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Evaluation of biogas production from co-digestion of cassava peels and selected animal wastes from Awka North and South Local Government Areas, Anambra State, Nigeria.

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ABSTRACT

Biogas is a renewable energy produced from anaerobic digestion of organic materials. The evaluation of biogas production from the co-digestion of cassava peels and selected animal wastes (cow dung, chicken droppings and goat droppings) from Awka North and South Local Government Areas, Anambra State, Nigeria was studied. Laboratory scale bio-digesters (one-litre conical flasks) were used for the anaerobic digestion of wastes at 27°C with a retention time of 30 days. Each digester was covered with a stopper to make it airtight. The ratio of cassava : animal wastes mix used for anaerobic digestion were: 1:1, 2:1 and 3:1. Each 200 g waste mixture was then combined with 600 mL of water to form a slurry. The biogas produced were trapped in inverted measuring glass cylinder and in polyvinylchloride ball. The volume of the gas trapped in glass cylinder was evaluated using displacement method, while components of the trapped gas in polyvinylchloride ball was analyzed using Gas Chromatographic method. The pH of the slurries was taken before and after each anaerobic digestion using pH meter. The slurry from the anaerobic digester was analyzed for methanogenic bacteria at the end of the digestion using 16S rRNA sequencing method. The cumulative biogas yield from the co-digestion of cassava peels and cow dung (CCD) with different combination ratios (1:1, 2:1 and 3:1) revealed that ratio (3:1) had the largest (880 cm^3) biogas volume, while ratio (1:1) had the least volume (87 cm^3) of biogas. Co-digestion of cassava peels and goat droppings (CGD) produced the highest volume (1,277 cm^3) of biogas with combination ratio (2:1) and the least volume (899 cm^3) with combination ratio (3:1). The highest volume (1,447 cm^3) of biogas production from the co-digestion of cassava peels and chicken droppings (CCH) was obtained from combination ratio

(2:1) and the least volume (838 cm^3) of biogas from the combination ratio (3:1). The pH of all the slurries decreased significantly after the anaerobic digestion of the wastes ($p< 0.05$). The co-digestion of cassava peels and animal wastes with combination ratio (1:1) showed that CCD had the highest methane (CH_4) concentration (69.95%), while CGD (61.92%) had the least CH_4 concentration ($p> 0.05$). Optimised combination ratio 2:1 had co-digestion of cassava peels and animal wastes (cow dung and chicken droppings) produce highest CH_4 concentration (79.38%). Bacterial species belonging to five phyla; Proteobacteria, Spirochaetota, Bacillota, Bacteroidota and Firmicutes, were involved in the anaerobic digestion. Co-digestion of cassava peels with chicken droppings gave the highest biogas yield. Addition of cow dung to cassava peels-chicken droppings mixture improved the percentage methane concentration.
Keywords: Biogas, Methane, Anaerobic digestion, Cassava peels, Animal wastes, Bacteria.

Introduction

Sustainable waste management is an issue of global concern due to the steady increase in population, urbanization and industrialization (Al Mamun and Torii, 2017). The rising environmental problems, involving greenhouse gases, air and water pollution, together with the energy crisis and resource scarcity necessitates the need to take actions toward a more sustainable society (Matsakas *et al.,* 2017). Efficient management of increasing volume of municipal, animal, agricultural and industrial wastes in minimizing their environmental impact is thus an urgent necessity (Yentekakis and Goula, 2017). Anaerobic biotechnology has been reported as a sustainable alternative to conventional disposal strategies because the volume of the organic waste is reduced and stabilized, a residue (compost) that can be used for soil conditioning is produced, and energy in the form of methane is recovered (Hartmann *et al*., 2002).

Biomass can be considered as every organic substance derived directly or indirectly from photosynthetic process (Jacobsson and Johnson, 2000). Generally, biomass is a combination of naturally derived materials, originating from microorganisms and plants such as bacteria, fungi, algae, shrubs, trees, crops as well as all the materials composed of organic matrix except for plastics originating from petrochemicals and fossil materials (Mckendry, 2002; Ravi *et al.,* 2021). Biomass resources such as cassava residue, fish waste, animal manure and municipal organic solid waste are deposited or discharged without any concern for the environment (Khanh Toan *et al.,* 2011), but could instead be used for generating energy rather than polluting the environment (Cu *et al.*, 2015).

Anaerobic digestion is generally a process where different bacteria degrade biological material (biomass) in the absence of oxygen and this process is carried out in a number of steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Nallamothu *et al.,* 2013; Akintokun *et al.,* 2017; Jameel *et al.,* 2024). The main outputs of the anaerobic digestion are biogas and slurry (Nallamothu *et al.,* 2013). Biogas is a valuable renewable energy produced from biodegradable organic materials via anaerobic digestion (Awe *et al.,* 2017).

The hydrolysis stage is primarily mediated by bacterial phyla such as Firmicutes, Actinobacteria, Bacteroidetes, Proteobacteria, Bacillota and Chloroflexi; they are the most common bacterial phyla in this phase (Cao *et al*., 2025; Valecha, 2021). During the acidogenesis stage, the dominant bacteria phyla mainly include Bacteroidetes, Bacillota and Firmicutes (Cao *et al*., 2025; Valecha, 2021). In the following

acetogenesis stage, Syntrophobacter genera (phylum Thermodesulfobacteriota), has been known to convert acid phase products into acetates and hydrogen (Valecha, 2021). In the final stage, methanogenesis, the microorganisms involved are primarily represented by the genera *Methanosaeta, Methanosarcina, Methanobacterium, Methanobrevibacter, Methanoculleus, Methanospirillum, Methanothermobacter, Methanobacterium, Methanococcus, Methanosclerotinia, Methanosalsus,* and *Methanosalts* (Venkiteshwaran *et al*., 2016).

