A Prototype of Anaerobic Biomass Digester for Biogas Production

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ABSTRACT

In this work, an anaerobic digester with semi-automated control was built for the purpose of understanding the production of biogas. Classical thermodynamics concepts were applied to the study of microbial behaviour in anaerobic digestion of an organic fraction of waste (OFW) for biogas (CH_4) generation. A 1000-litre plastic tank was used to design and assemble a prototype single-stage batch anaerobic digestion system which was operated and controlled by a computer via instrumentation subsystems. The factors considered in the design and operation include the type of organic material used as feedstock, temperature of operation of the digester, ease of construction and digester portability. The assembled digester was operated as a bench system for a cycle of 24 days under mesophilic temperature conditions. The maximum and minimum temperatures recorded during the operation of the digester were 38.5 °C and 32.4 °C respectively. The average operating temperature was 36.1 ± 1.5 °C. A slurry of fresh cow dung with calorific value of 26.45 MJ kg^{-1} was used as substrate for the study. A motorized stirrer and a thermostatically operated heat exchanger system were used to ensure that there were no temperature and concentration gradients during the operation of the digester. The final composition of the biogas produced was 60.2 % CH_4 and 39.7 % CO_2, with the highest daily gas production of 0.474 m^3, which was recorded on the 18th day. . The performance of the digester is deemed satisfactory and confirms that this pilot-scale prototype is a valid proof of concept and can therefore be used as the basis for the design and assembly of production-scale digester systems.

Keywords: Anaerobic digestion, mesophilic, biogas, thermodynamics

Introduction

Energy for Development

Energy is a system's capacity to do work and may exist as either kinetic (motion) or potential (stored) energy. Living organisms (organic matter) expend energy through interaction (mechanical), heat transfer, sound, chemical compound or electrical form. Organic matter contains energy, which can be converted into biogas through microbial action in anaerobic digestion technology. The main components of biogas are CH_4 (50-70%), CO_2 (30-40%), H_2 (5-10%) with traces of NO_2, and H_2S. CH_4, which is the combustible component of biogas, has an ignition temperature of 650 ^{0}C and burns with a clear blue flame without smoke. Methane is a source of clean renewable energy which can be integrated into the energy mix to replace the use of fossil fuel, as well as control atmospheric pollution (Abbasi *et al.,* 2012).

Clean source of energy is of great concern to both industrialized and developing countries for economic development (Zhai *et al.*, 2014). Current technological advancement largely depends on fossil fuel as energy source. It is feared that fossil fuel sources will be depleted in the near future because they are not renewable, yet largely depended on. In addition, in electricity generation, technological applications and

manufacturing processes, incomplete combustion results in the release of obnoxious gases into the atmosphere (You & Xu, 2010; Gupta & Ivanova, 2009; Zazzeri *et al.,* 2015), which have a negative impact on climate. Through microbial anaerobic digestion technology, CH_4 can be trapped and stored so that it can be used later. The capture of CH_4 mitigates climate change and can be used for cooking, heating, lighting, electricity generation and fuel for vehicles (Arshad *et al.,* 2018). The application of thermodynamics enables the study of the production of clean energy through microbial anaerobic digestion.

Biochemical Pathway of Methane Formation

Microbial anaerobic digestion is a stabilization process that reduces odour, pathogens, and mass. It involves a series of metabolic actions of biopolymer through a biochemical process that occurs in an oxygen free (closed) engineered system. A slurry is formed from substrate (biopolymer) by adding a proportionate amount of water (it could be wastewater) and inoculating with specific microbes. The microbes adapt to the environment where they produce specific enzymes to enable them to feed on the biopolymer substrate. The biochemical process begins with hydrolysis, which occurs by the addition of a proportionate amount of water to the substrate (1:1 molar ratio), where hydrolase enzymes such as protease, amylase and lipase use water to break down the complex biopolymer into simple forms. The biopolymer, which is mostly composed of protein, carbohydrates and lipids, breaks down into simpler forms (amino acids, monosaccharides and fatty acids respectively) (Vavilin *et al.,* 2008). Acidogenesis follows the first stage, where volatile fatty acids (acetic acid, butyric acid and propionic acid) are commonly formed from the products of the hydrolytic process. The volatile fatty acids are then converted, through acetogenesis, to acetic acid, carbon dioxide and hydrogen. The last step of the anaerobic digestion process is strictly anaerobic and referred to as methanogenesis. These anaerobic reaction steps are shown in equations 1 – 3.

Hydrolysis:

$$n(C_6H_{10}O_5) + nH_2O \rightarrow n(C_6H_{12}O_6) \quad (1)$$

Acidogenesis:

$$n(C_6H_{12}O_6) \rightarrow 3n(CH_3COOH) \quad (2)$$

Methanogenesis:

$$3n(CH_3COOH) \rightarrow 3(nCH_4 + nCO_2) \quad (3)$$

Typically, the methane forming step is dominated by microorganisms known as methanogens. Some of these microorganisms are methanobacterium, methanococcus, methanosarcina and methanosaeta. They use hydrogen, acetate, and CO_2 as substrate to produce mostly CH_4 and CO_2 through three main pathways towards methane production referred to as: (i) acetoclastic methanogenesis, (ii) hydrogenotrophic methanogenesis and (iii) homoacetogenesis. Most of the CH_4 (above 60 %) is formed by acetoclastic methanogens (methanosarcina and methoanosaeta), where methanosarcina utilize acetate, hydrogen, formate, methylamines and methanol to form CH_4, and methanosaeta uses only acetate to form CH_4 (Conrad, 1999; Ferry, 2011). Hydrogenotrophic methanogenesis converts H_2 and CO_2 to produce CH_4 and H_2O, while homoacetogenesis converts the same reactants (H_2 and CO_2) to produce CH_3COOH and H_2O. Due to the comparatively high Gibb's free energy of the hydrogenotrophic pathway (-135 KJ mol^{-1}), its forward reaction is thermodynamically more favourable than the homoacetogenic pathway (-104 KJ mol^{-1}). The hydrogenotrophic pathway therefore has a potential to keep the H_2 pressure low in the digester through its consumption.

Table 1 shows the main methanogenic reaction pathways indicating some of the microorganisms used as well as their corresponding standard Gibb's free energies.

