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INVESTIGATING THE ENERGY PROSPECT OF PIGEON PEA WASTE, RICE STRAW AND DONKEY RUMEN LIQOUR, USING A 25 - LITRES PLASTIC DIGESTER

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ABSTRACT
This study investigated the energy generation potential of pigeon pea waste ,rice straw, and donkey rumen liquor through anaerobic digestion using a 25-liters locally fabricated plastic bio-digester. The digester was constructed and operated at Enugu state university of Science and Technology, Agbani, and was charged with a feedstock-to-water ratio of 1:1:2:2 by mass(6kg each of rice straw and pigeon pea waste, 12kg of donkey rumen liquor and 12kg of water), achieving a 75% fill level. The retention period spanned 25 days, during which daily biogas production, ambient and slurry temperatures, gas pressure, and pH values were monitored. Biogas production commenced on the 9th day and peaked on the 19th day with a maximum daily yield of 920mL at a slurry temperature of 40°C. The cumulative biogas yield was 9,461mL over the 25-day period, indicating sustained gas production beyond the observation window. The biogas was purified using a multi-stage scrubbing system involving sodium hydroxide, silica gel, activated carbon and water, which resulted in the removal of approximately 92.6% CO_2 and 90% H_2S. Combustion tests confirmed the flammability of the purified gas, suggesting its suitability for domestic applications. Comparative error analysis and statistical tests (MBE, RMSE, MPE and t-test) demonstrated good performance of the constructed digester relative to a 45-liter reference model. The results affirmed the viability of co-digesting agricultural and animal wastes for sustainable energy production, offering a cost-effective solution for waste management and environmental conservation in Nigeria.

Keywords: Anaerobic Digestion, Biogas Production, Co-digestion, Agricultural Waste, Plastic Bio-digester, Renewable Energy, Waste Management

Introduction

Energy need and use has been the problem challenging human from the time of existence. Every organism; biotic and abiotic requires energy to carry out their daily functions. We require energy to operate our home appliances, vehicles industrial machines etc. This energy may come in different forms, which includes light, heat, electric, and mechanical. These energies are convertible to one another. As the world population increases the need for more available energy becomes monumental and the demand rises. In 2015, the world population hits 7.3 billion people and the world total energy consumption tends to increase by 1-2% per year (Hannah, 2020). This continuous increase in energy demand to meet up the 21st century energy need cannot be attained if the global energy crisis remain unsolved.

One of the ways to achieve sustainable energy supply is increasing the use of biomass to generate renewable energy (Angelideki *et al.,* 2018). Renewable energy are source of clean, inexhaustible and increasing competitive energy which are free from greenhouse gases (G.H.G) unlike the limited fossil fuel that are never abundant and has several environmental and public health challenges ranging from pollution , global warming, and climate change. Clean energy generated using renewable energy sources such as biomass, solar, wind etc. and emerging technologies proffer a permanent solution to the global energy challenges and Nigeria in particular as a developing nation.

Nigeria with the growing population requires sustainable energy sources like biomass to meet the growing need for all the sector of economy and achieve universal access to modern energy services. Universal provision of energy services for cooking and power are key objective of the national energy policies, in addition to priorities of energy affordability, energy security, reduced air pollution and carbon (IV) oxide (CO_2) emission. Renewable energy sources such as biomass can be a driving force to attain these goals due to their cost effectiveness and are available in a decentralized manner. According to NRERM (2023), the share of primary energy requirement met with renewable energy would reach 47% by 2030 and 57% by 2050. Nigeria has a biofuel policy and its faster adoption will help to sustainably meet growing transportation demand (Brimma *et al*., 2017). It is on this ground to meet high energy demand of the transport sector and the continuous rise in the price of premium motor spirit (PMS) that the Nigeria government under the current administration has purchased over 200CNG (Condensed Natural Gas) buses to curtail the effects of the national oil subsidy removal and the cost of CNG now reduced to N230 per litre against the high cost of PMS. Similarly, Enugu state government has approved the State climate policy known as Enugu State Climate Policy and Action Plan (ESCPAP), a move to mitigate the implication of over reliance to fossil fuel.

Currently, fossil fuel which accounts for 85% of the national energy demand is a non-renewable energy source, limited and contribute to climate change, their usage should be put in check. Sequel to that, the United Nations has held numerous summits and conferences geared towards addressing the issues of fight against climate change and global warming. These conferences have led to formulation 0f treaties that outlined the obligation of member states to decrease the release of greenhouse gases. One of the most significant outcome 0f these conferences was the paris Agreement which resulted from COP21 in 2015 (Tekayinfa *et al*., 2020)

To reduce the effects of non-renewable fuels on the environment, Biomass utilization has been globally accepted as a renewable energy source. In line with Adeleke *et al*. (2020), there is need to embrace the use of renewable energy sources as a substitute to conventional fossil fuels for domestic and industrial applications.

Biomass which is nearly unlimited, environmental friendly, storable and high energy efficiency is more attractive for its transformation into various products such as biofuel, bio based materials and chemicals. The component of biofuel varies from region to region and depends upon the sources and method of production. Nevertheless,the anaerobic digestion of biomass to produce renewable energy requires the use of a sealed vessels called digesters.

Hence, the focus of this research work was to locally construct a plastic bio digester and use it to investigate the energy generation potential of pigeon pea waste, rice straw and donkey rumen liquor.

Statement of problem

The impending danger of the use of non-renewable energy sources has aroused the need to embrace the use of renewable energy sources like biogas from biomass as substitutes for the conventional fossil fuel in domestic and industrial applications. This increasing interest in renewable energy has led to a renewed attention in anaerobic digestion of wastes which requires a digester. Different countries have designed different types of digesters to suit the climate and cultural conditions of their environments but each of these digester designs is not without a limitation. For instance, the floating cover digester is not recommended for cold or rainy areas since the gas reservoir is in contact with environment. Also, the fixed dome digesters is not suitable for areas with extreme temperature because of the cracks that appears on the dome which results from the extreme temperature change. The French model digester which would be suitable for both the tropical and cold part of the country is very expensive to construct due to the cost of the cylindrical steel enclosure. Hence, this work is tailored to construct and characterize a plastic bio-digester as an alternative for countries like Nigeria.

Aim and Objectives of the Study

The aim of this work is to construct and characterize a bio-digester. The objectives of the work are as follows:

1. To construct a bio-digester.
2. To characterize the digester using pigeon pea waste, rice straw and donkey rumen liquor.
3. Compare the volume of biogas produced from the digester using the co-substrates with volume obtained by other researchers and carry out some error analysis.

LITERATURE REVIEW

Sources of Biogas

Biogas is generally produced from biomass which are plant and animal materials that have not been completely decomposed. Biomass according to Denmeh *et al.* (2017) is divided into five main groups namely:

- Wastes and residue from agriculture and related industries,
- Municipal solid waste,
- Municipal liquid waste,
- Animal excrement,
- Industrial solid and liquid wastes.