Biogas is an alternative solution for the world increasing energy demands and helps in reducing waste and the greenhouse gases emissions (Awe *et al.*, 2017). Biogas is also regarded as carbon neutral because the carbon in biogas originates from organic matter (feedstocks) that captured the carbon from atmospheric carbon dioxide (Awe *et al.*, 2017). The major constituents of biogas are methane and carbon dioxide, with some quantities of contaminants, such as ammonia, water vapour, hydrogen sulphide, methyl siloxanes, nitrogen, oxygen, halogenated volatile organic compounds (VOCs), carbon monoxide and hydrocarbons. These constituents of biogas and quantities depend largely on the biogas source (Awe *et al.*, 2017) and the experimental conditions of biogas production (Karki *et al.,* 2015). The thermal heating value of biogas ranges between 15 and 30 MJ/m^3 (Yentekakis and Goula, 2017), making it a valuable source of renewable energy (Awe *et al.,* 2017).
Nigeria, known as a major producer of cassava generates large quantities of cassava peels; they also rarely utilize the values from semi-solid animal wastes. The country can harness enormous energy by converting these substrates into valuable energy sources. This work was carried out to evaluate biogas production from co-digestion of cassava peels and selected animal wastes from Awka North and South Local Government Areas, Anambra State. The study aimed to determine the volume and composition of biogas produced via the co-digestion of cassava peels with animal wastes.

Material and Methods

Study area and sample collection

Fresh cow dung and goat droppings were collected from Garki, Amansea, Awka North LGA, Anambra State (6°14'51"N 7°08'14"E), while, fresh chicken droppings were collected from Iweama's poultry farm at Commissioners quarters in Awka South LGA, Anambra state (6°14'36"N 7°05'41"E). Fresh cassava peels were obtained from a cassava mill at Amansea, Awka, Awka North LGA (6°15'20"N 7°08'14"E). The fresh animal samples were taken to Microbiology laboratory in sterile containers. The fresh cassava peels were sun dried, sorted and blended into powder.

Digester design

The bio-digesters were designed using the method described by Ugwuoke *et al*. (2026). One-litre conical flasks were used as the bio-digesters. The digesters were covered with stoppers to make them airtight. A hole was bored on each stopper through which a polyvinylchloride pipe was connected to allow the passage of biogas. The biogas produced were passed through a polyvinylchloride pipe and collected in a polyvinylchloride ball (for quanlitative analysis). However, the gases that were not collected directly in a polyvinylchloride ball, were collected using inverted measuring glass cylinder (for quantitative analysis). The digesters were operated at 27°C with a retention time of 30 days.

Experimental design

In this study, animal wastes (cow dung, chicken droppings and goat droppings) and agricultural waste (cassava peels) obtained

from local sources were co-digested to produce biogas. Biogas yields were thereafter determined, their compositions were analyzed and the bacterial communities were identified. Completely Randomized Design having nine treatments (slurry), each replicated twice was employed in the biogas production.

Slurry preparations and loading of digester for optimal biogas production

Slurry preparation

The combination ratio of wastes were done following the method described by Ofoefule and Uzodinma (2009) with slight modification. Cassava peels and each animal wastes were combined in various ratios (1:1, 2:1, and 3:1) to give a total of 200g of the waste. Each 200 g waste mixture was then combined with 600 mL of water to form a slurry. The slurry was prepared by mixing the wastes (cassava peels + animal wastes) with water at a ratio of 1: 3, yielding a total of 200g waste: 600mL water. Below are the formulations for the preparation of the waste mixture.

i. Cassava peels + Cow dung = 100g + 100g (1:1)
ii. Cassava peels + Cow dung = 133.3g + 66.7g (2:1)
iii. Cassava peels + Cow dung = 150g + 50g (3:1)
iv. Cassava peels + Chicken droppings = 100g + 100g (1:1)
v. Cassava peels + Chicken droppings = 133.3g + 66.7g (2:1)
vi. Cassava peels + Chicken droppings = 150g + 50g (3:1)
vii. Cassava peels + Goat dropping + = 100g + 100g (1:1)
viii. Cassava peels + Goat dropping = 133.3g + 66.7g (2:1)
ix. Cassava peels + Goat dropping = 150g + 50g (3:1)

Loading of digester for biogas production

Two hundred grams of the waste (cassava peels and animal waste) were gently weighed into a one-litre conical flask digester. Six hundred milliliters of water was added to the waste to turn it into a slurry, yielding a water to waste ratio of 3:1. The slurry was gently stirred with a sterile glass rod to homogenize the solution before the digester was corked.

Further studies on biogas production after optimisation

Further studies on biogas production were carried out using the slurry combination ratios of each animal waste mixed with cassava peels that yielded the highest biogas output in the first phase of the experiment, which optimised the mixture ratio. From the preliminary results, the optimal slurry combinations were identified as follows: 2:1 for cassava + chicken droppings, 2:1 for cassava + goat droppings, and 3:1 for cassava + cow dung. However, since the 2:1 ratio appeared most consistently across the trials, it was adopted as the standard combination for all types of animal waste. This choice ensured uniformity and allowed for direct comparison of results across the different waste sources.