Table 1: Reactions related to methanogenesis

Pathway	Reaction	ΔG° at 25 °C (KJ mol^{-1})	Microorganism
Hydrogenotrophic methanogenesis	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$	-135.0	Methanobacterium, Methanobrevibacter
Acetoclastic methanogenesis	$CH_3COOH \rightarrow CH_4 + CO_2$	-31.0	Methanosaeta, Methanosacina
Homoacetogenesis	$4H_2+CO_2 \rightarrow CH_3COOH + 2H_2O$	-104.0	Clostridium acetium

The maximum biogas yield can be estimated through the degradation efficiency of the biomass. An approximate equation enables the theoretical estimation of the maximum yield of CH_4 when the elementary composition of biomass is known. Equation 4 illustrates the modified form of Buswell's (1930) equation, which is a stoichiometric equation of biogas production from biopolymer.

$$C_nH_hO_oN_nS_s + yH_2O \rightarrow xCH_4 + nNH_3 + sH_2S + (c - x)CO_2 \quad (4)$$

Where

$$x = \frac{1}{8}(4c + h - 20 - 3n - 2s), and\ y = \frac{1}{4}(4c - h - 20 + 3n + 3s)$$

Aspects of Thermodynamics and Energetics

Classical thermodynamics, governed by three fundamental laws, deals with macroscopic processes occurring in systems activities in equilibrium. The first law is about energy conservation and is mathematically written as:

$$dU = dQ + dW \quad (5)$$

where dU is the internal energy of the system, dQ the heat energy and dW the work done either on or by the system. The second law (entropy) expresses the continuous increase in disorder in the universe. Entropy determines the spontaneity of a reaction, and the change in entropy (dS) in a reaction describes the direction of a reaction. A combination of the first and second laws of thermodynamics results in:

$$dU = TdS - pdV \quad (6)$$

where T is the temperature of reaction, pdV work done either by or on the system, and p the pressure of the system with volume change dV. An increase in temperature of a biochemical reaction (system) increases its rate because the additional heat increases the entropy (random molecular movement).

Two other useful quantities of thermodynamics are (i) the enthalpy (H) and (i) the Gibb's free energy. Enthalpy is a thermodynamic potential, which is the heat content (absorbed or emitted) during a biochemical reaction under an isobaric condition.

$$H = U + pV \quad (7)$$

where p is the pressure developed within the system and V is the volume of the system. At constant pressure, the enthalpy change (ΔH) equals the energy transferred within the system. When the measured change in enthalpy is positive (heat absorbed), the reaction is termed endothermic, and when it is negative (heat-released), exothermic reaction would have occurred. The second quantity (Gibbs free energy (G)) determines how fast a reaction, in this case, a metabolic process would occur. The Gibbs equation (8) incorporates the concepts of temperature, the Zeroth, the First and Second laws of thermodynamics, resulting in specifying the maximum useful work that is obtainable from a thermodynamic system.

$$dG = dH - TdS \quad (8)$$

A reaction will not occur spontaneously when the value for the Gibbs free energy is positive, but *dG,* when negative, shows that the process will occur spontaneously (Beard & Qian, 2008).

For a reversible biochemical reaction, we may write an abstract symbolic reaction equation (9), where n_a, n_b, n_c and n_d refer to the number of moles of the compounds A, B, C and D, respectively. This represents the stoichiometric equation of a biochemical reaction occurring at standard temperature of 298.15 K.

$$n_a A + n_b B \Leftrightarrow n_c C + n_d D \qquad (9)$$

The change in free energy is expressed as:

$$\Delta Gr = \Delta Gr^o + RT \log \frac{[C]^{n_c}[D]^{n_d}}{[A]^{n_a}[B]^{n_b}} \qquad (10)$$

where [C] and [D] are the molar concentrations of the reaction products, and [A] and [B] are the reactant concentrations. *R* is the gas constant = $8.31451 \cdot 10^{-3}$ $kJ \cdot mol^{-1} \cdot K^{-1}$, *T* is the thermodynamic temperature in Kelvin, and Gr^o is the change in Gibbs free energy of a reaction at standard conditions, which is calculated from the free energies of formation. Thus,

$$\Delta Gr = (G_C + G_D) - (G_A + G_B) \qquad (11a)$$

and

$$\Delta Gr^o = ({G_C}^o + {G_D}^o) - ({G_A}^o + {G_B}^o) \qquad (11b)$$

At equilibrium, $\Delta Gr = 0$, so equation (10) reduces to equation (12). This provides the link to the equilibrium constant K_{eq}.

$$\Delta Gr^o = -RT \log \frac{[C]^{n_c}[D]^{n_d}}{[A]^{n_a}[B]^{n_b}} \qquad (12)$$

$$\Delta Gr^o = -RT \log K_{eq} \quad or \; K_{eq} = e^{-\Delta Gr^o/RT} \qquad (13)$$

where

$$K_{eq} = \left[\frac{[C]^{n_c}[D]^{n_d}}{[A]^{n_a}[B]^{n_b}}\right]_{eq} \qquad (14)$$

Equations (10) to (14) show that the biochemical reactions are very sensitive to small changes in parameters, especially temperature (Alberty, 2006; Mosier & Ladisch, 2009; Rawlings & Ekerdt, 2002). These reactions are complex and are not easy to understand or control. To be able to control (stabilize) or follow a particular process pathway, electronic sensors were employed to collect data from an anaerobic digestion chamber. The data were analysed to offer quick information and realistic description of events, and hence give signals to apply a corrective response to the system within a short time interval. Electronic sensors and electrically actuated sub-systems have been constructed and configured in the control system to guide the biochemical reactions.

In order to ensure uniform mixing of the slurry in the digester, there was the need for an agitator or stirrer. The agitator selection depends on the viscosity range of the slurry, which in this case is below 3 Pa.s. The presence or absence of turbulence is correlated with the Reynolds number N_{Re} for the impeller.

$$N_{Re} = \frac{D_a^2 N \rho}{\mu} \qquad (15)$$

where D_a is the impeller agitator diameter, *N* is the number of rotational speed, ρ is the density of slurry, and μ is the slurry viscosity. When N_{Re} is less than 10 it implies laminar flow and when greater than 10^4 it means flow is turbulent (Froment *et al.,* 2011).

