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Characterization of fresh biowastes for biogas production and environmental health in Niger Delta, Nigeria

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Abstract

Background Environmental pollution is a public health problem in Niger Delta, Nigeria. Therefore, the aims of the present study were to: identify the major fresh biowastes in Bayelsa State, Niger Delta; quantify the biogas yields from mono-digestion and co-digestion of identified biowastes; determine the first day of biogas production during hydraulic retention time; assess pH variations during anaerobic digestion; and evaluate biogas flame colours.

Methods Fifteen communities in Bayelsa State were randomly selected, and on-the-spot assessment and quantification of the biowastes found in each community were carried out daily per week. Mono-digestion of 20 kg of each biowaste and co-digestion of 10 kg of animal waste with 10 kg of plant waste were carried out respectively under anaerobic conditions. Cumulative biogas yield and pH were measured using a pH meter and weighing scale respectively. Biogas flame colours during combustion were visually assessed.

Results Exactly 120.61 metric ton of fresh biowastes was found to be generated per week in Bayelsa State, Niger Delta. Industrial biowastes were the highest [47.6 tonnes, (39.46%)], followed by abattoir biowastes [33 tonnes (27%)], market and roadside sellers biowastes [25.5 tonnes (21.14%)], and farm biowastes [14.51 (12.03%)]. Biogas yields (kg) were: 0, 0, 0, 0, 0, 17, 14, 2, 18, 16, 17, 15 and 1 kg for palm oil mill effluent (POME), orange fruit waste (OFW), pineapple peels (PP), plantain peels, cassava mill effluent (CME), rumen digesta (RD), cow dung, sewage, PP-RD, plantain peels-cow dung, POME-rumen digesta, OFW-cow dung, and CME-sewage respectively. The first day of biogas production for RD, cow dung, sewage, PP-RD, plantain peels-cow dung, POME-RD, OFW-cow dung, and CME-sewage was on the 6th, 32nd. 56th, 1st, 26th, 18th, 25th, and 60th day of hydraulic retention time respectively. A dominant blue flame colour mixed reddish yellow or orange flames were found during biogas combustion. A slight increase in pH was found in all the biodigester media.

Conclusions In the present study, a variety of biowastes yielding various quantities and qualities of biogas were identified in Bayelsa State, Niger Delta. The study's findings have provided evidence-based data that might be explored as a road map and catalyst for policy creation against inadequate biowaste management and as sustainable alternatives to the expensive liquefied petroleum gas. The potential of current research study to be scaled up for commercial use is implicated in the present study.

Keywords Mono-substrate digestion, Co-substrate digestion, First day of biogas production, PH

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Background

Infectious diseases can be spread from biowastes, which serve as major environmental pollutants and routes for disease transmission to humans [1]. Environmental pollution is a major problem in Niger Delta, Nigeria. Indiscriminate disposal of refuse and sewage around Bayelsa State capital, Yenagoa, and Niger Delta environs, as well as in the mangrove forest and water bodies in Niger Delta is a regular occurrence [2, 3]. Open dump sites with foul smells are found along major roads in Niger Delta [4]. These call for the need for effective environmental pollution management system in Niger Delta. The recycling of biowastes into useful biogas might serve as an alternative to the current inadequate management of environmental pollution in Niger Delta and Nigeria as a whole. It might also serve as an alternative to the expensive liquefied petroleum gas (cooking gas) in Niger Delta and Nigeria at large. According to the National Bureau of Statistics (NBS), Bayelsa State in Niger Delta had the highest retail price for LPG (cooking gas) in 2023, although the state is a major producer of LPG [5]. Also, according to NBS, since the beginning of 2024 till date, the average retail price of LPG in Nigeria has been increasing by 28.33% on a month-on-month basis and by 46.88% on a year-on-year basis from 2023 to 2024 [6]. The ever-increasing cost of liquefied petroleum gas (LPG) in Nigeria calls for the need to research on cheaper alternatives to LPG.

A previous report by the International Renewable Energy Agency in 2020 showed that the cost of biogas is 50% less than the cost of LPG. As a result, waste-to-energy technology involving anaerobic digestion of biowastes for biogas production is emerging as an alternative to LPG in other continents and countries [7], with Europe, China, and the United States accounting for 90% of global biogas production [8] and India practicing household biogas production [9]. Nigeria and Africa at large are yet to fully embrace biogas production on a national or continental scale.

The Niger Delta region of Nigeria possesses a unique climate, culture, and tropical vegetation that influences their way of life, occupation, available industry, and the type of waste they generate [10, 11]. From one nation to another, the quantity of waste and the frequency at which it is produced vary. Even within a given nation, the quantity of waste, accessibility, composition, and frequency at which it is produced also vary due to several factors, such as the type of industries present, the human activities taking place, the level of affluence, customs, climate, and living conditions [12, 13].

