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Recovery of plant biomass by anaerobic digestion: case of plantain and yam peelings combined with cattle dung

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Abstract: Anaerobic digestion is a natural environmentally-friendly biological process. It breaks down organic waste to generate biogas in an anaerobic environment. As part of this study, the process was applied to plantain and yam peelings and cattle dung, with a view to contributing to the search for other sources of energy. The results of a characterization of these residues showed high volatile solids content (>75%), C/N ratios of between 20 and 30 and VFA/FAT ratios of less than 0.4. Methanization trials were then carried out over a period of 40 days. The results showed a good correlation between the volume of biogas and the biodegradability of volatile matter. The mixtures containing cattle dung showed the highest yields. In monodigestion, cattle dung had the best yield with 410 mL/g (VS) of biogas. In co-digestion, the binary mixture of yam peel and cattle dung collected the highest amount of biogas at 556 mL/g (VS). For the ternary mixtures, the maximum amount of biogas was recorded when the plantain peelings, yam peelings and dung were taken in proportions of 1/6, 2/3 and 1/6 respectively, giving 565 mL/g (VS) of biogas. An analysis of the biogas quantities showed that they contained good levels of methane (54.03% to72.98%)

1. Introduction

Human activity has always generated waste, which is often a potential source of illness caused by air, water and soil pollution (Ikram, 2021). In Côte d'Ivoire, more than 1.624 million tons of food waste are generated every year, representing 40 to 65% of municipal solid waste (Kouadio *et al.*, 2018; Kouakou *et al.*, 2022). The amount of food waste generated could increase as a result of population growth and rapid urbanization. This waste is often found in institutions such as restaurants, which generate large quantities of food waste (Kouakou *et al.*, 2021). However, recovering the energy

contained in this food waste is not only an economic opportunity, but also a major challenge for sustainable development (Rao *et al.,* 2018; Ma *et al.,* 2018; Lalander *et al.*, 2018). For this reason, anaerobic digestion remains the appropriate method for treating these wastes (Romero-Güiza & *al.*, 2016; Xu *et al.*, 2015). It is a natural and spontaneous process of biodegradation of fermentable organic matter, accompanied by the production of a methane-rich biogas that can be recovered (Laskri & *al.*, 2007; Rousseau & *al.*, 2020). The biogas produced by the anaerobic digestion of food waste can also be used to produce energy (Pisutpaisal *et al.*, 2014). Yamoussoukro, a crossroads and tourist town located in the center of Côte d'Ivoire, is the site of several transactions. To this end, this city is full of several restaurants whose basic menus are most often plantain, yam and rice. As a result, these restaurants are a potential source of food waste, including plantain and yam peelings that can be used as raw materials for anaerobic digestion. However, according to Kafle & Kim, (2013) and Isha & *al.*, (2020), a single anaerobic digestion of food waste leads to rapid acidification of the digester and inhibits the activity of methanogenic bacteria, which often hinders the proper functioning of the methane fermentation process. As this waste is highly biodegradable, using it as the sole substrate for methanisation does not give good results due to the rapid acidification of the medium, which inhibits the activity of the methanogenic bacteria. Therefore, to avoid a drop in pH in the digester, co-substrates are generally used (Xu *et al.*, 2017). The objective of our study is to optimize the biogas yield from the codigestion of plantain and yam peels collected from these restaurants by coupling with cattle dung as a co-substrate. Specifically, once the residues have been characterized, they will be anaerobically digested under mesophilic conditions using a mixing plan. This study could help to find another source of energy and reduce their harmful effects on the environment.
(Benabdellah *et al.*, 2006),

2. Methodology

2.1 Substrates

The plant biomass used as substrate in this study consisted mainly of plantain and yam peels. In order to facilitate the organic matter degradation process, we used cattle dung as a cosubstrate to boost the activity of the bacterial consortium (Soro *et* al., 2010) and also to correct any acidity in the anaerobic environments (Kpata, 2014). These residues were collected from restaurants in the city of Yamoussoukro for plantain and yam peelings, while the dung was taken from the farm of the National Polytechnic Institute-Houphouët Boigny (INP-HB) in the said city. Prior to the anaerobic digestion trials, the plantain and yam residues were ground in a blender to make them easily accessible to the micro-organisms. The dung was not pre-treated. Figure 1 shows images of the different residues used.

2.2 Determination of physico-chemical parameters of substrates

As part of this study, physicochemical analyses were carried out in two laboratories: the Plant and Soil Analysis Laboratory (LAVESO) at the Higher School of Agronomy (ESA) and the Industrial Processes and Synthesis of New Energies Laboratory (LAPISEN). Both laboratories are part of the National Polytechnic Institute-Houphouët Boigny (INP-HB) in Yamoussoukro, Côte d'Ivoire. The method used to determine moisture content is based on that proposed by the Association of Official Analytical Chemists (1990) (Kouame *et al.*, 2018) whose principle is based on the loss of mass of the initial sample (m_0) to a constant mass (m_1) at 105°C for 24 hours. The total solids content (TS) was deduced from the moisture content. The volatile solids content (VS) was calculated by the difference in weight between the mass of waste dried at 105°C (m_1) and the mass of waste calcined at 600°C (m_2) for 6 hours (Kouadio, 2020). Using the method described by Shang *et al.* (2016), the pH of each waste was easily determined. This method involves suspending 5 g of waste with 50 mL of distilled water in a 250 mL beaker under constant stirring for 5 minutes using a magnetic stirrer.

