Design and Construction of Air-Proof Metallic Digesters for Biogas Production from Varied Co-Digestion of Selected Agricultural Residue with Cattle Dung

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Abstract-
Biogas is produced from anaerobic digestion of biodegradable solid wastes in bio-digesters. Agricultural residues, comprising of animal manure and waste biomass, can constitute unfavourable environmental issues if not properly disposed. Studies aimed at converting these residues to energy need serious attention due to fast depleting rate of fossil fuel and its environmental hazard. Four cylindrical biogas digesters (A, B, C and D) of 0.052m³ capacity each were constructed and fed with cattle dung, sunflower leaves, pawpaw and potato peels at different percentage composition. The experimental set-up was left for a retention period of 40 days, after which biogas production stopped. Results revealed that the percentage Organic Dry Matter (%ODM) of cattle dung, sunflower leaves, pawpaw and potato peels were 94.91, 95.92, 97.75 and 96.60 respectively. The total volume and methane contents of biogas produced from digester a, b, c and d were 46.64, 45.80, 39.55 and 38.02 m³, and 71.82 %, 53.71 %, 66.80 % and 52.70 %, respectively. Analysis also revealed that digesters A had the highest Fresh Mass Biogas Yield (FMBY), Organic Dry Matter Biogas Yield (ODMBY), Fresh Mass Methane Yield (FMMY), and Organic Dry Matter Methane Yield (ODMMY). The Higher Heating Values (HHV) of biogas obtained from digesters A, B, C and D were 6.931, 5.680, 6.679 and 5.549 kcal/kg, respectively.

Key words: Agricultural residues, biogas digesters, co-digestion, retention period, higher heating value.

1. Introduction
Anaerobic digestion can be described as waste-to-energy technology which is being used in the management of organic wastes such as organic municipal organic fractions, sewage slurry, organic kitchen waste, livestock manure and others [1]. The demand for energy is increasing daily, most especially in developed nations where the population index is on the rise. Energy consumption is an integral element for measurement of economic modernization. The ability of every nation to provide efficient energy security by meeting up with the demand forecasts determines the level of their economy and development [2] [3].

The fossil fuel reserves are fleeting owing to the increasing demand for petroleum products by the manufacturing and transportation industries. Therefore, the development of renewable energy, such as biofuels, biogas, wind, solar, etc., has provided a reliable means of energy
security, particularly to the industrialized societies. More also, the Green House Gas (GHG) emissions associated with the use of fossil fuels make it imperatively needful to develop renewable sources of energy which are sustainable and have positive environmental impact [4].

The central aim of anaerobic digestion system is to create a suitable condition for fermentation of the biomass in the absence of air (oxygen). According to Abdullahi et al. [5], the success or failure of a biogas plant lies majorly on the design methodology adopted, many failures have been reported from biogas plants due to poor design methodology. In this airtight condition, methane gas is produced together with other gaseous products such as, carbon dioxide (CO₂), Hydrogen Sulphide (H₂S) and others.

Co-digestion refers to the concurrent digestion of energy-rich organic waste materials with animal or liquid wastes. It can also mean the speedy digestion of two or more substrates and co-substrate mixtures in the same unit [6]. The supporting benefits of co-digestion include efficient biodegradability, quality biogas yield, and a cost-effective utilization of bio-digesters for treatment of different organic waste and sewage [6, 7, 8]. A good number of scientific studies have shown that efficient co-digestion approaches of solid substrates and liquid wastes have resulted in quality biogas yield by as much as 60% compared to that obtained from single substrates [9, 10, 11, 12]. Utilization of co-digestion technology can help in the treatment and management of waste and also improve the quality of biogas generated from biomass, domestic and industrial wastes [13].

Co-digestion is basically carried out to support feedstock that relatively produce low biogas yields with animal wastes that are rich in volatile solids with the purpose of boosting biogas yield and quality [14]. For example, co-digestion of rice husk with cow dung yielded quality biogas [15], while higher methane production was achieved from anaerobic co-digestion of kitchen waste and cow dung under mesophilic temperature [16].

