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Investigation of Biogas Energy Derivation from Anaerobic Digestion of Different Local Food Wastes in Nigeria

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Abstract

This study was carried out to determine the derivative energy (biogas) from different food waste substrates. A fixed mass (5kg) of different food substrates and distilled water (5kg) were anaerobically digested in the ratio of 1:1, and their derivable energy were measured respectively for raw and purified biogas. Food substrates used for the process includes Beans, Rice, Yam, Fufu, Ripe Plantain, Garri, Corn, Unripe Plantain, Sweet Potatoes, Ripe Banana, Pineapple and Water Melon, but Garri yielded the highest raw biogas of 140g and highest purified biogas of 110g. This was followed by Fufu and Yam which yielded raw biogas of 120g and purified biogas of 90g. Among the aforementioned substrates digested, Sweet potatoes had the lowest raw biogas yield of 70g with the lowest purified biogas yield of 50g. It was observed that pH of feedstocks before digestion varied between 6.8 and 7.2, whereas, pH of the same feedstocks after digestion varied between 7.4 and 7.7, indicating that the by-product can be useful as a valuable product for compost manure after biogas recovery. Hence, this study has shown that biogas can be produced from different food waste, but some food waste has a higher biogas energy potential than other food waste.

Keywords: Biogas, Energy, Anaerobic digestion, Food substrates, Distilled water.

1. Introduction

Solid Waste generation is one of the most significant environmental challenges bedevilling Nigerian cities and the wellbeing of its inhabitants. Solid wastes are unwanted materials arising from human, animal or plant activities disposed as waste because it has no consumer value to municipal authorities [1]. Ifeanyi [2] reported that certain human activities such as open dumping of biodegradable waste materials can result Green House Gas (GHG) emissions which are the principal cause of climate change. Intergovernmental Panel on Climate Change (IPCC) 2001, defined climatic change in the United Nations Framework Convention on Climate Change (UNFCCC) as a change in climate that can alter the composition of the global atmosphere as a result of human activities. Although solid waste may be an asset when properly managed, the rate at which solid waste is generated in Nigeria is increasing tremendously in recent times as a result of population growth, consumption rate, industrialisation, socioeconomic development etc. [3].

Nigeria is the 6th most populous country in the world with estimated population of about 178 million [4], and since rapid human population growth is a key factor influencing the rate of waste generation, Nigeria is not an exception. For example, Adewumi [5] reported that over 0.58kg of solid waste is generated per person per day in Nigeria. Going by this figure, the total amount of waste generated daily in Nigeria can be estimated at about 103,240,000 Kg/day (103,240 tonnes/day). In addition, Ogwueleka [6] reported that more than 25 million tonnes of solid waste is generated annually in Nigeria, with average rate of generation ranging from 0.44 kg/cap/day in rural areas to 0.66 kg/cap/d in urban areas.

Considering the rate of solid waste generation and its effects on Nigerian cities, it is important to pay attention to Sustainable Development Goals (SGDs) and align its framework with the country's development plans, as this can go a long way in alleviating poverty, providing sustainable energy, securing our planet for present and future generation etc [7]. Energy is generally important for the growth and development of any society and should not be wasted because it can provide the essential benefits required for the wellbing of any given economy [8]. The growth and development of Nigeria's economy is currently dependent on fossil based fuel such as natural gas and crude oil. Although Nigeria exist as the 8th largest oil exporter in the world, with natural gas reserves accounted for about 5.2 trillion cubic metres, making it the world's 7th largest reserve of natural gas and the largest in Africa, demand for energy in Nigeria

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continues to increase rapidly (even with declining prices of oil and gas) due to insufficient energy for household consumption and to offset the ongoing reforms (generation, transmission and distribution of electricity) in the power sector of Nigeria [9, 10].

According to Akinlo [11], Electricity generation, transmission and distribution account for less than 1% of Nigeria's Gross Domestic Products (GDP). World Bank [12], reported that about 40% of Nigerian populace benefit from grid electricity supply, which is generally not reliable and often result in power outages.

