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Effect Of Bio-Digester's Shape On Biogas Production: A Comparative Analysis Of 3d-Printed Triangular And Hexagonal Shaped Biodigesters

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ABSTRACT
The design, development of triangular and hexagonal shaped digesters using 3D printing technology and their comparative analysis were carried out successfully in order to find out the effect of digester geometry on biogas yield using cow dung mixed with water as substrate which was digested in the 4-liter bio-digesters respectively. From the pH readings of the two digesters, the initial substrate pH of 6.40 was influenced by acidic cow dung, it decreases slightly to 6.20 over four days, indicating bacteria breaking down complex organic matter. Inflation of the gas tube correlated with pH rise from 6.9 to 7.8 (neutral to alkaline), indicating active methanogenesis and methane gas generation. Also, the temperature readings show that throughout the 24 days retention time, the digesters were maintained in the mesophilic temperature range (25-30°C). Furthermore, the gas yield shows that both digesters produced biogas, with the hexagonal geometry producing a higher percentage of methane gas than its triangular digester. The Hexagonal geometry produced 69.5% methane gas out of a total volume of 2518 ml, while the triangular geometry produced 61.99% methane gas out of a total volume of 3240 ml. Conclusively, the hexagonal shaped digester produced a higher percentage of the methane gas than the triangular shaped digester.

KEYWORDS: Digester geometry, biogas yield, 3D-printing, Hexagonal bio-digester, Triangular bio-digester, comparative analysis.

I. INTRODUCTION

In the today's world, energy production is the trendy topic of discourse amongst researchers. There has always been struggle to meet the ever-growing world energy demand using sources that are safe for humans and the environment. The renewable energy sources were found to be the solution to the challenges associated with the use of fossil fuel. In line with the 7th goal in United Nation Sustainable Development Goals, access to affordable, reliable, sustainable and modern energy buttresses the importance of search for alternative renewable energy. One source of energy that satisfies these requirements is biogas.

Also, the continuous increase in waste generation around the world suggests the need to channel these wastes to forms in which they could be utilize as potential source of energy. This will also help in checkmating the menace of pollution and environmental degradation. According to a World Bank report on waste management in Nigeria (2021), Nigeria's annual solid waste generation is estimated at 36 million tons, with only about 5% of this waste being properly disposed of. Majority of the waste is dumped in open landfills, causing significant environmental damage and increasing the risk of groundwater contamination".

Currently, there is a growing interest in the production of biogas from various biodegradable wastes sources because of its desirable features. Interestingly, it application scope has expanded from mere cooking gas to powering internal combustion engines of vehicles and electricity generators. Beyond serving as fuel,

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Omer (2021) submitted that "Biogas technology can not only provide fuel, but is also important for comprehensive utilization of biomass forestry, animal husbandry, fishery, agricultural economy, protecting the environment, realizing agricultural recycling, as well as improving the sanitary conditions, in rural areas". Also, Mbachu et al (2022) carried out a systematic review of the prospects, efforts and contemporary challenges on biogas as source of fuel and electricity generation. The paper submitted that there is great prospect for adoption of biogas technology in Nigeria. Sustainability of supply in copious quantity was mentioned as one of the major challenges in biogas technology.

The challenge of sustainability of supply has triggered researches in the various areas, with focus on investigation of factors that contributes to the yield and quality of biogas produced. These research efforts includes: Mbachu et al (2021a) - Modelling sustainability of a demand-based biomass to biogas conversion system; Mbachu et al (2021b) - Enhancing Biogas Production from Fresh Elephant Grasses, using liquid extract from plantain pseudo stem; Okwu et al. (2020) - Development of ternary models for predicting biogas yield in a novel modular biodigester using fuzzy Mamdani model (FMM), artificial neural network (ANN) and response surface methodology (RSM); Mbachu, Igboanugo and Alukwe (2019) - enhancing the pH of Substrate From Fresh Elephant Grass using locally prepared potash; Mbachu and Alukwe (2019) - investigating the potential of Liquid Extract from Plantain Pseudo Stem as substrate for biogas Production.

With respect to studying design parameters of digesters (digester surface area, diameter, and height; positioning of the inlet and outlet pipes; usable and gross volumes of the digester; and level of the substrate to the volume of biogas needed per day) for optimum biogas production, several authors (Florentino, 2003; Matheri et al, 2016; Ganas, 2022) have done some researches in that regard.