The digester is not completely insulated from its surroundings. It is bound to lose thermal energy. Following Fourier's law of heat conduction, the heat flow in the digester is given by:

$$Q = -kA\frac{dT}{dR} = \frac{-2\pi r_1 k(\dot{T}_2 - T_1)}{ln\left(\frac{r_2}{r_1}\right) r_1} = \frac{2\pi k(T_1 - T_2)}{\ln(\frac{r_2}{r_1})} \qquad (16)$$

where T_1, T_2 = temperature inside and outside respectively, r_1, r_2, = inside and outside radius respectively, k = thermal conductivity, Q = quantity of heat flow.

Studies show that Han-Qing (2014) performed a thermodynamic analysis on the acidogenesis of lactose where he used the calculation of Gibbs free energy to evaluate the different acidogenic patterns and mechanisms. He analysed acidogenic lactose culture by varied substrate levels in a 2.8 L up-flow batch reactor at 37 ^{0}C at pH 5.5, with a hydraulic retention time of 12 h. Thermodynamic analysis indicated a higher probability of butyrate forming with a minimum amount of Gibbs free energy of 4.5 – 5.7 KJmol^{-1}. Propanol was formed with a minimum of Gibbs free energy of 41.8 – 42.0 KJmol^{-1} (Yu *et al.,* 2004). Liu (2006) developed a general model for microbial growth by applying the thermodynamic laws. His model was evaluated with a least square method and data from literature was used to verify it. He concluded that there was an excellent agreement between the experimental data and his model equation, with a correlation coefficient of 0.999.

Sung (2014) studied the loss of thermodynamic spontaneity in a methanogenic consortium with ammonia contents. Clearly, this research dealt with the determination of the Gibbs free energy to ascertain the feasibility of a biochemical process. Sung's study applied a modelling approach to investigate thermodynamic limitations, by simulation of feedstock, in an isothermal and isobaric (298.15 K and 1 atm) batch digester. He used Gibbs free energy, enthalpy and entropy for his analysis. His result showed no evidence of thermodynamic limitation arising because of high concentrations of ammonium ion. By applying entropy analysis, he noticed a sudden loss of spontaneity when the initial concentration ratio of ammonia to the other solutes exceeded a threshold value. The loss of spontaneity was attributable to the depletion of carbonates occurring in anaerobic ammonium oxidation, with the limiting factor being the reduced activity of hydrogenophilic methanogens.

Methanobacterium, Methanococcus, Methanosarcina Methanobrevibacter and Methanospirillum are common examples of methanogens that produce CH_4 (Flickinger, 1999). Methanogenic reactions dissipate heat, which is used to regulate the microorganism's temperature. Excessive heat lost to the environment reduces the metabolic activity of the microbes, which impedes the forward spontaneous reaction that leads to production of CH_4. A 1000-litre tank at mesophilic (36.1 ± 1.5 °C) condition was used as a prototype single-stage batch reactor to produce CH_4. Anaerobic digestion, in addition to providing clean energy, is a technology for waste management to produce a clean and healthy environment (Singha, 2011).

Materials And Methods

Design Methodology

A 1,000-litre black horizontal cylindrical water storage tank, with equal torispherical heads, was used as the vessel of the prototype anaerobic digester. Two-inch PVC pipes were connected to it. One served as the inlet for influent substrate, and the other, installed directly on the other side of the digester, served as the outlet for the effluent. A gas pipe was fitted on top of the digester and connected to a biogas storage tank. A bevel gear coupled DC electric motor was fitted to drive a stirrer, which creates a homogeneous sludge. The digester was installed and operated in the Biomass Conversion Research Laboratory in the Physics Department of the University of Ghana. Figures 1 - 3 show the experimental set-up, the copper tubing heat exchanger and the motorized stirrer.

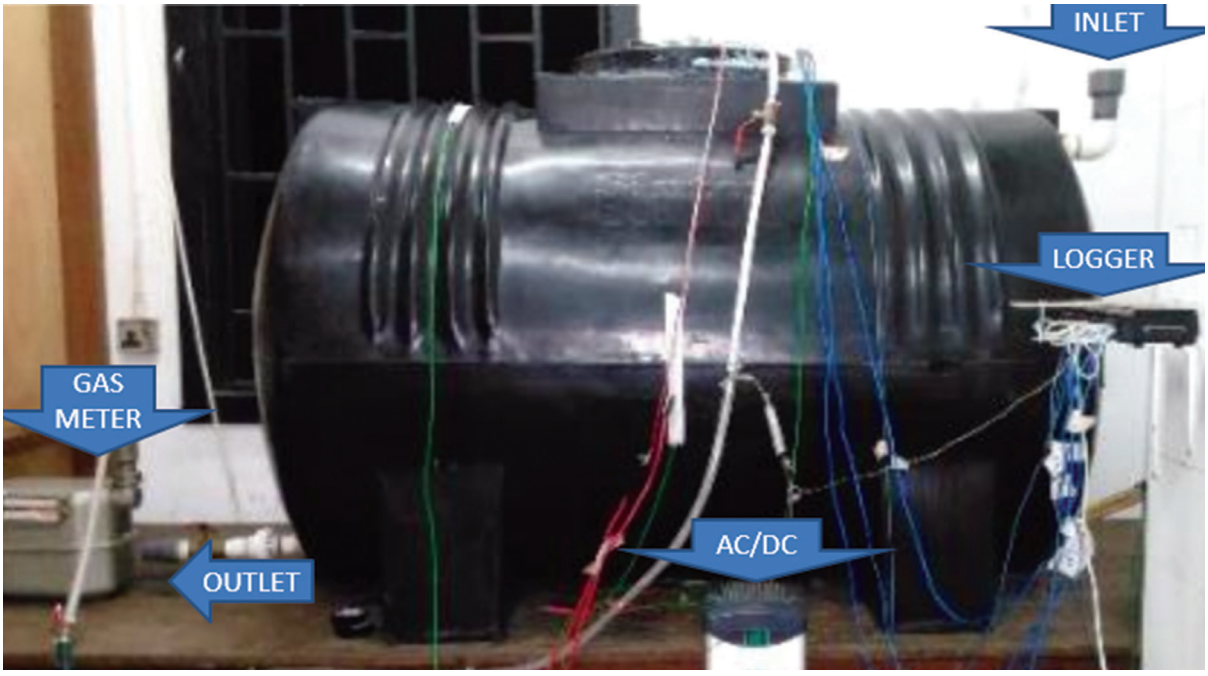
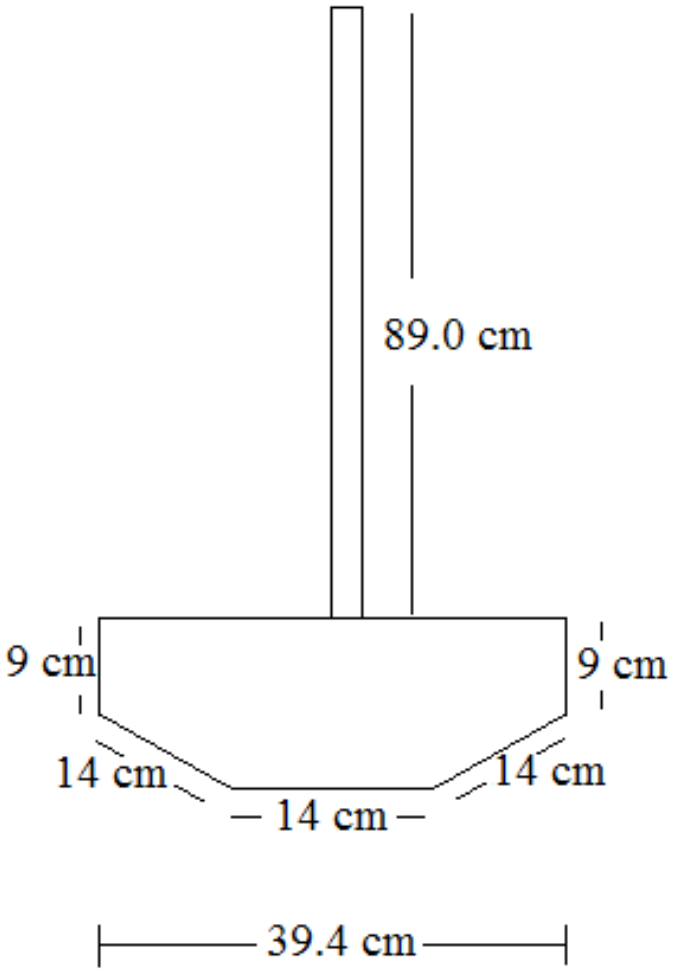