However, tackling the challenges posed by energy crisis in Nigeria would have to be a combine effort where Nigerian inhabitants begin to think and embrace technologies developed towards sustainable energy sources through which it can partner with the government or private energy sectors. One way of acquiring sustainable energy for the country Nigeria is looking inward at energy generated from organic waste materials (biogas) which is largely available in Nigeria. Organic materials such as food waste, animal excreter and generally decomposable materials are known for their energy potentials in terms of biogas which as a result of the breakdown of organic materials can be obtained. Ukpabi et al. [13] concluded from their investigation into biogas production using Cow Dung and Food Waste that biogas can be used as a fuel, for cooking and the solid digested substrates can be used as organic compost. Nallamothu et al. [14] studied the purification and storage process of biogas, a study that led to the conclusion that purification of biogas can greatly improve the calorific value of the gas. Faisal et al. [15] simulated the anaerobic digestion of food waste and indicated that biogas produced from food waste can be used for electric generation, heating homes or as vehicular fuel.

The derivable energy potential from different food waste was evaluated in this study.

2. MATERIALS AND METHODS

The experimental setup comprised a bio-digester equipped with control valves at the inlet and outlet, biogas gas extraction hose and pressure gauge (5 bar). The experimental setup also consisted of biogas scrubbing units interconnected with plastic hoses in which gases produced as a result of substrate decomposition passes through prior to entering the gas storage vessel. Figure 1 represents a test scheme showing all the necessary steps for biogas production. In some anaerobic digestion process where the gas pressure inside the bio-digester is not high enough to flow into storage vessels, automatic or manually operated compressors are can be employed to evacuate the gas into storage vessels. As shown in Figure 2, the first scrubbing chamber contained distilled (H_2O) to absorb Carbon dioxide (CO_2) which is the primary impurity present in biogas, whereas, the second scrubbing chamber contained Type B silica gel which is a moisture absorbent material that was used in absorbing moisture content present in the biogas. Deflated motorcycle tube of known mass (496g) was mounted right after the silica gel scrubber chamber to serve as storage vessel for the biogas produced which in the process of entering the tire tube caused it to inflate.