Recently, Ganas (2022) investigated the Influence of Digester Height-to-Diameter Ratio on biomethanation of Market Vegetable Wastes. Okunwande and Akinjobi (2017), on the other hand, used mathematical models to investigate the effect of digesters' configuration (surface area and height) on biogas production. An attempt to determine the mathematical relationship between digester diameters to working height (substrate height) ratio was made. The report showed that within the surface area investigated, biogas yield increased as digester surface area increased.

Thy et al (2005) compared the effect of the dimensions of plastic biodigesters (width to length ratio) on gas production and composition of effluent. The experiment had three treatments consisting of different dimensions of plastic bio-digesters: 2-m, 3-m and 5-m length and a constant diameter of 64 cm. Fresh pig manures were charged daily at a loading rate of 4 kg DM/m3 of liquid capacity into each digester. The design was a single changeover with experimental periods of 40 days on each retention time. The length: diameter ratios were 8:0.6, 5:0.6, 3:0.6 and 2:0.6 m with hydraulic retention times of 10 and 20 days. The results indicated that the gas production in all plastics tubular was almost identical, and that the diameter: length ratio did not have significant effect on the rate of gas production.

Obileke et al (2020) developed a plastic digester using high density polyethylene (HDPE) for biogas production. It developed design equations for determining the volume of the digester, inlet and outlet chambers and digester cover plate, and emphasized that digester dimensions and materials of construction are important factors to be considered while designing and fabricating biogas digesters. The shapes used in practice are either cylindrical or rectangular, but there is limited information available on the impact of other shapes on biogas production. It is known that the mixing of the contents inside the digester is crucial for the efficient functioning of the anaerobic digestion process. Since the mixing pattern is influenced by various factors, including the shape of the bio-digester, the mixing mechanism, and the type of substrate used, there is therefore need for investigation on the effect of the geometry of bio-digesters on biogas production, if any.

II. MATERIALS AND METHOD

The digesters were made of hexagonal and triangular shaped 3D printed containers of same size and thickness (4liters and 2.5mm thick). They were designed to accommodate 2.8 litres of substrate each, i.e. 70% of the digester volume. Batch digestion was adopted for the experiment and was reflected in the design. The digester's volume was selected based on the maximum build volume capacity of the available 3d printer.

The digesters consist of a 3D-printed substrate holding container and the cover; the gas collector unit which is made of an IVF (intravenous fluid) drip set and a 3.50 - 10 TR87 C.C Super tube with a diameter range of 3.50 to 10, utilizing the

TR87 connector specification; an Inlet unit, made of a 1¼” back nut, 1¼” back nut cover and 1¼” PVC pipe. An Outlet Unit for the daily collection of sample and discharge of slurry was made of a ½” PVC pipe, connected with ball valve. ZUMA PVC gum, 4-minutes Giwa Epoxy steel hardener and resin were used as sealant.

Actually, the volume of the digester reserved for gas collection is obtained using equation 1.

$$\mathbf{V_d = V_{gs} + V_{gc}} \quad (1)$$

Where; V_d is the total volume of the digester (4 liters); V_{gs} is maximum volume of substrate intake for the digester (2.8 liters) and V_{gc} is the volume of the chamber reserved for gas collection, which is computed as 1.2 liters. An additive manufacturing technique for producing plastic objects with regular or irregular shapes (3D printing) was adopted because of its characteristics such as: design freedom, cost efficiency, layer by layer approach.

2.1. Stress Analysis of the Digesters Due To Internal Pressure

The following assumptions were made as basis for the design and production of the digesters:

1. The Tensile stresses are uniformly distributed over the entire section and effect of edges and curvatures are negligible.
2. the ultimate tensile stress of a 3D shape printed at 90°C and above is 12.3 MPa (Nassim, 2013) noted that.