So, in the further studies, waste mixtures (200 g each) involving more than one animal source were prepared using cassava peels (two parts) combined with animal wastes (one part). For each mixture, equal portion of the respective animal wastes were included, as presented below:

i. Cassava peels + (Cow dung + Chicken droppings) = 133.3g + (33.35g + 33.35g) (2:1)
ii. Cassava peels + (Cow dung + Goat droppings) = 133.3g + (33.35g + 33.35g) (2:1)
iii. Cassava peels + (Goat dropping + Chicken droppings) = 133.3g + (33.35g + 33.35g) (2:1)

ix. Cassava peels + (Goat dropping + Chicken droppings + Cow dung) = 133.3g + (22.23g + 22.23g + 22.23g) (2:1)

pH of slurry

The pH of the slurry was determined using a pH meter (Hanna HI98107). The pH meter was first calibrated using a buffer solution (pH 7.0) before inserting the electrode into the slurry. The electrode was gently dipped into the slurry and allowed to stand for 2 minutes before the reading was recorded. The pH of the slurries was monitored before and after anaerobic digestion.

Measurement and analysis of biogas produced

The volume of biogas produced was measured using the procedure described by Tambuwal and Ogbiko (2018). The volume of biogas produced was measured daily by finding the volume of water displaced (downward displacement of water) by the gas in the inverted measuring cylinder that served as biogas collection system. The water used for trapping the biogas was acidified with 2% H_2SO_4. The gas in the polyvinylchloride ball was analyzed using Gas chromatography-flame ionization detector (GC-FID).

The analysis of biogas produced in the preliminary and final trials was carried out as described by Liu *et al.* (2018). Biogas was measured using Gas chromatography-flame ionization detector (GC-FID). Gas Chromatography was performed using an Agilent Technologies 6890 GC system (Agilent Technologies, USA) equipped with a flame ionization detector (FID) and Elite-5 capillary column (30m * 0.25mm * 0.25μm). The workstation was Totalchrom Navigator used for data processing. The temperature for column chamber, inlet chamber and detector was 150 ºC, 200 ºC and 250 ºC, respectively. High purity nitrogen was used for carrier gas in this study, and the flow rate for nitrogen was 2.0 ml/min. The split ratio of gas sample in inlet chamber was 20:1, which was used to control the amount of biogas flow into column, and prevent the unconventional peak, such as flat peak, trailing peak. The flow rate was 450ml/min for air produced by automatic air source (BCHP, SPB-300, China) and 45ml/min for hydrogen produced by hydrogen gas. The oven temperature was programmed as follows: 120 ºC held for 4 min, ramp at 10 ºC/ min to 180 ºC, held for 2 min, and finally ramp at 5 ºC/ min to 300 ºC. The injection volume of the GC was 10.0 μL. The total run time for a sample was 43 min.

Biogas Analysis.

$$\text{The \% of each gas produced} = \frac{\text{concentration of each gas produced (ppm)} \times 100}{\text{Total concentration of the gas produced (ppm)}}$$

Determination of microbial population in the slurry.

The bacteria in the digested slurry were identified via 16S rRNA sequencing as described by Naqib *et al*. (2018) and Bybee *et al*. (2011). Genomic DNA was extracted from the samples with QIAamp PowerSoil DNA kit (Qiagen) and processed on a QIAcube automated nucleic acid extraction system (Qiagen), according to the manufacturer's instructions. Samples were incubated for 10 min at 65°C before being homogenized with FastPrep-24 5G bead-beating device (MP Biomedicals) at 6 m/s for 40 sec. Metagenomic analysis was carried out on the samples at Research Resource Center, University of Illinois, Chicago, United States.

Data analysis

Statistical analysis of data was done using SPSS software version 20.0. Data from gas chromatographic analysis for biogas produced from the co-digestion of cassava peels and animal wastes were compared using One-Way ANOVA at 5% significance level ($p < 0.05$). pH data from the slurries before and after anaerobic digestion were compared using paired sample T-Test at 5% significance level.

Results

Biogas yield from co-digestion of cassava peels + animal wastes with different combination ratios.

The co-digestion of cassava peels + cow dung with different combination ratios produced the largest volume (880 cm^3) of biogas with combination ratio (3:1), while combination ratio (1:1) had the least volume (87 cm^3) (Figure 1). Co-digestion of cassava peels + goat droppings produced the highest volume (1,277 cm^3) of biogas with combination ratio (2:1) and the least volume (899 cm^3) with combination ratio (3:1) (Figure 1). The highest volume (1,447 cm^3) of biogas produced from the co-digestion of cassava peels + chicken droppings was obtained from combination ratio (2:1), and the least volume (838 cm^3) from combination ratio (3:1) (Figure 1). In Figure 1, the slurry that gave the highest biogas yield (1,447 cm^3) was cassava peels + chicken droppings mixture at combination (2:1), while cassava peels + cow dung ratio (1:1) produced the least volume (87 cm^3).

The highest volume of biogas was produced during the first 5-day retention period of the co-digestion of cassava peels + animal waste for all slurries, except for the 1:1 ratio combination of cassava peels + goat droppings, as shown in Figure 2. Biogas production from the co-digestion of cassava peels + goat droppings at a 1:1 ratio achieved the highest biogas yield (449 cm^3) during the final 5-day period (days 26 to 30) of the retention time.

Biogas yield from the further studies in the co-digestion of cassava peels + animal wastes at combination ratio 2:1 (cassava peels to animal wastes).