1 Generation of biogas from animal waste

Extensive researches have been carried out on some of these animal wastes such as cow dung, poultry droppings for generation of biogas in places like Europe, Kenya, Malaysia, India and China. In Ukpai and Nnabuchi (2012), Indian studies indicates that animal waste primarily cow dung account for 30% - 40% of the total biomass energy generated in the country. While in Nigeria studies have been carried out on the production of biogas from animal waste such as Swine wastes(Okogbue and Ojo , 2003), Goat, sheep and horse wastes(Zuru *et al*., 1998), cow dung(Itodo *et al*., 1995), Poultry waste(Itodo *et al*., 1995). According Smith in Ukpai and Nnabuchi (2012), animals under confinement would be most suitable for anaerobic digestion. The reason was that animals under confinement give out waste that are moist, little degraded and ideally suitable for biogas production. Animals kept on open feedlot would provide wastes that are exposed to degradation and desiccation on the surface for a long period and animals widely dispersed on pasture would provide dissipated wastes that are too dispersed for collection. The quality of wastes produced by a given animal depends on the type, size and the class of the animals and the digestibility of the feed.

However, stable compound like lignin and hemicelluloses which accompany Cellulose in plant are difficult to degrade by bacteria. Faeces of live stocks consist of undigested cellulose fiber and protein, excess mineral and residues from digested fluid (Loehr, 1984). The presence of worn out cells from intestinal- lining, mucus, bacteria and foreign materials ingested with the feed as well as other inorganic materials such as additives to feeds increase the productive performance of animals (Sambo, 2011).

2 Generation of biogas from agricultural waste

Agro-waste has been discovered to be a major source of biogas. They are waste from agricultural crops grown specifically for food, fiber or energy production. Crop residues cereals straw such as rice, maize, wealth and leaves and stem of agricultural crops have been identified as potential source of biogas production. According to Stanley (1978), waste water from food processing plants have also been used for biogas production. In Malaysia, carbohydrate residues from agro based industries, processed waste of oil palm, rubber, sugar cane, pineapple, coconut and cassava have been reportedly used in production of biofuels (Hutagalung, 2014).

In Nigeria, studies has been carried on generation of biogas from agricultural wastes; cowpea leaves and cassava peels (Ukpai and Nnabuchi, 2012); cassava peels and rice husks (Olorunmaiye *et al*., 2016) and domestic waste(MulibbuDin, *et al*., 2020).

Types of Bio-digester

The biogas technology used in any country depends on the climate, cultural, economic and social conditions of the country, hence many countries has made various biogas devices that are most compatible with the climate conditions of their environment for optimal production of biogas. The commonly used biogas digester falls into one of the following;

1 Floating Cover/Drum Digester (Indian Model)

The floating drum digester consists of an underground fermentation reservoir and a moving (floating) gas holder. The gas holder floats directly on the fermentation slurry. The gas is collected in the gas holder, which rises or moves down, according to the amount of gas stored. It is prevented from tilting by a guiding frame. If the drum floats in a water jacket, it cannot stuck even with substrate with high solid content. These types were mainly made in India in the past and are known as Indian Model. According to Mohammed *et al*. (2024), in these devices, the gas reservoir floats directly in the effluent of water, the raw materials from the inlet basin are directed into the fermentation reservoir located inside the ground and after the production of gas the fermented materials moves to the outlet basin which is located in line with the inlet basin, and the produced gas inside the gas holder which is placed upside down on the opening of the fermentation reservoir is collected. The floating cover digester is mainly used in digesting waste on a continuous – feed mode of operation. They are usually used for small or middle sized farmers (digester size: 5-15m^3) or institutions and larger agro industrial estates (digester size: 20–100m^3). They provide gas at constant pressure. This type is not recommended for cold or rainy areas since the gas reservoir is contact with environment. Therefore, it repels the heat of the device and gets rusted in contact with moisture.

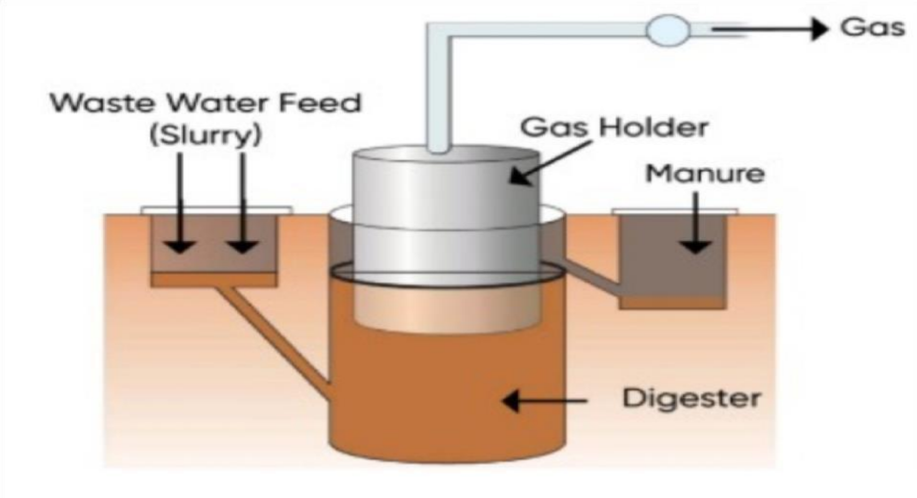

Figure 1: Floating Cover/Drum Digester (Fry, 1974)

2 Fixed-dome digester (Chinese Model)

This digester is built in the form of a dome-shaped reservoir deep in the ground. It consist of a fixed non-moveable gas holder, which sits on top of the digester and an underground brick mason compartment with a dome on top for gas storage.

That is to say that the fermentation reservoir and gas holder are shared, and due to the location of the device in the depth of the ground, it is very important and efficient in term of saving the required space and heat stabilization and resistance of the device in cold and saturated areas. Fixed dome reservoirs are mostly commonly in China. Hence the name Chinese Model, when gas production starts in the digester, the waste mixture is displaced into the compensation tank and as the amount of gas produced increases, its pressure increase. The gas pressure becomes too high if the gas production is high hence the gas should be passed out to a separate storage tank to prevent gas leakage or possible explosion. The device is consist of a cylindrical chamber and is made completely underground protecting it from physical damage and saving space. The fixed dome digester is not suitable for areas with extreme temperature fluctuations and this is due to the cracks that appear on the dome, which are the result of extreme atmospheric changes between 10 and 44^{0}c in winter and summer (Anyaoha *et al*., 2023 and Mohammed *et al*., 2024). The construction of fixed dome digester is labor-intensive, thus creating local employment; the digester is not easy to build and should only be built where construction can be supervised by experience biogas technicians, otherwise plants may not be gas-tight, due to porosity and cracks (Garba *et al.*, 1996).