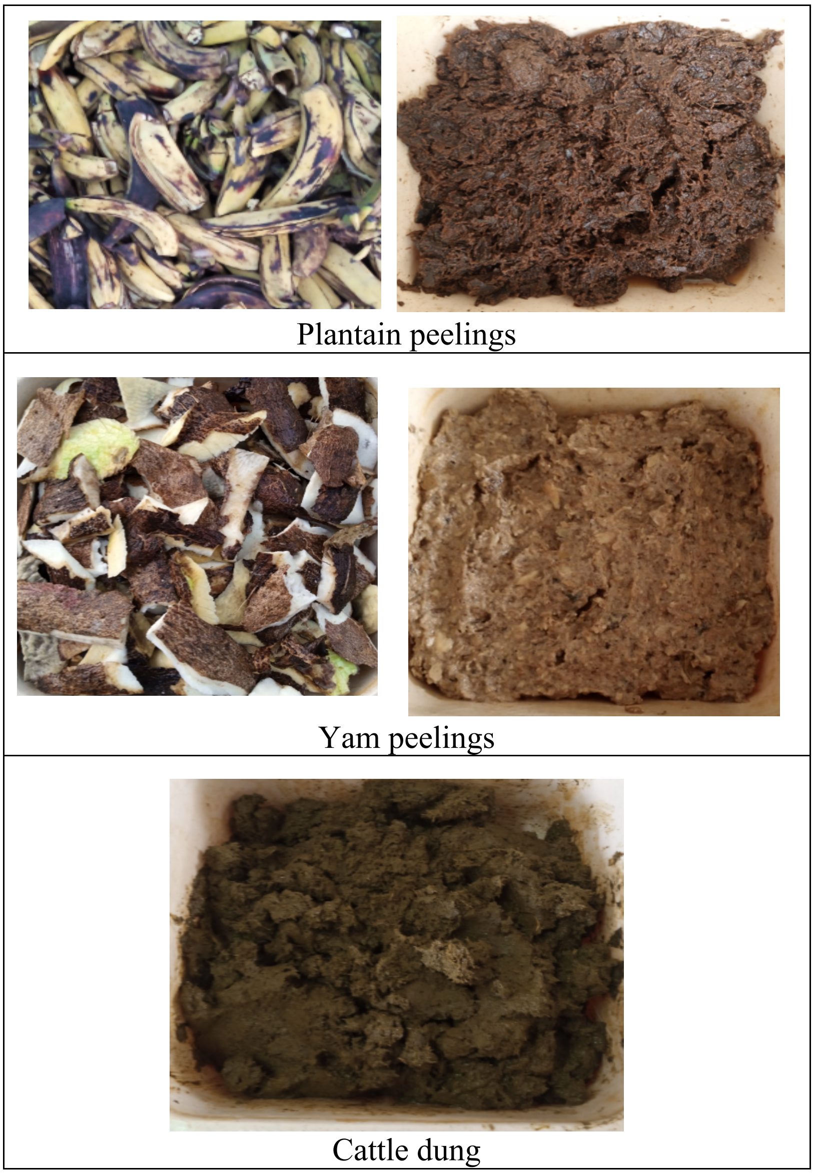


Figure 1. Anaerobic digestion inputs

The suspension was left to stand for 30 minutes, after which the pH of the filtered solution was measured using a HANNA HI 8424 pH meter. The volatile fatty acid (VFA) content was determined using the titrimetric method (Jean *et al.*, 2009). This is a global assay method that involves acidifying a volume "v" of sample to pH 3.5 with sulphuric acid (0.1 M). The leachate is then heated for 3 minutes to degas the carbon dioxide. After cooling to room temperature, the pH of the solution was adjusted to 4 with NaOH (0.1N) (V_1) and then to 7 (V_2). The volatile acidity is determined by the difference between these volumes. The titrimetric method is also used to obtain the full alkalimetric titre (FAT). This method involves adding a titrated solution of sulphuric acid H_2SO_4 (0.1M) to a known volume of sample placed in a beaker, until a pH of 4.5 is reached. This volume of sulphuric acid added to the sample enables us to determine the alkalinity of the substrate (Ikram, 2021). With regard to mineral elements, carbon (C) was determined using the method of Walkley and Black (1933). Nitrogen (N) levels were obtained using the Kjeldahl method (Bremner, 1996), while phosphorus (P) and potassium (K) levels were determined using atomic absorption spectrophotometry (AOAC, 1990).

2.3 *Definition of mixing proportions*

The mixing proportions were defined using *Design Expert 11* software based on Henry Scheffé's Augmented Simplex-centroid designs. These proportions were based on the volatile matter contained in the plantain and yam peelings and cattle dung, which we set at 16 g (VS) per mixture. The experimental matrix (**Table 1**) gives the composition of all the digesters in random order.

Table 1. Experimentation matrix

Order of tests	Proportions		
Standard	Plantain	Yam	Cattle dung
D2	0	1	0
D9	0.167	0.667	0.167
D10	0.167	0.167	0.667
D6	0	0.5	0.5
D5	0.5	0	0.5
D3	0	0	1
D8	0.667	0.167	0.167
D4	0,5	0,5	0
D7	0.333	0.333	0.333
D1	1	0	0

D: digester

2.4 *Anaerobic digestion tests*

All the tests were carried out in batch digesters for 40 days. The experimental digester is a 1200 mL vessel with a usable volume of 1000 mL and a headspace of 200 mL. Once the waste was in the digester, the final volume was adjusted to 1000 mL with distilled water and sealed with a screw cap to be placed in a device thermostatic at 37 ± 2°C using a JBL PROTEMP S 300 temperature controller. Each digester was manually agitated for two minutes twice a day to prevent the formation of layers on the surface of the digester contents. Daily biogas production was measured using the water displacement method (Adou *et al.*, 2022). The diagram opposite (**Figure 2**) shows the system used to carry out our anaerobic digestion trials.

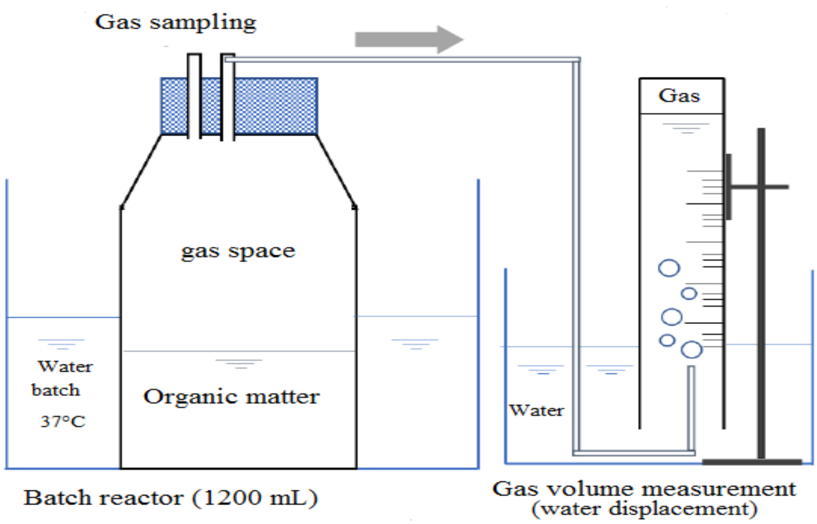


Figure 2: Schematic diagram of anaerobic digestion trials

3. Results and Discussion

3.1 physical-chemical characteristics of substrates

The results of the pre-test waste characterization are shown in **Table 2**. This table highlights several physical-chemical parameters determined for this study. With regard to pH, the values recorded are 5.27, 5.78 and 8.14 for plantain peelings, yams and cattle dung in that order. Only the dung had a pH (8.14) within the range recommended for good anaerobic digestion, i.e. between 6.5 and 8.5 (Kouadio, 2020). It is therefore favorable to the growth of methanogenic bacteria (Kalloum *et al.*, 2007). The acidity of the other two substrates is due to organic acids (Wassila, 2017) which can have a negative impact on biogas production. However, the basic pH of dung can raise that of the anaerobic environment in the context of codigestion with acidic substrates (Kpata, 2014). In terms of moisture content (H), **Table 2** shows 87.01%, 74.34% and 86.90% respectively for plantain peelings, yam peelings and cattle dung.

Table 2. Physical-chemical characteristics of substrates

Parameters	Plantain peelings	Yam peelings	Cattle dung
pH	5.27	5.78	8.14
H (%)	87.01	74.34	86.90
TS (%)	12.99	25.66	13.10
VS (%)	86.07	94.58	76.98
Carbon (%)	38.72	30.19	42.83
Nitrogen (%)	1.36	1.23	1.66
Phosphorus (%)	0.04	0.12	0.04
Potassium (%)	2.15	2.05	1.75
C/N	28.4705	24.5447	25.8012
VFA (mg(CH3COOH)/L)	409.006	397.094	276.106
FAT (mg($CaCO_3$)/L)	850.324	906.607	1136.239
VFA/FAT	0.481	0.415	0.243

We note here that these substrates contain a large quantity of water, which would make them highly fermentable for improved anaerobic digestion (Afilal *et al.*, 2014). In addition, the dry matter rates (TS) obtained for plantain (12.98%), yam (25.65%) residues and cattle dung (13.09%) remain below 40%. This gives them a preference for dry anaerobic digestion (Boutoute, 2022). In terms of volatile dry matter content (VS), we obtained 86.07%, 94.57% and 76.97% respectively for plantain peelings, yam peelings and cattle dung. These proportions for plantain and yam peels are almost identical to those obtained by Thomsen *et al.* (2014) in their work on biofuel production from West African agricultural residues. They determined 85.20% and 94.80% as organic matter contents for plantain and yam peelings. Compared with the work of Kouadio (2020) where the volatile solid content was 80.91% for the dung used, we estimate that our dung, which has a volatile matter content of 76.98%, is less rich in organic matter. However, it has a higher volatile solids content than the dung used by Lacour (2012) where the volatile solid content was only 55%. With these high organic loads, these wastes would be suitable for anaerobic digestion technology. The table also shows that dung contains the most nitrogen (1.66%) and carbon (42.83%), while phosphorus is more abundant in yam residues, with a content of 0.12%. Plantain has a higher potassium content of 2.15%. These components are essential for biogas production (Ali *et al.*, 2010) as they are involved in microbial growth during biomethanization (Weiland, 2010). In addition, monitoring volatile fatty acids (VFA) and alkalinity remains important during biogas production. The alkalinity of the medium regulates the pH following the increase in VFA up to the point where a sudden and irreversible drop in pH occurs. The ratio of these two parameters has been identified as a warning indicator of dysfunction linked to acidosis (Pautremat *et al.*, 2018). VFA/FAT ratios below 0.4 are indicators of the stability of the anaerobic digestion process (Kafle and Kim, 2013). In our case, the VFA/FAT ratios are 0.481, 0.415 and 0.243 respectively for plantain and yam residues and cattle dung. This ratio is higher than 0.4 for plantain and yam peelings but lower than the same value for dung. This would indicate a malfunction in the anaerobic digestion of these peelings, as opposed to dung, for which it predicts a better anaerobic digestion process. Furthermore, all the substrates have C/N ratios favorable to their biodegradability. These C/N ratios are 28.47, 24.54 and 25.80 for plantain and yam peels and cattle dung. These values are of interest for the stability of biological conversion processes because they are within the range indicated by Gunaseelan (2007). This stability would be more favored by cattle dung, whose C/N ratio (25.80) is closer to the optimum value of 25 (Slimane, 2014; Vlona, 2015; Askri, 2015).