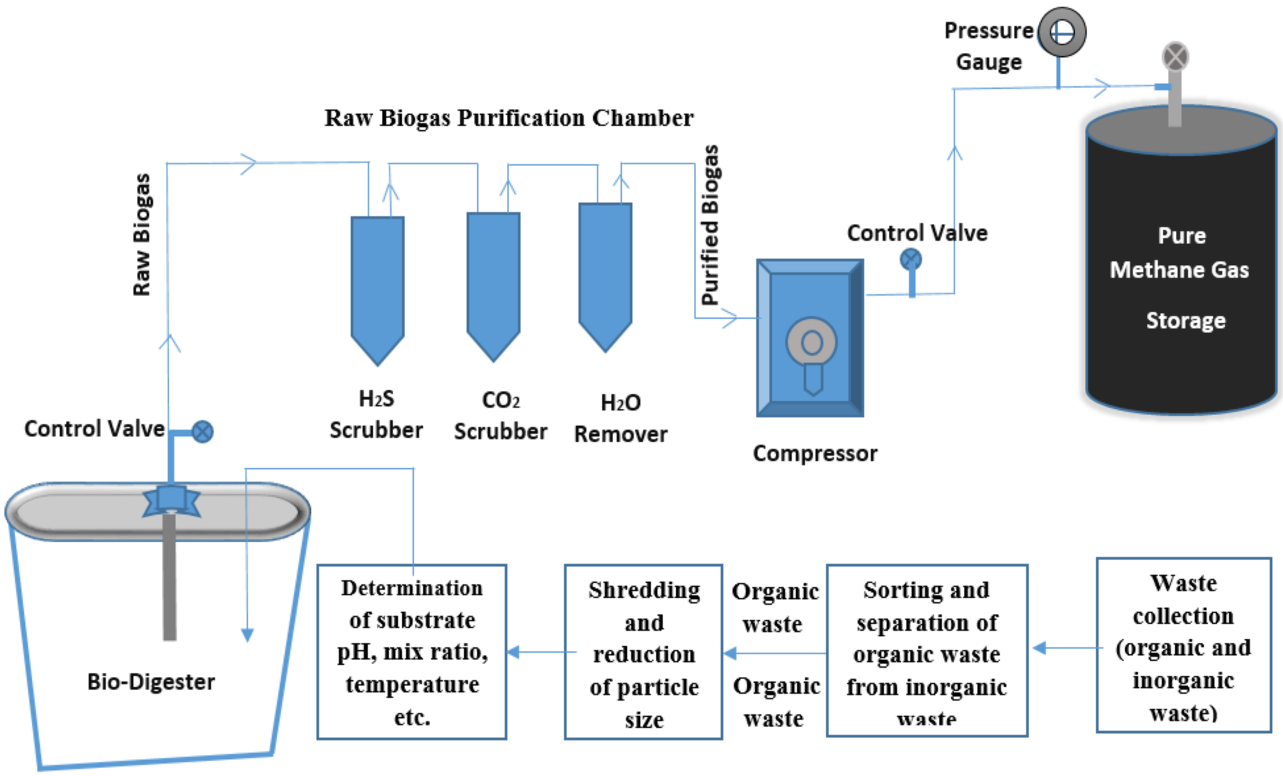

Figure 1. A Test Scheme showing the necessary Steps for Biogas Production

Figure 2. Experimental Setup for Anaerobic Digestion of Food Waste

2.1. Experimental Procedure

Experimental procedure for biogas production from different food waste substrates is highlighted as follows;

i. 5kg of water was added to 5kg of cooked individual food substrate.
ii. The water and food substrate were thoroughly mixed together until the mixture became slurry.
iii. pH of the food waste substrates were tested before and after digestion using digital handheld pH meter.
iv. The water and food mixture was poured into the bio-digester through the inlet and after which, the digester inlet valve was closed.
v. The initial gauge pressure was recorded at 0.0 bar.
vi. After digestion, the raw and purified biogas collected in the motorcycle tube was measured using weighing balance.
vii. After digestion, the raw and purified biogas collected in the motorcycle tube was also analyzed using Optima 7 Biogas analyser.
viii. The same procedure were repeated for individual food substrate feed to the digester.

2.2. Biogas Analyser (Optima 7 Biogas)

Optima 7 biogas is an electrochemical cell device capable of deriving electrical energy from chemical reactions. In this case the cell reacts with the percentage composition of the gas to be analysed. This in turn produces an electrical signal proportional to the concentration, where the analyser then translates this signal in to a physical concentration value. The main components are an infrared source (lamp), a sample chamber or light tube, a wavelength sample chamber and gas concentration is measured electro-optically by its absorption of a specific wavelength in the infrared (IR). The IR light is directed through the sample chamber towards the detector. The detector has an optical filter in front of it that eliminates all light except the wavelength that the selected gas molecules can absorb. Ideally other gas molecules do not absorb light at this wavelength, and do not affect the amount of light reaching the detector to compensate for interfering components. Optima 7 Biogas analyser also comprises a Teflon filter for protection against dirt and soiling, with robust stainless steel connectors (gas ports) through which one end of a hose was connected while the other end was connected to the motorcycle tube which was used to store the biogas produced from different food substrates as shown on the experimental setup in Figure 2. Different gas composition present in the biogas exhibited cross sensitivity in the infrared spectrum, and that enabled the percentage composition of the biogas to be measured. Technical specifications of Optima 7 Biogas analyser and pH meter (pH-2011) are presented in Table 1. As shown in Table 2, the raw and purified biogas composition produced from 5kg of cooked beans and 5kg of water in a mix ratio of 1:1 is shown in Figure 3.