A study carried out in Lyon, a city in France, found that garden biowastes, restaurant biowastes, household biowastes, and supermarket biowastes were the major biowastes found for biogas production [14]. Another study carried out in India found that grass, hemp, wheat straw, leaves, cattle manure, pig manure, poultry manure, peanut hull, yard waste, maize, cattle slurry, sewage sludge, rice straw, municipal solid waste, wastewater leachate, pulp and paper mill sludge, food waste, and kitchen waste were the major biowastes found for biogas production [15]. In Malaysia, animal dung was found to be the major biowaste for biogas energy production [16]. Various forms of biowastes have also been found in other geographical locations [17, 18]. Thus, characterizing the biowastes in a given locality may help determine the feasibility of sustainable biogas production in that area. It may also help to determine the most suitable biogas production methodology to be employed [17, 18].

Aside from serving as biowastes, animal faeces, such as cow dung, also serve as inoculum for biogas production because they contain all the microorganisms, especially methanogens, needed for the anaerobic conversion of biowastes to biogas [19, 20]. The co-digestion of plant wastes and animal wastes has been reported to enhance biogas production [19, 20]. This justifies the co-digestion of plant waste and animal faeces. Although the justification for the co-digestion of plant wastes and animal faeces is well known, evidence-based data to support the absence of biogas production from the mono-digestion of plant wastes is sparse in the literature. This gap in research is what the present study intends to fill.

The core of Niger Delta, Nigeria, is Bayelsa State. The state is inhabited by the Ijaw-speaking tribe of Nigeria, and their major occupations are fishing, farming, palm oil milling, lumbering, local gin making, trading, and carving [21, 22]. Poor waste management and environmental pollution has been previously reported in this region [2–4]. However, studies on waste management and environmental pollution management through the recycling of biowastes for biogas production have not been previously reported in Bayelsa State, Niger Delta. Information from such studies are needed to inform the feasibility of sustainable biogas production in the State.

Therefore, the aims of the present study were to: identify the major fresh biowastes in Bayelsa State, Niger Delta; quantify the biogas yields from mono-digestion and co-digestion of identified biowastes; determine the first day of biogas production during hydraulic retention time; assess pH variations during anaerobic digestion; and evaluate biogas flame colours.

Methods

Study location

The study was conducted in Bayelsa State, Niger Delta. Bayelsa State is one of the 36 states in Nigeria and is situated in the core of Niger Delta. The coordinates of Bayelsa State are 6.06990° E latitude and 4.77190° N longitude. The State primarily consists of rural settlements, except for the capital city, which features urban areas. This rural predominance can be attributed to the riverine and swampy nature of the terrain, which hinders major infrastructural development. Bayelsa State is a coastal State that is heavily waterlogged with a high underground water table. Many of the indigenous people live by the seashore, or along river banks and engage in fishing and farming as their primary occupations [23, 24]. Bayelsa State comprises eight Local Government Areas (LGAs) which are Ekeremor, Kolokuma/Opokuma, Yenegoa (the state capital), Nembe, Ogbia, Sagbama, Brass, and Southern Ijaw, as shown Fig. 1.

Sampling of the fifteen representative study communities in Bayelsa State

Multistage random sampling was used to select fifteen representative communities for the study [26]. In the first sampling stage, six LGAs were randomly selected out of the eight LGAs in the state, as shown in Table 1. In the second stage, two communities were randomly selected from each of the selected LGAs, except for Yenegoa, where four communities were randomly selected, and Sagbama LGA, where three communities were randomly selected, as shown in Table 1. Four communities were randomly selected from Yenegoa because Yenegoa is the state capital city and has several markets as well as roadside vendors that generate biowastes. Three communities were randomly selected from Sagbama LGA because Sagbama LGA houses three tertiary institutions and several agro-allied industries that generate biowastes.

Identification and quantification of major biowastes in Bayelsa State, Niger Delta, Nigeria

On-the-spot assessment of the biowastes in each of the selected communities was carried out on a daily basis per

Fig. 1 Maps of Nigeria and Bayelsa State. The map of Nigeria shows the location of Bayelsa State within Nigeria while the map of Bayelsa State shows the eight LGAs in the State [25]

Table 1 Randomly selected LGAs and communities

Randomly selected LGAs	Randomly selected communities in each LGA
Ekeremor	Aleibiri, Ayamasa,
Kolokuma/Opokuma	Kaiama, Odi
Ogbia	Elebele, Otuoke
Sagbama	Ebedebiri, Sagbama town, Toru Orua
Southern Ijaw	Amassoma, Angiama
Yenegoa	Akenfa, Swalli market, Zarama market, Melford Okilo express road
	(Tombia – Imgbi road)

week per community. For each community, a tour around the community to map the available biowaste clusters and roadside sellers that generate biowastes was first carried out. Then the types and quantities of biowastes generated on a daily basis were noted and quantified using a digital weighing scale for a period of one week for each community. For large quantities of biowastes, the total area or volume where the biowaste was found was measured and recorded. Then a small area was marked out, and the biowaste in that small area was collected, categorized by sorting, and each category was quantified using a weighing scale. The quantity of biowaste in the small area was used to extrapolate the total quantity of biowaste in the whole area. For locations where the biowastes were scattered around, the biowastes were first gathered together before measurement and quantification. A representative sample of each major biowaste was collected from each study location for biogas production. The recorded weights and volumes were used for data analysis, and the results were expressed as tonnes of biowastes per week [14]. The handling of biowastes was carried out according to the National Environmental Standards and Regulations Enforcement Agency's (NESREA) guidelines for the handling of environmental wastes [27].