Co-digestion of cassava peels and animal wastes (cow dung, chicken droppings and goat droppings) with combination ratio 2:1 (cassava peels to animal wastes) over a 30-day retention period showed that the co-digestion of cassava peels with cow dung + chicken droppings produced the highest volume (880cm^3) of biogas, while co-digestion of cassava peels with cow dung + goat droppings produced the least volume (134 cm^3) (Figure 3). Biogas production at intervals of 5-day period in the co-digestion of cassava peels with animal wastes showed that the volume of biogas produced was highest on the first 5-day period of the digestion (Figure 4).

pH of the Slurry Before and After Anaerobic Digestion

Table (1) illustrated the pH of the slurries before and after the anaerobic digestions of the various organic wastes. The pH of the different slurries reduced significantly after the anaerobic digestion of the organic wastes ($p < 0.05$)

Composition of biogas produced by the co-digestion of cassava peels + animal wastes with combination ratio (1:1)

The GC-FID analysis report showed that the co-digestion of cassava peels + cow dung had the highest methane (CH_4) concentration (69.95%) in its biogas composition compared to cassava peels + goat droppings co-digestion (61.92%) and cassava peels + chicken droppings co-digestion (67.62%) (Table 2). Co-digestion of cassava peels + goat droppings produced the least concentration of CO_2 (15.36%) in

its biogas composition, while cassava peels + chicken droppings co-digestion produced the highest percentage of CO_2 (20.32%) in its biogas composition (Table 2).

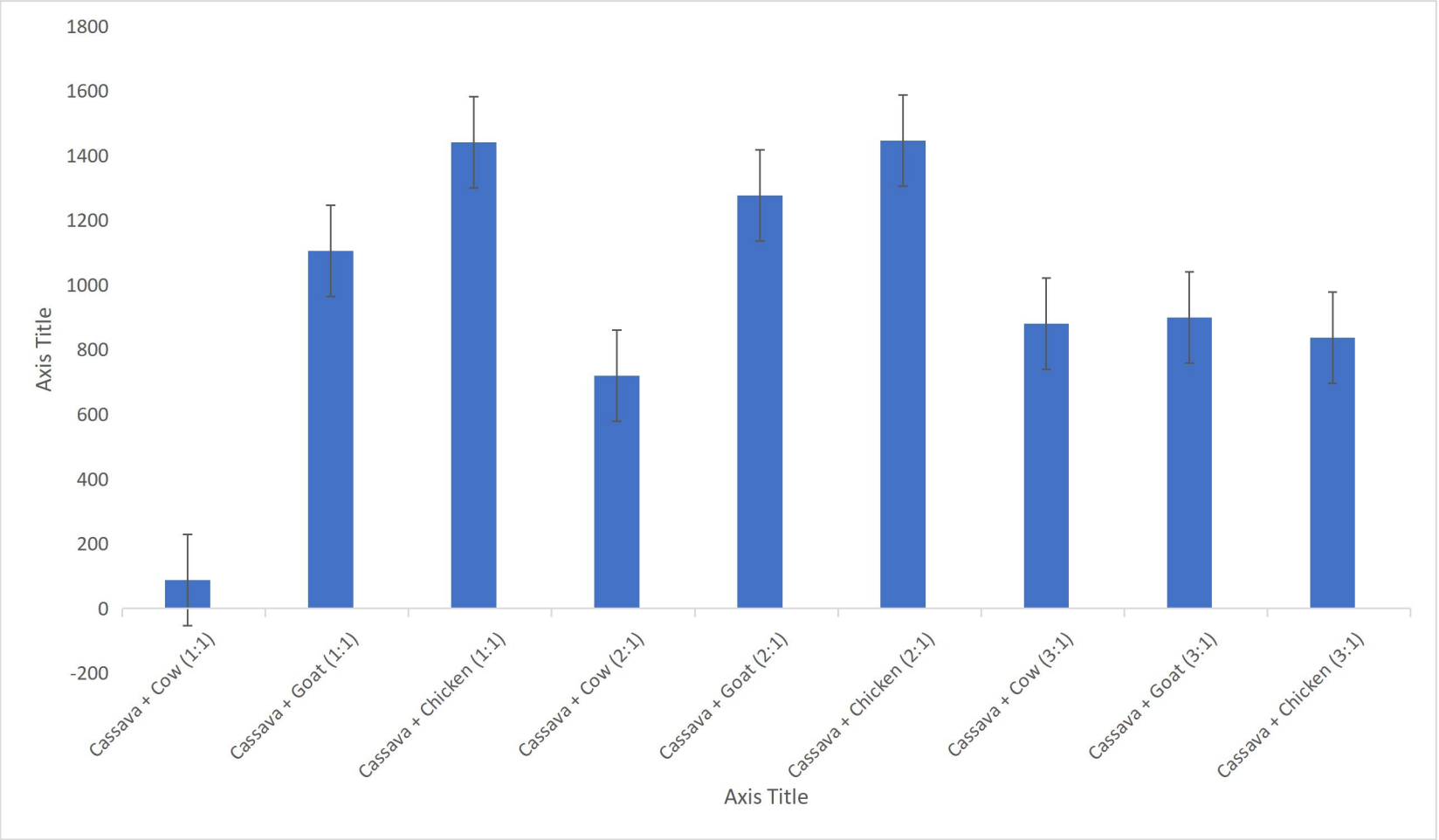


Figure 1: Total volumes of biogas produced by the co-digestion of agricultural waste (cassava peels) and animal wastes (cow dung, goat droppings and chicken droppings) with different combination ratios on a 30-day retention period.

