Biogas Production Potential of Sorghum Residues Using a Batch Reactor at Mesophilic Temperature

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ORIGINAL RESEARCH

Abstract— Energy production via biogas has the potential to contribute significantly to economic development and growth. The utilization of plant residues for biogas production is a step in the right direction towards energy sufficiency because of its abundance. Therefore, the aim of this research is to determine the biogas production potential of sorghum residues using a batch reactor at mesophilic temperature. The experiment was carried out at the Department of Agricultural Engineering, Faculty of Engineering and Technology, Ladoke Akintola University of Technology, Ogbomoso, Oyo-state, Nigeria. Sorghum residues from the farm were collected and reduced in size to about 1 cm particle. The feedstock was subsequently charged into the digester and was kept airtight. The digester was stirred daily to ensure proper mixing of the feedstock. The Digester was kept at a mesophilic temperature of 37 °C. The biogas produced was collected in graduated gas sampling tube that was inserted in a confining liquid within a definite period of 35 days and measurement of the gas produced was taken daily. Gas sampler, Model 6800 DGA was used to measure the percentage of methane present in the gas produced. It was observed that sorghum residue accumulated 944.3 IN/KgFM and 938.6 IN/KgFM of biogas in the first and second replicate, respectively. Biogas production progressed steadily daily and peaked on day 20 of the experiment before declining gradually till the 35th day when the experiment was terminated. Also, an average of 81.57% of methane was recorded when the biogas produced was analyzed.

Keywords— Biogas, Crop residue, Methane yield, Sorghum residue, Thermophilic temperature.

1 INTRODUCTION

Energy has been described as the essential component of a modern society and the scale with which economic development and true growth can be measured (Adebayo et al., 2014). Non-renewable sources of energy have continued to lead to serious consequences such as significant increase in emission of greenhouse gases, environmental pollution (Ibikunle et al., 2018), acidification potential (Ayodele et al., 2018), global warming, climate change (Weiland, 2010). and economic instability. Biofuel as an alternative and renewable source of energy is capable of meeting the increasing global demand for energy. Biofuel offers two major benefits – they are infinitely available (or renewable) and can be used without causing environmental problems (Sokan-Adeaga and Jain, 2019). Sorghum is a C4 annual grass, which can produce high forage biomass yields per unit of land (Rooney et al., 2007). Therefore, the abundance and massive production of sorghum combined with its high biomass yield has positioned it as an important plant for biogas production (FAO, 2019). Although the use of fossil fuels has dominated the energy production scene since the nineteenth century, alternative energy sources are gradually being considered as a replacement. The use of animal waste such as feaces and abattoir waste, even though more popular than biomass generation from plant sources, has its attendant challenges such as air pollution, contamination, complex treatment and processing (Samoraj, 2022). Therefore, plant waste from thousands of hectares of cultivated arable farmland which are lost to cultural practices such as bush burning can be utilized for the production of biogas (Adebayo *et* al., 2013; Archana et al., 2021; Iye and Bilsborrow, 2013; Jekayinfa et al, 2015 and Clarke et al., 2011). Sorghum has been reported to yield more residue because of its morphology (Iye and Bilsborrow, 2013; Clarke et al., 2011). Due to high availability of sorghum residues, it has the potential to supply biomass needed for biogas production. However, there is still a dearth of information on the potential and ability of sorghum residues to produce quality biogas at mesophilic temperature.

Therefore, the aim of this research is to determine the biogas production potential of sorghum residues using a batch reactor at mesophilic temperature while the objectives were to: investigate the chemical properties and mineral element content of sorghum residues, evaluate the biogas yield of sorghum residues at mesophilic temperature and determine the methane content of the gas produced.

2 MATERIALS AND METHODS

2.1 Location of Study

The experiment was carried out at the Farm Power laboratory of the Department of Agricultural Engineering, Faculty of Engineering and Technology, Ladoke Akintola University of Technology, Ogbomoso, Oyo-state, Nigeria.

2.2 Collection of Feedstocks and Substrate Analysis

Sorghum plants was harvested from Ladoke Akintola University of Technology Teaching and Research Farm, Ogbomoso and grains were separated from the stalk. Samples were prepared from the stalk (stem and leaves) and were kept in the laboratory at ambient temperature after size reduction prior to feeding into the digester. The substrate was analysed for its chemical and mineral element component.

2.3 Biogas Production

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Biogas production and quality from sorghum plant was analyzed in a batch anaerobic digestion test at a mesophilic temperature. The method described by Linke and Schelle (2000) was used where batch experiments was carried out in lab-scale vessels and replicated two times. Mesophilic temperature was maintained through a thermostatic cabinet. In order to induce a faster reaction, materials that have been anaerobically digested from a previous batch experiment was used as inoculum in this study (Adebayo et al, 2013).