These results of analyses relating to the physical-chemical composition of substrates highlight certain specific characteristics of the latter that may favor or inhibit the anaerobic digestion process. They also highlight the possibilities, and even the needs, for pooling these physical-chemical characteristics through co-digestion between substrates.

3.2 Monitoring stability parameters in co-digestion trials

3.2.1 Production of volatile fatty acids

The concentration of VFA is a characteristic parameter whose evolution makes it possible to judge the stability of the process (Ahring *et al.*, 1995; Michael *et al.*, 2014). It was calculated on the basis of the acetic acid equivalent. The results show concentrations between 228.907 and 530.404 mg/L. These values, which are below the inhibition limit value (5000 mg/L), suggest good anaerobic digestion (Rizwan *et al.*, 2015). **Figure 3.a** shows that there was initially an accumulation of VFA in the digesters for 15 to 18 days after the start of digestion.

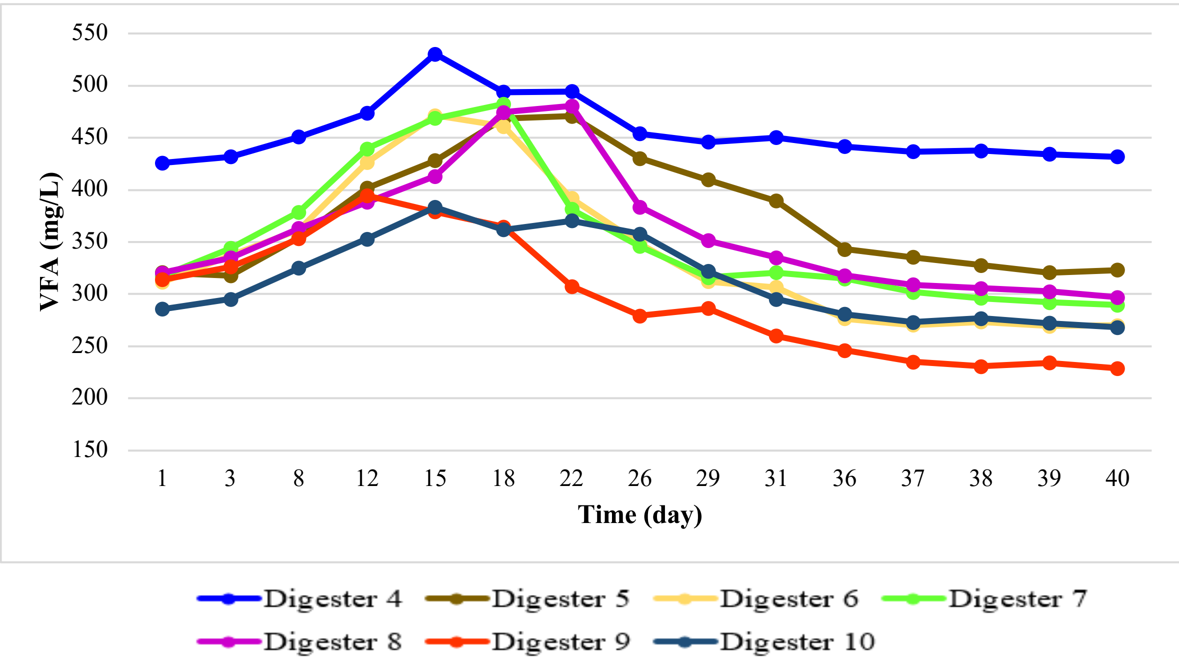


Figure 3a. Evolution of Volatile fatty acid during anaerobic digestion

For the same quantity of organic matter (16 g(VS)), VFA production varies from one digester to another during its degradation. The maximum VFA concentrations during this period were 530.404; 470.794; 471.404; 482.406; 480.562; 394.576 and 383.258 mg/L for D4, D5, D6, D7, D8, D9 and D10 respectively. This VFA production lasted about a week in digesters D4, D6, D9 and D10 before dropping, while digesters D5, D7 and D8 waited until 18th day before seeing this VFA content drop. The drop in VFA content continued until the end of the process. We also note that digester D4 generated the most VFA along the process as predicted by Kafle and Kim (2013) and Isha *et al.* (2020). The high VFA production during the first two weeks is thought to be related to the first two phases of anaerobic digestion (hydrolysis and acidogenesis) when easily biodegradable substrates disintegrated (Rasi *et al.*, 2013). The drop in VFA concentration is explained by a balance between the bacterial consortium in the acetogenesis and methanogenesis phases for its consumption for biogas production (Kalloum *et al.*, 2007). The plot shows a change in VFA concentration consistent with that obtained by Dahou *et al.* (2020) and Aoun and Bouaoun (2006) on improving biogas production from lagoon sludge and on the physical-chemical parameters of biomethanization of household waste respectively. This work showed a first part of the evolution of the VFA content characterized by an increase in the concentration of VFA in the medium and a second part showing its continuous decrease indicating a progressive exhaustion of the organic matter.

3.2.2 Full alkalimetric titre

Alkalinity is a parameter that determines the buffering capacity of a digester and therefore its ability to maintain a stable pH. It is assessed using the FAT. The graph opposite (Figure 3b) shows FAT values between 778.015 and 1489.962 mg/L. The recommended range for good anaerobic digestion is 1000 to 3000 mg/L (Dahou, 2019). However, at the start of digestion and in each digester, a FAT value lower than the required standard was found. These FAT values fell in all the digesters before rising until they reached the desired range. This period of falling FAT lasted 12 days for digesters D4, D6, D7 and D9, then 15 days for digesters D5, D8 and D10. This drop in FAT would be due to the consumption of carbonate ions by hydrogen ions generated by the dissolution of volatile fatty acids formed during hydrolysis and acidogenesis (Derbal, 2017).