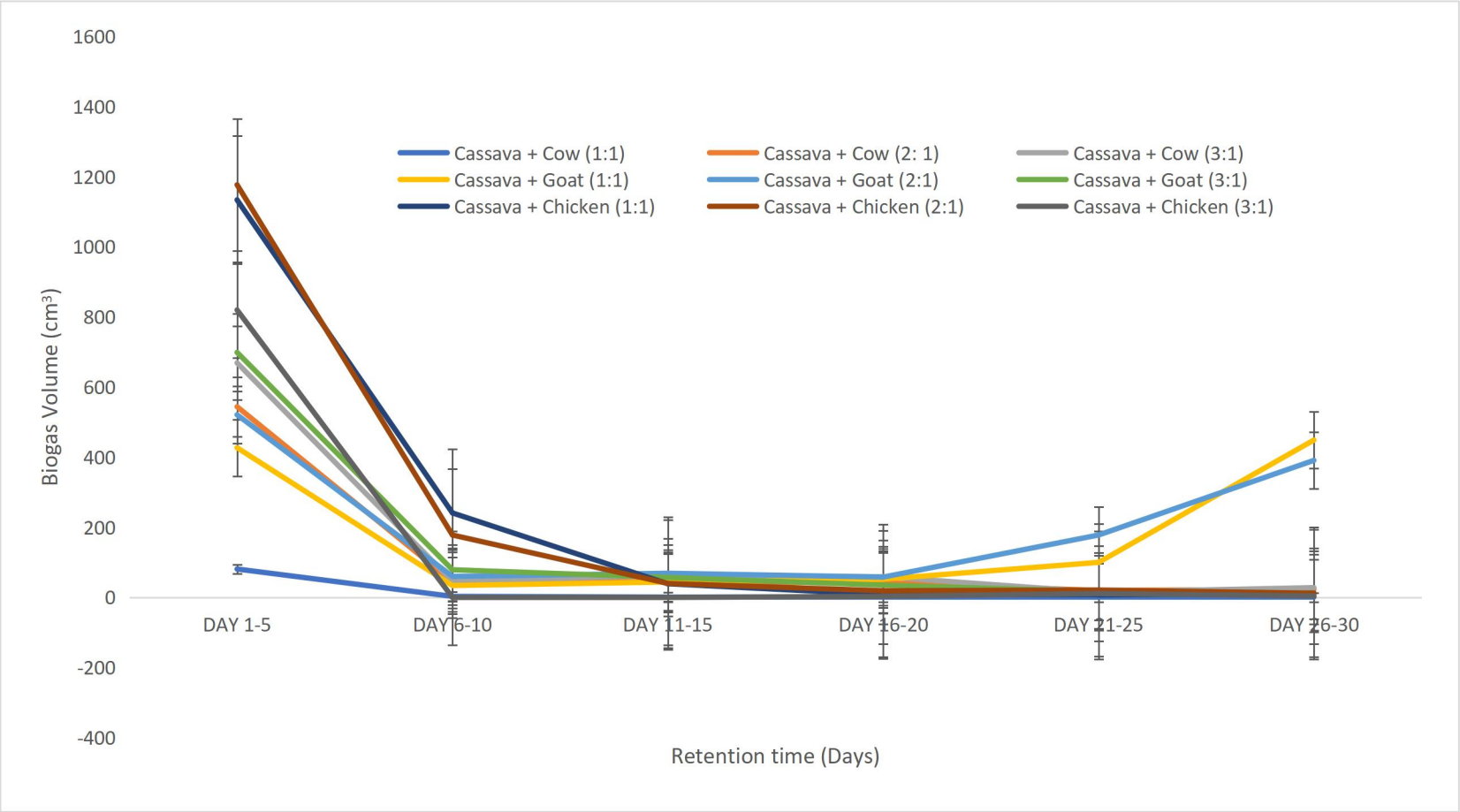


Figure 2: Volumes of biogas produced by the co-digestion of agricultural waste (cassava peels) and animal wastes (cow dung, goat droppings and chicken droppings) with different combination ratios at intervals of five days.

