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Efficiency of a modified plastic tank as a bio-degradation system in Sub-Saharan African countries

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Abstract: The efficiency of three modified plastic digesters (3.6 m^3 each) using food waste for biogas generation in cooking food was evaluated. The experiment was laid out based on a completely randomised design. A plastic tank was modified as a biodegradation system for food waste digestion to generate a biogas. The biochemical and chemical oxygen demand ranged from 44.58 to 49.62% and 130.42 to 139.20%, respectively, before digestion, but decreased significantly ($P < 0.05$) after digestion. The pH of the fermenting slurry fluctuated (6.24–6.86) and an average biogas of 0.574 m^3 (505–601 $L \cdot day^{-1}$) per day was generated from the three experimental waste proportions which would be sufficient to cook three meals per day for 3 to 4 people. The methane gas significantly increased ($P < 0.05$) while the carbon-dioxide significantly decreased ($P < 0.05$) at the peak of the biogas production. The generated biogas significantly cooked ($P < 0.05$) faster than kerosene, but not faster than liquefied petroleum gas. The flammable biogas generation and high significant ($P < 0.05$) percentage change in the physico-chemical properties of the wastes after digestion implied high efficiency performance of the digesters modified from the plastic tanks.

Keywords: biodigester; biogas; cassava; cow dung; methane

In Sub-Saharan African countries, research in biogas technology has been invigorated by the efforts of various international organisations and foreign aid agencies through their publications, meetings and visits, as this could be the cause of an increased construction of biodigesters in the area (Mshandete, Parawira 2009; Parawira 2009; Ngumah et al. 2013; Olugasa et al. 2014). Studies have already been carried out on the biogas generation from cow dung, chicken droppings, food waste, dairy waste, fruit and vegetable waste using biogas digesters (Mshandete, Parawira 2009; Parawira 2009; Nwankwo et al. 2017).

Most digesters such as fixed dome, floating drum and plug flow digesters have been installed in several Sub-Saharan African countries, utilising a variety of waste such as food, animal, human, municipal and industrial waste, but few of them are operational, which are also unreliable and show poor performance in most cases because of the economical, technical and social-cultural constraints (Akinbami et al. 2001; Mshandete, Parawira 2009). Thus, there is a need to learn from the experiences, adapt the biogas technology from Europe and Asia for local circumstances through research of more efficient digesters to improve both the biogas yields and the reputation of this technology (Mshandete, Parawira 2009; Parawira 2009; Mwirigi et al. 2014). Effort should also be made to improve the technical performance, social acknowledgment, economic benefits and environmental impact in order to promote the biogas innovations in energy poor communities (Akinbami et al. 2001; Mshandete, Parawira, 2009; Garfi et al. 2016).

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In modern times, there is a rise in the demand for energy and to explore and exploit new sources of energy which are renewable as well as those that are environmentally friendly (Mshandete, Parawira, 2009; Nwankwo et al. 2017; Roubík et al. 2018). If properly harnessed, biogas technologies offer a captivating platform for the exploration and utilisation of certain categories of biomass (agricultural waste, animal waste and food waste) as an alternative source of energy as well as replacing an inorganic nitrogen fertiliser with an organic nitrogen one from anaerobic digesters for agricultural use (Opeh, Okezie 2011; Vu et al. 2012; Adeoti et al. 2014). The modification of bio-digesters from plastic tanks for the biogas production using food waste for household use could be the leeway to a cost effective and environmentally friendly energy substitute for cooking foods compared to liquefied petroleum gas and kerosene (Herout et al. 2011). In Nigeria, research into biogas technologies and their practical application has not received the deserved attention thus far (Mshandete, Parawira 2009; Opeh, Okezie 2011). Work has been undertaken by evaluating the efficiency of the biogas digester through physico-chemical studies (Nwankwo et al. 2017). The digester was designed so that the food waste generated at home could be poured directly into the digester for the biogas production for cooking food instead of disposing it as just waste. However, this research focused on evaluating the efficiency of the modified plastic digester using the generated biogas from different types of food waste in cooking food.