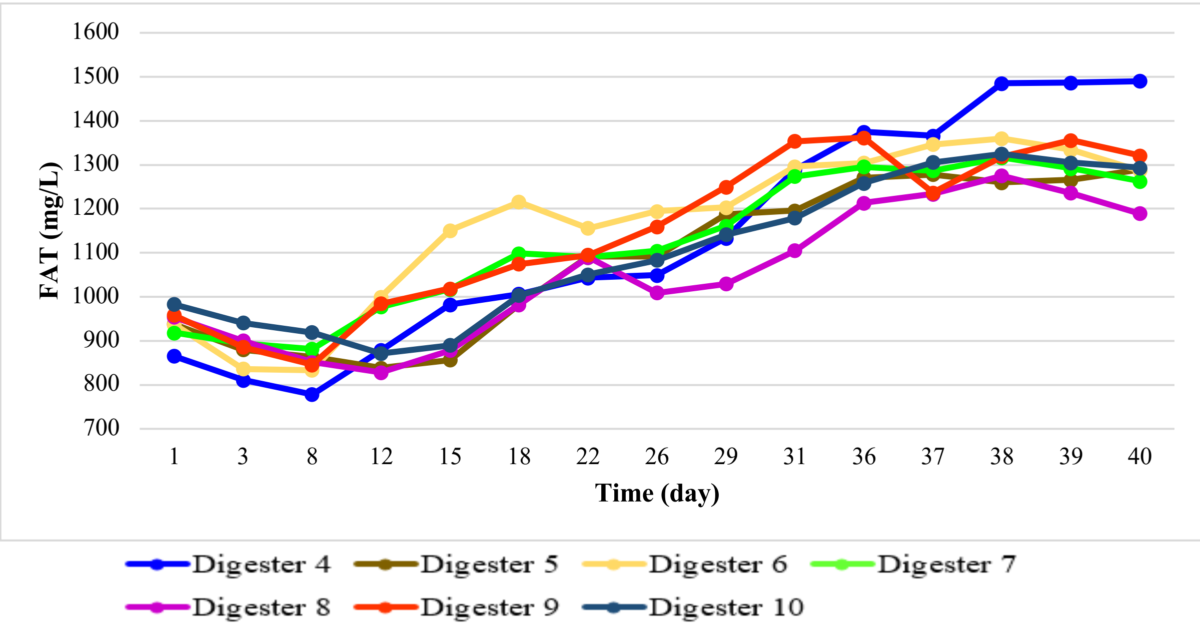
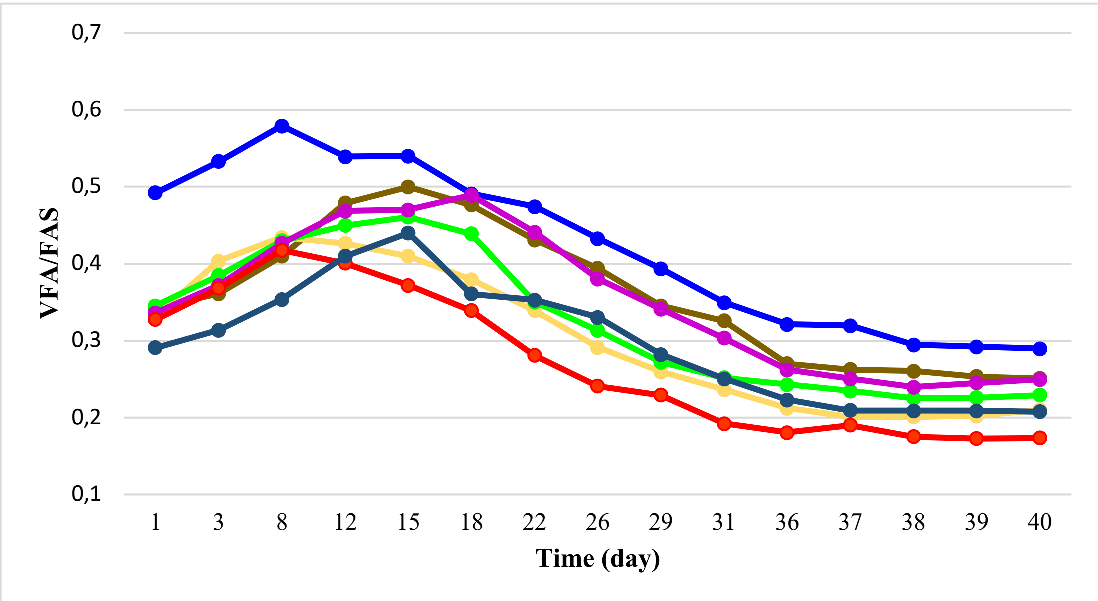


Figure 3b. Evolution of full alkalimetric titre during anaerobic digestion

Subsequently, a significant increase in FAT values was observed in the digesters. This increase in FAT is due to the consumption of VFA by methanogenic bacteria to counteract the fall in pH (Bjornsson, 2000) and convert them into methane (Hajjaji *et al.*, 2016). This graph (Figure 2(b)) also shows that the evolution of the FAT is almost opposite to that of the VFA. These same remarks are made by some authors, notably Tahri (2019) and Lahbab (2022) who have respectively conducted studies on the production of electricity from anaerobic digestion and on modelling the performance of a reactor for the production of renewable energy.

3.2.3 VFA/FAT ratio

It has already been reported that a VFA/FAT ratio greater than 0.4 is considered to be a sign of malfunction in methanization. For this reason, this ratio must not exceed this limit value in order to ensure the stability of the methanization process for better biogas production. According to **Figure 3.c**, the VFA/FAT ratios obtained are between 0.1 and 0.6. During the early stages of the process, this ratio exceeded 0.4 in each digester. This lasted 26, 22, 15, 18, 22, 12 and 15 days for digesters D4, D5, D6, D7, D8, D9 and D10 respectively. In particular, this time was longer for digesters D4, D5 and D8, but shorter for digester D9. During this same phase, these ratios were higher in digester D4, with the highest value recorded (0.58). Furthermore, this increase in VFA/FAT ratios coincides with high VFA production during the same period. This could partly explain the low biogas yield during the latent periods. After this period, the VFA/FAT ratio remained below 0.4 for all the digesters until the end of the process. This is explained by the consumption of VFA in the medium to be transformed into biogas. This is what Kaidi *et al.* (2017) and Zhai *et al.* (2015) seem to confirm when they argue that the reduction of VFA through the gradual adaptation of the bacterial consortium to the anaerobic environment promotes the conversion of VFA into biomethane.



(c) VFA/FAT ratio

Figure 3c. Evolution of VFA/FAT ratio during anaerobic digestion

3.2.4 Hydrogen potential

The hydrogen potential (pH) is also a very important parameter in the stabilization and smooth running of anaerobic digestion, as methanogenic organisms are very sensitive to its variation (Hery, 2017; Wassila, 2017). The optimum values for this parameter for good biogas yield are estimated at between 6.5 and 8.5 (Kouadio, 2020; Saïdi-Boulahia *et al.*, 2018). Figure 3d shows pH values between 4.15 and 7.5. Monitoring of the process revealed similar variations in the FAT. First, a decrease in pH was observed in all digesters. Over a period of 22, 18, 12, 12, 18, 12 and 15 days, a drop in pH ranging from 5.19 to 4.15, 6.62 to 5.7, 6.67 to 5.9, 6.56 to 5.83, 6.32 to 5.38, 6.76 to 5.97 and 6.84 to 5.76 was noted in digesters D4, D5, D6, D7, D8, D9 and D10 respectively. This drop would have been the consequence of the degradation of organic matter with the formation of organic acids and volatile fatty acids during the acidogenesis phase (Kalloum *et al.*, 2007). The drop in pH during the first few days of the anaerobic digestion process has also been noted by Djaâfri *et al.* (2009) and Laskri *et al.* (2007). Following this, through self-adjustment, the pH values improved until they stabilized in order to promote good anaerobic digestion. Nevertheless, the pH values in digester D4 remained below 6.5. Singularly, pH values were favorable in digesters D5 to D10, but more so in digesters D6, D7, D9 and D10, where biogas yields were highest (at least 500 mL/g(VS)). We can attribute this performance of these six digesters to the contribution of cattle dung. In contrast, digester D4, which had no cattle dung, had a low biogas yield. Some authors, such as Kpata (2014) and Girault *et al.* (2013) have the same assessment with regard to animal dung. Indeed, for Girault *et al.* (2013) animal residues can increase the methanogenic potential in codigestion, whereas for Kpata (2014) cattle dung rich in nitrogenous elements can raise the pH of the anaerobic environment. Finally, the pH remained stable towards the end of the process. This pH stabilization phase was mentioned in the work of Djaâfri & *al.* (2009), Kalloum *et al.* (2007) and Saïdi-Boulahia *et al.* (2018). According to Djaafri *et al.* (2014), at this stage, the organic matter contained in the substrates would have been almost exhausted, resulting in a low VFA content and a low biogas yield at this period.