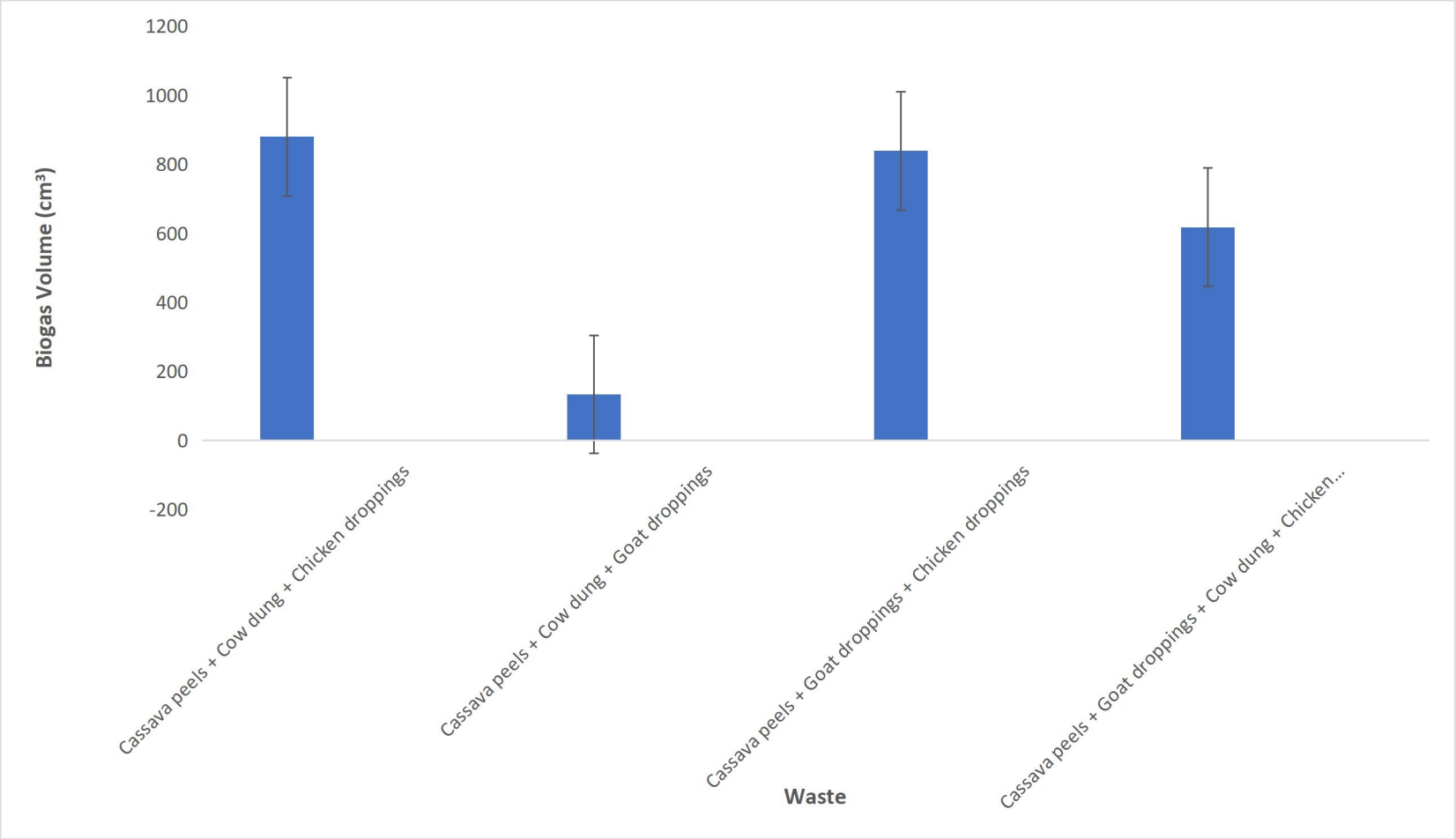


Figure 3: Total volumes of biogas produced by the co-digestion of agricultural waste (cassava peels) and animal wastes (at 2:1 combination ratio) on a 30-day retention period after optimisation.

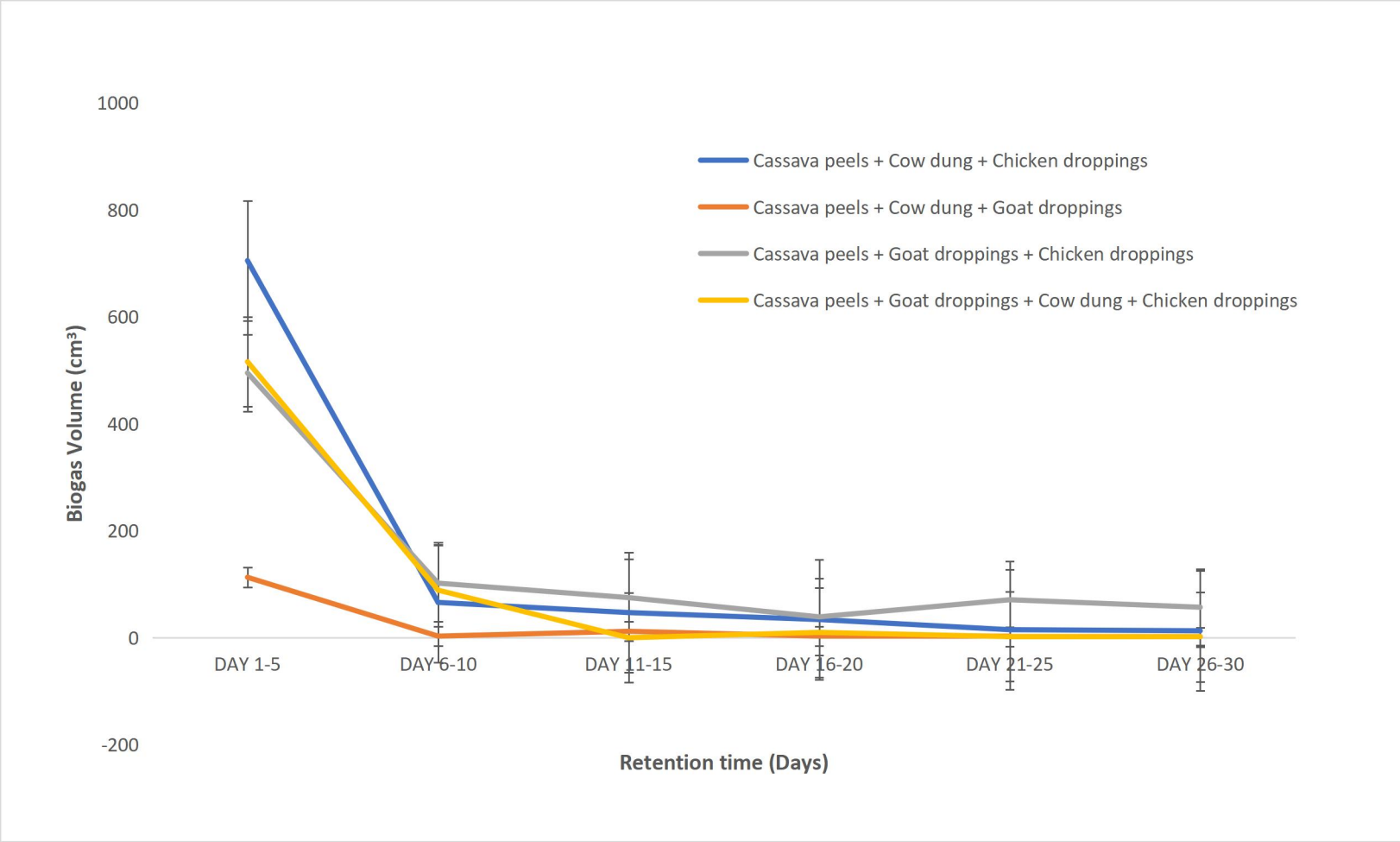


Figure 4: Volumes of biogas produced by the co-digestion of agricultural waste (cassava peels) and animal wastes (at 2:1 combination ratio) at intervals of five days after optimisation.