MATERIAL AND METHODS

Cow dung, yam peels, cassava peels and vegetable waste were used. The materials used for the bio-digester modification were a black PVC plastic tank (3.60 m^3), a 1" back nut, a 4" back nut, a 4" plastic ball valve, a 4" male adapter, a 4" 45° bend, a 4" PVC pipe, a 1" × ¾ bushing, tapered foam cork, a T joint, a valve, a pressure nozzle, thread tape, a gas hose, a tyre tube, 20 litres gallon, a rubber cork, silicone/PVC glue and a pressure gauge.

Three batches of an experimental anaerobic bio-digestion waste were conducted for 28 days involving 50% cow dung and 50% yam peel and vegetable waste (WB_1), 50% cow dung and 50% yam peel waste (WB_2), 50% cow dung, 50% vegetable waste (WB_3). Each waste was weighed and diluted with water (1 : 3) and anaerobically digested for the same period in three different 3.6 m^3 capacity plastic digesters (Figure 1).

The physico-chemical characteristics (wet basis) and total viable count of the waste were determined (AOAC 2010). The biogas produced was characterised by a portable combustion analyser (RASI 700 BIO EIUK, UK). The generated biogas from each waste was used to cook foods (yams and rice) three times daily and the efficiency of the generated biogas in cooking the food was compared to liquefied petroleum gas and kerosene and the cooking time was determined by the use of a stop watch (Itodo et al. 2007).

The digester cover was designed with a hard foam material. The digester cover was about 0.152 m in height, with a 0.023 m upper diameter and a 0.021 m lower diameter with a wooden handle (0.04 m in diameter and 0.111 m in height). The agitator (mass = 7.84 kg) was made of circular arms (0.24 m in diameter each) joined with an iron steel rod 0.61 m in length to enable the agitator to move to and fro freely (Figure 2). The digester influent chamber was

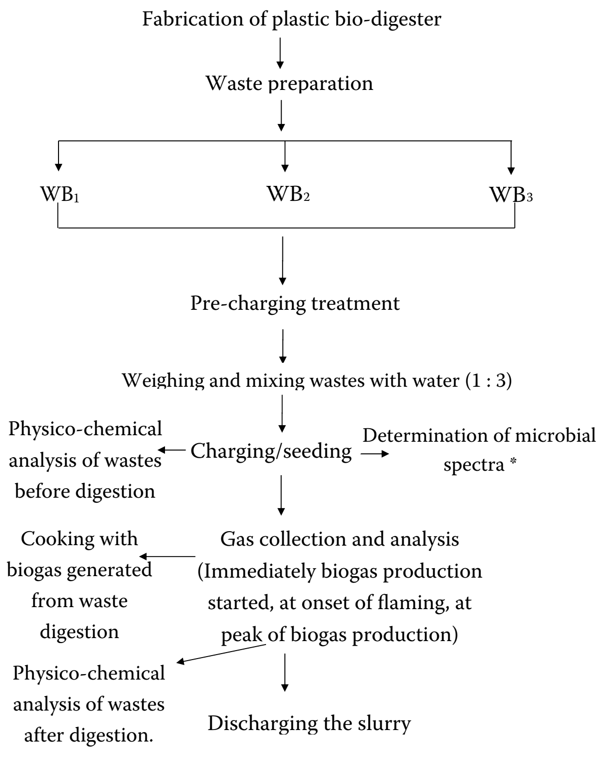

Figure 1. Flow chart for co-digestion of kitchen waste and cow dung for biogas generation

WB_1 – 50% cow dung, 50% yam peel and vegetable; WB_2 – 50% cow dung and 50% yam peel, WB_3 – 50% cow dung and 50% vegetable; * after charging, immediately biogas production started, at the peak of biogas production, at point of discharging