The volumes of the hexagonal and triangular digesters were given as equation 1a and 1b respectively:

$$\mathbf{V_d} = \frac{3ah\sqrt{3}}{2} \quad (1a)$$

$$\mathbf{V_d} = \frac{a^2 h\sqrt{3}}{4} \quad (1b)$$

The height (h) was selected as 160mm and 209mm respectively, while the widths were computed using equation 1a and 1b. The width (a) values obtained were 98.09mm and 209.73mm

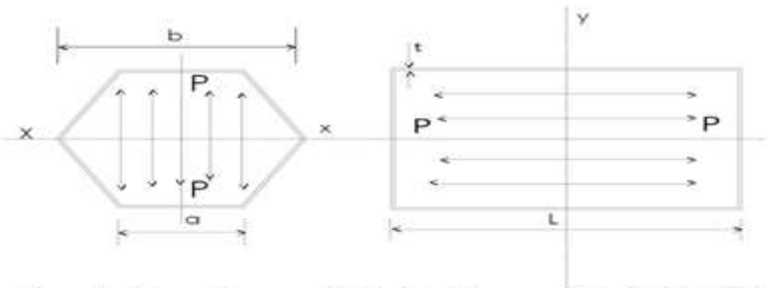

Figure 1: Internal Pressure Distribution Diagram of the Hexagonal

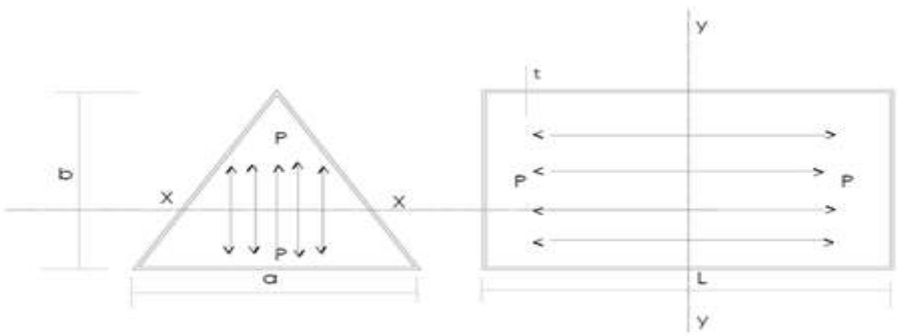

Figure 2: Internal Pressure Distribution Diagram of the Triangular

y-y section

Total Pressure force acting perpendicular to the y-y section,

$$F_p = P_{max}\frac{a^2 3\sqrt{3}}{4} \quad (i)$$

The total resisting force,

$$F_r = ST\ 6at \quad (ii)$$

Where,

$P_{max} =$ Maximum design permissible pressure $= 2.8\text{bar} = 0.28\ \text{N/mm}^2$

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ST= Ultimate tensile stress of a 3D shape printed at 90 degrees and above 12.3 MPa.

t = Wall thickness of the digester.

From equations I and ii,

$t = \frac{3aP_{max}\sqrt{3}}{24S_T} = \frac{3*98.90*0.28*\sqrt{3}}{24*12.6} = 1.89$ mm

x-x section

Total Pressure force acting perpendicular to the x-x section,

$F_p = P_{max}\ bL$

(iii)

The total Resisting force,

F_r = ST 2tL (… of two sections)

(iv)

Where,

bL = Projected Area; t = Wall thickness of the digester.

From equations iii and iv,

$t = \frac{P_{max}\ b}{2S_T} = \frac{3*157.20*0.28}{2*12.6} = 1.79$ mm

For the triangular digester the pressure and the total resisting force are computed using equation 5 and 6.

y-y section

Total Pressure force acting perpendicular to the y-y section,

$F_p = P_{max}\ \frac{a^2\sqrt{3}}{4}$

(v)

The total Resisting force,

$F_r = ST3at$

(vi)

Where, t = Wall thickness of the digester; 3at = Area under stress

From equations v and vi,

$t = \frac{aP_{max}\sqrt{3}}{4S_T} = \frac{210*0.28*\sqrt{3}}{4*12.6} = 2.07$ mm

x-x section

Total Pressure force acting perpendicular to the x-x section,

$F_p = P_{max}\ aL$

(vii)

The total Resisting force,

F_r = ST 2tL (... for the two sections)

(viii)

Where, aL = Projected Area; t = Wall thickness of the digester.

From equations (vii) and (viii), $t = \frac{aP_{max}}{2S_T} = \frac{210*0.28}{2*12.6}$ = 2.39mm

The maximum calculated thickness (t) is 2.39mm, considering a factor of safety of 0.11; 2.5mm was taken as the thickness of the bio-digester.