Anaerobic biodigester fabrication and set up

Polyvinyl chloride (PVC) drums were fabricated into biodigesters. One of the fabricated biodigesters is shown in Fig. 2a. Briefly, three openings were made on each PVC drum. The first opening, a large hole, was created on top of the drum and was fitted with a biowaste inlet pipe. A second opening (a smaller hole) was created on top of the PVC drum and was fitted with a small biogas outlet pipe. The third opening was created at the side of the PVC drum and was fitted with an effluent pipe. A control valve was fitted on each pipe. The biogas outlet pipe was connected to a biogas storage bag through a hose. A representative biogas storage bag made from tarpaulin and fitted with a hose was made for biogas storage as shown in Fig. 2b. Each set-up was made airtight by applying silicon gum to the edges of the pipes and bags [14]. Typical operation pressures for biogas storage balloon ranging from 2—8 mBar [28] was used in the present study. The pressure used for the present study was set at 4 mBar [28].

The inlet pipe is the large pipe on top of the drum used to feed biowastes (substrates) into the anaerobic biodigester. The effluent pipe is the pipe at the side of the drum used for the discharge of liquid waste out of the anaerobic biodigester. The biogas outlet pipe is the smaller pipe on top of the drum used for the passage of biogas from the anaerobic biodigester into the biogas storage bag through a hose. The storage bag (Fig. 2b) is flat, indicating that no biogas has been produced. The biodigester was placed under direct sunlight to warm it up to its optimal

a  b

Fig. 2 **a** A representative biodigester set up and **b** A representative biogas storage bag anaerobic temperature, while the biogas storage bag was kept inside a store room.

Moisture content determination of biowastes

Loss of water during oven drying was used to determine moisture content and the result was expressed in percentage. Briefly, 5 kg of each sample was placed in an oven for 16 h at 105 ± 2 °C and dried until a constant weighed was obtained. The moisture content was calculated by using the formular below [29].

$$\text{Moisture content} = \frac{\text{Weight of moisture (grams)}}{\text{Weight of sample (grams)}} \times 100$$

Mono- and co-anaerobic digestion of identified biowastes

Given that previous studies have shown that the mixing ratio of animal faeces and organic waste is 1:1 and that this ratio ensures that there is a balanced mixture of carbon and nitrogen, which is essential for the efficient breakdown of organic matter and the production of biogas [19, 20], the present study utilized a mixing ratio of 1:1 for animal faeces and plant wastes for co-digestion. Also, the widely used mixing ratio of 1:1 for animal faeces and water [30] was utilized in the present study for mono-substrate digestion. Solid plant waste samples were grinded and made into slurry by adding equal volume of water before feeding into the anaerobic biodigester. After feeding, the first day of biogas production during hydraulic retention time was observed and recorded [19, 20, 30].

Flame colour test

Visual examination of the colours of the flames produced during the combustion of the various biogas was carried out as previously described [31, 32].

Measurement of biogas yield

A weighing scale in kilograms was used to measure the biogas produced daily for one week and results were recorded as cumulative biogas yield per week [14, 19].

Measurement of the pH of the biodigester medium

The initial and final pH of the biodigester medium were measured using a using glass electrode pH meter with a ratio of 2:1 for biowastes to water suspension [19].

Statistical analysis

SPSS version 22 was used for data analysis. Values were presented as cumulative sums and as mean ± standard error of mean.

Results

Major fresh biowastes in Bayelsa State, Niger Delta, Nigeria

Results for the major fresh biowastes found in Bayelsa State, Niger Delta, are presented in Table 2 and Fig. 3, respectively. As shown in Fig. 3, a variety of biowastes were found. Also, as shown in Table 2, 120.61 metric ton of fresh biowastes was found to be generated per week in Bayelsa State, Nigeria. Industrial biowaste was the highest group of biowaste [47.6 tonnes, (39.46%)], followed by abattoir biowaste [33 tonnes (27%)], market and roadside sellers biowastes [25.5 tonnes (21.14%)], and farm biowastes [14.51 (12.03%)]. The most common biowastes found in all the study locations were plantain peels and empty fruit bunches of plantain. A significant difference was found in the biowastes generated from the selected communities. Cassava mill effluent was found to be channeled into nearby rivers and creeks in most cassava mills. Thus only a small quantity of cassava effluent could be assessed and collected for quantification. Additional information on Table 2 is presented as a Supplementary material.