The demand for biogas as a domestic fuel requires that effective technology for co-digestion of energy-rich biomass and agricultural residues should be developed. There is abundance of biomass in Africa owing to the favourable tropical rain forests. Sunflower leaves, pawpaw and potato peels, which are all available densely in the rainforests of Africa, were collected and co-digested with cow dung at different mass compositions in four separate digesters. This study presents an overview of cost-effective digesters which were designed and constructed from cheap materials and the resulting quality parameters of the biogas generated from the four digesters.

2. Methodology

Four metallic digesters were constructed to digest cattle dung, pawpaw peels, potato peels and sunflower leaves at different mass composition. The following sections explain the biogas digester detailed design and procedural experimental steps for co-digestion of the feedstock for improved biogas production.
2.1 Design of biogas digester

The bio-digesters designed for the anaerobic digestion are cylindrical in shape and manually operated. All the materials used were sourced locally. The bio-digesters were designed to have means of feeding the feedstock, probes for measuring pH, temperature and pressure, and outlets for releasing the digested sludge and collecting gas. Airtightness was ensured as much as possible to ensure the enzymatic biodegradation activity of the methanogenic bacteria.

Mild steel was chosen as the most suitable material for the digester construction due to its high strength and corrosion resistance ability. The exploded and isometric views of the digester are shown in Figure 1. The following dimensions were used in the design of the bio-digester:

- Height of the drum = 640 mm
- Yield stress, \( Y_s \), of Mild steel = 200 MN/M²
- Diameter of the drum = 320 mm

The total volume of the digester is obtained from Equation 1.

\[
V_T = \pi r^2 h
\]

Where \( V_T \) = total volume of the digester,
- \( r \) = radius of the digester (0.16m),
- \( h \) = height of the digester (0.64m),
- \( \pi = 3.142 \) (a constant).

\[
V_T = \pi r^2 h = 3.142 \times (0.16)^2 \times 0.64
V_T = 0.052 m^3
\]

Figure 1: Exploded and isometric view of the bio-digester
The assumptions used for design of the pressure expected to be generated during incubation include:

i. The biogas to be produced would comprise majorly, methane 60% and carbon dioxide 40% by volume

ii. It was assumed that the substrate will occupy one-third of the total volume of the digester. That is \( \frac{1}{3} \) of \( V_T = 0.017 \text{m}^3 \) while the gas produced will occupy two-third of the total volume of the digester, that is \( \frac{2}{3} \) of \( V_T = 0.035 \text{m}^3 \)

iii. That a maximum temperature of 40°C (313K) was attainable in the digester.

The maximum expected pressure by the gas produced therefore is given by Equation 2.

\[
P_T = P_{CH_4} + P_{CO_2}
\]

Where \( P_T \) is maximum expected pressure

\( P_{CH_4} = \) partial pressure of methane

\( P_{CO_2} = \) partial pressure of carbon dioxide

The partial pressure of methane is given by Equation 3.

\[
P_{CH_4} = \frac{3M_{CH_4}R_oT}{2V_T}
\]

The partial pressure of carbon dioxide is given by Equation 4.

\[
P_{CO_2} = \frac{3M_{CO_2}R_oT}{2V_T}
\]

Where \( R_o \) = specific gas constant (J/kgK)

\( T = \) maximum absolute temperature attainable (313K)

\( M_{CH_4} = \) molecular mass of the methane (16kg)

\( M_{CO_2} = \) molecular mass of carbon dioxide (44kg)

But, \( R_o = \frac{R}{M} \) (5)

Where \( R = \) the universal gas constant (8.314 J/kgK)

\( M = \) molecular mass of a gas concerned

From Equation 5,

\[
R_o(CH_4) = \frac{8.314}{16} = 0.519625 \text{ J/kgK}
\]

\[
R_o(CO_2) = \frac{8.314}{44} = 0.188954 \text{ J/kgK}
\]

Using Equation 3,

\[
P_{CH_4} = \frac{3 \times 16 \times 0.519625 \times 313 \times 0.6}{2 \times 0.052} = 45039.494 \text{ N/m}^2
\]

\[
P_{CO_2} = \frac{3 \times 44 \times 0.188954 \times 313 \times 0.4}{2 \times 0.052} = 30026.244 \text{ N/m}^2
\]

\[
P_T = 45039.494 + 30026.244 = 75065.74 \text{ N/m}^2
\]

\[
= 0.7506574 \text{ MN/m}^2
\]

The thickness of the digester vessel was also designed accordingly.