Fig. 1: Experimental set-up

Fig. 2: Copper tubing heat exchanger



(a) (b)

Fig. 3: Motorized stirrer with schematic diagram

Experimental Approach

Fresh cow dung was collected from the farms of the Council for Scientific and Industrial Research-Animal Research Institute (CSIR-ARI), Ghana. Aspects of the dung's physical characteristics determined are listed in Table 2. The amount of dry mass (22.9 %) of the dung indicated that to operate a wet digestion water had to be added to the dung until the fraction of total solids reduced to less than 15 %. The calorific value of the dung was determined to be 26.45 MJ kg^{-1} (equivalent to 7.35 kWh). The pH of the slurry 7.24 ± 0.01 falls within the range where methanogens are active. Hence, the slurry preparation was done without introducing any buffer solution. Fadalla & Omer (2003) stated that one cow with daily production of waste (dung) of 10 kg produces biogas at 0.25 m^3d^{-1} - 0.40 m^3d^{-1}.

Table 2: Physical characteristics of the cow dung

Parameter	Fresh cow dung
Colour	Greenish
Dry mass	22.9 ± 0.4 %
pH	7.24 ± 0.01
Moisture content	77.1 ± 0.4 %
Gross energy value	26.5 ± 0.7 MJ kg^{-1}
Sulphur	0.096 ± 0.003 %

Physical Pre-treatment of Cow Dung

The pre-treatment of the feedstock was carried out to intercept large objects that could (i) impede the smooth operation of the stirrer, (ii) hamper the rate of digestion and also to prevent clogging. Visual inspection, screening, particle size reduction of lumps and removal of debris were carried out as the pre-treatment of the cow dung. Visual inspection was done by stirring the feedstock while it was in its original container. This was not thoroughly done since coarse screening was to follow shortly. Coarse screening, which was done after preparing the slurry, was carried out with a plastic basket (screen opening 4 cm^2) during the transfer of the slurry into the digester. Debris (twigs, plastics, etc.) seen was isolated, whereas lumps intercepted were pulverised into reduced size.

Cow Dung Slurry Preparation and Charging of Digester

To perform a wet digestion, the total solid content of slurry should be less than 15 % (Abbassi-Guendouz *et al.,* 2012). For the slurry (influent) prepared out of the cow dung, solid content was achieved by adding water with composition 0.35 m^3 of dung: 0.49 m^3 of water (ratio of 1:1.4) at 8.7 % total solids with moisture content of 91.3 ± 0.1 %. This resulted in a slurry volume of 0.75 m^3, creating a headspace of 0.25 m^3 (which represents 75 % slurry volume with 25 % headspace). It was noticed that the coarse porous medium of the dung absorbed water as air bubbles were expelled during the mixing of dung and water. No chemical pre-treatment was applied because the pH 7.24 ± 0.01 was within the medium in which methanogens are active. Since the dung contains the microorganisms needed for the operation of the digester, there was no need to inoculate it. The gravity feeding method was applied in transferring the slurry into the digester. Since bulk feeding was done, the largest opening of the digester (opening for cover) was used for the influent transfer. After charging the digester, the relevant openings were closed and gas leakage tests done. This test was repeated until the digester had been properly sealed. This day was reckoned as day one of the operation of the digester.

Activation of Accessories and Daily Operation of the Digester

To operationalize the digester, its accessories were activated. The datalogger, which had been configured to monitor the temperature of the operation of the digester, was triggered to acquire a 24-hour cycle data of the temperature of (i) the slurry, (ii) the digester headspace, (iii) the exiting gas, (iv) the inner and outer surfaces of the digester, (v) the laboratory environment and (vi) the hot water circulated. The stirrer was operated with an electric DC motor powered with a variable AC/DC power converter. The stirrer was powered with a suitable speed of 26 rpm at 10 V DC. The circulating bath temperature controlled heater (0.010 m^3 capacity), which was used to heat distilled water for circulation in the digester, was set at 60.0 °C to facilitate the initial heating of the slurry. Once the slurry temperature reached 38.0 °C the thermostat of the water heater was reduced to 38.0 °C, which is 1.0 °C above expected operating temperature. The 1.0 °C was to provide a minimum heat flow into the digester when stirring had ceased.