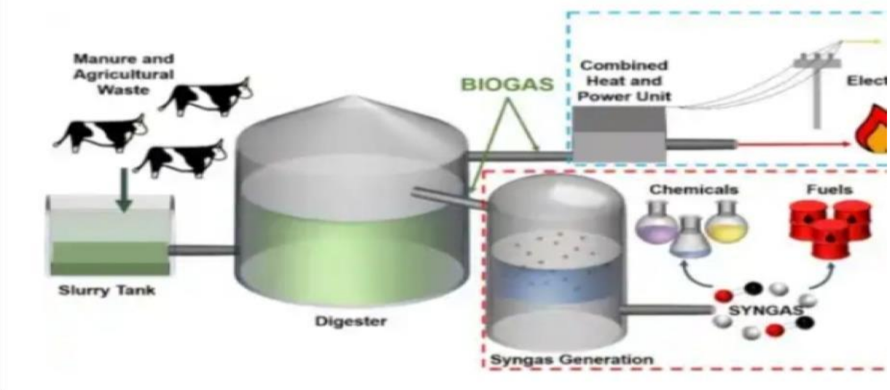

Figure 2: Fixed-dome digester (Chinese Model) (Qdais, 2010)

3 Balloon Digester (Taiwanese Model)

The balloon digester is made of a plastic or rubber bag in which the emitted gas is stored in its upper joint. Similar to the fix-dome type, this type combine the digester and gas holder, the wall of the balloon and the gas is stored at the upper part of the balloon, when the balloon is filled with gas, it acts like a stationary gas reservoir, which means that if the balloon is not inflated, it does not have much elasticity. The gas pressure is achieved through the elasticity and with the weight added, if the gas pressure exceeds a limit that the softy valves are required or gas pump for higher pressure. The device can be made of different materials like metals, PVC and fiber glass which are weather and ultra-violet resistant. The use of balloon type digester in Taiwan dates back as early as 1960. The Taiwanese digester consist of a long cylinder of polyvinyl chloride (PVC) and has advantages of low cost and ease of transportation, cleaning and emptying, maintenance and high temperature of fermentation chamber (Mohammed *et al*., 2024). The balloon digester has high efficiency in tropical regions and lacks efficiency in cold regions.

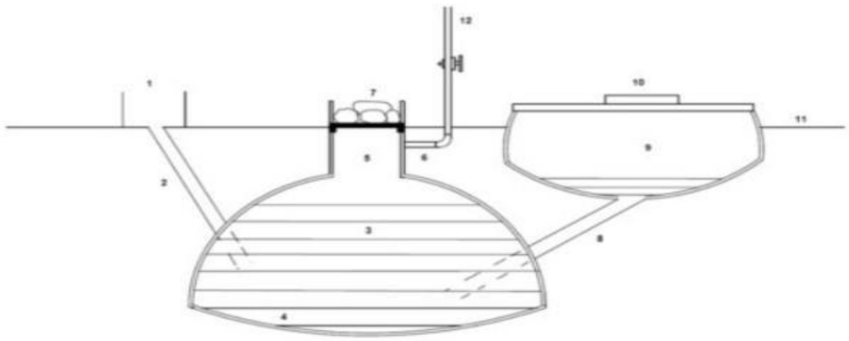

Figure 3: Balloon Digester (Mohamed *et al., 2024*)

(1) Combination reservoir (2) Inlet pipe (3) Digestion reservoir (4) Heavy settled materials (5) Gas reservoir (6) Gas outlet pipe (7) Digestion reservoir (8) Outlet pipe (9) Outlet fertilizer (10) Drainage reservoir (11) Ground level.

4 French Model Digester

This consist of a cylindrical steel enclosure of diameter 1.54m and height 1.54m made by connecting 12mm mild steal sheets. The lid of the chamber is made airtight and filled with a gas valve. The roller is covered with bitumen, wrapped in a polythene bag and buried in municipal solid waste. ¾ of the chamber is the digestion region. The biogas produced is stored in 5 freight wagon tire tubes connected through the ends of the tubes. According to Mohammed *et al*. (2024), the French type bio digester work more efficiently in cold seasons and are recommended for areas where the atmospheric temperature reaches below zero. It is equally most suitable for high fiber biomass. Atmospheric temperature drop in winter does not affect the amount of biogas production. The internal temperature of the digester reservoir has been recorded up to 56^0c, since these devices work naturally in hot temperatures, it is possible to install them even when the air temperature reaches below zero. This type of device can be recommended for use in Nigeria since it will be suitable for both the tropical and cold part of the country.

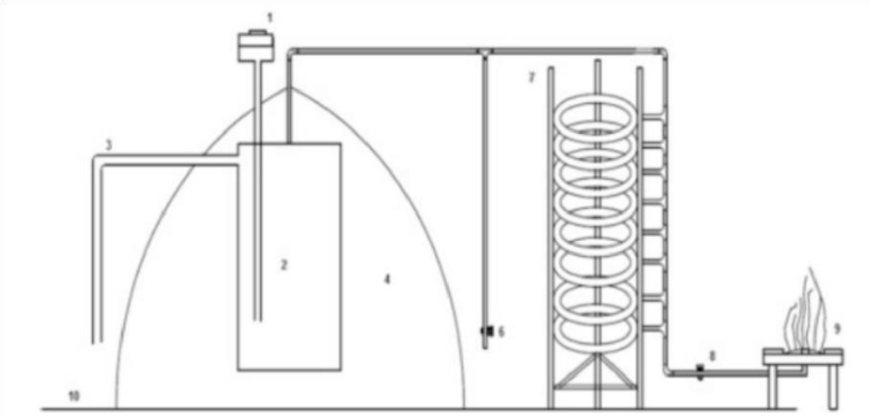

Figure 4: French Model Digester (Mohammed *et al*., 2024)

(1)Inlet pipe (2) Stainless steel digester reservoir (3) Outlet pipe (4) Biomass roller with steel cover (5) Gas line (6) Water valve (7) Freight wagon tire tube (8)
Gas valve (9) Stove (10) Earth surface.

Biogas Treatment and Upgrading

Upgrading biogas account for about 90% of total bio methane produced worldwide today. The upgrading technologies make use of the different properties of the various gases contained within biogas to separate them with water scrubbing and membrane separation accounting for almost 60% of bio methane production globally (Mohammed *et al*., 2024). Biogas scrubbing involves removing compound that are not useful like hydrogen sulfide (H_2S) and carbon (IV) oxide (CO_2) which combines with water vapor to form acids These acids can cause corrosion of metal parts. H_2S and CO_2 are separated from biogas by passing the gas through concentrated solution of sodium Hydroxide Na_2 (OH) and the use of gas chromatograph (Dioha *et al*., 2003). The chemical equation of the reaction are;

$$2NaOH+CO_2 = Na_2CO_{3(s)}+H_2O_{(L)} \quad 1$$

$$Na_2CO_3+excessCO_{2(g)} = 2NaHCO_{3(s)}. \quad 2$$

$$Ca(OH)_{2(acq)}+CO_2 = CaCo_{3(s)}. \quad 3$$

We can equally use dry scrubbing to remove H_2S which is more economical. Here, the gas is passed over iron fillings or iron (iii) oxide mixed with wood shavings (Pudi *et al., 2022)*
The reaction is as follows:

$$Fe_2O_3 + 3H_2S = Fe_2S_3 + 3H_2O \quad 4$$

$$2Fe_2S_3 + 3O_2 = 2Fe_2O_3 + 3S_2 \quad .... \quad 5$$

Biogas contains a large amount of combustible gas that can burn and be used as a power source. The combustion of biogas that release heat and light can be shown in the following equations:

$$CH_4 + 2O_2 = CO_2 + 2H_2O + H\Delta. \quad 6$$

According to Arnold *et al.,* (2020), the lowest temperature needed to ignite and promote the reaction between combustible gases and oxygen is important. That is ignition temperature relates to the chemical components and physical properties of combustible gases, the density and mixing extent of gas and oxygen, the shape and size of the reaction chamber, velocity and pressure of the gases.