In order to fully re-suspend the sediments and the scum layer, the fermentation vessels were properly and manually shaken each day. The biogas produced was collected in a graduated gas sampling tube that was inserted in a confining liquid within a definite period of 35 days and measurement of the gas produced was taken daily. This duration is to fulfill the test criterion postulated for terminating batch anaerobic digestion experiments given in VDI 4630 (this is because daily biogas rate is less or equal to only 1% of the total volume of biogas produced up to that time). A gas sampler, Model 6800 DGA was used to measure the amount of methane present in the gas produced. This was determined at least two times in a week for the four weeks of the batch experiment. Biogas production of only the inoculum without substrate was recorded to serve as a control. The biogas and methane yields were then calculated at the standard temperature and pressure (0 °C, 1013 mbar).

Readings of the gas production (ml), air pressure (mbar), gas temperature (°C) (Wang et al., 2019) and time of the day was taken on daily basis throughout the period of the experiment. The gas factor was calculated as well as the fresh mass biogas yield and fresh mass methane yield. The volatile solid biogas and methane yields were also determined on daily basis. The amount of gas formed was converted to standard conditions (273.15 K and 1013.25 mbar) and dry gas. The factor was calculated according to Equation (1).

$$F = \frac{(p - P_{H_2O})T_O}{(t+273.15)p_o} \quad (1)$$

Where;

T_o is 273.15 °C (Normal temperature)

T is Gas temperature in °C

P_o is 013.25 mbar (standard pressure)

P is Air Pressure

The vapour pressure of water PH_2O is dependent on the gas temperature and amounts to 23.4 mbar for 20 °C. The respective vapour pressure of water as a function of temperature for describing the range between 15 and 30°C is given as in Equation (2).

$$P_{H_{2O}} = y_o + a.e^{bt} \quad (2)$$

The normalized amount of biogas volumes is given as

$$Biogas[N\ ml] = Biogas[ml] \times F \quad (3)$$

Normalized by the amount of biogas, the amount of gas taken off of the control batch is given as

$$Biogas\ [N\ ml] = (Biogas[Nml] - Control[Nml]) \quad (4)$$

The mass of biogas yield in standard liters / kg FM fresh mass (FM) is based on the weight

The following applies:

1 standard ml / g FM=1 standard liters / kg FM = 1 m3/ t FM

$$Mass\ of\ biogas\ yield = \sum \frac{Biogas[N\ ml]}{Mass\ [g]} \quad (5)$$

The oDM biogas yield is based on the percentage of volatile solids (VS) in substrate

$$oDM\ biogas\ yield = \sum \frac{Biogas\ [N\ ml]\ 100}{Mass\ [g]VS[\%FM]} \quad (6)$$

$$CH_{4corr} = \frac{CH_4\ [vol\%]100}{(Mass[g]+CO_2\ [vol\%])} \quad (7)$$

$$Fresh\ Mass\ Methane\ Yield = \frac{Fresh\ mass\ biogas\ yield \times CH_{4corr}}{100} \quad (8)$$

$$oDM\ Methane\ yield = \frac{oDM\ biogas\ yield \times CH_{4corr}}{100} \quad (9)$$

Mass of substrate charged into the digester was calculated using the equation below:

$$M_s = \frac{M_i C_i}{2C_S} \quad (10)$$

2.3.1 Data Analysis

The amount of gas produced were recorded daily and data collected was subjected to statistical analysis using Microsoft Excel (Batch Test Format) package, 2019.

3.0 RESULTS AND DISCUSSION

3.1 Chemical properties and mineral element concentration of sorghum residues and inoculum

Table 3.1 and 3.2 show the results of the laboratory analysis of the substrate and inoculum.

Table 3.1. Chemical properties of sorghum residues and inoculum

Parameters	Sorghum residues	Inoculum
Dry Matter (%DM)	83.87	78.56
ODM (%ODM)	87.63	75.13
ODM (%FM)	73.50	21.4
Crude Fibre (%)	93.70	16.06
Ash Content (%)	10.38	3.43
Fat Content (%)	1.30	0.42
pH	6.80	7.70

Table 3.2. Concentration of mineral elements in sorghum residues

Mineral Element	Concentration
Calcium	22.10
Zinc	0.615
Potassium	36.21
Iron	3.795
Phosphorus	0.10
Magnesium	13.10
Sodium	9.795