Table **1**: pH of cassava peels + animal wastes before and after co-digestion of the wastes.

SN	Wastes combinations	Initial pH	Final pH
1	Cassava peels + Cow dung (1:1)	6.8	6.5
2	Cassava peels + Cow dung (2:1)	6.6	6.1
3	Cassava peels + Cow dung (3:1)	6.3	5.7
4	Cassava peels + Goat droppings (1:1)	6.9	6.5
5	Cassava peels + Goat droppings (2:1)	6.8	6.2
6	Cassava peels + Goat droppings (3:1)	6.6	5.7
7	Cassava peels + Chicken droppings (1:1)	6.6	6.1
8	Cassava peels + Chicken droppings (2:1)	6.3	5.7
9	Cassava peels + Chicken droppings (3:1)	6.0	5.3
10	Cassava peels + (Cow dung & Chicken droppings) 2:1	6.4	6.0
11	Cassava peels + (Cow dung & Goat droppings) 2:1	6.6	6.2
12	Cassava peels + (Goat droppings & Chicken droppings) 2:1	6.5	6.2
13	Cassava peels + (Goat droppings & Cow dung & Chicken droppings) 2:1	6.5	6.2
T value = 4.2736, p-value = 0.000132, p< 0.05		statistically significant	

Table 2: Gas chromatographic analysis report of biogas produced by the co-digestion of cassava peels + animal wastes at a combination ratio of 1:1.

S/No	Constituents	% Composition of biogas constituents		
		CCD	CGD	CCH
1	CO	0.04	1.90	0.04
2	CO_2	16.05	15.36	20.32
3	Methane	69.95	61.92	67.62
4	Acetic acid	3.83	8.47	0.14
5	Methanol	2.17	2.55	1.76
6	Ethyl Acetate	3.11	1.54	1.69
7	SO_2	2.42	2.40	2.20
9	Acetone	1.61	0.47	4.06
10	Acetonitrile	0.83	5.38	2.16
F statistics = 0, p-value = 1, p > 0.05		not significant		

keys: CCD: cassava peels + cow dung
CGD: cassava peels + goat droppings
CCH: cassava peels + chicken droppings

Composition of biogas produced by the co-digestion of cassava peels with cow dung + chicken droppings at combination ratio (2:1)

Table 3 shows the Gas Chromatographic analysis report of biogas produced by the co-digestion of cassava peels with semi solid animal wastes (cow dung + chicken droppings). The report shows that the methane and carbon dioxide contents of biogas are 79.38% and 17.38% respectively.

Table 3: Gas chromatographic analysis report of biogas produced by co-digestion of cassava peels with cow dung + chicken droppings.

S/No	Constituents	% Composition of biogas constituents
1	CO	0.25
2	CO_2	17.38
3	Methane	79.57
4	Acetic acid	0.50
5	Methanol	0.87
6	Ethyl Acetate	0.45
7	SO_2	0.05
9	Acetone	0.94
10	Acetonitrile	0.00
	Mean	11.11

Bacteria identified in anaerobic digestion for biogas production

Bacteria species from different genera were identified to be involved in the co-digestion of cassava peels and animal wastes in anaerobic digestion system (Table 7). The identified bacteria genera include; *Burkholderia, Escherichia, Caproiciproducens, Staphylococcus, Caproicibacterium, Bacillus, Klebsiella, Lactobacillus, Listeria, Clostridium, Enterococcus, Limosilactobacillus, Prevotella, Niameybacter, Caproicibacter, Pseudomonas, Cellulosilyticum, Romboutsia, Veillonella, Treponema* and *Salmonella*. These bacteria species belong to five phyla namely Proteobacteria, Firmicutes, Bacillota, Spirochaetota and Bacteroidota. *Burkholderia* sp. from the phylum Proteobacteria was the genus with the highest mean relative abundance, whereas the phylum Firmicutes had more diversity of bacterial species belonging to different genera.

Table 7: Result of targeted genomic sequencing (16S rRNA sequencing)

SN	Phylum	Species
1	Firmicutes	*Caproicibacterium* spp., *Lactobacillus* spp., *Listeria* sp., *Veillonella* sp., *Bacillus* spp., *Clostridium* spp., *Cellulosilyticum* sp., *Romboutsia* sp., *Caproicibacter* spp., *Caproiciproducens* spp.

2	Proteobacteria	*Burkholderia* sp., *Escherichia* spp., *Klebsiella* spp., *Pseudomonas* sp., *Salmonella* sp.
3	Bacillota	*Staphylococcus* sp., *Enterococcus* sp., *Limosilactobacillus* spp., *Niameybacter* spp.
4	Spirochaetota	*Treponema* spp.
5	Bacteroidota	*Prevotella* spp.