Bio Digester 3d CAD Model

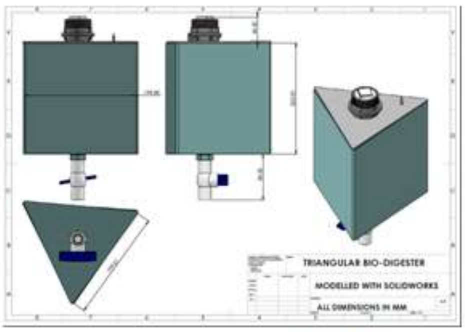

Figure 3: Triangular Bio-digester Model

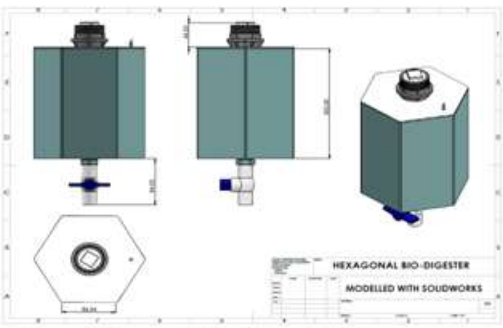

Figure 4: Hexagonal Bio-digester Model

2.2. Material Selection

Acrylonitrile butadiene styrene (ABS), a copolymer that is composed of three monomers: acrylonitrile, butadiene, and styrene, was selected. It offers a range of potential advantages, including good impact strength, rigidity, chemical resistance, good adhesion properties, printability, and resistance to solvent cracking. According to Nassim (2013) the ultimate tensile strength of an ABS 3d printed shape at 90°C and above is 12MPa with a modulus of elasticity of 0.74GPa.

After the 3D printing, the bodies of the containers were smoothed out with emery cloth, and gaps found during the leak test were filled with the acetone/ABS slurry (gum). In order to attain design precision, this is done to guarantee leakproof surfaces and evenness on all sides. The printed triangular and hexagonal shaped containers are both shown in figure 5. The holes for the input manifold and that of the outflow manifold were bored and fitted with the specified PVC fittings as shown in figure 5. PVC glue and Giwa Epoxy sealant were used to attach the pipes to the flanges.

Figure 5: Parts and Stages of the Digester's fabrication

Printer Specifications

The original Prusa i3 MK3S+ printing machine was used in printing the digesters, see figure 6. It has a build volume of length = 250mm (9.84"), width = 210mm (8.30") and Layer height of 0.05 – 0.35mm, with Lilament diameter of 1.75mm. A wide range of thermoplastics such as pla, petg, asa, abs, pc (polycarbonate), cpe, pva/bvoh, pvb, hips, pp(polypropylene), flex, can be printed on the machine. The printer has a print speed of 60mm/s and Maximum travel of 200mm/s. The Maximum nozzle temperature and Maximum heat-bed temperature are 300^{o}Cand 120^{o}C respectively. While the Printer dimensions is 7 kg, 500 x 550 x 400 mm with an approximate Power consumption of 80w and 120w for pla and asb setting respectively. The available connectivity options include usb, wi-fi, or Ethernet.

Figure 6.: The original Prusa i3 MK3S+ printing

The cow dung was sorted for debris as shown in figure 7(a). In order to create a slurry, 1500g of fresh cow dung from the Ama-hawusa Abattoir at Obinze, Owerri, Imo state, was measured with a weighing instrument as in figure 7(b), and 1500 mL of water with a beaker and mixed at the ratio of 1:1. The substrate's pH and temperature were measured at the point of loading

International Journal of Advances in Engineering and Management (IJAEM)
Volume 6, Issue 04 Apr. 2024, pp: 1198-1209 www.ijaem.net ISSN: 2395-5252

and the digesters were kept in an open area. Based on Filer (2018) submission, manually stirring and shaken were adopted and done twice daily for 30 seconds.

Figure 7(a): Pre-treatment exercise – Selection. Figure 7(b): Measuring of Cow Dung

The experimental setup is shown in figure 8. It comprises the anaerobic digester, the biogas collection mechanism, the gas storage tube, the substrate inlet valve and outlet (sampling) valve. The hydrogen ion activity and temperature of the slurry sample were assessed daily using a pH meter, while gas collection was done using a tube as show in figure 8. Water displacement method as shown in figure 9c, was used in measuring the volume of gas produced. The quality of the biogas produced based on the methane content was measured using Gas chromatography-flame ionization detector (AOAC 1995), manufactured by Agilent Technologies (6890, USA).