Periodic attention to the digester system with its accessories was an important component of its operation. Since the digester was not fully automated, it required daily physical presence of the operator to inspect all the various components. The necessary adjustments were then made for the continuous operation of the system. The key daily steps that were taken for the smooth operation of the digester included (i) visual inspection of the digester, (ii) temperature control and (iii) stirrer regulation.

Visual inspection of the digester and the various subcomponents was conducted daily. Adequate responses were provided to reset the digester to optimal operation. Whenever the temperature of the slurry dropped below 37.0 °C, the circulating bath temperature controlled heating source was raised to 45.0 °C and the stirrer was activated. When the temperature reached 38.0 °C, the temperature setting was reset to 38.0 °C. Stirring was done to coincide with the periods of heating. The duration of operation was 3 hours continuously, which was not exceeded. This was to prevent the stirrer motor from overheating.

Results and Discussion

A 1000-L plastic water tank with PVC connecting pipes and accessories has been assembled into a single stage anaerobic digester. The function of this digester is to use the organic fraction of waste to generate CH_4 gas for energy use. The results of the full operation of the digester as a batch system with a hydraulic retention time of 24 days are discussed, detailing the temperature performance and the quantity and quality of biogas yield. This was sufficient to analyse the behaviour of the digester and the quality of the biogas generated. The information obtained from this operation represents the fundamental phase of this study that can be used to evaluate the feasibility of this new intervention.

Temperature Profile

The daily temperature profiles of various sections of the digester and the ambient temperature profile of the laboratory are shown in Figure 4. The temperature profiles of the various sections include those of (i) the slurry, (ii) the digester headspace, (iii) gas exiting the digester and (iv) the ambient temperature. It was generally observed that the slurry temperature was higher than that of the gaseous headspace, which in turn had a higher temperature than the ambient temperature. The exit gas temperature had a profile almost the same as that of the headspace gas. In the section that follows, emphasis has been laid on the slurry temperature.

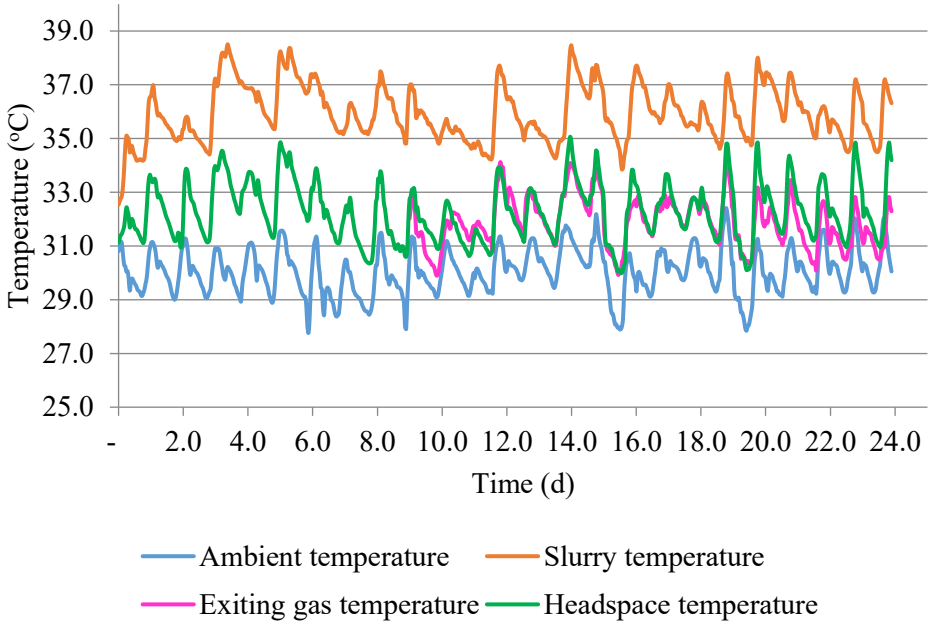


Fig. 4. Temperature profiles of various sections of the digester and of the ambient temperature

Temperature Profile of the Slurry

The temperature profile of the slurry represents the daily rise and fall of the temperatures during the heating and the non-heating periods of the slurry. Heating was done with an external electrical heating source that circulated hot water through copper tubing into the inner bottom of the digester. The general pattern of the temperature profile indicated steep positive slopes during the heating periods. This can be attributed to the fast rate of heat being absorbed by the slurry. Relatively, gentle negative slopes were seen during the non-heating periods. This slow rate of temperature drop can be associated with the slow rate of heat loss from the slurry into the environment. The high heat capacity of water also contributes to containing the heat for a long period. On the first day, heating began with the slurry at 32.5 °C and continued until an increase of 4.0 °C was attained. The maximum temperature of the slurry recorded during the study was 38.5 °C. It occurred on the 4th and the 15th days. The minimum value recorded was 32.5 °C, which occurred on the 1st day of operation of the digester. This was expected, since there was no preheating of the slurry before introducing it into the digester. The averages of the daily maximum and minimum temperatures were 37.4 ± 0.7 °C and 34.9 ± 0.9 °C respectively. The average temperature of the digester was 36.1 ± 1.5 °C.

Temperatures of Digester Headspace and Exiting Gas

The temperature profile, as shown in Figure 4 of the exiting gas, was almost the same as that of the headspace. This is expected and it indicates that there was an avenue for heat loss. In such a situation, copper tubing, which is a good conductor of heat, will not be advisable for use as gas pipe. It will increase the rate of heat loss by the digester to the surroundings. If the use of good conducting material cannot be avoided, two basic things have to be done. One approach to reducing heat loss through the gas pipe is to insulate the pipe. The other approach will be to use a gas pipeline with a small cross-sectional area. This reduces the total boundary surface of the pipe and its surroundings, hence the rate of heat loss to the surroundings will be minimized.