Moisture state of the feedstock selected for biogas production and the state at which the material was grinded

The moisture state of the feedstock selected for biogas production and the state at which the materials were grinded are presented in Table 3. POME, cassava mill waste water, and sewage from septic tanks were in a liquid state. These required no grinding and no further addition of water before feeding into the biodigester. The sewage used in the present study was very watery with a very high moisture content. Excessive seepage of underground water into septic tanks was found in the present study.

Biogas yield from mono-digestion and co-digestion of biowastes used as feedstock

Figures 4 and 5 show the cumulative biogas yield from the mono-digestion and co-digestion of the biowastes used as feedstock for biogas production in the present study. Beginning from the first day that biogas production was observed, biogas was collected daily from the biodigester over a period of 7 days. Thus Figs. 4 and 5 show the cumulative biogas yield over a period of 7 days. As shown in Fig. 4, mono-digestion of animal waste yielded biogas as well as the co-digestion of plant waste and animal waste. However, mono-digestion of plant wastes yielded no biogas. Co-digestion of pineapple peels and rumen digesta yielded the highest quantity of biogas (18 kg of biogas/20 kg of biowastes), while co-digestion of cassava mill waste water with sewage yielded the lowest quantity of biogas (1 kg of biogas/20 kg of biowastes). However, plant-only digestion yielded carbon dioxide gas that extinguished a glowing splinter and turned lime

Table 2 Major fresh biowastes in Bayelsa State, Niger Delta

Biowastes (Tonnes/week)										
Study	**Industrial**			**Market & road side sellers**			**Farm**		**Abattoir**	
Location	**POME**	**EFBP**	**Cassava mill effl**	**Plantain wastes**	**Orange wastes**	**Pineapple wastes**	**Cassava peels**	**Cow dung**	**Rumen digesta**	**Total**
Aleibiri	Nil	Nil	0.01	0.30	0.00	0.00	0.01	0.00	0.00	**0.32**
Ayamasa	Nil	Nil	0.01	0.34	0.00	0.00	0.04	0.00	0.00	**0.39**
Kaiama	Nil	Nil	0.01	0.30	0.01	0.01	0.01	0.15	0.69	**1.18**
Odi	4.56	2.50	0.01	0.20	0.00	0.01	0.02	0.00	0.00	**7.30**
Ogbia	12.02	7.90	0.00	0.36	0.00	0.00	0.05	0.00	0.00	**20.33**
Elebele	3.15	1.50	0.01	0.36	0.00	0.00	0.01	13.50	0.08	**18.61**
Ebedebiri	Nil	Nil	0.01	0.20	0.00	0.00	0.21	0.00	0.00	**0.42**
Sagbama	5.00	3.6	0.01	0.38	0.02	0.06	0.04	0.10	0.55	**9.76**
Toru Orua	Nil	Nil	0.01	0.40	0.01	0.02	0.06	0.01	0.00	**0.51**
Amassoma	Nil	Nil	0.01	0.30	0.01	0.01	0.01	0.00	0.00	**0.34**
Angiama	Nil	Nil	0.00	0.30	0.00	0.00	0.01	0.00	0.00	**0.31**
Igogbene	Nil	Nil	0.00	2.53	0.20	0.13	0.00	0.00	0.00	**2.86**
Inside town	Nil	Nil	0.00	4.03	1.10	1.75	0.00	0.00	0.00	**6.88**
Swalli market	Nil	Nil	0.00	2.00	1.14	1.00	0.00	0.25	31.68	**36.07**
Zarama	5.27	2.0	0.01	8.00	0.01	0.01	0.03	0.00	0.00	**15.33**
Total 120.61	**30.00**	**17.50**	**0.10**	**20.00**	**2.5**	**3.00**	**0.5**	**14.01**	**33.00**	
(%)	**(24.87)**	**(14.51)**	**(0.08)**	**(16.58)**	**(2.07)**	**(2.49)**	**(0.41)**	**(11.62)**	**(27.37)**	**(100)**
	47.6 (39.46%)			**25.5 (21.14%)**			**14.51 (12.03%)**		**33 (27.37%)**	

POME Palm oil mill effluent, *EFBP* Empty fruit bunch of oil palm, *effl* effluent

water milky. Also, as shown in Fig. 5, inflated storage bags signify the presence of biogas.