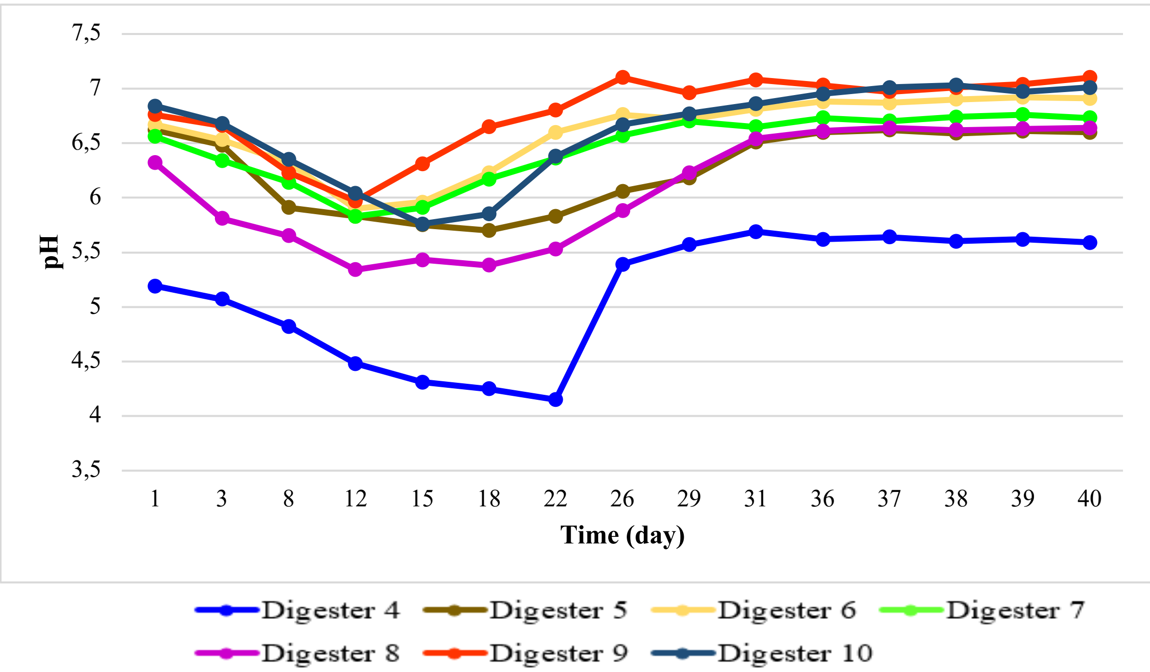


Figure 3d. Evolution of Hydrogen potential ratio during anaerobic digestion.

3.3 Results of anaerobic digestion

The cumulative quantities of biogas after 40 days of anaerobic digestion are shown in **Figure 4a** to **Figure 4c**. This graph (**Figure 4.a**) shows the cumulative biogas yields from the monodigestion trials carried out on plantain peelings (D1), yams (D2) and cattle dung (D3). During the entire experimental period, the cumulative volumes of biogas were 410 mL/g (VS) for cattle dung, 373 mL/g (VS) for yam peelings and 133 mL/g (VS) for plantain residues. **Figure 4.b** shows the cumulative biogas production curves for D4 (1/2 plantain; 1/2 yam), D5 (1/2 plantain; 1/2 dung) and D6 (1/2 yam; 1/2 dung). Cumulative biogas volumes recorded were 241, 370.5 and 556 mL/g (VS) for D4, D5 and D6 respectively. **Figure 4.c** shows the cumulative biogas production where codigestion of ternary mixtures took place. These are D7 (1/3 plantain; 1/3 yam; 1/3 dung), D8 (2/3 plantain; 1/6 yam; 1/6 dung), D9 (1/6 plantain; 2/3 yam; 1/6 dung) and D10 (1/6 plantain; 1/6 yam; 2/3 dung). Here, the cumulative quantities of biogas were evaluated at 555.6, 485, 565 and 502 mL/g (VS) for D7, D8, D9 and D10 respectively. Faye *et al.* (2020) studied the anaerobic digestion of cashew apple pulp and cattle dung under mesophilic conditions with 333 g (VS). Compared with their study, our quantity of fixed volatile solids (16 g (VS)) remains very low. However, the same quantity of residues (333 g (VS)) would give us better yields than Faye *et al.* (2020), both in monodigestion and codigestion. These results are therefore encouraging and this study could be the subject of a project.

According to the work of certain authors, this methanization process followed three phases during its course. A first, short phase characterized by slow, low biogas production, which is referred to as the latency period (Sakouvogui *et al.*, 2018; Igoud *et al.*, 2002). The second phase is characterized by rapid biogas generation with a fairly high yield. This is known as the exponential growth phase (Baichata and Tamali, 2019). The last short stage, known as the plateau phase, is also characterized by low biogas production, like the first phase (Zerrouki & al., 2017).

Latency phase: In monodigestion (**Figure 4.a**), the lag time was long in the digesters containing plantain peelings (20 days) and yam peelings (15 days). The dung (D3) took a week to generate biogas properly. During this period, digesters D1, D2 and D3 generated 38, 34 and 25 mL/g (VS) of biogas respectively. For the co-digestion of binary mixtures (**Figure 4.b**), the start-up period was 14 days for digester D5 and 8 days for digester D6, giving each digester 45 mL/g (VS) of biogas. However, this phase was longer for digester D4, which lasted 20 days and produced 71 mL/g (VS) of biogas. Codigestion of the ternary mixtures (**Figure 4.c**) showed 8 days of latency for digester D7 with 28 mL/g(VS) of biogas, while digester D8 accumulated 47 mL/g (VS) of biogas in 12 days. Digester D9 also had a latency period of 7 days and supplied 29 mL/g (VS) of biogas. With digester D10, it was 11 days of latency for 38 mL/g (VS). This low quantity of biogas observed indicates the non-adaptation of microorganisms still at the growth stage in order to carry out the first three stages of anaerobic digestion, namely hydrolysis, acidogenesis and acetogenesis (Baichata and Tamali, 2019 ; Sakouvogui *et al.*, 2018).

Exponential growth phase: In contrast to the first phase, the exponential growth phase produced good yields. In the monodigestion trials, we recorded 89 mL/g (SV) for digester D1, 330 mL/g(VS) for digester D2 and 374 mL/g(VS) for the cattle dung digester (D3). These values indicate high biogas production in the dung. As in monodigestion, the binary mixture digesters also produced large quantities of biogas during this second phase. Digester D6 produced 493 mL/g (VS), the largest quantity of biogas. Digester D5 came second with 310 mL/g (VS) accumulated during this phase.