The slurry temperature and that of the tank showed a direct correlation with a coefficient factor of 0.85 (Fig. 5). There was no significant correlation between ambient temperature and tank temperature. This is because of the external heating that compensates for any heat lost. In the tropics, alternative sources of heating such as solar thermal energy can provide cheap heating. As long as such heat can compensate for heat losses by the digester, providing insulation is not necessary and therefore further complications in digester design can be eliminated, hence reducing cost, as required skills remain low.

pH Profile

The pH of the slurry varied slightly throughout the operation (Fig. 6). This is because of the metabolic activities that go on at different stages of the biochemical processes of anaerobic digestion. At the beginning of the operation, the pH was 7.21, but it dropped to 7.1 after one week. This drop is attributed to the accumulation of volatile fatty acids (VFA) because of the breakdown of complex organic substances into simple forms. This is explained by the on-set of the hydrolysis and acidification processes. Accumulation of VFA occurs because the methanogens, which convert VFA into $CH_{4,}$ had not been sufficiently formed. At the end of the batch operation, the pH had risen to 7.24. The slight increase toward the end of the operation occurred because of the consumption of hydrogen during the formation of methane.

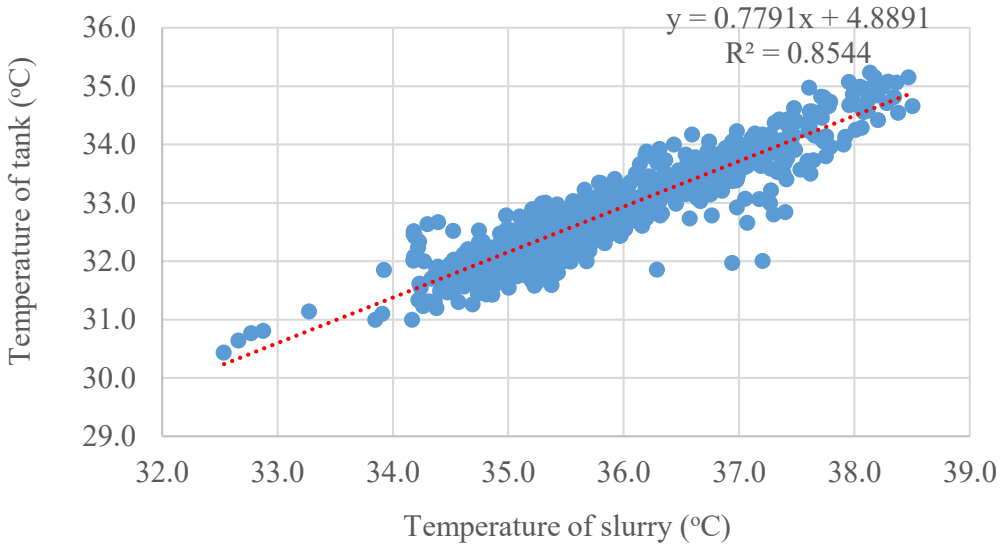


Fig. 5: Correlation between temperature of the slurry and the plastic tank

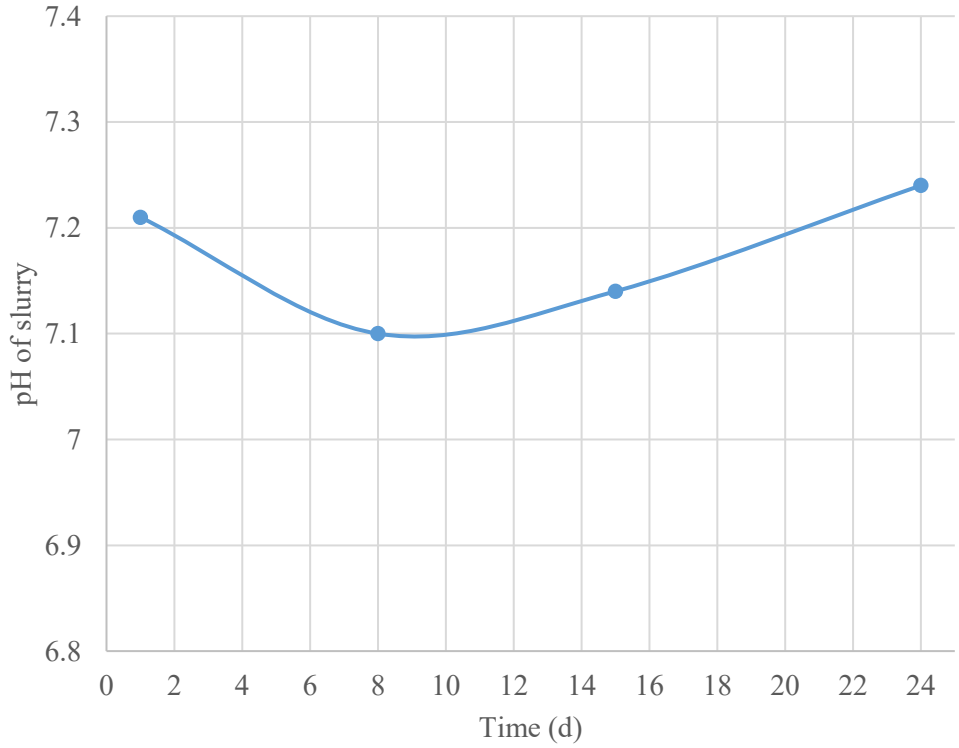


Fig. 6: Variation of pH of the slurry during the operation of the digester

Biogas Production and Composition

The ultimate aim in assembling the digester was the production of biogas. This section reports the volumes of gas generated by the digester and the various tests performed in order to ensure its suitability for use as fuel. The rate constant and the order of reaction were determined using the cumulative biogas yield data to fit the first kinetic order equation.

The profiles of the daily biogas production are illustrated in Figure 7. The measurement of biogas production began on the 4th day of operation of the digester. Presumably, the first three days were used by the microorganisms present in the slurry to adjust to their new environment as well as secrete enzymes necessary for the anaerobic processes. The first measurable volume of the biogas was 0.013 ± 0.001 m^3. This was obtained on the 4th day of operation of the digester. Daily biogas production was low during the first 12 days; it fluctuated between 0.008 ± 0.001 m^3 and 0.044 ± 0.001 m^3. The daily average biogas yield for the first 12 days was 0.032 ± 0.019 m^3. This initial low biogas yield could be due to (i) the high accumulation of VFA and (ii) the low presence of methanogens. The first step of the anaerobic processes, which involves the breakdown of the complex substrates, results in acid formation, thereby lowering the pH of the slurry. The low pH impedes the formation of CH_4. Low pH also slows the population of the methanogens, so that CH_4 formation is slow. On day 16, there was a significant increase of biogas yield to 0.141 ± 0.001 m^3. At this time, the increasing methanogens had begun converting the accumulated VFA into biogas at a faster rate. The depletion of the VFA agrees with the rise in the pH of the slurry and an increase in the function of the methanogens. The highest daily gas yield of 0.474 ± 0.001 m^3 was recorded on the 18th day. The daily average biogas volume measured for the last 9 days of the cycle was 0.31 ± 0.11 m^3. The cumulative gas yield for the entire period (24 d) was 3.17 ± 0.03 m^3.