3.2 Fresh mass biogas yield and organic dry matter biogas yield from sorghum residues

Daily biogas yield of the substrates was recorded and presented in the Table 3.3 and Figure 3.1. Daily biogas yield ranged from 0.8 IN/kgFM to 47.0 IN/kgFM in the first replicate while it ranged from 0.4 IN/kgFM to 46.2 IN/KgFM in the second replicate. The biogas yield from sorghum residue increased gradually after an initial low-production period, reaching a peak of approximately 45–48 mL g^{-1} FM around days 18–20, indicating optimum microbial activity and efficient conversion of biodegradable organic matter. Thereafter, biogas production declined steadily as the readily available substrate became depleted. The fluctuations observed before the peak may be attributed to variations in the anaerobic digestion stages and the lignocellulosic nature of the sorghum residue. Similar trends have been reported by Lama-Calvente et al. (2023) and Pasteris et al. (2022), who highlighted the influence of substrate characteristics and biodegradability on biogas and methane production. Also, Figure 3.2 also shows the organic dry matter biogas yield for sorghum residues. The oDM-based biogas yield increased gradually, with a rise after the first 10 days and a plateau of approximately 0.25–0.35 N m^3 kg^{-1} oDM between days 18 and 35. This pattern indicates the gradual depletion of readily biodegradable organic matter, while the remaining lignocellulosic fraction was less susceptible to degradation. Similar trends have been reported for plant biomass, with biogas yield and digestion performance largely influenced by biomass composition and lignocellulosic characteristics (Adebayo et al., 2014; Anunputtikul et al., 2007)

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3.3 Methane yield and organic dry matter methane yield from sorghum residue and inoculum

An average yield of 82.43% of methane concentration was observed in the experiment. The sorghum residue in the first replicate yielded 1.47 CH4/KgFM out of the 1.81 IN/KgFM biogas produced representing about 81.65% of methane. The second replicate produced total biogas of 1.78 IN/KgFM with 83.23% methane. These results are presented on Table 3.4 and Figure 3.3. The pattern reflects progressive substrate degradation, with the later decline attributed to the depletion of readily biodegradable organic matter and the resistance of the remaining lignocellulosic material. Similar trends were reported by Lama-Calvente et al. (2023), who observed an initial lag phase, rapid methane production, and a subsequent decline as the available substrate was depleted. Also, methane yield for organic dry matter of sorghum residue shows a similar trend with that of biogas yield (Figure 3.4.)

Table 3.3. Daily biogas yield of sorghum residues and inoculum

Days	Temp. (°C)	Substrate (Rep 1) (IN/kgFM)	Substrate (Rep 2) (IN/kgFM)
1	36.5	0.8	0.4
2	37.8	9.8	1.6
3	37.0	9.0	9.0
4	37.0	12.0	6.0
5	37.0	23.0	19.0
6	37.2	29.0	25.0
7	36.9	36.1	24.1
8	38.0	40.6	33.3
9	38.1	37.4	34.4
10	37.0	36.5	39.4
11	37.0	37.0	37.5
12	37.5	41.9	40.8
13	37.6	34.0	42.0
14	37.1	36.0	46.0
15	37.9	37.7	46.2
16	36.5	38.6	44.6
17	36.5	42.1	44.2
18	37.2	44.0	41.8
19	38.5	47.7	43.9
20	38.0	46.6	46.0
21	36.4	35.7	41.6
22	36.9	36.0	38.8
23	37.0	32.1	34.1
24	37.2	27.2	29.4
25	37.1	27.3	28.6
26	37.8	23.8	22.2
27	37.6	22.0	22.4
28	37.0	18.0	20.4
29	38.9	18.4	19.9
30	38.5	18.8	17.2
31	36.5	13.7	12.7
32	36.7	10.8	9.8
33	37.5	8.5	6.4
34	37.6	7.3	5.9
35	36.4	4.9	4.0