Economic Importance of Biogas Residues

Analysis reported carried on the residue revealed that it contains almost twice the concentration per pound of The biogas residue as the organic compound remaining in the digester after the anaerobic digestion .The slurry or effluent is rich in nutrients like ammonia, phosphorus, potassium and more than a dozen of trace element. The residues is an excellent soil conditioner, and can be used as a livestock feed and additive when dried. Any toxic compounds that are in the digester feedstock may become concentrated in the effluent, therefore, it is important to test the effluent before using it on a larger scale. Studies carried out by Beena *et al*., (2012), indicates that oven dried brewery spent grain digester manure supported plant growth better than humans and undigested residues, and was therefore a better fertilizer. This residues is high quality organic fertilizer containing expired bacterial bodies, partially digested or undigested organic matter. The biogas residue is preferred as a better soil fertilizer than aerobically made compost because there are no losses of nitrogen and the inorganic nitrogen is converted within the slurry (Beena *et al.,* 2012).

Analysis carried out on the residue revealed that it contains almost twice the concentration per pound of nitrogen, potassium, phosphorus and mineral as the manure that was fed originally into the digester (Dioha *et al.,* 2003). This is because in the process of the digestion, only carbon, hydrogen and oxygen element were removed and the residue is always odorless after any digestion is completed.

Review of Related Literatures

Ezekoye *et al.* (2014), carried out a study on characterization of biogas produced from rice husks and algae using a metal fixed dome as bio-digester. The biogas produced using a total of 35kg of slurry made in the ratio of 1:6 of rice husks to algae mixed in water at a mesophilic temperature range of 29.0^{0}C- 33.45^{0}C for over 75 days was 156.25litres with the percentage of methane as 52.32%.

In an empirical study on energy prospect of cassava peels, cow dung and saw dust by Olawale *et al*. (2017), where the feedstock were mixed with water in ratio 1:0:1:4, 1:1:0:4 and 1:0:0:2 respectively, the overall result shows that a blend of saw dust and cow dung produce a total yield of 80.238ml is the most viable waste combination for biogas production over those of cassava peels and cow dung with total yield of 77.712ml when the slurry were left for a retention time of 20 days. Ukpai and Nnabuchi (2012), a comparative study of biogas production from cow dung, cow pea and cassava peeling using a 45 litres biogas digester. In the study, the digester was charged differently with these wastes in the ratio of 1:2, 1:3 and 1:5 respectively. The mesophilic ambient temperature range attained within the digestion period were 20-32^{oc} and the slurry temperature of 22-36^{oc} .The result obtained from the gas production showed that cow pea produced the highest methane content of 76.2% followed by the cow dung with 67.9% and cassava peeling has the least methane content of 51.4%. Which reveal that the cow dung has the highest cumulative biogas yield of 124.3litres but cow pea produced the highest flammable gas and the gas flamed on the 7th day.

MATERIALS AND METHOD

Materials

The research design for this study was an experimental research design with a quantitative approach. The key feedstocks used included pigeon pea waste, rice straw, and donkey rumen liquor—chosen for their local availability and high organic content. A 25-liter plastic bio-digester was fabricated and served as the main reactor for the digestion process. Essential instruments used for measurement and analysis included a top-loading balance for weighing the feedstocks, a pressure gauge and flow meter for monitoring gas pressure and flow rate, and a graduated 5-liter keg for collecting and measuring biogas volume. Additionally, four plastic buckets facilitated the mixing and preparation of the substrate, while a pH meter was used to track the acidity or alkalinity of the slurry during the digestion period. A Bunsen burner was employed for combustion tests to assess the flammability of the produced gas, thereby confirming its energy potential. For data analysis, SPSS software was utilized to perform statistical evaluations, ensuring the reliability of the results.

Pigeon pea waste Rice Straw Donkey rumen liquor Figure 5: The selected feedstock for the experiment (By the Researcher)

3.2 **Method**

1 Construction of the digester

The fabricated digester operates in a continous feed of operation and was made of a 25-litres plastic drum as the digestion area and 5-litres keg as gas storage tank. This bio-digester was used in this research work as the main reactor for the digestion of the substrates from animal and plant based waste. The construction of the digester requires a small plastic drum, 3units of

8mm industrial gas tap, stirrer shaft made with one inch pvc pipe bar shaped stirrer , pvc pipes , a laboratory thermometer(-10 to 110ºC) ,pressure gauge, valves, the scrubbing material and hosts. The digester contains the following components; fermentation unit, bar -shape stirrer and stirrer shaft, slurry inlet pipe, cylindrical outlet mouth, gas storage unit and the scrubbing containers . The construction of the bio-digester was supervised by a biogas expert to ensure that the fabrications, welding and fittings are gas tight to prevent gas linkage.

2 Sources of the waste

The waste used for charging the digester for the purpose of this research work including: pigeon pea waste (PP), rice straw (RS) was collected from local farmers in Eha-Amufu, Isi-Uzo Local Government Area Enugu State and donkey rumen liquor (DRL) was collected from an Abattoir in Eha-Amufu. The fresh donkey rumen liquor was obtained from the intestine of donkey slaughtered for human consumption and no living animal was harmed for the purpose of this work. The fresh rumen liquor contains the normal microbial floral as found in the rumen of cows which increase bacterial activities in the digester. The donkey rumen liquor is of two types. The bloody part and watery part. The bloody part were allowed to settle at the bottom of the bowl and watery part were gently decants. The digester were loaded with the mixture of pigeon pea waste (grounded), rice straw (grounded) donkey rumen liquor and water in the ratio shown in table 1.

3 Pretreatment of the waste

There is need to ensure the purity of the collected waste and make them free from other contaminants like leaves roots, dust etc. the plant based waste was thoroughly examined to remove foreign materials. In order to increase surface area of the waste for optimum gas production during the anaerobic digestion, after sun drying, the rice straw was chopped into smaller pieces with cutlass and later grinded into powdered form, for easier slurry formation .The animal waste was collected fresh the day it was used to ensure optimum bacteria activities.

Figure 6: Hand picking of leaves and other contaminants (By the Researcher)

4 Slurry preparation

Four units of plastic buckets was used to prepare the slurry. The buckets was labeled PP ,RS, DRL and W containing 6kg of pigeon pea waste, 6kg of rice straw, 12kg of donkey rumen liquor and 12kg of water respectively, mixed in a rubber basin in the ratio of 1:1:2:2. The ratio of solid waste to liquid in the basin was 1:1:4 as recommended by Fagbenle *et al.* (2022). The required quantity of waste and water was thoroughly mixed before loading into the digester. The quantity of slurry to be charged into the digester to maintain the 75% fill level of the digester as recommended by Nwankwo *et al*. (2017) was predetermined before charging the digester.

Figure 7: Slurry Preparation (By the Researcher)

5 Method of Charging the Digester

After the slurry preparation, the slurry was charged into the digester through the slurry inlet pipe. The waste was loaded up to 3/4 of the digester volume and made airtight to provide anaerobic environment for biogas production. The digester and its content was allowed to stay over a retention period of 25days, taking record of the daily volume of gas production and slurry temperature.