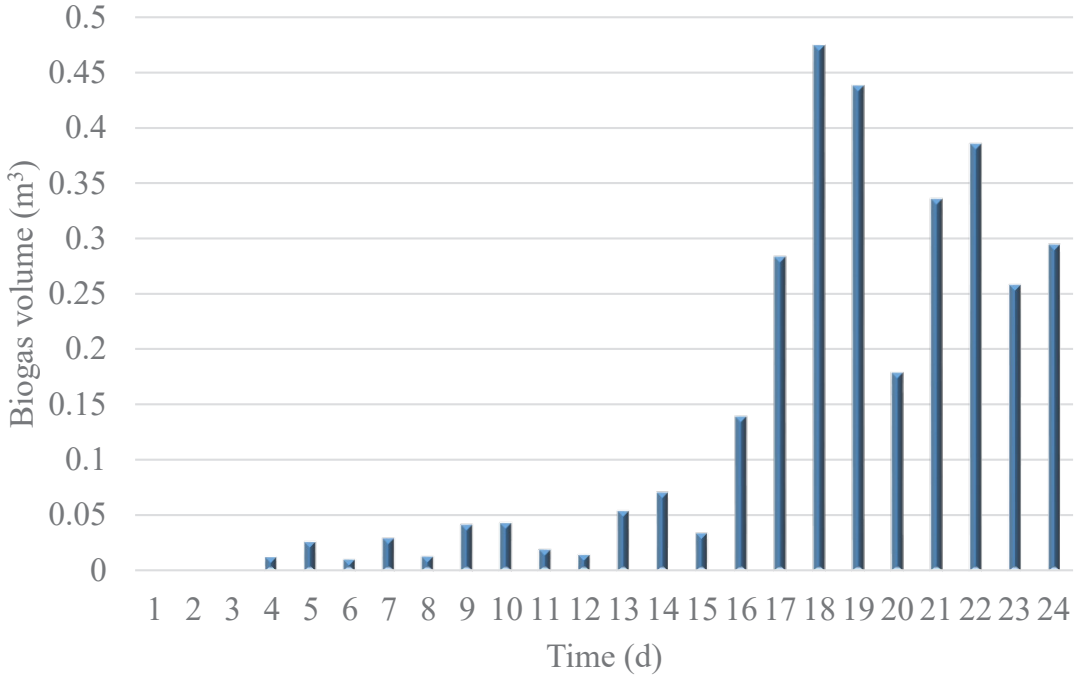


Fig. 7: Daily biogas production, first gas measurement was taken on the 4th day

Generally, the volume of production of biogas with its associated fluctuation in the daily yield can be associated with (i) temperature (ii) enzymic activities, and (iii) the rate of decomposition of various components of the feedstock. Each of these factors is considered in turn. Even though external heating was provided to offset heat losses due to the environmental conditions in the laboratory, it was realized that the intermittent heating resulted in a slight average daily temperature variation of 2.5 ± 0.8 °C. This temperature difference is sufficient to influence the microbial activity in the slurry. The various enzymic activities can either speed up or slow down a particular stage of the anaerobic processes (Li *et al.,* 2015). This is done by the faster growing enzymes that colonize the slurry and assimilate substrates faster. Fast hydrolase can produce VFA to dominate the slurry, hence slowing methanogenic action. This action of colonization of the substrates complements the effect of the overall reaction kinetics and the rate of decomposition of the particulate nature, cellulose, hemicellulose, and lignin content of biomass, leading to biogas production.

One of the main characteristics of biogas is its chemical composition: it is primarily a mixture of combustible CH_4 and an inert CO_2, with traces of other chemicals. Figure 8 illustrates the weekly percentage compositions of the biogas generated from dung slurry. Samples of the gas drawn from the digester were analysed at the beginning of every week with a gas analyser. The first day of the experiment did not realize any collection of gas in the gasholder; hence, no biogas composition was recorded for the first week. As indicated, biogas was first measured on the 4th day. At the beginning of the second week, the gas sample analysed was composed of 29.0 ± 0.1 % of CH_4, which was significantly lower than the 49.7 ± 0.1 % measured as CO_2. Very small quantities of O_2 and H_2S were measured in week two. The initial low yield of CH_4 reflects the low activity of the small population of methanogens present in the digester. Methanogens take the longest time to grow and adjust to their environment.