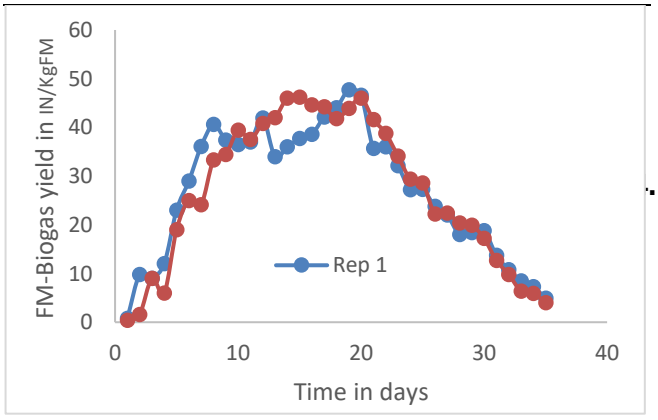

Fig 3.1. Fresh-Mass Biogas yield of sorghum residue

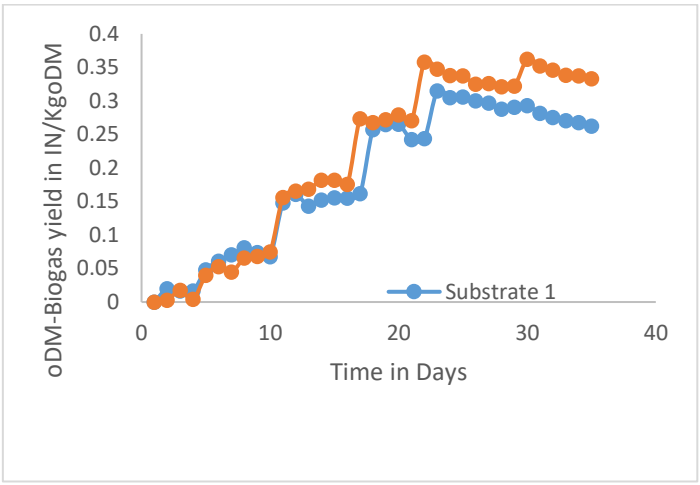

Fig 3.2. Organic Dry Matter Biogas yield of sorghum residue

Table 3.4. Total Biogas and Methane yield of Sorghum residue

Sub	FMBY	oDMBY	FMMY	oDMMY	Meth.Conc.
Sorghum 1	0.19	0.26	0.16	0.21	80.53
100% Sorghum1	0.24	0.33	0.20	0.27	82.39
Avg	0.22	0.30	0.18	0.24	81.57

FMBY: Fresh mass biogas yield; oDMBY: Organic dry matter biogas yield; FMMY: Fresh mass methane yield; oDMMY: Organic dry matter methane yield; Meth.Conc.: Methane concentration.

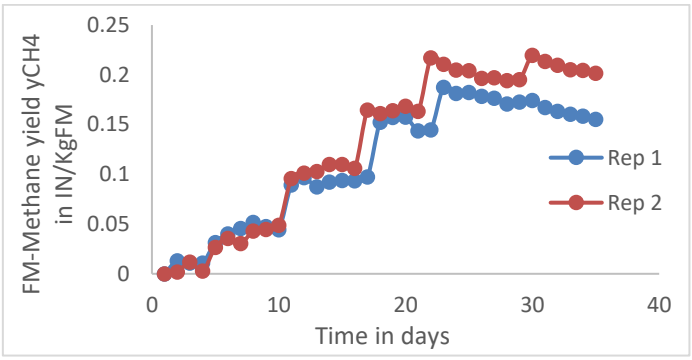

Fig 3.3. Fresh-mass Methane-yield of Sorghum residues

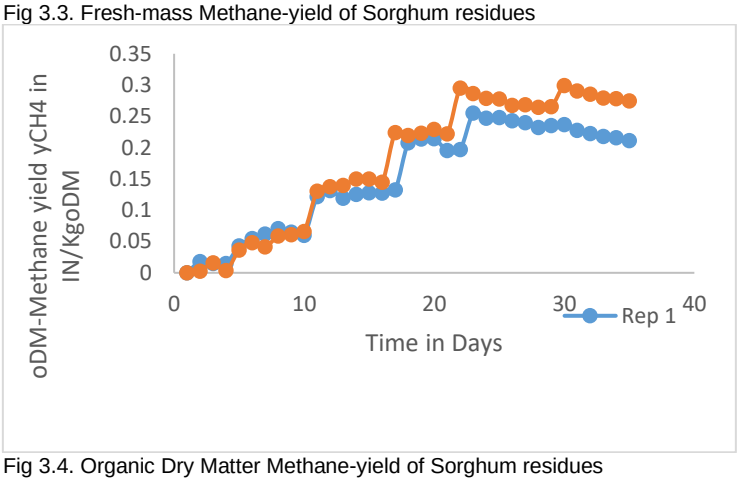

Fig 3.4. Organic Dry Matter Methane-yield of Sorghum residues

4 CONCLUSION

Sorghum residues biogas yield was found to be 944.3 IN/KgoDM for the first replicate while the second replicate accumulated biogas yield of 938 IN/KgoDM. The experiment was replicated twice and biogas production in each of the replicates were found to be similar. Biogas production started immediately and gradually increased till a peak on day 20 of the experiment followed by a gradual decline of gas production. The gas production had almost halted by the 35th day when the

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experiment was terminated. The gas produced was tested for methane using a gas sampler and was found to have an average of about 82.43% for both replicates.

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