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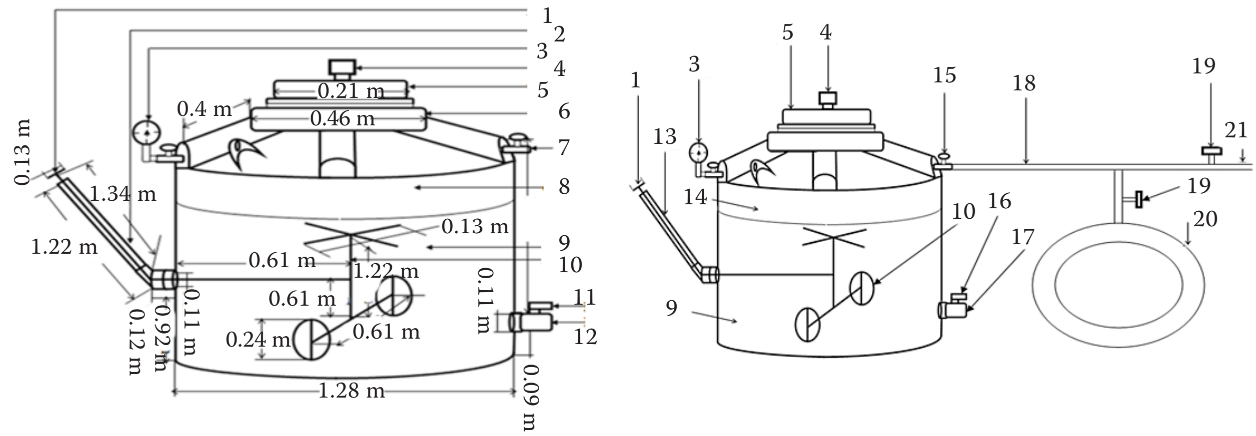

Figure 2. Schematic diagram of digester (A) the fermenation tank and (B) whole digester assamble

1 – agitator handle; 2 –influent chamber; 3 – pressure gauge; 4 – cork handle; 5 – tapered foam cork; 6 – base of the cork; 7 – biogas outlet; 8 –gas collecting chamber; 9 – fermentation chamber; 10 – agitator; 11 – plastic ball handle; 12 – effluent chamber; 13 – slurry inlet; 14 – gas storage chamber; 15 – nido pressure nossle; 16 – ball gauge control; 17 – slurry outlet; 18 – gas hose; 19 – nido valve; 20 – tyre tube for pressure control; 21 – gas outlet

designedwith a 4" (0.11 m) PVC back nut, a 4" (0.11 m) PVC male adapter, a 4 (0.11 m) PVC 45° elbow bend and a 4" (0.11 m) PVC pipe. The agitator handle was allowed to pass through the influent chamber (Figure 2). The effluent chamber was designed with a 4" (0.11 m) PVC back nut, a 4" (0.11 m) PVC male adapter and a 4" (0.11 m) plastic ball valve so that all the slurry could be easily discharged after digestion (Figure 3). Since 75% of the total volume of the digester will be filled with waste and water, then (Equations 1–3):

$$\frac{75}{100} \times \frac{\text{total volume of digester}}{1} = \text{total volume of waste and water} \quad (1)$$

Total volume of digester = 3 600 L

$$\frac{75}{100} \times \frac{3600}{1} = 2700 \text{ L} \quad (2)$$

$$\frac{\text{total volume of waste and water}}{\text{total ratio}} = \text{volume of each ratio} \quad (3)$$

Total volume of waste and water = 2 700 L; since ratio of waste to water is 1 : 3 then the total ratio = 4
From the Equation 3:

Volume of each ratio = 675
Ratio of waste to water = 1 : 3; then the weight of waste = 675 × 1 = 675 kg
Volume of water = 675 × 3 = 2 025 L

The study adopted an experimental design. The experiment was laid out based on a completely randomized design. The data generated were analysed using a one way analysis of variance and an independent *t*-test ($P < 0.05$).