Figure 3. Biogas Composition Measurement Handheld Device showing Raw and Purified Biogas Composition

Table 1. Technical specifications of the biogas analyser and pH meter

Pen Type pH Meter (pH-2011)		Optima 7 Biogas	
Range	0.00-14.00 pH	Temperature	5ºC-45ºC
Resolution	0.01 pH	Battery	Lithium-ion Battery 6-8 Hours
Accuracy	±0.1 pH	Weight	750 g with 7 Sensors
Battery	4x1.5 V (AG-13)	Dimension	110mmx225mmx52mm
Temperature Compensation	0ºC – 50º C	CO_2 Accuracy	±0.3%
Dimension	151mmx33mmx20mm	CH_4 Accuracy	±0.3%
Weight	53 g	H_2S Accuracy	±5 ppm
Acidity	1-6	Gas Flow Velocity	1-40 m/s
Alkalinity	8-14	Power specification	90-240 Vac/50-60 for battery charging with USB port
Neutrality	7	Biogas Sampling Line	3x2 mm Viton with 5 m length and stainless steel gas inlet port

3. RESULTS AND DISCUSSION

The results obtained from the experimental procedure used for the anaerobic digestion process of different food substrate in this study is presented in this section. Also, the results obtained from each experimental procedure is tabulated in Table 2 which shows the variation in terms of biogas potential from each food waste subjected to anaerobic digestion process from the experimental setup shown in Figure 2. The graphs in Figure 4 and 5 are presented to show the relationship between the biogas quantity and the pH values which biogas was recovered from the experimental set-up. Each point on the graph can be traced with respect to the values presented in Table 2.

Table 2. Results of Biogas Production from Different Food Waste Substrates

Raw Biogas				Purified Biogas				pH-Reading	
HRT (Days)	Biogas Yield (g)	Pressure (Bar)	Biogas Composition (%)	HRT (Days)	Biogas Yield (g)	Pressure (Bar)	Biogas Composition (%)	pH Before Digestion	pH After Digestion
Substrate - Beans									
14	20	0.13	54% CH_4, 37% CO_2, 1.6% N_2, 6% H_2, 0.5% H_2O.	14	10	0.13	96.2% CH_4, 0.8% CO_2, 0.2% N_2. 0.1% H_2O	7.1	7.6
15	50	0.16		16	40	0.17			
16	30	0.14		17	20	0.12			
18	10	0.17		18	10	0.14			
Sum	110		99.1		80		97.3		
Substrate - Fufu									
21	20	0.12	54% CH_4, 37% CO_2, 1.8% N_2, 6% H_2, 0.6% H_2O.	21	20	0.13	97.5% CH_4, 0.6% CO_2, 0.3% N_2, 0.1% H_2.	6.9	7.5
22	30	0.14		22	10	0.12			
25	50	0.17		25	40	0.16			
26	20	0.13		26	20	0.13			
Sum	120		99.4		90		98.5		
Substrate - Yam									
12	30	0.14	56% CH_4, 39% CO_2, 1.5% N_2, 2% H_2, 0.8% H_2O.	12	20	0.13	97.2% CH_4, 0.6% CO_2, 0.3% N_2, 0.1% H_2.	7.1	7.5
14	50	0.17		13	40	0.15			
16	10	0.12		15	10	0.12			
17	30	0.14		17	20	0.13			
Sum	120		99.3		90		98.2		
Substrate - Ripe Plantain									
14	10	0.12	59% CH_4, 35% CO_2, 1.6% N_2, 3% H_2, 0.6% H_2O.	14	10	0.12	97.4% CH_4, 0.5% CO_2, 0.2% N_2, 0.2% H_2.	7.1	7.5
15	30	0.14		15	20	0.13			
16	50	0.17		16	40	0.16			
17	20	0.13		17	10	0.11			
Sum	110		99.2		80		98.3		
Substrate - Garri									
12	20	0.13	58% CH_4, 36% CO_2, 2.1% N_2, 2.6% H_2, 0.9% H_2O.	11	20	0.12	98.1% CH_4, 0.3% CO_2, 0.2% N_2, 0.1% H_2.	7.1	7.7
14	40	0.15		13	50	0.15			
15	30	0.14		14	10	0.13			
16	50	0.16		17	30	0.12			
Sum	140		99.6		110		98.7		
Substrate - Corn									
13	10	0.12	55% CH_4, 40% CO_2, 1.6% N_2, 2.1% H_2, 1% H_2O.	13	10	0.12	96.8% CH_4, 0.9 % CO_2, 0.3% N_2, 0.2% H_2, 0.1% H_2O	7.2	7.6
14	40	0.15		14	30	0.14			
16	40	0.15		16	30	0.14			
17	20	0.13		17	10	0.12			
Sum	110		99.7		80		98.3		
Substrate – Unripe Plantain									
13	20	0.13	57% CH_4, 39% CO_2, 1.2% N_2, 1.7% H_2, 0.8% H_2O.	12	10	0.12	96.2% CH_4, 0.8% CO_2, 0.5% N_2, 0.6% H_2.	6.9	7.4
14	30	0.14		14	20	0.13			
16	10	0.12		15	10	0.12			
18	40	0.16		17	30	0.14			
Sum	100		99.7		70		98.1		
Substrate – Sweet Potatoes									
17	10	0.12	52% CH_4, 42% CO_2, 1.7% N_2,	16	10	0.12	94.5% CH_4, 0.6% CO_2,	7.1	7.5
18	20	0.13		17	30	0.14			
19	30	0.14		18	10	0.12			