Figure 8: The Experimental Setup

Figure 9(a) Initial pH and Temperature

Figure 9(b): Daily pH and temperature readings

Figure 9(c): Measuring of volume of gas produced

III. RESULTS AND DISCUSSION

3.1. Substrate pH result

Within the 24 days retention time, the pH values for the substrates in the triangular digester (TD) and hexagonal digester (HD) were recorded for both morning and afternoon as shown in table 2.

Table 2: pH values for the Triangular digester (TD) and Hexagonal digester (HD) within the 24days retention time.

	CD/WATER (TRIANGULAR DIGESTER)		CD/WATER (HEXAGONAL DIGESTER)	
Day	TD. Morning pH	TD Evening pH	HD. Morning pH	HD. Evening pH
1	6.40	6.40	6.40	6.40
2	6.30	6.30	6.10	6.10
3	6.20	6.20	6.20	6.20
4	6.20	6.20	6.30	6.30
5	6.50	6.10	6.70	6.40
6	6.40	6.50	6.20	6.50
7	6.70	6.70	6.40	6.60
8	6.10	6.60	6.10	6.50
9	6.30	6.60	6.40	6.70
10	6.00	6.10	6.90	6.60
11	6.20	6.30	6.70	6.60
12	6.40	6.70	6.60	6.70
13	6.80	7.10	6.90	6.90
14	6.90	7.00	7.10	7.00
15	7.80	7.00	7.60	6.90
16	7.10	6.90	7.10	6.90
17	6.90	6.90	6.80	6.90
18	7.00	7.10	7.00	6.90
19	7.00	6.90	7.00	7.20
20	7.10	7.00	7.10	7.00
21	7.00	7.00	7.00	6.90
22	7.00	6.90	7.00	7.00
23	6.80	6.50	6.80	6.80
24	6.40	6.50	6.70	6.80

It was observed that the pH of the substrate was 6.40 from the start of loading this is due to the acidic content of cow dung, but decrease slightly from 6.40 to 6.20 in the first four days. This initial decrease suggested the breaking down of complex organic matter into simpler organic compounds by hydrolytic bacteria which is followed by acidnogenesis. The gas tube started inflating when the pH rose to 6.9 on the 14th day and continued until the 23rd day. This aligns with the onset and continuation of methanogenesis process. The increase in pH is an indicator of the methanogenic process becoming more active, leading to the production of gas with significant methane content.

