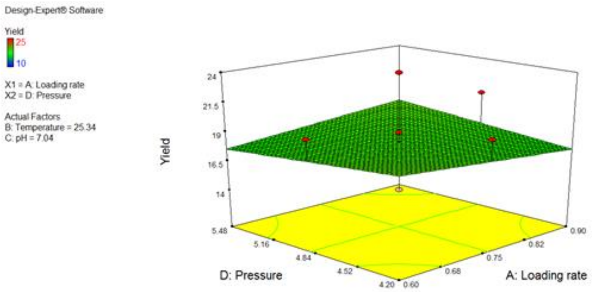

Figure 10. Effect of interaction of temperature and pH on biogas yield

Figure 10 was a 3D response surface plot of the interaction effect of temperature and pH when loading rate and pressure were held constant at 0.75 and 4.84 respectively. The value of pH is likely to be unaffected with an increase in temperature. Further increase in temperature beyond the optimum may kill the decomposition of anaerobic bacteria which will, in turn, slow down the rate of decomposition resulting in a decrease in the yield of the biogas.

Figure 11 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 0.75 and 7.04 respectively. The interaction between the temperature and pressure was observed to be inversely proportional as an increase in temperature reduces the pressure and vice versa. The optimum yield of biogas was found to be 23 litres.

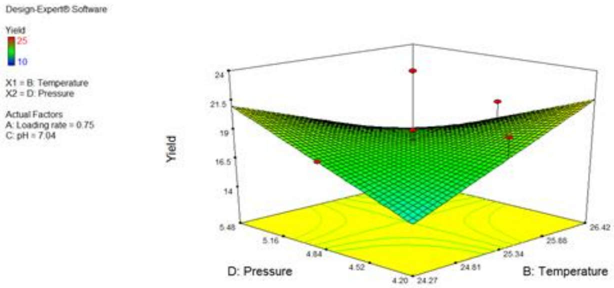

Figure 11. Effect of interaction of temperature and pressure on biogas yield

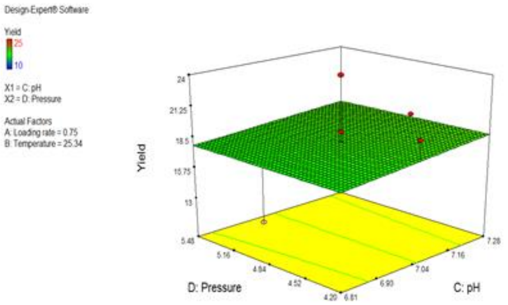

Figure 12. Effect of interaction of pH and pressure on biogas yield

Figure 12 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 optimum yield of biogas was found to be 23 litres.

From Figures 7-12, the optimum values of the process parameters for the optimum yield of biodiesel (23 litres) were found to be: loading rate (0.75 kgVDM/m^3), temperature (25.34°C), pH (7.04) and pressure (4.84 kPa).

4. Conclusion, recommendations, and contribution to knowledge

4.1. 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 54% which generated 5.24 kWh of electricity within 84 days.

4.2. Recommendations

The following recommendations will be pivotal to further work on the development of biogas plants with monitoring system:

i. A metering system should be added to measure the amount of biogas produced on the gas outlet line per day as water displacement method requires close human monitoring.
ii. A wireless module should be added to the system to make the system fully smart and communicate to as an 'Internet of Things' device.
iii. A non-conventional heating system e.g., passive solar heating using water and solar insolation should be considered to raise the temperature to the thermophilic range for faster biogas production.
iv. Implementation of a packaging system that will enhance the value of the produced fertilizer.

4.3. Contribution to knowledge

The work contributes to knowledge as follows:

i. Improvement in process control and monitoring with the use of sensors and a micro-controller.
ii. Incorporation of a low-cost monitoring system for the small-scale biogas plant.
iii. Provision of a design framework for small-scale biogas plant for laboratory and experimental purposes.

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