20	10	0.12	1.8% H_2, 1.2% H_2O.	19	0	0	0.8% N_2, 0.9% H_2.		
Sum	70		98.7		50		96.8		
Substrate – Rice									
11	20	0.13	54% CH_4, 40.3% CO_2, 1.7% N_2, 2% H_2, 1.2% H_2O.	11	10	0.12	96.1% CH_4, 0.8% CO_2, 0.7 % N_2, 0.6% H_2.	7.0	7.4
13	40	0.15		13	30	0.14			
14	30	0.14		14	20	0.13			
15	10	0.12		15	10	0.12			
Sum	100		99.2		70		98.2		
Substrate – Ripe Banana									
15	10	0.12	55.2% CH_4, 39.6% CO_2, 1.4% N_2, 1.5% H_2, 1.2% H_2O.	16	10	0.12	96.3% CH_4, 0.5% CO_2, 0.4% N_2, 0.7% H_2.	7.1	7.5
16	20	0.13		17	30	0.14			
18	40	0.16		19	20	0.13			
20	20	0.13		21	10	0.12			
Sum	90		98.9		60		97.9		
Substrate – Pineapple									
14	20	0.13	52.3% CH_4, 42.1% CO_2, 1.7% N_2, 1.6% H_2, 1.4% H_2O.	14	10	0.12	96.1% CH_4, 0.6% CO_2, 0.7% N_2, 0.6% H_2, 0.1% H_2O.	6.8	7.6
15	40	0.15		15	20	0.13			
16	10	0.12		17	10	0.12			
17	10	0.12		18	10	0.12			
Sum	80		99.1		50		98.1		
Substrate – Water Melon									
10	20	0.13	50.8% CH_4, 42.5% CO_2, 1.4% N_2, 1.7% H_2, 2.4% H_2O.	10	10	0.12	95.4% CH_4, 0.7% CO_2, 0.6% N_2, 0.8% H_2, 0.1% H_2O.	7.0	7.4
12	30	0.14		12	20	0.13			
13	20	0.13		13	10	0.12			
14	10	0.12		14	10	0.12			
Sum	80		98.8		50		97.6		