Comparison of the beginning of biogas production for the various feedstock during hydraulic retention time

Figure 6 shows the variations that were found in biogas production commencement date during hydraulic retention time among the various biowastes. Figure 6 shows the first day that biogas emission from the anaerobic biodigester was observed after feeding and not the duration of complete digestion. Production of biogas started on the 6th, 32nd. 56th, 1st, 26th, 18th, 25th, 60th day of the retention period for rumen digester (RD), cow dung, sewage, pineapple peels (PP) and RD mixture, plantain peels and cow dung mixture, POME and RD mixture, orange fruit wastes (OFW) and cow dung mixture, and

Fig. 3 A cross section of some biowastes found in the present study during on-the-spot assessment of biowastes in Bayelsa State, Niger Delta, Nigeria. **a** Empty bunches of oil palm fruits, **b** Palm oil mill effluent inside a well, **c** Empty fruit bunches of plantain, **d** A bucket of cow dung slurry, **e** Pineapple peels, **f** Cassava peels, **g** Sheaths of corn

Table 3 Moisture state of feedstock and the state at which the material was grinded

Feedstock	Moisture state before grinding	Moisture state after grinding
Plantain peels	wet (10.1%)	wet (15%)
POME	liquid (97%)	not grinded
Cow dung	wet & sticky (80%)	not grinded
Rumen digesta	wet (15%)	not grinded
Orange peels	wet (10.01%)	wet (15.4%)
Pineapple peels	wet (84%)	wet (87.3%)
Cassava mill water	liquid (98%)	not grinded
Sewage	liquid (98.9%)	not grinded

cassava mill effluent (CME) and sewage mixture respectively. Co-digested pineapple peels and rumen digesta had the earliest biogas production commencement date, while co-digested cassava wastewater (cassava mill effluent) and human faeces had the longest biogas production commencement date during hydraulic retention time.

Flame colours of the various biogas produced

Table 4 shows the colours of the flames generated during the combustion of the various biogas produced in the present study. As shown in Table 4, a dominant blue flame was visualized in all the biogas produced, which was mixed with various shades of reddish yellow or orange flames.

Variations in pH during anaerobic digestion of biowastes

As shown in Fig. 7, an increase in pH during anaerobic digestion of biowastes was observed across all the biodigester media. Slight variations between the mean initial and final pH were found. The pH values for the media

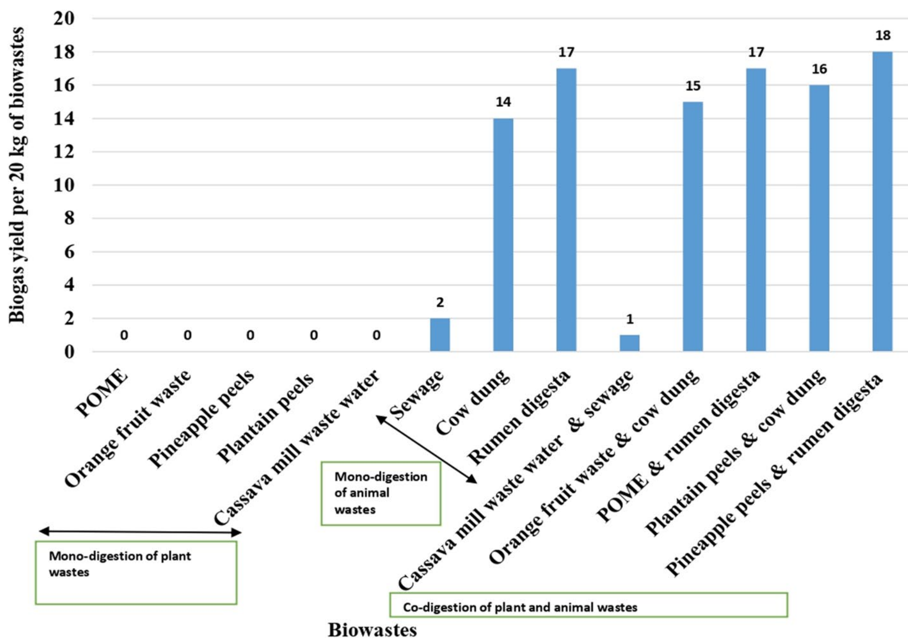

Fig. 4 Cumulative biogas yield collected over a period of 7 days from the mono-digestion and co-digestion of 20 kg of biowastes. POME: Palm oil mill effluent

Fig. 5 A representative cross section of the different biogas storage bags used for the daily collection of the biogas generated from the mono-digestion and co-digestion of biowastes in Bayelsa State, Niger Delta, Nigeria. Black tyre tube, 2 L (left), small biogas storage bag, 500 L (left), medium biogas storage bag, 4000 L (right). The maximum pressure the bags can withstand 4 mBar

that produced combustible biogas varied from low acidity to slightly alkaline, while the pH values for the plant-based biowastes that yielded no biogas varied within the acidic range.

Discussion

In the present study, we have characterized the biowastes found in Bayelsa State, Niger Delta. The quantity of biowastes and locations where they can be abundantly found on a weekly basis within Bayelsa State, Niger Delta, have been presented in this study. The biogas quality in terms of flame colours and the first day of biogas production during hydraulic retention time in the biodigester, as well as the quantity of biogas produced from the mono-digestion and co-digestion of substrates (biowastes), have also been presented in this study. Finally, variations in pH during the anaerobic digestion of the different biowastes were also determined in the present study.