Based on the factor of safety 2, the thickness of the vessel was designed as follows:

\[
\delta_1 = \frac{\delta y}{n}
\]
Where $\delta_1 =$ allowable working stress
$n =$ factor of safety (2)
$\delta_y =$ yield stress of steel (200 MN/m$^2$)

\[
\delta_1 = \frac{200}{2} = 100 \text{ MN/m}^2
\]

The thickness of the digester vessel is given by Equation 7:

\[
t = \frac{P_r r}{\delta_1} \quad (7)
\]

Where,
$P_r =$ total expected pressure
$r =$ radius of the digester

\[
t = \frac{0.07506574 \times 0.16}{100} = 0.0001201 \text{ m}
\]

Since the retention time can last for at least 40 days therefore,

\[
t = \frac{0.00012011}{40} = 3.003 \times 10^{-6} \text{ m}
\]

Therefore, a mild steel of thickness 1.2 mm was recommended and used in the construction of the digester.

The strain of the digester vessel was designed as follows:

The longitudinal stress of the vessel is given by Equation 8.

\[
\delta_2 = \frac{\delta_1}{2} \quad (8)
\]

Where $\delta_2 =$ the longitudinal stress of the digester vessel

\[
\delta_2 = \frac{100}{2} = 50 \text{ MN/m}^2
\]

The hoop strain of the digester vessel is given by the Equation 9.

\[
\epsilon_1 = \frac{P_r r}{2E}(2 - V) \quad (9)
\]

Where
$\epsilon_1 =$ hoop strain of the digester vessel.
$E =$ modulus of elasticity of steel, (190 GPa or 190 x $10^3$ MPa)
$V =$ Poisson’s ratio of mild steel (0.27)
$t =$ thickness of the digester vessel ($1.2 \times 10^{-3}$ m).
$r =$ radius of the digester vessel (0.16 m)

\[
\epsilon_1 = \frac{0.07506574 \times 0.16}{2 \times 1.2 \times 10^{-3} \times 190 \times 10^3}(2 - 0.27) = 4.5566 \times 10^{-5}
\]

The longitudinal strain of the digester vessel is given by Equation 10.

\[
\epsilon_2 = \frac{P_r r}{2tE}(1 - 2V) \quad (10)
\]

Where $\epsilon_2 =$ the longitudinal strain of the digester vessel

\[
\epsilon_2 = \frac{0.07506574 \times 0.16}{2 \times 1.2 \times 10^{-3} \times 190 \times 10^3}(1 - 2 \times 0.27) = 1.2116 \times 10^{-5}
\]

2.2 Experimentation
The loading and setting up of the four digesters was done simultaneously at the same atmospheric temperature and pressure. The batch-feed experimental set-up was chosen. The first digester, labelled as A, was fed with 5kg of cattle dung, 2kg of pawpaw peels, 2kg of potato peels and 2kg of sunflower’s leaves. The second digester, B, was fed with 5kg of cattle dung, 3kg of pawpaw peels, 1kg of potato peels and 2kg of sunflower leaves. In the same manner, the third digester, C, contained 5kg of cattle dung, 2kg of pawpaw peels, 3kg of potato peels and 1kg of sunflower and the last digester, D, was fed with mixture of 5kg of cattle dung, 1kg of pawpaw peels, 2kg of potato peels, and 3kg of sunflower leaves.