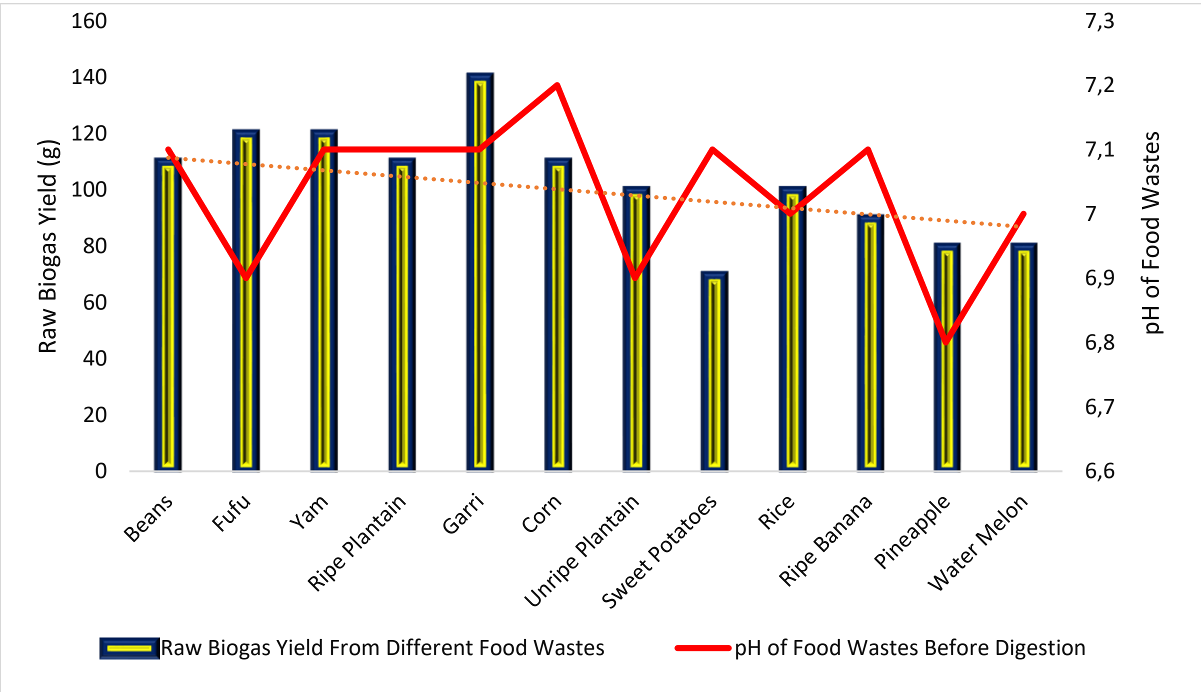

Figure 4. Raw Biogas from Different Food Substrates

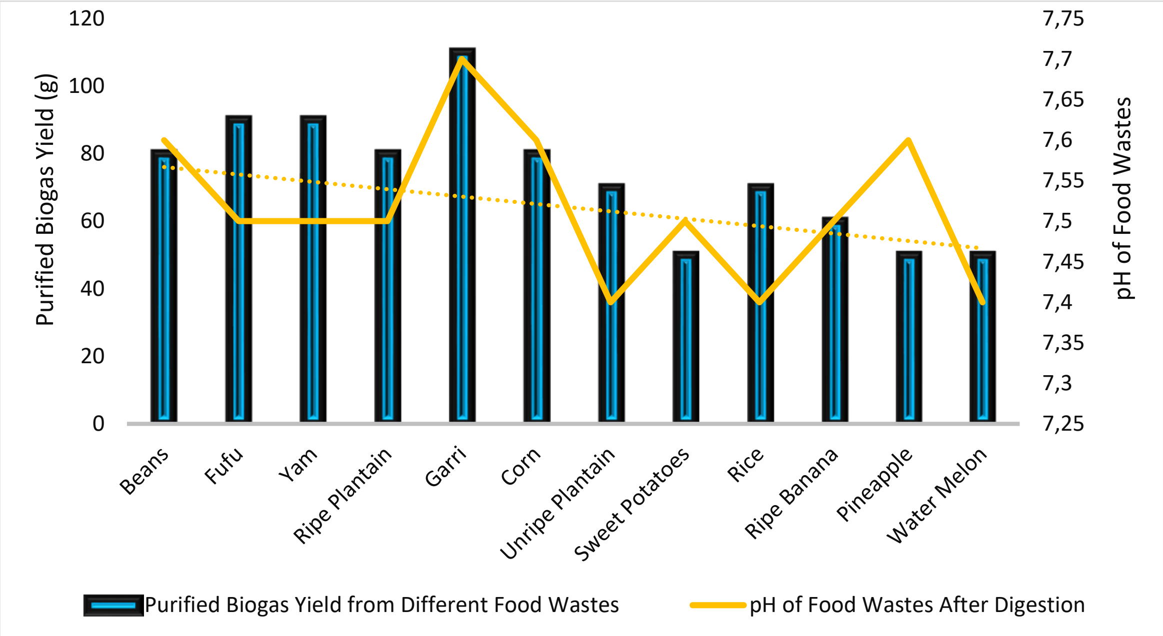

Figure 5. Purified Biogas from Different Food Substrates

Hydraulic Retention Time (HRT) in Table 2 represents the duration in days from when each food waste was charged into the bio-digester to the period when biogas production starts and ends. Table 2 represents biogas yield from 5kg of 12 different food substrates including Beans, Rice, Yam, Fufu, Ripe Plantain, Garri, Corn, Unripe Plantain, Sweet Potatoes, Ripe Banana, Pineapple and Water Melon. Figure 4 and 5 are graphical representation of biogas for each individual substrate. While the total amount of raw biogas yielded by Garri waste substrate was 140g, this further reduced to 110g when allowed to pass through the water scrubber and silica gel particles. Using Optima 7 biogas composition determining device, it was observed that the raw biogas obtained from garri waste substrate predominantly contained 58% CH_4, and 36% CO_2 alongside other gases in fractions, whereas, the purified biogas obtained from garri waste predominantly contained 98.1% CH_4 with other gases in minute percentages. CH_4 is dominant in the purified biogas from garri waste because of 36% CO_2 in the raw biogas was absorbed by distilled water contained in one of the scrubbers, thereby giving room for CH_4 to dominate while the CO_2 and water interaction became carbonic acid (H_2CO_3). A significant change was also observed in terms of pH of the garri waste substrate which before digestion increased significantly from 7.1 which in the pH ranking is considered by Soil Survey Division [16] as neutral to 7.7 which is considered as slightly alkaline. This implies that as the substrate undergoes digestion, the pH slightly increases while simultaneously producing biogas; and when the pH increases further in the alkaline range, the substrate no longer contain nutrients for the microorganisms to feed on. At this stage microbial activity may reduce or stop as well as biogas production. This is in conformity with the studies carried out by Mata-Alvarez et al [17]; Murto et al. [18]; Stabnikova et al. [19]; Zhang