6 Methods of Data Collection

The daily volume of biogas produced from the mixture of wastes was obtained from the reading of the flow meter on the lid of the digester and further confirmed using downward displacement of water. The ambient and slurry temperature was obtained using the laboratory thermometer (-10 to 110^{0}C). The ambient temperature was obtained by displaying the thermometer in air and recording the temperature when the mercury thread reaches a steady point. Also, the slurry temperature was measured and recorded by inserting the thermometer into the slurry through the inlet pipe of the digester and recording the steady temperature for the retention period of 25 days. The daily volume of gas produced was measured using the flow meter attached between the digester and gas storage keg and confirmed using downward displacement of water. The pressure gauge measures the gas pressure. After determining the volume composition of the biogas produced by the waste combination, the pressurized gas was discharged to prevent bursting of the keg. To determine the volume of methane produced from the waste mixture, combined adsorption and absorption process was employed for treatment of the biogas produced. Powdered activated charcoal, aqueous solution of calcium hydroxide, silica gel and water was used for this upgrading process. When the tap connecting the gas storage keg was opened, the biogas collected passed through the pipe to the first filter containing aqueous solution of calcium hydroxide removing carbon (IV) oxide (CO_2) present in the biogas. The gas pass to the second filter but between the first and the second filter is a powdered activated charcoal that remove Hydrogen Sulfide (H_2S) before getting to into the filter. The silica gel contained in the third filter removes water vapor. Previous studies by Fagbenle *et al*., (2022), has shown that the gas passing to fourth container is mainly methane with very little trace of other contents and gas analyzer only identifies methane. The volume of methane in the fourth container was obtained using downward displacement of water in the beaker. The combustibility of the biogas produced was tested using the burner.

Figure8: Picture of the constructed plastic digester (By the Researcher)

RESULT AND DISCUSSION

Results

The results obtained from the experiment are presented in tabular form and the graphical analysis was done using SPSS and discussed accordingly. The measured value of mixed ratios is presented in table 1. The daily and cumulative volume of biogas produced by the mixture of feed stock is presented in table 2. Table 3, contains summaries of the ambient and slurry temperature of the mixture of feed stock. The summary of the results for the mixture of waste (pigeon pea waste, rice straw, donkey rumen liquor and water) is presented in table 4.

Table 1: mixed masses of feed stock and water

Water	mass of waste (kg)	mix ratio
Rice straw	6	1
Pigeon pea waste	6	1
Donkey rumen liquor	12	2
Water	12	2
Total mass	36	1:1:2:2

Table 2: Daily and cumulative volume of gas produce.

RetentionTime (days)	Daily volume of gas (mL)	Cumulative volume of gas (mL)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	52	52
10	141	193
11	298	491
12	395	886
13	650	1536
14	655	2191
15	495	2686
16	788	3474
17	800	4274
18	755	5029
19	920	5939
20	640	6579
21	588	7167
22	575	7742
23	589	8331
24	600	8931
25	530	9461

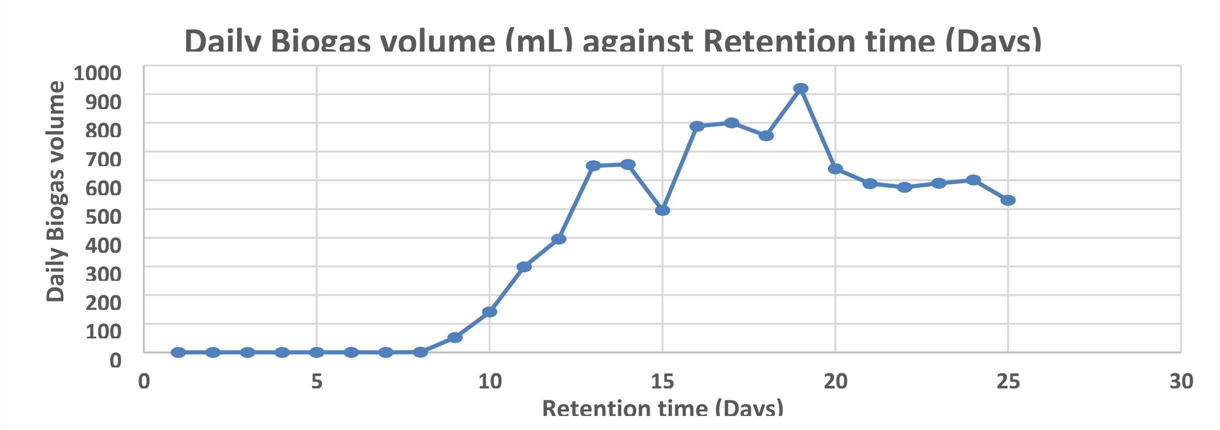

Figure 9: Graph of Daily gas volume versus Retention time

Table 3: Ambient and slurry temp of the mixture of waste.

Time (days)	Ambient temperature.(^{0}C)	Slurry temperature(^{0}C)
1	27	27
2	32	24
3	31	26
4	33	28
5	25	24
6	28	24
7	28	28
8	34	32
9	26	28
10	23	28
11	23	24
12	28	28
13	27	32
14	31	34
15	34	30
16	34	33
17	36	38
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21	33	36
22	32	30
23	35	28
24	34	34
25	30	34

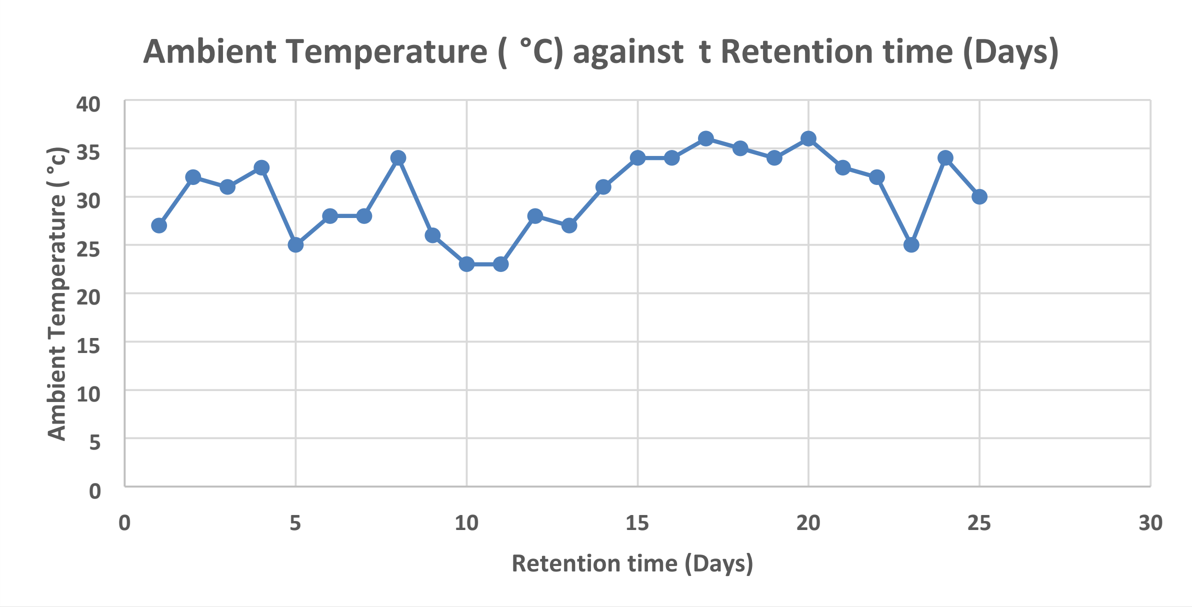

Figure 10: Graph of Ambient Temperature versus retention time.