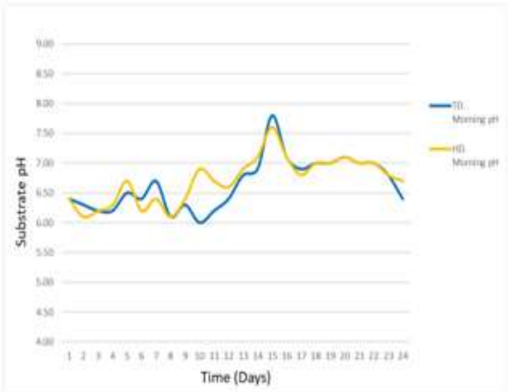

Figure 10(a): Plot of morning substrate pH

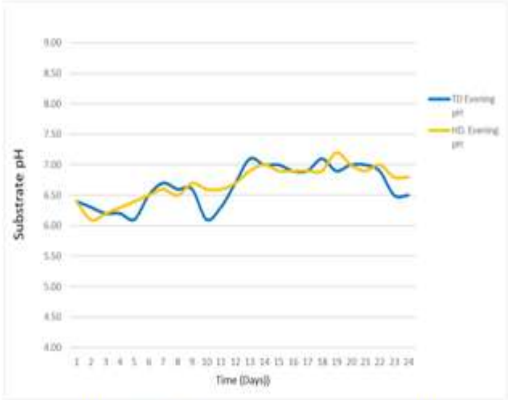

Figure 10(b): Plot of evening substrate pH

Figure 10 (a & b) present a graphical view of the change in the pH of the substrate over time. It was observed that pH of the substrate in the triangular and hexagonal bio-digesters were similar both in the morning and evening time. It seems the shape of the digester does not significantly affect the pH of the substrate being digested. From the correlation coefficient computed, the correlation coefficient between pH of the substrate in the morning and the evening in the triangular and hexagonal bio-digesters were 0.80 and 0.81 respectively. This shows a very strong correlation between the pH values in the morning and evening in both digesters. Hence, it will be safe to say that the time of the day does not have significant effect on the pH. Similar high positive correlation coefficients were obtained for pH of the substrate in the triangular and hexagonal bio-digesters in the morning and the evening (0.82 and 0.82 respectively). Similarly, this suggests that the shape of the digester does not have significant effect on the pH of the substrate being digested.

3.2. Substrate and Atmospheric Temperature Result

Within the 24 days retention time, the temperature of the substrates in the triangular digester (TD) and hexagonal digester (HD) were recorded for both morning and evening session. The ambient temperature was also measured and recorded in table 3.

Table 3: Substrate and Atmospheric Temperature for the Triangular and Hexagonal Bio-digesters

	CD/H2O (TRIANGULAR DIGESTER)		CD/WATER (HEXAGONAL DIGESTER)			
Days	Triangular Digester (TD) Morning SUB. TEMP. °C	Triangular Digester (TD) Evening SUB. TEMP. °C	Hexagonal Digester (HD) Morning SUB. TEMP. °C	Hexagonal Digester (HD) Evening SUB. TEMP. °C	ATM. Morning TEMP. °C	ATM. Evening TEMP. °C
1	25.7	25.7	25.7	25.7	-	-
2	27.3	27.3	27.2	27.2	-	-
3	26.7	26.7	26.8	26.8	-	-
4	27.6	27.6	26.9	26.9	-	-
5	27.8	28.3	27.6	27.8	-	-
6	25.6	26.8	26.0	27.1	-	28.6
7	26.3	26.5	26.3	26.7	27.1	27.3
8	25.6	26.1	25.8	26.3	26.3	27.2
9	25.8	25.3	26.3	25.3	27.1	25.5

International Journal of Advances in Engineering and Management (IJAEM)
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10	26.8	26.4	26.9	26.5	27.6	27.5
11	28.0	27.1	28.5	27.9	28.8	27.4
12	26.1	28.3	27.5	28.7	27.8	28.8
13	27.6	26.1	27.1	26.8	27.2	26.8
14	25.4	25.6	25.4	28.1	29	28.5
15	29.1	26.4	28.6	26.4	31.9	27.3
16	26.2	27.3	26.0	26.4	26.8	27.3
17	26.3	26.5	26.2	26.4	26.8	27
18	26.2	25.3	26.0	25.4	26.7	25.4
19	25.5	24.5	25.5	26.5	26	25.3
20	26.0	26.9	26.0	26.8	27.1	26
21	25.5	26.5	25.9	26.9	26.2	27.7
22	25.4	26.8	25.6	26.1	26.7	26.5
23	25.3	26.5	25.4	26.1	26.8	26.3
24	25.3	26.3	26.0	26.5	25.8	26.8

It was observed that the temperature of the substrate was 25.7°C in both digesters immediately after loading the digester. This perambulated between 25.1 and 29.1 in the two digesters, at different time of the day. The temperature range was found to be within the mesophilic temperature, hence there is no need of external source of heating.

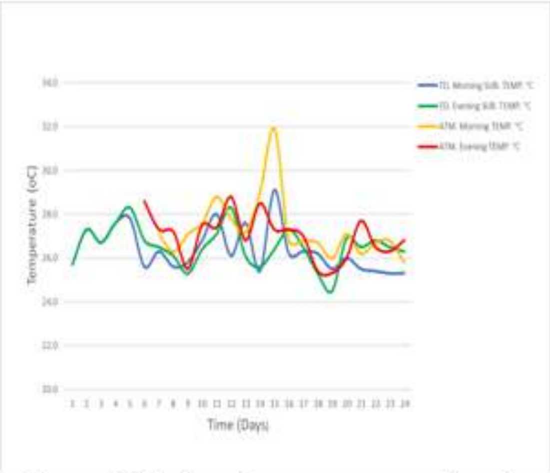

Figure 11(a) plot of temperature against time (24days) for the triangular digester