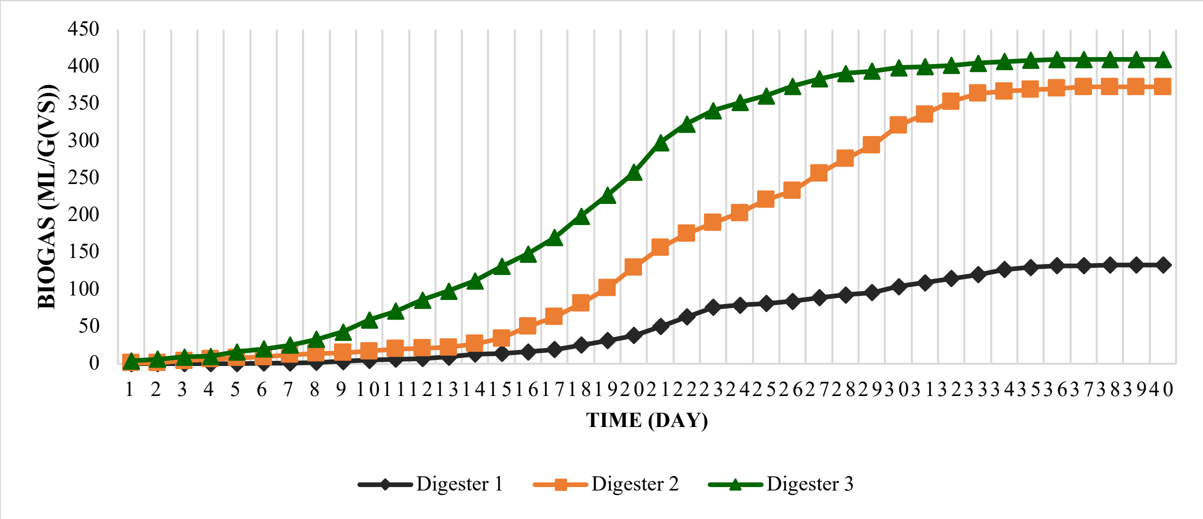


Figure 4a. Cumulative volumes of biogas from the monodigestion trials

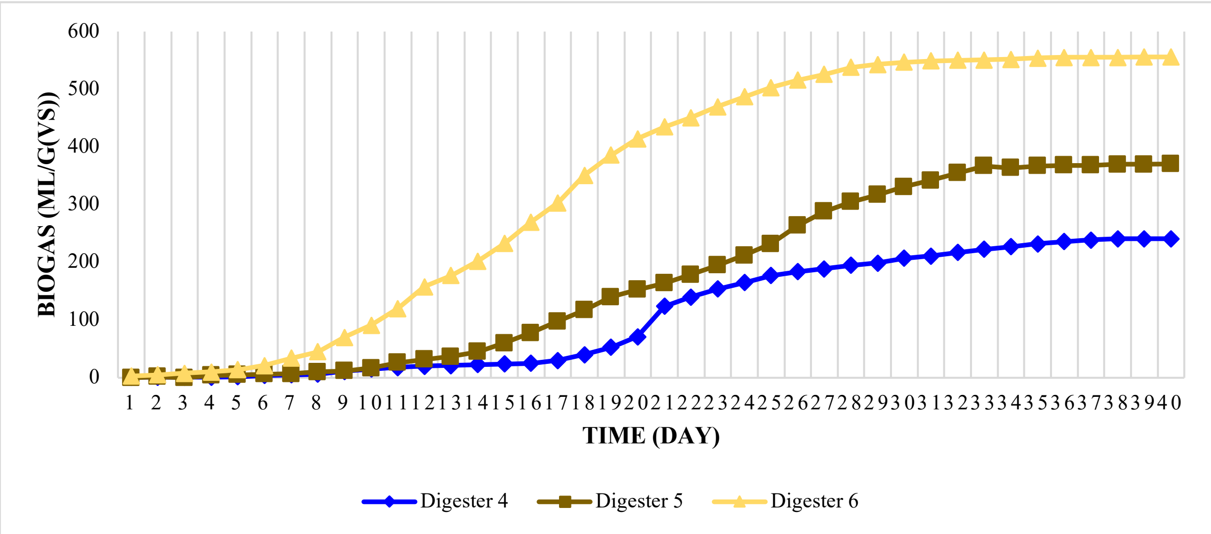


Figure 4b. Cumulative volumes of biogas from codigestion of binary mixtures

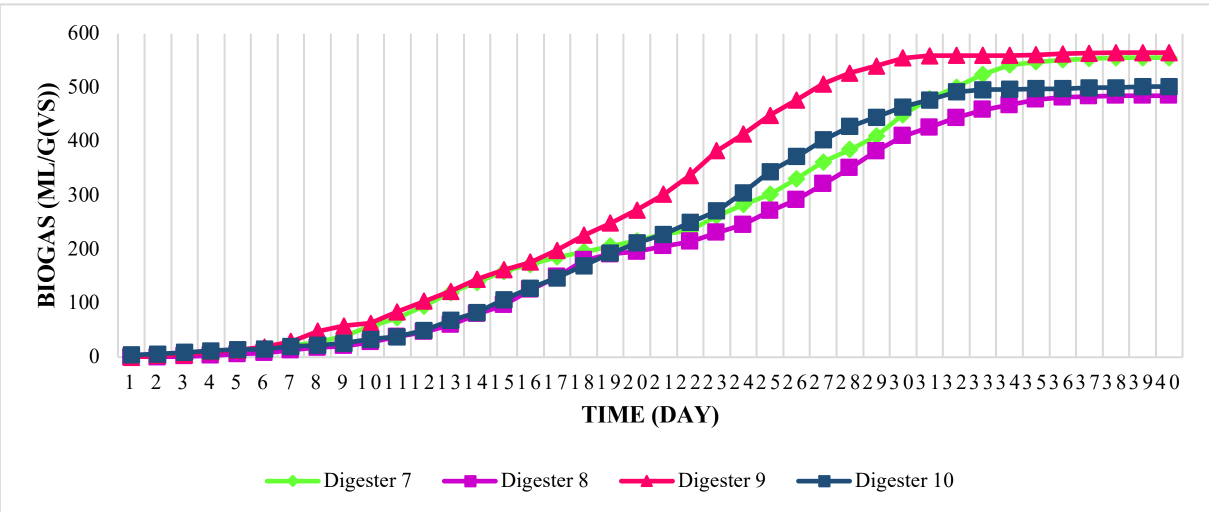


Figure 4c. Cumulative volumes of biogas from codigestion of ternary mixtures

Digester D4 produced 161 mL/g (Vs) of biogas. In the case of ternary mixtures, digester D9 provided the most biogas with 526 mL/g (VS). The other two digesters, D7 and D8, generated 514 and 431 mL/g (VS) respectively. This high biogas production over this period is thought to be linked to the successful hydrolysis, acidogenesis and acetogenesis processes carried out earlier by the micro-organisms (Abollé *et al.*, 2022). This led to maximum activity of the methanogenic bacteria. Mono-digestion showed that dung had better biomethanogenic potential than plantain and yam residues. This fact is corroborated by certain authors who have carried out methanization work on agricultural waste (Abo *et al.*, 2017; Lacour, 2012). As far as codigestion is concerned, the best yields come from mixtures where there is good synergy between the substrates so as to combine their biomethanogenic potential.

Bearing phase: after a period of abundant biogas production, the yield from each digester declined. In monodigestion, it was 6 mL/g (VS) for plantain peels (D1), 9 mL/g (VS) for yam residues (D2) and 11 mL/g (VS) for dung (D3). The binary mixtures provided 9, 15.5 and 18 mL/g (VS) of biogas for digesters D4, D5 and D6 in that order. In turn, the ternary mixtures also achieved a low biogas yield. Digester D7 yielded 13.6 mL/g (VS). Digester D8 produced 7 mL/g (VS), while digesters D9 and D10 each produced 10 mL/g (VS). We can say that this phase of decline characterized by low yield is caused by the depletion of the digestion substrate, the nutrient and energy source for the microbiological flora that is directly responsible for biogas production (Igoud *et al.,* 2002).

3.4 Synergistic effect of substrates on biogas production

Figures 5.a to 5.d show the contribution of each substrate to biogas production in the context of anaerobic codigestion. The aim was to compare the biogas yield from codigestion with the sum by volume of biogas from monodigestion of the codigested residues. To this end, we made up four mixtures in different proportions: M_1 (50% plantain peelings; 50% yam peelings), M_2 (50% plantain peelings; 50% cattle dung), M_3 (50% yam peelings; 50% cattle dung), M_4 (33% plantain peelings; 33% yam peelings; 33% cattle dung). This figure also shows that the M_1 mixture had a positive but small synergistic effect on biogas yield, in contrast to the M_2, M_3 and M_4 mixtures, which showed a very large positive synergistic effect. The synergistic biogas of M_1 was 241 mL/g (VS) (**Figure 5.a**). This amount is below the expected biogas amount (253 mL/g (VS)). The mixture M_2 accumulated 370.5 mL/g (VS) (**Figure 5.b**), a quantity exceeding the expected total biogas (271.5 mL/g (VS)). In the same order, M_3 collected 556 mL/g (VS) (**Figure 5.c**). Since the expected total biogas is 391.5 mL/g (VS), the synergistic quantity is greater. We also note that the ternary mixture M_4 provided 555.6 mL/g (VS) (**Figure 5.d**). Compared with the total quantity of biogas envisaged (299.29 mL/g (VS)), this synergistic volume is the largest. Analysis of these figures showed that plantain and yam peelings and cattle dung have complementary characteristics. This complementarity favored an increase in biogas production by anaerobic codigestion treatment, with the exception of the binary mixture of plantain and yam peelings. This is why, in order to optimize biogas production, co-digestion of these residues is desirable.