Table 4: Daily volume of gas and ambient temperatures.

Retention time (days)	Daily vol.(mL)	Ambient temperature.(oC)
1	0	27
2	0	32
3	0	31
4	0	33
5	0	25
6	0	28
7	0	28
8	0	34
9	52	26
10	141	23
11	298	23
12	395	28
13	650	27
14	655	31
15	495	34
16	788	34
17	800	36
18	755	35
19	910	34
20	640	36
21	588	33
22	575	32
23	589	35
24	600	34
25	530	30

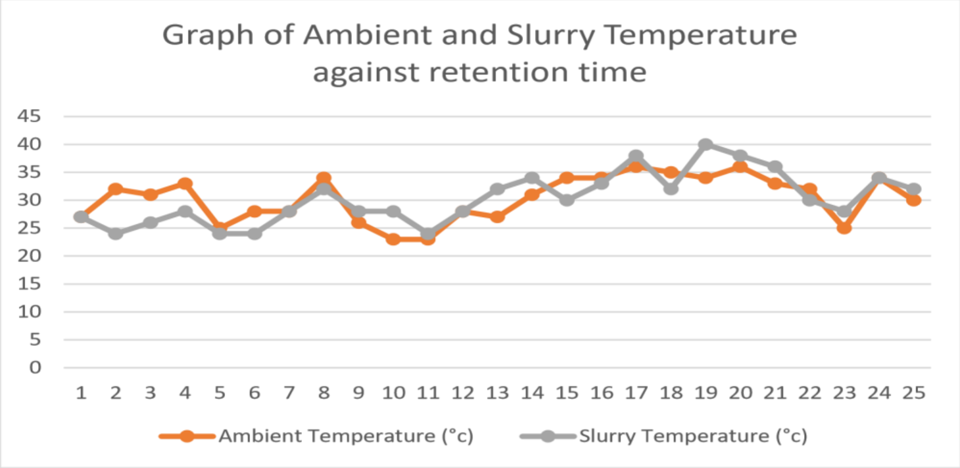

Figure 11: Graph of Ambient and Slurry Temperature against retention time

Table 5: Slurry Temperature and Daily Volume of Gas Produce.

Time (days)	Ambient temperature.(0^c)	Slurry temperature.(0^c)
1	27	27
2	32	24
3	31	26
4	33	28
5	25	24
6	28	24
7	28	28
8	34	32
9	26	28
10	23	28
11	23	24
12	28	28
13	27	32
14	31	34
15	34	30
16	34	33
17	36	38
18	35	32
19	34	40
20	36	38
21	33	36
22	32	30
23	35	28
24	34	34
25	30	34

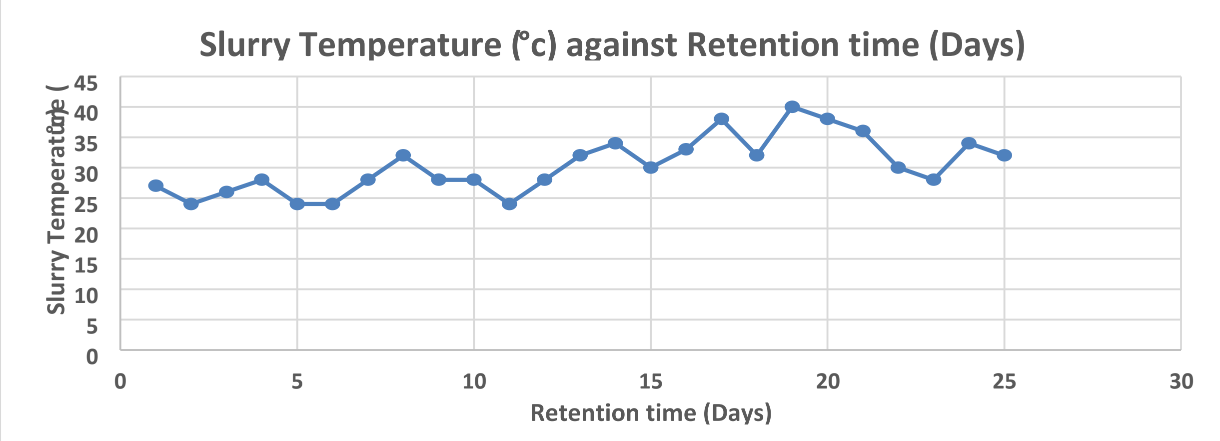

Figure 12: Graph of Slurry Temperature versus retention time

Table 6: summary of the Results for the mixture of wastes

Items	Values for the mixture
Massofwasteused(kg)	16
Totalmassofslurry	40
Massofwater	24
Retention time (days)	25
Total volume .of gas produced (mL)	9,461
Maximum ambient temperature (oC)	36
Maximum slurry temperature (oC)	40
Peak volume of biogas produced (mL)	920
Minimum Ambient temperature.	23
Minimum slurry temperature	24

Table 7: Slurry PH and retention time

Retention time (Days)	Slurry PH
1	4.34
2	4.68
3	4.68
4	5.68
5	5.52
6	6.58
7	6.58
8	6.75
9	6.78
10	6.81
11	6.84
12	6.88
13	6.85
14	6.58
15	5.48
16	6.92
17	7.12
18	7.00
19	7.20
20	6.10
21	6.15
22	6.18
23	6.4
24	5.10
25	4.98

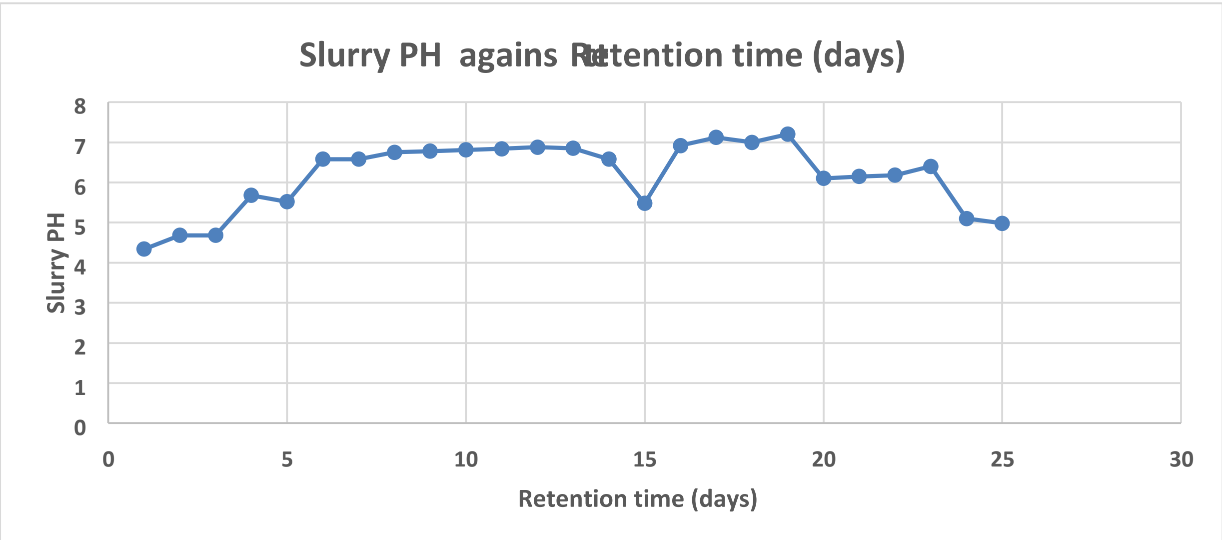

Figure 13: Graph of slurry PH versus Retention time

Discussion.