All the substrates were mixed with water in ratio 1:2 and proper stirring of the slurry was done after. The slurry was fed into the biogas digester through the inlet opening and all the valves on the gas outlets and slurry outlets were closed. The total weight of solid waste and water were maintained equal in all the digesters. The collection of gas from all the digesters was done in all the retention days of the bio-digestion.

The volume of the bio-digesters filled with substrate mixtures was maintained at about 350 litres (two-third of the digester volume) and run under unrestrained pH i.e. no addition of acid or base. The ambient and slurry temperatures and pressures were measured daily at 1pm using a thermometer.

The experimental set up was left for 40 days retention time, as suggested by Ostrem et al. [17]. Immediately biogas production commenced, the gas was collected in tyre tubes which were fixed to the gas outlet of the digesters, and the volume of biogas generated daily was obtained using Equation 13 [18]. After the digester has been operated for a while, it was observed that gas production reduced in volume. Therefore, some effluent slurry was removed and recharged into the digester for more buffering of the slurry inside the digester. Gas production and collection was immediately commenced after this.

\[
R_o = \frac{R}{M} \times \%\text{composition} \tag{11}
\]

\[
R_{o\text{ mixture}} = RCO_2 + RCH_4 \tag{12}
\]

\[
V = \frac{R_{o\text{ mixture}} \times T_{\text{digester}}}{P_e} \tag{13}
\]

Where \( R_o \) = specific gas constant of a gas (J/kgK),
\( R = \) universal gas constant (J/kgK),
\( M = \) molecular mass of the gas concerned,
\( R_{o\text{ mixture}} = \) Total specific gas constant of the assumed biogas composition (that is, CH\(_4\) and CO\(_2\));
\( P_e = \) estimated daily pressure of the digester,
\( T_{\text{digester}} = \) estimated daily temperature in °C of the digester;
And \( V \) = volume of biogas generated in m\(^3\).
3. Result and discussions

From the cumulative biogas yields collected in the first 10 days, highest biogas volume was recorded from Digester B. This followed by Digesters A, C, and D in the decreasing order of biogas yields. Between incubation period of 15 to 30 days, the FMBY obtained from digester B dropped owing to drastic reduction in the slurry pressure within the digester, and biogas yield from digester A was noticed to increase rapidly. At the end of 40 days retention time, highest FMBY was recorded from digester A, followed by digester C, B, and D in the decreasing order cumulatively yields.

The total volume and methane contents of biogas produced from digester A, B, C and D were 46.64, 45.80, 39.55 and 38.02 m³, and 71.82 %, 53.71 %, 66.80 % and 52.70 %, respectively. Analysis also revealed that 9.65, 8.56, 8.80 and 7.99 m³/kg FM of FMBY, with 83.20, 67.44, 75.93 and 76.09 m³/kg ODM of ODMBY were obtained from digesters A, B, C and D, respectively. Digesters A, B, C and D yielded, 7.28, 6.89, 6.23 and 4.90 m³CH₄/kgFM of FMMY, respectively while digesters A, B, C and D yielded, 62.75, 54.30, 53.75 and 46.68 m³CH₄/kg ODM of ODMMY, respectively.

The summary of results from the four digesters is given in Table 1. The results obtained from the quality measurement of biogas shows that digester A had the highest methane content of 71.82% and lowest carbon dioxide content of 23.43%. This indicates that biogas from digester A has the highest quality which is attributed to the high Carbon/Nitrogen (C/N) ratios and ODM of both pawpaw and potato peels [19].

Digester B has an average of 53.71% methane content and 32.59% carbon dioxide content. The water content was found to be higher than that of biogas generated from digester A and C. Higher percentage content of pawpaw peels (27.27%) in the substrates fed into digester B is responsible for the reduced quality [19].

The percentage of methane and carbon dioxide contents in biogas generated from digester C were found to be 66.80% and 27.59% respectively. The quality is relatively better compared to biogas collected from digester B and D. This can be related to higher percentage composition of potato peels (3kg) in digester C than other digesters. The dry matter, carbon and ammonium-nitrogen content of potato was found to be higher than pawpaw peels and sunflower leaves [20].