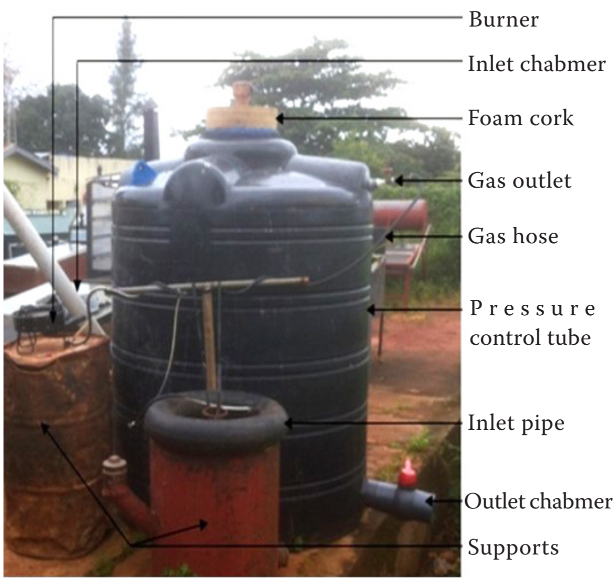

Figure 3. The whole digester assemble

RESULTS AND DISCUSSION

Physico-chemical properties of the waste before and after digestion. The total solids, volatile solids, carbon, free fatty acids, chemical and biochemical oxygen demand decreased significantly ($P < 0.05$) and the moisture content of the different waste increased significantly ($P < 0.05$) after digestion. Similar result was reported by Yadav et al. (2014) which was attributed

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to the activities of the microorganisms for the biogas production. Great variation was found in the moisture content ranging from 78.08 to 80.88% before digestion, but increased after digestion and WB_1 and WB_2 have values close to each other (Table 1). The high moisture content before digestion encourages the movement and contact between the microorganisms and organic molecules (Yadav et al. 2014). The moisture increased due to a decrease in the amount of volatile and total solids (Eze, Agbo 2010; Yadav et al. 2014). The total solids (9.48–12.48%) of the waste were in the range reported to be optimal for biogas production. The total solid was highest in WB_3 which may be as a result of the fibrous nature of the vegetable included in WB_3 and Yadav et al. 2014 reported that slurries of higher total solid concentrations were more acidic than that of lower concentrations. The proteins, carbohydrates and volatile solids were highest in WB_2 before and after digestion. The reduction of the carbon content in the waste after digestion could be due to the production of organic acids (Yadav et al. 2014). The free fatty acids of the waste ranged from 0.06 to 0.10% and decreased significantly ($P < 0.05$) after digestion. The biochemical oxygen demand ranged from 45.41 to 50.58%, while the chemical oxygen demand ranged from 130.42 to 140.80% before digestion. The conversion of the organic matter into a biogas may be reason for the decrease in the chemical and bio-chemical oxygen demand of the waste.

Effect of digestion duration on the total viable count. The total viable count was 3.82×10^7 for WB_1, 2.84×10^7 for WB_2, and 2.42×10^8 for WB_3 immediately after charging, but increased significantly ($P < 0.05$) immediately after the biogas production started (Figure 4). Similar results were reported