Discussion

The co-digestion of cassava peels and cow dung produced the least cumulative volume of biogas for all the mixing ratios of cassava peels and animal wastes except for combination ratio 3:1, where it is slightly higher than the volume of biogas produced by cassava peels and chicken droppings co-digestion at the same ratio. Ofoefule and Uzodinma (2009) reported that the co-digestion of cassava peels with poultry droppings gave a higher cumulative biogas yield when compared to cassava peels and cow dung co-digestion. Whereas, Adelekan and Bamgboye (2009) reported that the co-digestion of cattle waste and cassava peels had higher biogas yield for all the selected mixing ratios when compared to the biogas yield from the co-digestion of cassava peels and poultry waste. The reduction in biogas production could be due to the inhibition of fermentation by high levels of hydrocyanic acid, resulting from a high ratio of cassava peels to chicken droppings (Adelekan and Bamgboye, 2009).

This study revealed that the co-digestion of cassava peels with animal wastes (goat droppings and chicken droppings, respectively) produced the lowest volume of biogas at a ratio of 3:1 for each combination. Smith *et al*. (1985) reported that anaerobic digestion of cassava peels could induce excess acid production and the release of cyanide, which are toxic to methanogenic arches, hence reduces biogas production. Jayaraj *et al.* (2014) explained that a low pH in the digester inhibits the activity of microorganisms involved in the digestion process particularly methanogenic bacteria. The above findings could be the reason why the co-digestion of cassava peels with goat droppings and chicken droppings produced the least volume of biogas at combination ratio 3:1.

The highest biogas yield from the anaerobic co-digestion of cassava peels with animal waste occurred during the first 5 days of the retention period, except for the cassava peels and goat droppings mixture at a 1:1 mixing ratio. Aisien and Aisien (2020) reported that biogas production from the co-digestion of fresh and stale cassava peels with cow dung had their highest biogas yield on the day 10 to day 15 (with the peak on the 13th day) of the anaerobic digestion period. The high hydrocyanic acid content found in both fresh and stale cassava peels inhibited microbial activity, resulting in delayed biogas production (Ogbonna *et al*., 2023; Ben and Michael, 2018).

The combination of cassava peels with different mixtures of animal waste (cow dung, goat droppings, and chicken droppings) at a mixing ratio of 2:1 showed that the cassava peels, cow dung, and chicken droppings mixture gave the highest cumulative volume (880 cm^3) of biogas (Figure 3). This high yield may be due to the nutrients available for bacterial

fermentation, as nutrient availability directly determines the volume of biogas produced (Zieliński *et al*., 2019).
The pH of the slurries reduced after anaerobic digestion of the wastes. In contrast, Yaru *et al*. (2020) observed that substrate pH increased as the proportion of cassava peels decreased. Smith *et al*. (1985) reported that the anaerobic digestion of cassava peels could induce excess acid production, which could reduce the pH of the slurry.

Analysis of the biogas composition from the co-digestion of cassava peels and animal wastes showed that the cassava peels and cow dung mixture had the highest methane content (69.95%), while cassava peels and goat droppings mixture had the least methane content (61.92%). Conversely, Adelekan and Bamgboye (2009) reported that a cassava peels and poultry waste mixture at a mixing ratio of 1:1 had a higher methane content than the cassava peels and cattle waste mixture. The difference in the methane contents could be caused by the presence of hydrocyanic acid present in cassava peels that inhibited fermentation. Biogas analysis from the co-digestion of cassava peels with animal waste (cow dung + chicken droppings) at a mixing ratio of 2:1 showed a higher percentage of methane than when the cassava peels were digested with animal wastes individually (Table 2 and 3). This indicates that the combination of two animal wastes provides better nutrient enrichment and a wider variety of bacterial consortia for more effective fermentation of the slurry for biogas production (Ma *et al.,* 2020).

The bacteria identified in this study are from the phyla Proteobacteria, Firmicutes, Bacillota, Spirochaetota and Bacteroidota. Senes-Guerrero *et al*. (2019) and Stoyancheva *et al*. (2023) reported that the phyla Proteobacteria, Firmicutes, Bacteroidetes and Actinobacteria led bacterial domain in read relative abundance among biogas producing microbial composition, which agrees with the bacteria identified in this research. In solid feedstocks treatment, Abendroth *et al*. (2015), Stolze *et al*. (2015) and Tuan *et al*. (2014) reported that Firmicutes dominated the community, which explains the diversity of species in the community. When utilizing liquid feedstocks during digestion, Guo *et al*. (2015) and Yang *et al*. (2014) reported that Proteobacteria, Firmicutes, and Bacteroidetes were the dominant bacterial phyla; this aligns with the findings of this study, where Proteobacteria was the most abundant phylum during the anaerobic digestion.

Conclusion

Co-digestion of cassava peels with chicken droppings yielded the highest biogas production from anaerobic digestion. Addition of cow dung to cassava peels + chicken droppings mixture improved the percentage methane concentration. The co-digestion of cassava peels and cow dung had the highest methane concentration than other waste mixtures. Bacterial species that aided in the co-digestion of the wastes belong to the phyla Proteobacteria, Spirochaetota, Bacillota, Bacteroidota and Firmicutes. The use of cassava peels and animal wastes for biogas production is a sustainable waste to energy system that will improve environmental, animal and human health.

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Conflict of Interest

The authors declare no conflict of interest.

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Author’s contribution

All the authors contributed to the conceptualization of the study. Preparation of the manuscript was done by Onyinyechukwuka Goodluck Ugwuoke and Uche Ogugua Chukwura-Osoagba. The data collection collections were performed by Onyinyechukwuka Goodluck Ugwuoke. The field work and data collection were supervised by Edna I. Chukwura and Vivian N. Anakwenze.

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