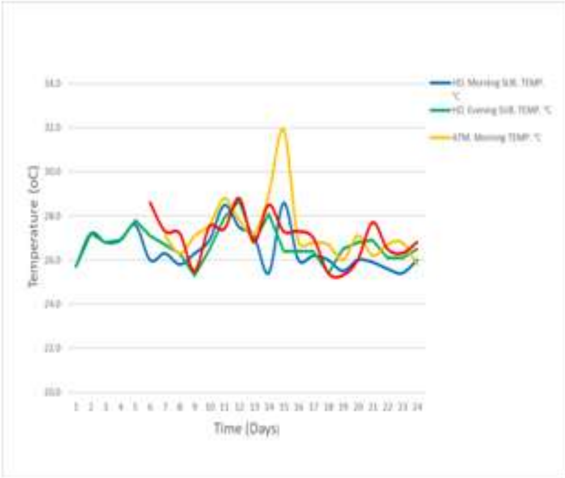

Figure 11 (b) plot of temperature against time (24 days) for the hexagonal digester

From the graph, it was deduced that the morning ambient temperatures were higher than evening ambient temperatures. The variation was caused by morning sunlight exposure which can cause the environment to absorb heat and increase the ambient temperature. The irregular shape of the graphs was caused by variations in the weather; particularly the experiment was carried out during the raining season. Due to the digesters' unregulated temperature, it was also observed that their interior temperatures reflected those of their surroundings. For the triangular geometry, the minimum and maximum digester temperatures were 25.30°C and 28.0°C for morning hours and 25.3°C and 28.3°C for evening hours respectively. While the hexagonal Geometry has its minimum and maximum digester temperature to be 25.70°C and 28.60°C for morning hours and 25.30°C and 28.70°C for evening hours. These temperatures however, are within the mesophilic temperature range which sustains the methanogenic process.

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3.3. Cumulative Biogas Production Volume and Quality

The total biogas produced from the triangular digester was 3240 ml after the 24-day hydraulic retention time, while that from the hexagonal digester was 2518 ml. The difference in biogas of 722ml could result from the fact that the triangular digester has a greater surface area.

From the result shown tables 4 and 5, the hexagonal digester obtained the highest concentration of methane at 69.99% during the 24-day experiment while the triangular digester produced a methane concentration of 61.99%. So, it was observed that the hexagonal geometry produced an optimum yield of biogas as opposed to the triangular geometry. Other gases detected included: CO2, SO2, CO, Methanol and Phenol and their respective percentages were tabulated respectively for the two digester geometries in tables 4 and 5.

Table 4: Triangular Digester bio-gas Result

Gases present	External (mg/ml)	percentage concentration
CO2	5.4958	15.18%
Methanol	0.4656	1.29%
Phenol	0.163	0.45%
Acetone	0.1458	0.40%
Methane (CH4)	22.445	61.99%
SO2	1.4003	3.87%
Acetic Acid	2.4376	6.73%
Chloroform	0.0855	0.24%
Co	3.1402	8.67%
Ethanol	0.4276	1.18%
Total Concentration	36.2062	

Table 5: Hexagonal Digester bio-gas Result

Gases present	External(ppm)	% concentration
CO	1.0206	1.23%
CO2	10.8573	13.11%
Acetone	2.0559	2.48%
Fluorene	0	0.00%
Acetic Acid	0.5901	0.71%
Methanol	2.0438	2.47%
methane (CH4)	57.5407	69.50%
Oxygen	4.9843	6.02%
Ethanol	0.9188	1.11%
Hydrogen	1.7795	2.15%
Phenol	0.9999	1.21%
Total Concentration	82.7909	

IV. CONCLUSION

In conclusion, both the triangular and hexagonal geometries demonstrated the capability to generate biogas using cow dung and water, confirming their suitability for methane production. There was no remarkable difference in the pH and temperature of the substrate throughout the retention period. However, the yield and quality of gas produced, using same substrate and operating condition, varied across the shape (hexagonal and triangular shape). The hexagonal digester gave better quality of gas, while the triangular had higher yield of biogas. Hence, the geometry of the digester has effect on the yield and quality of biogas produced.

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