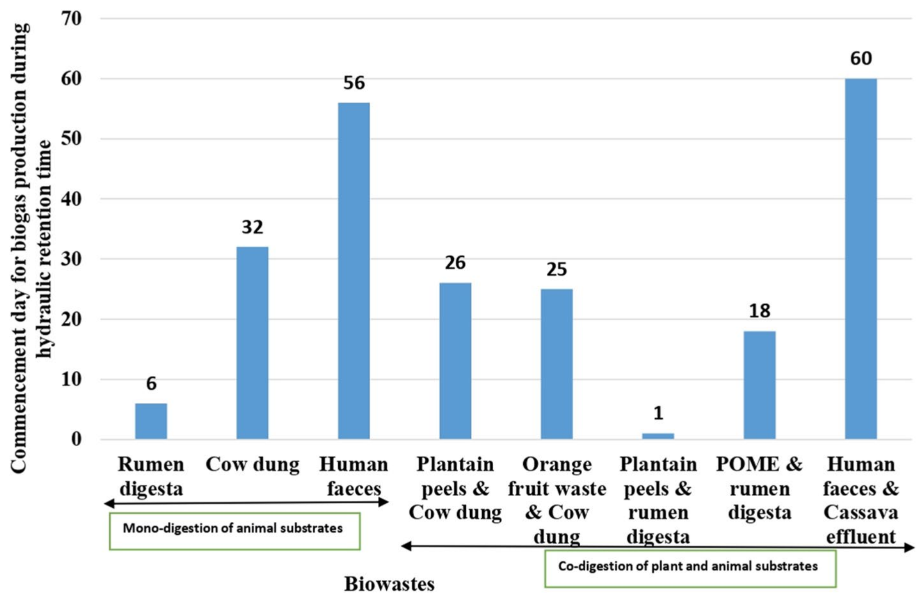

Fig. 6 First day of biogas production for various biowastes during hydraulic retention time in the biodigester. Values for the mono-digestion of plant substrates not available because no biogas was produced from the mono-digestion of plant wastes

Table 4 Flame colours of the biogas produced in Bayelsa State, Niger Delta, Nigeria

Biowastes	Flame colours of biogas produced
Pineapple peels & rumen digesta	Dominant blue with tiny shades of reddish yellow
POME & rumen digesta	Dominant blue with tiny shades of reddish yellow
Plantain peels & cow dung	Dominant blue with tiny shades of orange
Orange peels & cow dung	Dominant blue with tiny shades of orange
Cassava mill effluent & cow dung	Dominant blue with tiny shades of orange
Rumen digesta	Dominant blue with tiny shades of reddish yellow
Cow dung	Dominant blue with tiny shades of reddish yellow
Human faeces	Dominant blue with tiny shades of orange

Domestic biowastes were not found as major biowastes in the present study. On the contrary, a previous study carried out in Lyon, a city in France, found that domestic biowastes were a major component of biowastes [14]. Also, although another study carried out in Central African Rebulic found that market biowaste was not a major component of biowastes [17], the present study found that market and road seller`s biowastes (empty bunches of plantain peels, pineapple peels, and orange peels) were major components of biowastes. This shows that from one region of the world to another, the composition of biowastes varies. Thus, in carrying out biogas production, a knowledge of the biowastes locally available as raw materials or feedstock in a given area is important.

Also, although human faeces have been previously reported as a good raw material for biogas production [33], however, the present study found a low quantity of biogas yield from human faeces (sewage) as shown in Fig. 1. This might be due to the high moisture content of the sewage used in the present study. The high moisture content was due to the excessive watery nature of the sewage. The excessive watery nature of the sewage was as a result the seepage of underground water into the sewage in the septic tank, thereby resulting in the excessive watery sewage utilized in the present study. Bayelsa State lies on a swampy terrain with a high underground water table [34]. The present study found that seepage of underground water into septic tanks in Bayelsa State occurred in most septic tanks visited in the communities selected for the present study [34]. This excessively watery sewage together with the excessively watery cassava mill waste water used in the present study might be responsible for the decrease in biogas yield of sewage upon co-digestion with cassava mill waste water which was found in the present study.