3.5 Quality of biogas from the various digesters

The quality of the biogas was assessed by determining its components. A portable BOSEAN biogas analyzer was used for this purpose. This measuring device has an inlet and an outlet. The gas inlet pipe is connected to the inlet port of the device. The incoming gas comes into contact with sensors capable of identifying the components of the biogas. These are displayed on the unit's screen. The outlet port is used to evacuate the gas after reading. The values obtained in this study are shown in **Table 3**.

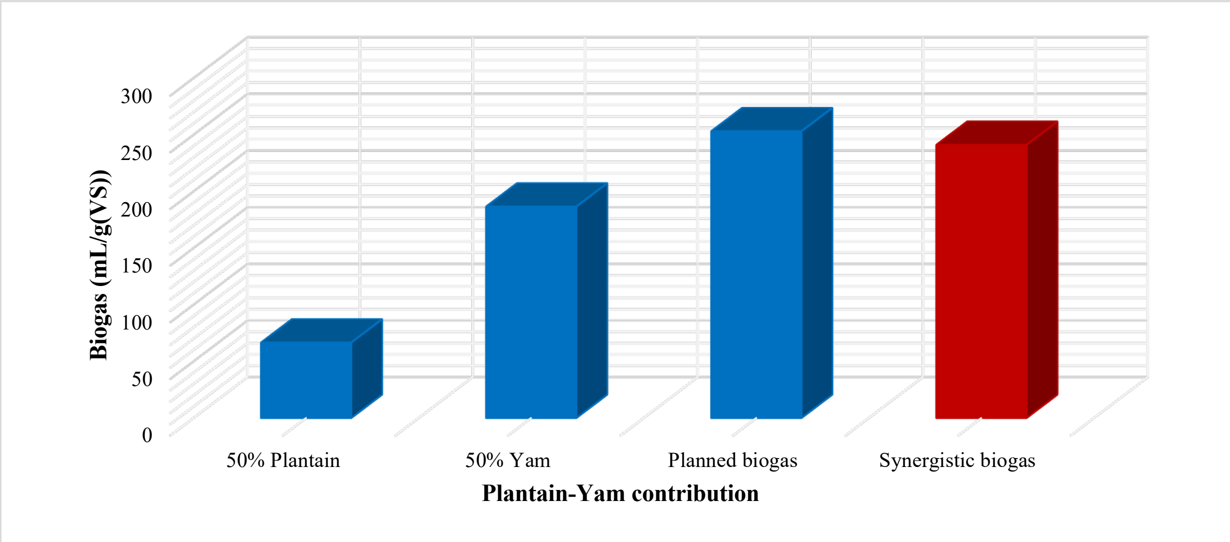


Figure 5a. Contribution of Plantain – Yam to biogas yield in codigestion

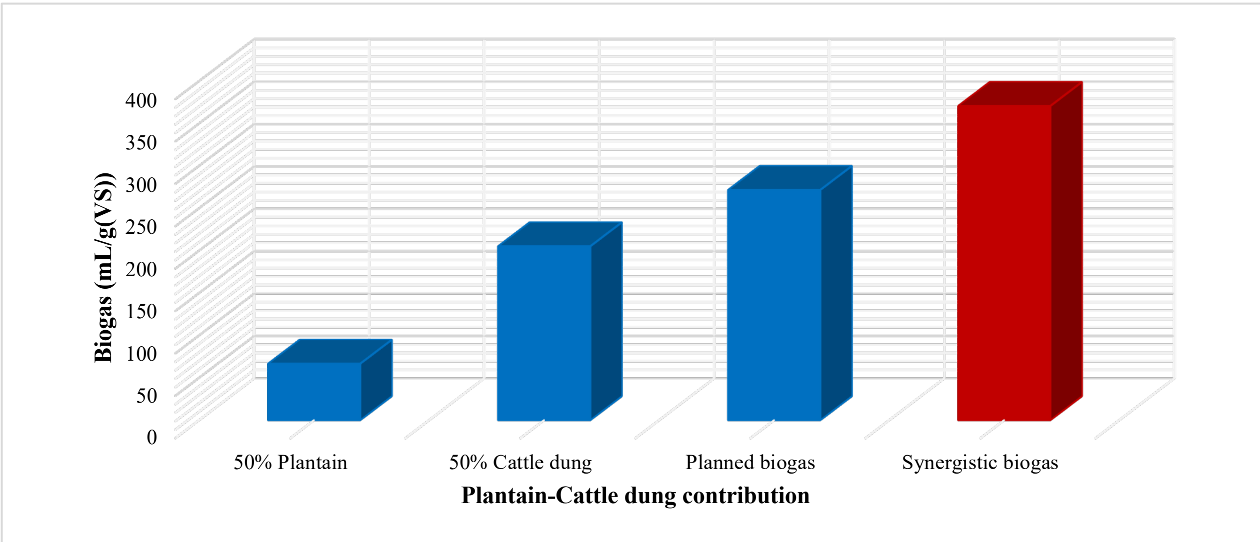


Figure 5b. Contribution of Plantain – Cattle dung to biogas yield in codigestion

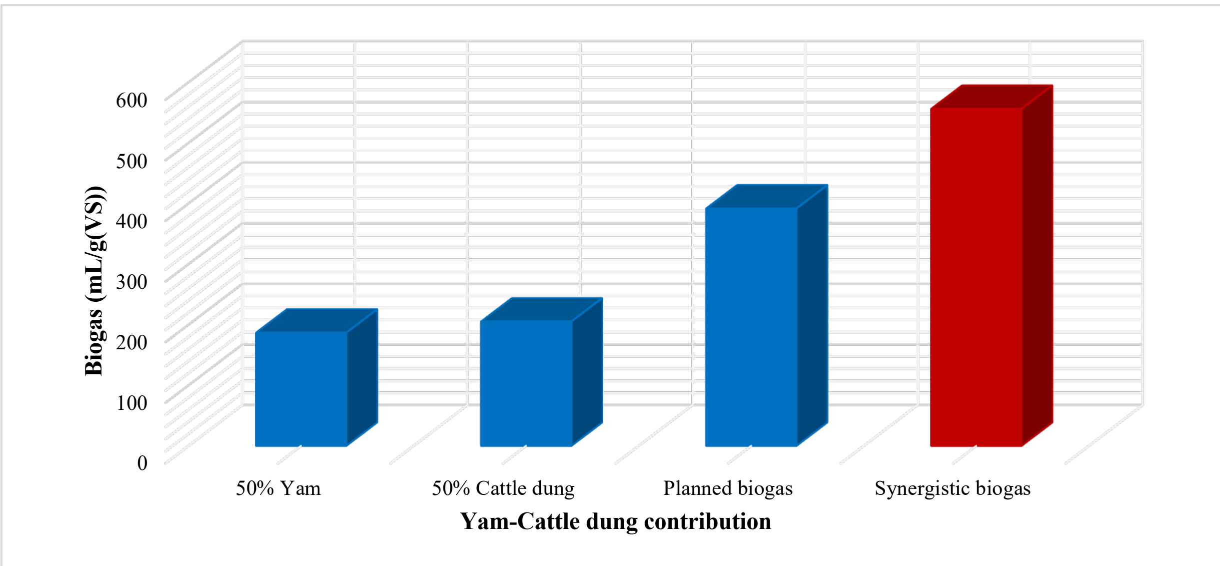


Figure 5c. Contribution of Yam – Cattle dung to biogas yield in codigestion

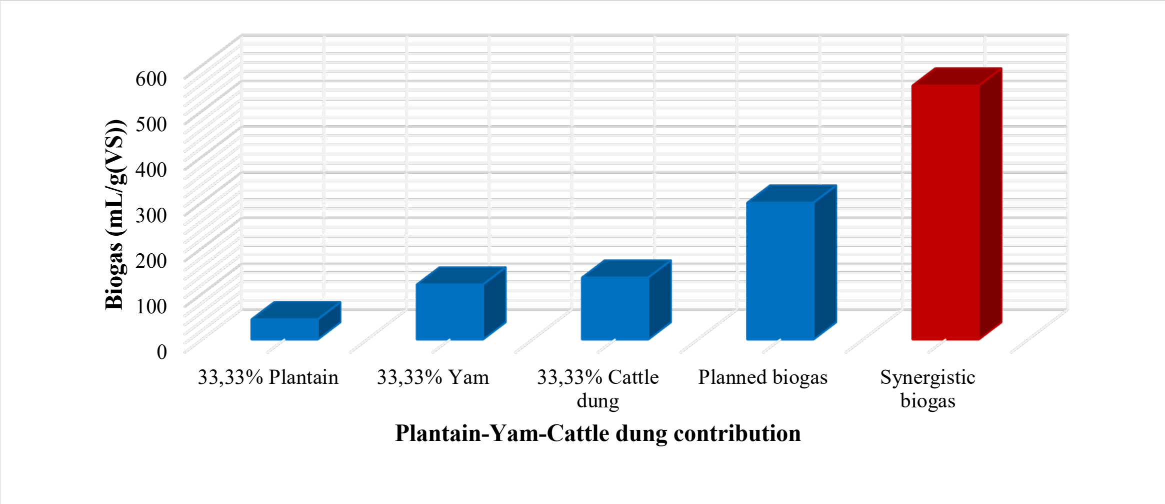


Figure 5d. Contribution of Plantain-Yam – Cattle dung to biogas yield in codigestion

The quantities of biogas shown in this table are mainly composed of methane (CH_4) and carbon dioxide (CO_2). The CH_4 and CO_2 contents of these biogases are in line with the general composition of biogas (50 to 75% CH_4 and 25 to 50% CO_2) (Bahlali *et al.*, 2015) following the example of other methanization studies (Adjiri *et al.*, 2008; Igoud and *al.*, 2002). Other impurities found in these biogases are hydrogen sulphide (H_2S) and carbon monoxide (CO). In some digesters (D1, D2, D4 and D8), H_2S concentrations exceed the exposure limit value (5 ppm) recommended by the French National Institute for Research and Safety (INRS) (Adjiri et *al.*, 2008). As for CO, the concentrations obtained do not exceed 100 ppm. Compared with the work of Gbangbo *et al.* (2023) where CO concentrations varied from 20 to 160 ppm, our values are consistent. However, if this biogas is to be used, a purification treatment would be appropriate.

Table 3. Composition of biogas

Digesters	$\%CO_2$	$\%CH_4$	H_2S (ppm)	CO (ppm)
D1	33.17	54.03	>5	37
D2	35.97	56.83	>5	34
D3	16.02	72.98	0.02	7
D4	30.72	59.51	>10	45
D5	30.49	57.51	2	27
D6	32.67	62.33	1.8	24
D7	22.06	65.94	2.2	19
D8	30.49	63.28	> 5	23
D9	21.48	67.52	1.5	17
D10	27.51	69.49	0.08	10

3.6 Biogas yield in relation to the biodegradability of volatile solids