Cumulatively, it was noticed that digester D had the lowest methane content. With an analyzed value of 52.70% and 33.22% of methane and carbon dioxide, the carbon dioxide content decreased the calorific quality (heating value) as compared with other biogas obtained from the other digesters. It was observed that the greater percentage content of sunflower leaves in digester D reduced the methane content and increased impurities in the biogas produced [20].

Biogas from digester A has highest heating value of 6.931 kcal/g which was followed by biogas generated from digester C (6.679 kcal/g). The biogas from digester D has the least heating value
of 5.549 kcal/g while biogas from digester B has heating value of 5.680 kcal/g next to biogas from digester C.

The minimum (25 °C) and maximum temperature (45 °C) of the slurry satisfies the mesophilic temperature range of 20°C – 45°C (Ostrem et al., 2004). Digester A yielded the peak volume of biogas at 34°C while digester B yielded the peak volume of biogas at 38 °C. Digester C and D yielded their peak volume of biogas at 29°C. This confirms what Ostrem et al. [17] ascertained that a mesophilic digester must be maintained between 30º to 35ºC for optimal functioning of methanogenic bacterial and for maximum biogas yield.

| Table 1: Summary of results from the four digesters |
|-----------------------------------------------|

| Items                          | Digester A | Digester B | Digester C | Digester D |
|-------------------------------|------------|------------|------------|------------|
| Total mass of waste used (kg) | 11         | 11         | 11         | 11         |
| Mass of water used for mixing (kg) | 22         | 22         | 22         | 22         |
| Total mass of the slurry (kg)  | 33         | 33         | 33         | 33         |
| Number of retention days      | 40         | 40         | 40         | 40         |
| Total volume of gas generated (m³) | 46.64       | 45.58       | 39.55       | 39.45       |
| Maximum ambient temperature (°C) | 35         | 35         | 35         | 35         |
| Maximum ambient pressure (kN/m³) | 102.52     | 102.52     | 102.52     | 102.52     |
| Maximum slurry temperature (°C) | 45         | 39         | 44         | 44         |
| Maximum slurry pressure (kN/m³) | 32.00      | 30.00      | 50.66      | 34.66      |
| Peak volume of gas (m³)        | 1.96       | 1.98       | 1.93       | 1.98       |
| Minimum ambient temperature (°C) | 25         | 25         | 25         | 25         |
| Minimum ambient pressure (kN/m³) | 100.93     | 100.93     | 100.93     | 100.93     |
| Minimum slurry temperature (°C) | 26         | 26         | 26         | 26         |
| Minimum slurry pressure (kN/m³) | 10.67      | 11.20      | 10.67      | 9.33       |
| Heating values of biogas (kcal/g) | 6.931      | 5.680      | 6.679      | 5.549      |

4. Conclusion

The following conclusions were thereby drawn:

i. Fluctuating weather condition causes rise and fall in temperature and pressure of the digester and this consequentially affect microbial activities in the raw biogas yield from each digester. That is, when temperature rises, digesters yield more biogas but when temperature falls, biogas yield also falls.

ii. Digester A has highest overall volume of biogas yield.

iii. The maximum daily biogas yield was obtained at temperature range of 30 °C to 38 °C, which is a mesophilic temperature.

iv. At uniform high percentage mass composition of pawpaw peels and potatoes peels with low percentage mass composition of sunflower leaves, co-digested with cattle dung, highest heating value of biogas was generated.

5. Recommendations
The following recommendations are suggested for further studies on the effective co-digestion of agricultural residues and organic wastes:

i. For a batch co-digestion experiment under uncontrolled atmospheric condition, a mesophilic digester must be maintained at temperature between 30 °C to 38 °C for optimal functioning.

ii. A means of sustaining a controlled mesophilic temperature condition should be developed.

iii. Effect of longer incubation period on biogas yields should be investigated on these sets of experiments.

iv. Provisions of microbial catalysts should be made to support the concerted action of anaerobic bacteria in the digester and the effect of the catalyst should be investigated on the retention time biogas yields.

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