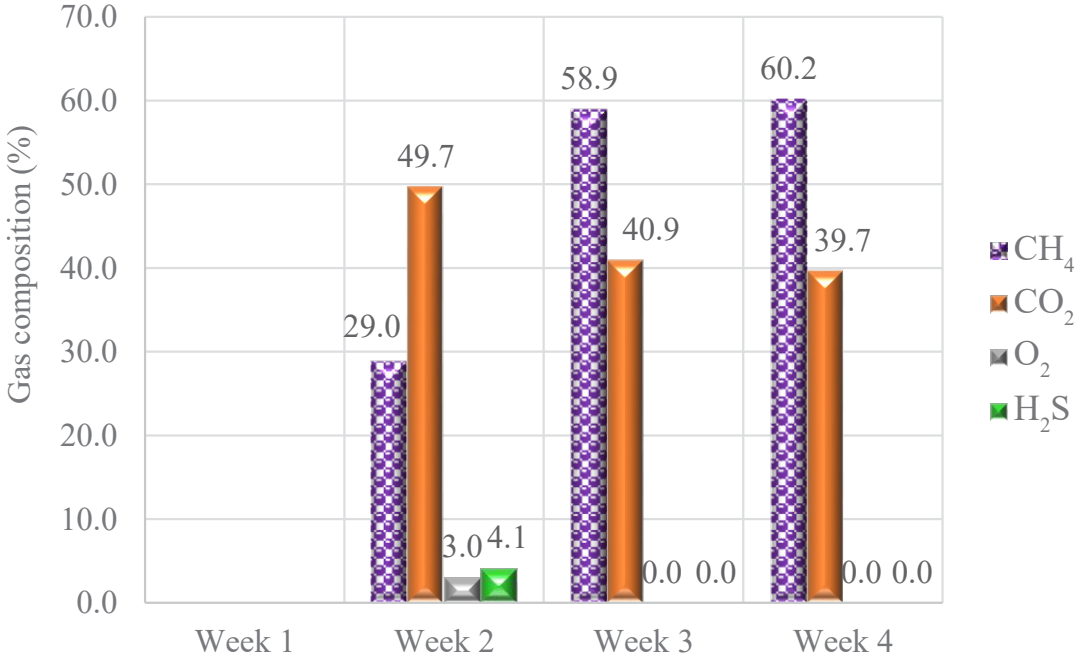


Fig. 8: Biogas composition

Therefore, it is most expected that CH_4 formation initially will be very small. In addition, in the AD processes, methanogenesis occurs last, after the sequential processes of hydrolysis, acidogenesis, and acetogenesis. So it is least expected that CH_4 can be formed in large quantities at the beginning of the operation of the digester. This is so, also because the slurry was prepared from fresh dung. There is therefore the microbial growth period, which must take place for successful operation of the digester.

In studies where slurry is taken from an active functioning digester, especially where slurry of both functioning digester and a new one are the same, the various microbes and enzymes have already populated and adjusted to their system. In such a situation, the introduction of the slurry from the existing digester into the new one does not require the lag phase. Production of gas in the new digester can start immediately because of the availability of the methanogens.

The presence of a large amount of CO_2 could be from two main sources (i) air inside the digester headspace at start of operation, and (ii) formation of CO_2 as an intermediate step of the CH_4 production. At the beginning, as the digester was charged with slurry, air inside the digester was gradually displaced. This went on until the desired quantity of slurry had been fed to the digester. At this point, some amount of air (N_2= 78.09 %, O_2 = 20.95 % and CO_2 = 0.04 %) still occupied the headspace. In addition to this source of CO_2 is the production of CO_2 as part of the AD processes. Further on, in the third and final weeks of the operation of the digester, it was noticed that CH_4: CO_2 ratio had become 1.44:1 and 1.52:1 respectively. This reduction in CO_2 is supported by the fact that both hydrogenotrophic and homoacetogenic methanogenic pathways consume CO_2 to produce CH_4.

The little amount of O_2 detected during the first week was non-existent in the third and fourth weeks. A small amount of H_2S was recorded in week 2, but none in the following and the last week of data collection. This explains that the cow dung contains a high proportion of cellulose, which is to be expected since the cow is a herbivore and as such feeds on only plant matter (grass). The gas analyser used in this study does not measure the amount of N_2 and any other possible trace element that might have existed in the sample of gas collected. This was what was accounted for as the balance (BAL). 14.2 ± 0.9 % BAL measured could be attributed to N_2 present. The BAL in the 3rd and 4th weeks reduced insignificantly to 0.1 %. By the beginning of week three almost 99 % of the biogas collected was composed of CH_4 and CO_2.

Conclusion

This work is concerned with the sustainability of energy sources and systems in human endeavours. It is now generally accepted that conventional energy resources are depletable and environmentally unfriendly. Consequently, there are global efforts to explore such non-depletable sources as solar, wind, geothermal, hydro, and biomass. One such effort focuses on the production of biogas from organic waste materials. Extensive studies have been conducted, especially in countries with advanced economies. The tendency is to use results of such studies for decision-making in other regions of the world, such as the developing countries, which have different climatic conditions. For example, results of studies in the temperate regions are not necessarily completely applicable to the tropical climate of the developing countries. Hence, the need has arisen for similar studies to be undertaken using local material, systems and resources.

A 1000-liter plastic water tank was used as the reactor for an anaerobic digester system to produce biogas from biomass. The feedstock used was fresh cow dung. Such operating parameters as temperature, pH, pressure, volume of biogas yield and biogas composition were closely monitored. The temperature of the slurry was controlled using an external electrical thermostatic heating system. The daily maximum slurry temperature exceeded the daily maximum ambient temperature by an average of 6.1 ± 0.9 °C. The average of the daily average temperature was 36.1 ± 1.5 °C. Intermittent stirring was provided with an internally mounted 10 DC V motorized stirrer.

From the results and discussions presented in this study, the following conclusions can be drawn:

The fundamental laws, aspects of the concepts and the principles of thermodynamics have been successfully applied to the design, assembly, and operation of a single stage, low rate anaerobic digester using cow dung as feedstock for biogas production.

Anaerobic digestion of slurry prepared with fresh cow dung of 22.9 ± 0.4 % solid content and 77.1 ± 0.4 % moisture content was used in a locally available plastic water tank to produce combustible biogas. The mixing ratio of the cow dung to water was 1:1.4 to obtain a slurry of 8.7 ± 0.1 % solid content that allowed the stirrer to operate without overloading the stirrer motor. An initial 1:1 ratio was too viscous to allow the stirrer to turn easily.

The volume of the first measurable biogas was 0.013 ± 0.001 m^3. This was obtained on the 4th day of operation of the digester. Daily biogas production was low during the first 12 days and fluctuated between 0.008 ± 0.001 m^3 and 0.044 ± 0.001 m^3. Daily biogas production for the last 9 days increased to an average of 0.31 ± 0.11 m^3. The highest daily biogas yield of 0.474 ± 0.001 m^3 was recorded on the 18th day. The cumulative biogas yield for the entire period (24 d) was 3.17 ± 0.03 m^3.

The rate of biogas production was found to be 0.14 ± 0.02 $m^3 d^{-1}$ with a gas production rate constant of 0.2506 s^{-1}; the rate confirms a first order reaction. Here the microorganisms initially adjust to their environment, then increase exponentially.

Analysis of the biogas produced from our digester shows that:

- after one week, the biogas produced contained 29.0 ± 0.1 % of CH_4 and 49.7 ± 0.1 % as CO_2. The high percentage of CO_2 made the biogas incombustible.
- by the final week of the operation of our digester, the CH_4 composition increased to its highest volume of 60.2 ± 0.2 %, with CO_2 dropping to 39.7 ± 0.2 %.
- an insignificant amount of 4.1 ppm of H_2S was recorded in the second week. During the final week, the biogas sampling did not record any H_2S.

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