Studies comparing the biogas yield of several biowastes under the same set of experimental study conditions are sparse in literature [19, 20, 29, 32, 33]. The present study investigated the feasibility of biogas production from industrial biowastes, market and roadside sellers'

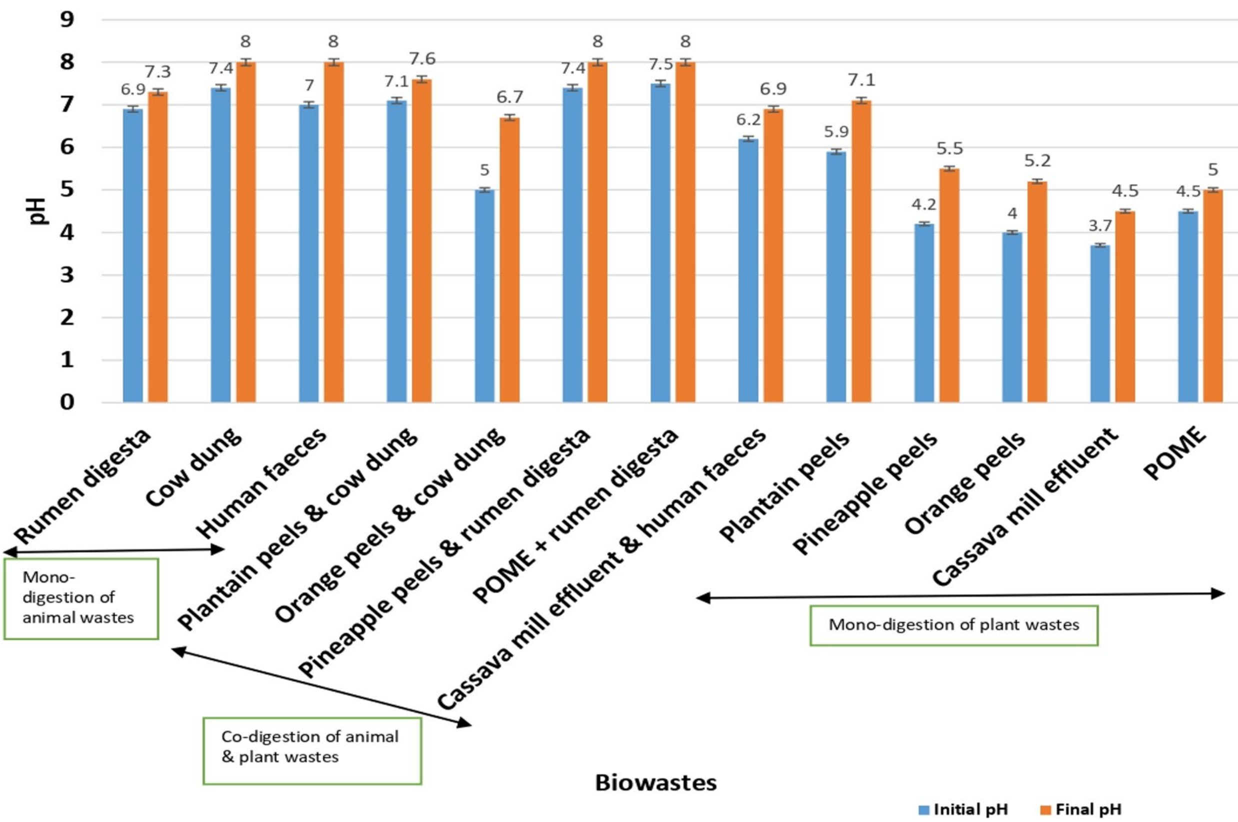

Fig. 7 Variations in pH during anaerobic digestion of biowastes

biowastes, farm biowastes, and abattoir biowastes. This has provided a snapshot of the contributions of several biowastes to biogas production. Mono-digestion of plant biowastes did not yield biogas in the present study. Thus, this pattern of biowaste digestion is not recommended for future biogas production. When producers are provided with the biogas production efficiency of several locally available biowastes, they will be able to make a better informed choice of the best raw material to use for biogas production, as well as the biogas production process to be employed. This will make biogas production more flexible, feasible, sustainable, and appealing.

Hydraulic retention time is the duration that feedstock stay in a digester during anaerobic digestion. Biogas production can commence any day within the hydraulic retention time and continue till the last day of the retention time [35–38]. "Comparison of the beginning of biogas production for the various feedstock during hydraulic retention time" section, showed the biogas production commencement dates for the various biowastes during hydraulic retention time. Compared with other biowastes, the co-digestion of pineapple peels and rumen digesta had the earliest biogas production commencement date during hydraulic retention period. This might be due to the variations in the proximate composition of the various biowastes as previously reported [35–38]. The high content of simple sugars and other simple carbon compounds in pineapple peels, may have made pineapple peels very easy to digest [35]. This may have resulted in the early biogas production commencement observed for pineapple peels mixed with rumen digesta unlike the other biowastes which had high content of complex carbon compounds such as cellulose and lignin which take longer periods to be broken down [39]. the present study found that the complex biowastes had longer commencement date for biogas production during hydraulic retention time or digestion period [39]. The findings of the present study corroborate the findings of previous studies [36–38]. Thus, a careful selection of biowastes with early biogas production start date may improve biogas production efficiency. Characterization of the commencement date for biogas production of a variety of biowastes during hydraulic retention time is limited in literature. Retention times are usually given in literature without indication of the exact biogas production commencement date within the retention time. Thus, the present study has filled a major gap in research. It must be noted that the values presented in Fig. 6 referred to the first day that biogas emission from the biodigester was observed after feeding the digester and not the day that complete digestion of the biowastes occurred. For example, although biogas emission was observed within 24 h from the biodigester containing a mixture of pineapple peels and rumen digesta however, complete digestion continued till the next seven days, as evident by the continuous production of biogas till day seven of biogas emission [35–38].