Table 2,5 and 6 above revealed that Biogas production started on the 9th with a low volume of 52mL. This late start of gas production may be attributed to two things; Microbial population and surface area of the slurry which determines the activities of the extracellular enzymes and mass transfer of the anaerobes within the digester (Surendra *et al.*, 2014).

Concentration of the slurry since the digestibility of the feed stocks are affected by high or low concentration. According to Sun *et al*. (2015), if the waste are too diluted the particles will settle down in the digester and if it is too thick the particle will impede the flow of the gas formed at the lower part of the digester and in both cases, gas production will be less than optimal.

As the production begins on the 9th day, the cumulative daily gas volume continues to increase until the 15th day when there was a sharp decline in volume as can be observed from the Table 2 above. This may be attributed to decrease in temperature between 14th and 15th resulting from rainfall or change in atmospheric conditions. The biogas production in the digester attain its maximum on the 19th at a very high slurry temperature of 40^0C as can be seen from the Table 3. This maximum volume (920mL) of gas at high temperature is within what is expected as this value of temperature is within mesophilic range where methanogens are very active for optimum gas production.

Table 2 shows the summary of the daily and cumulative volume of gas produced for the retention period of 25 days. A close look on the table shows that the cumulative gas volume of 9, 461 mL was recorded at the retention period of 25days and the daily volume 530 mL on the 25th day showing that gas production is still on continuum. This observation shows that the waste used has a high prospect in energy generation and can be established that pigeon pea waste, rice straw, donkey rumen liquor are excellent co-substrates in biogas production. Comparing this result with the result obtained by Ukpai and Nnabuchi (2012) with a metal digester of 45-liters capacity to digest cow dung, cowpea and cassava separately. The result shows the cow dung started producing gas on the second day with a peak on the 10th day with daily production of 8.2 liters of biogas and a cumulative of 124.3 liters after the 30 days retention time in the cow pea, gas production started on the 6th day after charging the digester. The gas production ranges from 4.8 – 7.3 liters and accumulative of 97.5 liters. For the cassava pealing, daily gas production started on 15th day and has the lowest volume of 6.3 liters at the end of the 30 days retention. In general, the present study shows lower cumulative volume of biogas produced by the mixture of the feed stocks but tend to last longer as can be deduced from high volume of gas after the retention period of 25 days. The study has established the fact that the mixture used are perfect co-substrates for biogas production and has a very long retention period compare to when they are digested separately, also, the work of Fagbenl *et al*.,(2022) in production and purification of biogas from cassava peeling using cow dung as inoculums, a cumulative volume of 937.3 liters of biogas was produced after 30 days digestion period and there was no gas production on the first day ,gas production started on the 4th day and had a peak on the 10th and 12th days of digestion with a volume of 48.9 liters

Table 3, shows the values of the ambient and slurry temperatures for the mixture. The average slurry temperature range from 24°C - 40°C which fluctuate due to rainy season and change in weather conditions. The table reveals that biogas production is a function of temperature as can be deduced from the table that gas volume increases with temperature and vice versa. From the table 3, the highest volume of gas (920ml) was obtained on the 19th day when the temperature was 40^0c.

Table 9: Daily gas volume and slurry temperature produced by the Reference digester.

Time	Daily gas volume.	Slurry temperature.
1	0.0	31
2	0.0	22
3	0.0	34
4	0.0	30
5	4.0	33
6	3.4	23
7	1.3	32
8	3.3	34
9	6.6	34
10	5.8	35
11	6.2	21
12	4.3	32
13	6.3	33
14	6.8	35
15	4.3	22
16	3.5	30
17	7.3	31
18	6.4	28
19	5.2	33
20	2.4	33
21	1.3	30
22	2.3	32
23	1.6	30
24	1.4	27
25	2.7	32
26	3.5	29
27	2.1	24
28	2.3	33
29	3.2	33
30	4.8	31

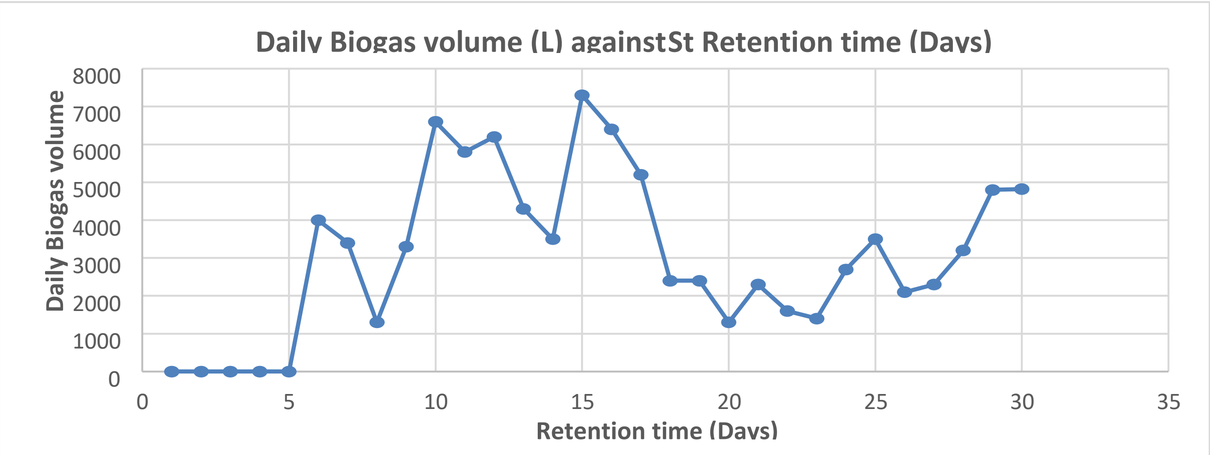

Figure 14: Graph of daily gas volume versus retention time, obtained from the reference digester.