Table 1: Physico-chemical properties of the undigested and digested wastes

Parameters	Treatments	Waste blend (%)		
		WB_1	WB_2	WB_3
Moisture	undigested	$78.08^b \pm 0.01$	$75.07^c \pm 1.20$	$80.88^a \pm 0.50$
	digested	$80.64^b \pm 0.20$	$80.04^b \pm 0.27$	$84.76^a \pm 0.70$
Ash	undigested	$4.76^a \pm 0.27$	$4.46^a \pm 0.34$	$4.86^a \pm 0.11$
	digested	$3.45^a \pm 0.40$	$3.29^a \pm 0.24$	$3.20^a \pm 0.70$
Fibre	undigested	$4.25^a \pm 0.30$	$4.47^a \pm 0.40$	$4.82^a \pm 0.70$
	digested	$2.16^a \pm 0.20$	$2.12^a \pm 0.27$	$2.82^a \pm 1.60$
Fat	undigested	$1.11^a \pm 0.40$	$1.03^a \pm 0.30$	$1.01^a \pm 0.11$
	digested	$0.56^b \pm 0.27$	$0.40^c \pm 0.33$	$0.30^c \pm 0.12$
Protein	undigested	$0.92^c \pm 0.30$	$1.24^b \pm 0.54$	$0.81^d \pm 1.14$
	digested	$1.62^b \pm 0.14$	$1.74^a \pm 0.42$	$1.24^b \pm 1.60$
Carbohydrate	undigested	$12.22^b \pm 0.02$	$14.93^a \pm 0.52$	$9.28^c \pm 1.14$
	digested	$10.26^a \pm 0.16$	$11.24^a \pm 0.44$	$6.02^b \pm 0.19$
Total solid	undigested	$9.48^b \pm 0.41$	$10.28^b \pm 0.22$	$12.48^a \pm 0.42$
	digested	$7.36^b \pm 0.21$	$7.48^b \pm 0.51$	$7.46^b \pm 0.48$
Volatile solid	undigested	$7.98^b \pm 0.21$	$8.10^b \pm 0.71$	$6.52^b \pm 0.20$
	digested	$6.10^b \pm 0.31$	$6.17^b \pm 0.31$	$4.26^c \pm 0.64$
Carbon content	ndigested	$5.58^a \pm 0.21$	$3.12^a \pm 0.41$	$3.14^a \pm 0.24$
	digested	$1.16^b \pm 0.40$	$1.24^b \pm 0.06$	$0.08^c \pm 0.52$
Free fatty acid	undigested	$0.08^a \pm 0.20$	$0.10^a \pm 0.041$	$0.06^a \pm 0.22$
	digested	$0.02^c \pm 0.62$	$0.04^b \pm 0.04$	$0.02^c \pm 0.40$
Biochemical oxygen demand	undigested	$50.58^c \pm 0.02$	$47.54^b \pm 0.41$	$45.41^c \pm 0.06$
	digested	$16.48^c \pm 0.41$	$15.20^b \pm 0.11$	$15.42^{bc} \pm 0.31$
Chemical oxygen demand	undigested	$140.80^b \pm 0.71$	$130.42^c \pm 0.22$	$133.12^d \pm 0.72$
	digested	$65.70^c \pm 0.11$	$82.40^a \pm 0.34$	$60.78^d \pm 0.54$

The values are the means ± standard deviation of three determinations; the values in the same row with the different letters with different superscripts are significantly ($P < 0.05$) different; the values in the same column with numbers with different superscripts are significantly ($P < 0.05$) different; WB_1 – 50% cow dung and 50% yam peel and vegetables; WB_2 – 50% cow dung and 50% yam peel; WB_3 – 50% cow dung and 50% vegetables

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by Eze and Agbo (2010), Ofoefule et al. (2010) and Asikong et al. (2016). The initial increase in the microbial load may involve large populations of microorganisms in the hydrolytic and acidogenic phases of the methane biogenesis (Asikong et al. 2016). At the peak of the biogas production, the microbial load increased significantly ($P < 0.05$) more than the initial stage of the biogas production, which were 5.81×10^8 for WB_1, 4.87×10^8 for WB_2, and 4.78×10^8 for WB_3. The higher microbial counts recorded in the waste with WB_1 than the other waste could be due to the nature and varying amount of nutrient contents as this would definitely determine the type of fermentative microorganisms (Asikong et al. 2016). At the point of discharge, the microbial loads decreased significantly ($P < 0.05$) which reduced the biogas production. These observations conformed with the report of Ofoefule et al. (2010) and Asikong et al. (2016). The significant ($P < 0.05$) decrease in the microbial loads at the point of discharge may be due to the fluctuation in the pH, temperature of the slurry, deposition of the microbial metabolites and gradual exhaustion of nutrients in the waste (Asikong et al. 2016).

Biogas composition at the different stages of gas production during waste digestion. The biogas production immediately started the methane (CH_4), which was in range of 45.12 to 47. 34% and the carbon dioxide (CO_2) composition was in range of 39.39 to 41.38%, while the carbon monoxide (CO) was in range of 14.40 to 15.49% (Figure 5). The low percentage of CH_4 shows that the