The present study also found that the various biogas produced in the present study gave a dominant blue flame colour and various shades of orange or reddish yellow flames during the combustion. Flame colours of biogas have been previously reported in a study carried out by Ketuk et al. [31], where the flame color of the biogas from cow dung and goat manure starters was found to be redder than the flame colour from the biogas from leachate starter. Also, another previous study found that the average flame colour of unpurified biogas from coffee waste materials was 60.16% blue and 39.84% red flame [32]. However, the present study has expanded the findings of theses previous studies [31, 32] by providing information on the flame colours produced of the biogas produced from a range of other substrates not previously reported. Previous studies have showed that biogas with a high degree of reddish yellow or orange flames are of lower quality and generates lower heating temperature compared with biogas with blue flame which are of higher quality and generates higher heating temperature [31, 32]. In the present study the biogas from POME was redder than the biogas produced from the other biowastes. This implies that heating with the biogas from POME will take a longer time due to its lower temperature compared with biogas with a higher degree of blue flame. The findings of the present study is quite novel given that till date, no study has characterized the flame characteristics of the biogas produced from a range of biowastes in a single study. The present study has thus helped to fill the gap in research.

Flame colour is a qualitative measure of biogas purity. Flame testing can be used to determine fuel quality because flame is a combustion chemical reaction and burning is influenced by fuel quality [31, 32]. A yellow or red flame on gas stove is dangerous, as it is indicative of incomplete combustion and carbon monoxide (CO) generation [31, 32]. This could lead to health hazard and wastage of biogas as well as taking longer period of time for heating to occur. It can also result in the generation of soot on the appliances used for heating [31, 32]. In addition, the present study found that plant only biowastes did not generate any flame, rather they emitted a gas that extinguished a glowing splinter. This suggests that plant-based wastes must be co-digested with animal intestinal or feacal waste for biogas production to occur. However, further study is recommended.

It is a known fact that pH is an important factor in biogas production [38]. Non-methanogenic bacteria, which carry out the first stage of anaerobic digestion, can adapt to a pH range of 4.0–8.5, while methanogenic bacteria, which carry out methanogenesis, the second stage of anaerobic digestion, are limited to a pH range of 6.5–7.2 [38]. This might explain why only the mediums with a nearly neutral to slightly alkaline pH produced more biogas in the present study compared with mediums with a lower pH.

The underlying uniqueness and significance of the study's findings, particularly in terms of biowaste management in the Niger Delta, is that the study`s findings have provided evidence-based data that might be explored as a road map for policy creation against the inadequate biowaste management, and environmental pollution in Niger Delta [2–4]. In addition, the underlying uniqueness and significance of the study's findings, particularly in terms of biogas production in Niger Delta, is that the study`s findings have provided an action plan that might serve as a catalyst for the implementation of biogas production using the available biowastes in Niger Delta as cheap sources of feedstock. This might serve as an alternative to the highly expensive cooking gas in the Niger Delta and Nigeria as a whole [5, 6].

Conclusion

The present study highlighted the qualitative and quantitative characteristics of the major biowastes found in Bayelsa State, Niger Delta. The present study also demonstrated variations in the yield and flame colours of the biogas produced from various biowastes. Variations in the commencement date for biogas production during anaerobic digestion hydraulic retention time for the various biowastes were also demonstrated in the present study. The present study also found excessive moisture content in the sewage from septic tanks in Bayelsa State due to the high underground water table in Bayelsa State. Further study to dewater the sewage in Bayelsa State, Niger Delta, for efficient biogas production is recommended. The potential of current research study to be scaled up for commercial use is implicated in the present study.

Abbreviations

CO	Carbon monoxide
EFBP	Empty fruit bunch of oil palm
LPG	Liquefied petroleum gas
NBS	National Bureau of Statistics
POME	Palm oil mill effluent
PP + RD	Pineapple peels + Rumen digesta
PVC	Polyvinyl chloride

Supplementary Information

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Supplementary Material 1

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Authors' contributions
FAO, AAO and HIO designed the concept and scope of the work. FAO, AAO and HIO carried out field survey for data collection. FAO and HIO analyzed and interpreted the data regarding the quantity of fresh biowastes, biogas yield and pH. FAO, AAO and HIO reviewed the manuscript. All authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate
The study does not involve human participants. Hence, no ethical approval was needed.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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