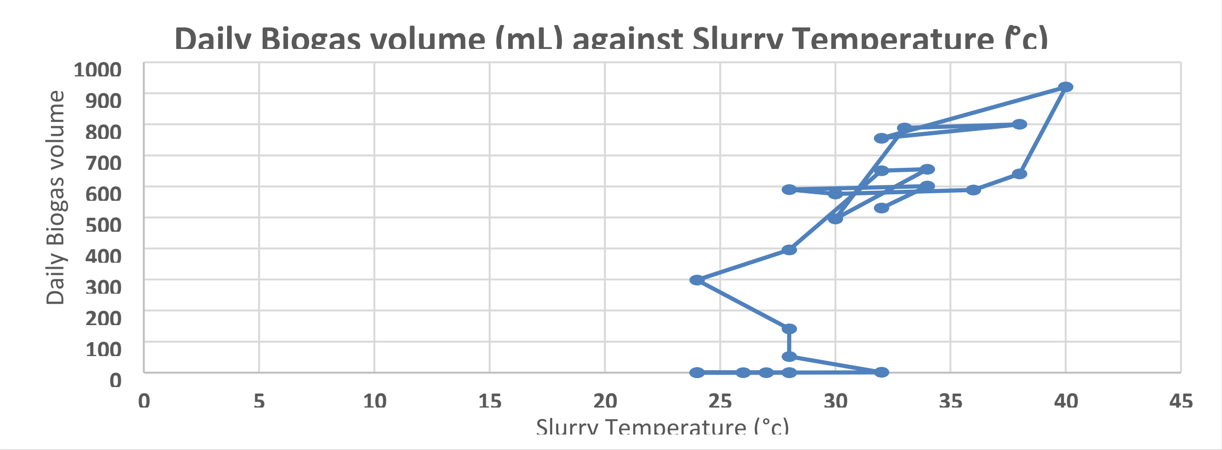

Figure 15: Graph of daily gas volume versus slurry temperature

Correlation Analysis of the Data

Table11: Spearman Product Moment Correlation

Time(days)	X	Y	X^2	Y^2	XY
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	4.0	0	16.00	0
7	0	3.4	0	11.56	0
8	0	1.3	0	1.69	0
9	0.52	3.3	0.27	10.89	1.72
10	1.41	6.6	1.99	43.56	2.72
11	2.98	5.8	8.91	33.64	17.33
12	3.95	6.2	15.64	38.44	24.52
13	6.50	4.3	42.43	18.49	27.98
14	6.55	6.8	42.95	12.25	44.57
15	4.95	4.3	24.55	18.49	21..31
16	7.88	3.5	62.14	12.25	27.59
17	8.00	7.3	64.05	53.29	58.42
18	7.55	6.9	57.06	47.61	52.12
19	9.20	5.2	84.71	27.04	47.86
20	6.40	2.4	41.02	5.76	15.37
21	5.88	1.3	34.66	1.69	7.65
22	5.75	1.6	33.14	2.59	9.21
23	5.89	1.4	34.66	0.96	8.24
24	6.00	2.7	36.11	7.29	16.25
25	5.30	3.5	28.12	12.25	18.56
	$\sum x = 94.76$		$\sum x^2 = 612.36$		$\sum xy = 401.41$

Using Pearson Product Moment correlation: x is the daily volume of gas obtained from the constructed digester and y is the daily gas volume obtained from the reference digester. Here, we tend to quantify the strength and directions of a linear relationship between the volumes of biogas produced with the constructed digester and the reference digester. Using the Pearson correlation formula, we obtain r value of -1.13. The negative value of the correlation coefficient (r) indicates a relationship between the two values. The very small value of r suggests that on average the value is lower than the actual value and this could be interpreted based on the size of the digesters. The constructed digester is 25L capacity while the reference digester is 45L capacity which implies that volume of waste loaded to the constructed digester is far below that of the reference digester and this volume of mass differences result in the low volume of gas produced in the constructed digester compare to the reference one.

Error Analysis and T-test Statistic

The error analysis was carried out on the locally constructed digester to test its accuracy with respect to other selected digester designs. This was done by calculating the mean bias error

(MBE), root mean square error (RMSE), and the mean percentage error (MPE) defined as follows:

$MBE=sum(V_{iRD}-V_{iCD})/n.$ 14

$RMSE=\{[sum(V_{iRD}-V_{iCD})^2]/n\}1/2$ 15

$MPE=\{[sum(V_{iRD}V_{iCD})/V_{iRD}]\times 100\}/n$ 16

$T=[(n-1)MBE^2/(RMSE^2-MBE^2)]1/2$ 17

Where V_{iRD} and V_{iCD} are the ith (i=1, 2, 3, 4....n)

Volume of Biogas produced by the reference and constructed digester respectively while n is the total number of observations (25 days).

Here, we tend to access the constructed digester, the design and experimental procedure to satisfy the values obtained with the constructed digester. Mean Bias Error (MBE) reflects the average differences between the reference digester and constructed one. A positive MBE suggest overestimation while a negative MBE indicates underestimation. The closer the MBE is to zero, the better .hence the negative value of MBE(-0.55) obtained in this result indicate good performance of the constructed digester in terms of bias.

In the result for root mean square, (RMSE) and mean percentage error (MPE) to access the accuracy of values obtained, the constructed digester has a lower value of MPE and RMSE which indicates higher accuracy while higher values suggest greater error. 4.12 and 2.75 are obtained as value of the mean percentage error(MPE) and root mean square error (RMSE) of the volume of gases obtained These moderate values suggest a good level of accuracy even though that the volume of the two digester were not the same. In the estimated t-value of the two digesters, value 0.92 was obtained indicating there is a little significance differences between the volume gases obtained with the constructed digester and that of the reference digester- as a large t-statics suggests a greater difference between the groups compared.

Summary

A 25-litres plastics digester was fabricated for anaerobic digestion of locally available biomass. For testing of the functionality of the digester, it was used to digest pigeon pea waste, rice straw and donkey rumen liquor obtained locally to investigate the energy prospects in the feed stocks under a retention period of 25 days. It was discovered that gas production varied with slurry temperature. As the experiment was carried out during the rainy season between April to May 2025, the minimum and maximum ambient temperature within the retention period are 23^0C and 36^0C respectively. The importance of biogas as a source of alternative energy has been encouraged and it is the focus of this research work. This constructed plastic digester can generate up to 5.2 liters of biogas when loaded with waste at the required ratio under standard temperature and pressure (STP) of gas per day. The biogas produced can combust exactly like a liquefied natural gas (LNG) making it suitable for domestic and other applications. The study have also investigated other parameters like the effect of PH of the waste, effect of ambient and slurry temperature to volume of gas produced. This can be obtained from the graphs of these parameters.

Conclusion

The prototype bio digester constructed was used to produce 9,461mL cumulative biogas volume and is capable of producing up to 5. 2 Liters of biogas per day at optimum temperature, which is enough for supplementing the energy needs of a family. The study has shown that biogas can be produced from mixture of pigeon pea waste, rice straw and donkey rumen liquor.The use of plastic and the design adopted for the digester is suitable for areas with extreme temperature change like Nigeria.The over all results affirmed the viability of co-digesting agricultural and animal wastes for sustainable energy production, offering a cost-effective solution for waste management and environmental conservation in Nigeria. The research has also shown that the anaerobic digestion of agricultural waste to biogas is economically variable and has vast employment opportunities as contrustion of the digester can serve as an employment.

Recommendations

Based on the result of this study, the following recommendations are made:

1. Further work should be carried out using this feed stocks and higher volume of water to dissolve them since their dry nature shows that they have less moisture content. This is to further investigate the late start of gas production and the relatively small cumulative gas volume.
2. It is advisable that users of this digester should place it outside for optimal temperature if there is no special heating system provided. This is because the sun rays will be providing optimal temperature that would lead to high volume of gas production
3. Since bio digester can reduce the cost of purchasing chemical fertilizers by rice farmers through the convection of their waste to manure. Government should empower local farmers with bio digester so that they can convert their farm waste to wealth.
4. Sensitization and biogas education should be carried to local farmers and rural dwellers to discourage indiscriminate dumping of waste as they can be turned to energy.
5. There should be intensified effort to carry out research on the design and fabrication of biogas burner.

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