et al. [20]. In subsequent anaerobic digestion processes in this study such as that of Fufu (5kg) and Yam (5kg) waste substrate which their biogas yielding rates were the same, both substrates yielded a total raw biogas of 120g with purified biogas of 90g, following biogas yield from 5kg of garri. In terms of the major compositions, raw biogas from Fufu waste contained 54% CH_4, and 37% CO_2 while the purified biogas predominantly contained 97.5% CH_4, whereas, the major compositions of raw biogas from Yam waste contained 56% CH_4 and 39% CO_2 while the purified biogas predominantly contained 97.2% CH_4, slightly lower than purified biogas from Fufu by 0.3% and garrii by 0.9%. pH obtained before digestion of Fufu was 6.9 while that of Yam was 7.1 which are both in the neutral range whereas, pH for both substrates increased significantly to 7.5 after digestion which slighly alkaline. Orhorhoro (2016) [21] investigated the effect of pH on anaerobic digestion of organic waste in Benin City, Nigeria, where pH values in the range of 5.2-9.6 was obtained for different samples. Result of the findings indicated that pH values in the range of 7.0-7.4 are optimum for biogas production from anaerobic digestion process which are not quite different from the pH values obtained in this experiment. However, pH of the distilled water used as one of the purifying reagents was tested after purification of the biogas and pH ranging from 3.4-4.1 which is highly accidic was obtained. This correlates with the findings of Ebunilo et al. [22] were water acidity test after biogas purification was found to b in the range of 3.2-6.7. Some of the benefits of biogas purification is that, it minimizes the rate of organic waste disposal at open dumpsites, diversifies the waste treatment methods in Nigeria and also controls the emision of GHGs into the atmosphere. On this basis, Ikpe et al. [23] reported that if waste disposal at open dumpsite continues in Nigeria, organic waste disposal at dumpsites is expected to increase the proportion of waste in Nigerian dumpsites as well as GHG emissions. For example, open dumpsites are the third largest anthropogenic source of GHGs, accounting for about