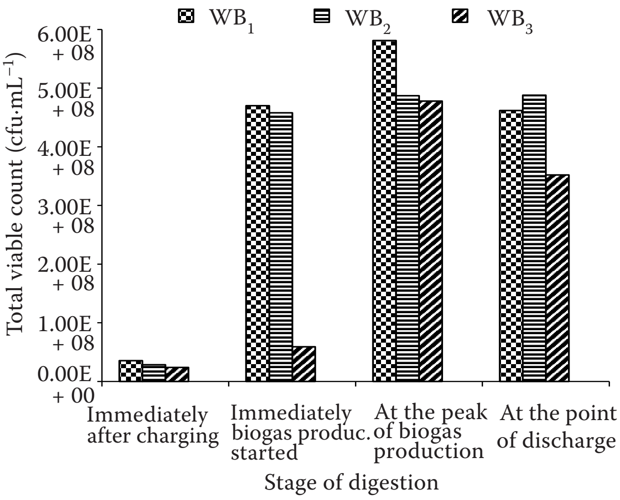

Figure 4. Effect of the digestion duration on the total viable count

WB_1 – 50% cow dung and 50% yam peel and vegetables, WB_2 – 50% cow dung and 50% yam peel, WB_3 – 50% cow dung and 50% vegetables

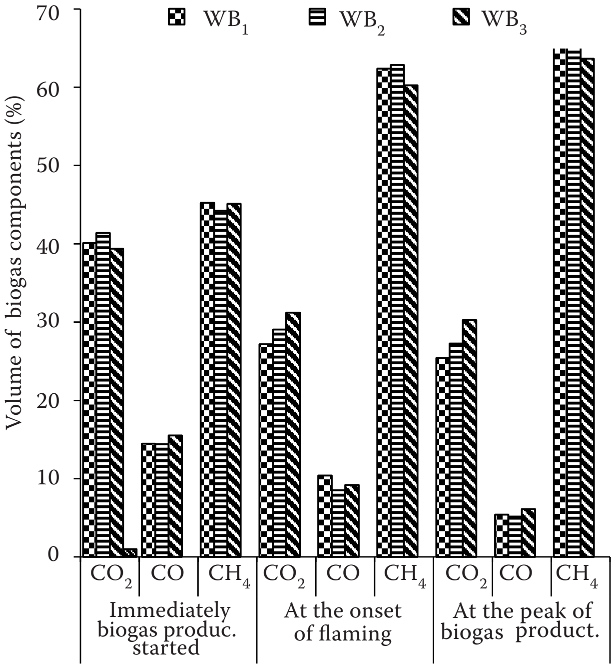

Figure 5. Biogas composition at the different stages of the gas production during the waste digestion

for explanation see figure 4

methanogenic microorganisms were not using most of the CO_2 as an electron acceptor for the methane production (Herout et al. 2011). The methane was highest in WB_1 (50% cow dung and 50% yam peels and vegetable) probably due the varying proximate composition of the different substrates and varying number of methane producing microorganisms. The biogas flammability was observed on the 6th day for WB_1, and on the 5th day for WB_2 and WB_3. Similar results were reported by Herout et al. (2011) and Ukpai et al. (2015). At the point of flaming, the CH_4 content of the biogas increased significantly ($P < 0.05$), while the CO_2 content decreased significantly ($P < 0.05$) with WB_1 and WB_2 having values close to each other. At the peak of the biogas production, the CH_4 again increased significantly ($P < 0.05$) to 69.42, 66.70%, and 63.62% for WB_1, WB_2, and WB_3 while the CO_2 content decreased significantly ($P < 0.05$) to 25.43, 27.29, and 30.25%, respectively. An increase in CH_4 indicates an increase in the heating power of the biogas (Herout et al. 2011; Beevi et al. 2013).