The biogas yield in relation to volatile solids degradation is summarized in Fig.6. The highest volatile solids reductions were obtained for digesters D6 (78.09%), D7 (77.13%), D8 (71.01%), D9 (85.57%) and D10 (73.23%). These digesters produced 556, 555.6, 485, 565 and 502 mL/g (VS) of biogas respectively. An average reduction in volatile matter was also observed in digesters D2 (54.84%), D3 (60.78%) and D5 (54.49%). In this order, 373, 410 and 370.5 mL/g (VS) were obtained. However, the lowest degradabilities were found for digesters D1 (29.10%) and D4 (43.70%), which provided 133 and 241 mL/g (VS). These results showed a good correlation between biogas production and volatile solids reduction. This correlation is expressed by an almost perfect superposition of the biogas curve and the biodegradability curve. The greatest reductions produced the largest quantities of biogas, while the smallest reductions produced small quantities of biogas. This proportionality between biogas yield and volatile solids degradation was observed by Kouadio (2020) during his work on the physicochemical and energy characterization of the Akouedo landfill. Similarly, the work of Quideau and Lagadec (2013) showed that biogas production from the organic matter contained in pig droppings was proportional to the quantity of volatile solids eliminated. The greater the reduction in volatile solids, the greater the volume of biogas produced (Dahou *et al.*, 2020).

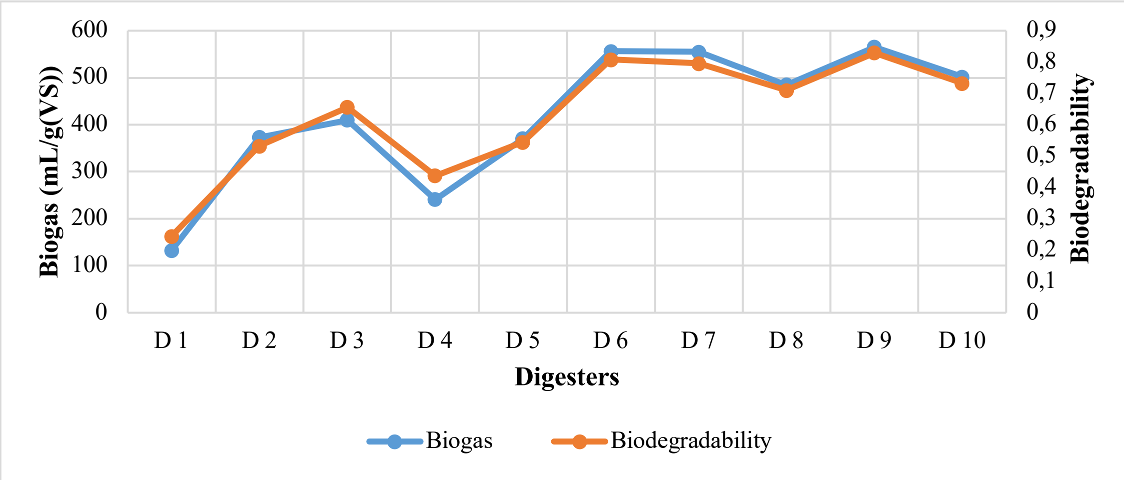


Figure 6. Correlation between the quantity of biogas and the biodegradability of volatile solids

Conclusion

This study focused on the anaerobic digestion of plantain peelings, yam peelings and cattle dung using Henry Schffé's mixing plan with increase. Analysis of the physical-chemical parameters of these residues showed that they are favorable to the anaerobic digestion process. Methanization trials under mesophilic conditions produced quantities of methane-rich biogas with some impurities to be eliminated. The mixtures containing cattle dung gave the best yields. In particular, optimum biogas production was obtained for anaerobic co-digestion of plantain peel, yam peel and cattle dung in proportions of 1:6, 2:3 and 1:6 respectively. The study also showed a good correlation between biogas yield and the quantity of organic matter degraded. Taken together, these results represent a major achievement for the energy recovery of plantain, yam and cattle dung residues by biomethanization. As part of a policy to find new sources of energy for sustainable development in Côte d'Ivoire, this source of biomass could be considered

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects

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