13-20% of global methane (CH_4) emissions or over 223 Million Metric Tons of Carbon dioxide (CO_2) [24], of which CH_4 is 21 times more potent than CO_2 when released into the atmosphere. This can also help in minimizing ground water contamination, irritating odour, poor aesthetics, attraction of vermin and pests, sever health risk, breeding of disease spreading vectors such as *mastomys natalensis* (responsible for Lassa fever) etc. [25]. Using the same 5kg for subsequent digestion of other food waste substrates such as Beans (yielded 110g of raw biogas and 80g purified biogas), Ripe Plantain (yielded 110g of raw biogas and 80g purified biogas), corn (yielded 110g of raw biogas and 80g purified biogas) yielded similar quantities of raw and purified biogas with variable compositions and pH values. However, using the same 5kg for subsequent digestion of other food waste substrates such as Unripe Plantain (yielded 100g of raw biogas and 70g purified biogas), Rice (yielded 100g of raw biogas and 70g purified biogas) yielded similar quantities of raw and purified biogas with different compositions and pH values. 5kg of Ripe Banana yielded 90g of raw biogas and 60g purified biogas with different compositions and pH values, whereas, 5kg of Pineapple and Water melon yielded 80g of raw biogas and 50g of purified biogas with different compositions and pH values; but Sweet potatoes yielded the lowest amount of raw biogas (70g) compared to other substrates with 50g of purified biogas similar to that of Pineapple and Water melon, with different compositions and pH values. At each evacuation and purification phase, it was observed that gas molecules passing through a stream of distilled water in the water scrubber was characterized by continuously agitated bubbles within the scrubber vessel. This was also used as a determining factor to know when the gas is no longer flowing to the storage tube since the gas pressure was relatively low and the pressure gauge reading was infinitesimal as shown in Table 2. The anaerobic digestion process in this study was carried under mesophilic temperature range. There are primarily two temperature conditions that can provide optimum decomposition of biodegradable materials for methane production, and this includes mesophilic and thermophilic temperature condition. Generally, mesophilic range is between 20^o-40^{o}C, but optimum temperature for anaerobic digestion under mesophilic condition from 35^{o}C and above. On the other hand, thermophilic temperature range is about 50-65^{o}C, or at elevated temperature up to 70^{o}C [26]. However, at temperature below 20^{o}C which is the psycrophilic temperature, the anaerobic digestion process is relatively slow and may require more than three times the average mesophilic temperature for one digestion cycle. Mesophilic species is usually higher in number and the condition is considered to be more stable compared thermophilic, whereas, thermophilic condition is considered to be less stable with high energy requirement to maintain the high temperature which in turn facilitates digestion rate and increase biogas yield [27, 28]. Higher temperatures particularly in the thermophilic range often result in higher rates of biochemical reactions due to increasing growth rate of methanogenic microorganisms. Moreover, it can significantly increase biogas yield and also produce higher solubility and lower viscosity. This is in line with the findings of Ramaraj and Unpaprom [29] on the effect of temperature on the performance of biogas production from duckweed.

4. CONCLUSION

This study investigated the derivable energy potentials in terms of biogas production from different food waste substrate in Nigeria using locally designed anaerobic digester. It was shown that locally designed anaerobic digester could serve as alternative to open dumping of organic waste materials and harnessing of biogas during its biodegradation. The anaerobic digestion process took place under mesophilic temperature (25^{o}C-33^{o}C) whereas the range of pH at which the process took was between 6.8-7.7 which implies that the condition was between the neutral and slightly alkaline range. Optima 7 biogas handheld device was used to measure the percentage composition of both raw and purified biogas produced from each substrate of which the recoverable quantity of methane for Garry and Fufu and Yam outnumbered that of all other substrates. This may have been due to the high carbohydrate concentration in these substrates which is broken down during hydrolysis. This study has also shown that methane (CH_4) concentration in purified biogas is higher than its concentration in raw biogas, but carbon dioxide (CO_2) concentration in raw biogas is higher than its concentration in purified biogas which is an indication of the relative effectiveness of the bio-waste digester setup and purification system.

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