Temperature, pH and Volume of gas production per day. The ambient temperature ranges from 29 to 36 °C and slurry temperature ranges from 31 to 37 °C (Table 2). Similar results were reported by Ukpai et al. (2015). The higher slurry temperature than ambient

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temperature was because of the higher heat holding capacity of the slurry than ambient temperature. The slurry temperatures were within the mesophilic range, which was reported to favour optimal microbial activities for a high biogas production (Ukpai et al. 2015). The pH of WB_1 remained steady at 6.70 for first three days of charging and it afterward ranged from 6.70 to 6.72 throughout the retention period (Table 2). The fluctuation in the pH may be due to the higher acidogenesis and lower methanogenic activities, and vice versa (Beevi et al. 2013). The pH of WB_2 increased on the day of charging from 6.24 to 6.78 on the 8th day, after which it decreased and remain steady at 6.75 from the 12th to 14th day; afterward, it ranged from 6.72 to 6.79 throughout the retention period. The result was not surprising, as a similar result was reported by Asikong et al. (2016) and the gradual reduction in the pH may be due to the production of the volatile fatty acids (Aragaw et al. 2013). The pH of WB_3 fluctuated from the first day to the 11th day between 6.60 and 6.86 after which it remained steady at 6.81 from the 12th to 17th day and began to fluctuate again between 6.70 and 6.80 for the remaining days of the retention period. The steady pH

Table 2. Temperature, pH and volume of the gas production per day

Retention time (days)	Waste blends									
		WB_1			WB_2			WB_3		
	Ambient temp. (°C)	Slurry temp. (°C)	pH	Vol. of biogas (L·day^{-1})	Slurry temp. (°C)	pH	Vol. of biogas (L·day^{-1})	Slurry temp. (°C)	pH	Vol.of biogas (L·day^{-1})
Charging day				0			0			0
1	32	33	6.70	0	31	6.24	0	33	6.76	0
2	29	32	6.70	399	32	6.28	0	33	6.70	396
3	30	31	6.70	456	36	6.26	454	34	6.72	464
4	31	31	6.71	466	35	6.42	462	34	6.60	468
5	32	30	6.71	474	32	6.76	540	32	6.71	464
6	30	31	6.70	534	33	6.72	634	34	6.70	538
7	29	32	6.70	574	35	6.76	663	35	6.76	554
8	32	33	6.71	710	31	6.78	723	32	6.70	604
9	30	35	6.71	675	29	6.78	727	33	6.86	644
10	32	32	6.72	652	29	6.78	689	34	6.84	640
11	30	33	6.72	648	33	6.74	682	35	6.84	652
12	35	32	6.72	682	31	6.75	687	34	6.81	668
13	33	32	6.72	668	29	6.75	674	33	6.81	654
14	35	31	6.71	701	32	6.75	677	32	6.81	572
15	32	32	6.71	587	30	6.77	634	31	6.81	666
16	31	31	6.71	590	32	6.74	596	31	6.81	576
17	30	32	6.70	572	32	6.74	612	32	6.81	652
18	30	33	6.72	672	32	6.72	577	36	6.70	668
19	32	33	6.70	684	29	6.72	598	35	6.80	551
20	30	32	6.70	712	31	6.73	599	34	6.80	574
21	30	31	6.71	668	31	6.74	577	35	6.80	534
22	30	29	6.71	572	30	6.76	604	35	6.80	554
23	32	32	6.71	584	29	6.74	602	32	6.78	598
24	31	31	6.71	668	29	6.72	594	31	6.78	585
25	32	30	6.71	572	29	6.77	591	34	6.77	538
26	32	33	6.71	560	30	6.78	583	36	6.78	518
27	34	32	6.72	524	30	6.79	577	34	6.76	534
28	32	31	6.72	558	33	6.75	554	36	6.78	542
Total	31.28	31.78		16 162	31.7		15 910	33.57		15 408
mean	1.68	1.19		577.21		6.68	568.21	1.52	6.77	550.28

Vol. – volume; for more explanation see Table 1

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observed from the 12th to 17th day may be attributed to the balance in the acid production by the acidogen and acetogen and the quick consumption of the acid by the methanogen for the biogas production. In WB_1, the biogas production started on the 2nd day (399 L) and increased gradually until it got to the 8th day (710 L); after which its production began to fluctuate (Table 2). A similar result was reported by Asikong et al. (2016). The highest biogas production was on the 20th day (712 L). This might be attributed to the positive synergistic effect on the digestion of the cow dung and food waste, which provided more balanced nutrients (Aragaw et al. 2013) and the acclimatisation of the methogens after the substrate hydrolysis (Asikong et al. 2016). The biogas production from WB_2 started on the 3rd day (454 L) and increased each day to the maximum on the 9th day (727 L), afterward the biogas production began to fluctuate (554 and 689 L·day^{-1}). In WB_3, the biogas production started on the 2nd day (396 L) and increased each day to the maximum on day 12 (668 L) after which it began to fluctuate (518 and 668 L·day^{-1}). The highest biogas production was on the 12th and the 18th day (668 L). Similar results were reported by Aragaw et al. (2013) and Nwankwo et al. (2017).

Cooking time of yams and rice using different heat sources. Yams and rice, as conventional foods in a Sub-Saharan African country, were used to compare the cooking time of the biogas from different waste compositions (WB_1, WB_2, and WB_3), liquefied petroleum gas (LPG) and kerosene (Figure 6). It was observed that the liquefied petroleum gas (11.20 and 32.14 minutes) cooked significantly ($P < 0.05$) faster than the kerosene (18.56 and 44.17 min) and the biogas generated from the different waste compositions, while the biogas generated from the different waste compositions cooked significantly ($P < 0.05$) faster than the kerosene, but no significant ($P > 0.05$) difference between the cooking time of the biogas from the different waste compositions was found. Though the LPG cooked faster than the biogas, but is very costly and not easily accessible to people below a middle-class stature in a Sub-Saharan African country. Biogas can end up being an awesome option in contrast to both LPG and kerosene for an average family in developing countries, taking that it is cheap and eco-friendly into account (Adeoti et al. 2000). Different cooking times for yams and rice were reported by Eze (2012) though it may depend on the quantity of the yams and rice used for the cooking. Abdulkareem (2005) concluded that refining biogas before using it could improve its efficiency because the carbon dioxide in the biogas could reduce its cooking efficiency (Eze 2012).

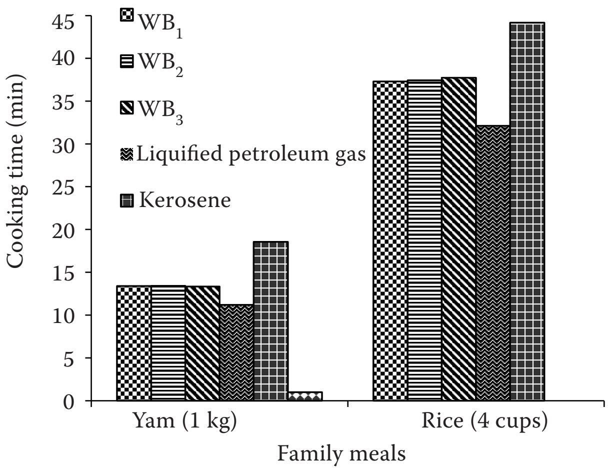

Figure 6. Cooking time of the yams and rice using the different heating sources
for explanation see figure 4

CONCLUSION

The bio-degradation system modified from 3.6 m^3 capacity plastic tank was able to generate an average biogas of 0.574 m^3 per day from the three experimental waste compositions which could be sufficient to cook three meals per day for 3 to 4 people. The generation of a flammable biogas from the waste and highly significant ($P < 0.05$) percentage change in the physico-chemical properties of the wastes after digestion was an indication of the high efficiency performance of the bio-degradation system modified from the plastic tank. It was observed that the pH of the fermentation slurry fluctuated in accordance with the conditions inside the digester in the course of biogas production. Moreover, the basic perception of the temperature effect showed that the biogas production increased as the ambient and slurry temperatures increased from the morning to the afternoon, but the biogas production decreased toward the evening as the ambient and slurry temperatures decreased. The characterised biogas generated from the different waste compositions showed that the methane gas increased significantly ($P < 0.05$) while the carbon dioxide and carbon monoxide decreased significantly ($P < 0.05$) at the onset of flaming and at the peak of the biogas production.

There was a significant ($P < 0.05$) difference in the cooking time of the generated biogas and other

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heating sources (liquefied petroleum gas and kerosene). Therefore, every household in the Sub-Saharan African countries, especially Nigeria, are encouraged to fully adopt and practice this technology in cooking foods.

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