Study of the energy potential of substrates of plantain (Musa paradisiaca): A Case Study of NZerekore Prefecture, Republic of Guinea

Abstract

Biogas, an ecological and economical solution to the challenges of climate change and the energy transition, also makes it possible to manage waste and produce sustainable energy. The experiment involves nine 20-liter digesters for the production of biogas through anaerobic fermentation. A gasometer stores biogas, and a tank collects the condensed water. Analysis of plantain substrates reveals differences between leaves, stems, and skins: the stem is the most humid (93.22%), followed by leaves (83.42%) and skins (83.5%). Leaves also have the highest organic matter content (90.7%) and low organic carbon (9.29%), unlike skins (26.11%). Waste production shows a large amount of leaves (363.525 kg/day), while stems (7.975 kg/day) and skins (0.5 kg/day) are less abundant, highlighting the potential of leaves as a substrate for biogas. Temperature fluctuations influence methanization, and biogas production varies accordingly. The leaf production curve shows continuous growth, unlike those of the stems and skins, which are more limited. The leaf biogas combustibility test reveals an intense and stable flame, indicating a high methane content and few impurities. These results show that plantain leaves are a promising source of biogas, offering a sustainable alternative to conventional energy sources and contributing to organic waste management.

Keywords: digester, plantain leaf, stem, skins, biogas potential.

1. Introduction

Fruits are natural sources of useful fiber, minerals, and vitamin (**Oyeyinka and Afolayan, 2019**). The banana and plantain belong to the Musaceae family and have been available for human use for ages (**Denham et al., 2003 and 2004**). Bananas are monocotyledons of the order Scitaminales or Zingiberales belonging to the Musaceae family (**Simmonds, 1966**). It originated in Southeast Asia and is now cultivated in many parts of the world, mainly in Latin America and Africa (**Swennen and Vuylsteke, 2001 ; Tchigossou et al., 2019**). According to **Ganry et al,. 2012**, the other main importing countries are Saudi Arabia with nearly 114 000 tonnes in 2013, followed by South Africa with nearly 95 000 tonnes, and the European Union with more than 80 000 tonnes. Plantain banana not only provides a rich source of dietary energy but also contributes, thanks to its high nutritional value, to qualitatively improving the diet of populations (**Ganry et al,. 2012)**.

The recovery of organic waste through biogas production is emerging as a sustainable alternative in a context of energy transition and reduction of dependence on fossil fuels (**IEA, 2022**). However, produced by anaerobic fermentation, biogas results from the microbial degradation of organic matter such as agricultural residues, food waste and livestock effluents, generating mainly methane (CH_4) and carbon dioxide (CO_2) (**Zhang et al., 2019**). Its performance depends on several parameters, including substrate composition, temperature and retention time (**Weiland, 2010**). This biogas can be used to produce electricity and heat, and it has significant potential in the circular economy and the reduction of greenhouse gas emissions (**Angelidaki et al., 2018**).

However, the integration of biogas meets a dual objective: improving waste management and ensuring sustainable energy production (**Holm-Nielsen et al., 2009**). By using agricultural by-products, it limits the use of chemical inputs thanks to its digestate, which can be used as fertilizer (**Amon et al., 2007**). In Africa, biogas is an alternative to firewood, thus mitigating deforestation and air pollution (**Kemausuor et al., 2018**). However, its deployment remains hampered by the cost of infrastructure, the absence of regulatory frameworks and technical challenges (**Mata-Alvarez et al., 2014**). Technological advances and incentive policies could encourage its adoption.

In sub-Saharan Africa, the energy crisis is forcing a diversification of energy sources. Dependence on wood and charcoal is increasing deforestation and the health impacts of air pollution (**IEA, 2021**). With an electrification rate of 48% in 2020 (**World Bank, 2021**), biogas represents a solution adapted to rural needs. Furthermore, it recycles local organic waste, reduces greenhouse gas emissions and improves soil fertility through digestate (**Mwirigi et al., 2014**). However, its development faces financial and technical obstacles. To address these, the implementation of subsidies and the strengthening of local capacities are essential. The integration of this technology requires institutional support and a favorable energy policy.

In Guinea, access to energy remains limited, particularly in rural areas, where 80% of the population depends on wood as their main source of energy (**Ministry of Energy and Hydraulics, 2020**). This dependence promotes deforestation and ecological degradation. However, agriculture generates significant quantities of organic waste, particularly from plantains (***Musa paradisiaca***). These residues have significant methanogenic potential, which can be optimized by controlling parameters such as pH, temperature and carbon/nitrogen ratio (C/N) (**Kaba et al., 2017**). Their conversion into biogas would not only generate clean energy, but also optimize the management of agricultural waste.

In the prefecture of NZerekore, the high production of plantain bananas and the lack of infrastructure for processing agricultural waste leads to their burning, worsening air pollution (**Camara et al., 2020**). The recovery of this waste through methanization would reduce these nuisances while generating a sustainable source of energy. However, the efficiency of the process depends on precise physicochemical parameters (**Mendoza Martinez et al., 2021**). In addition, the digestate from methanization constitutes an organic fertilizer, contributing to the improvement of soil fertility (**Zhou et al., 2023**).

The adoption of methanization in NZerekore requires studies on the optimization of biogas yields and raising awareness among farmers. An appropriate institutional framework, combined with technical and financial support, would promote the integration of this technology (**Koné et al., 2019**). In addition, in-depth research on improving the physicochemical parameters of substrates would strengthen the efficiency of this sector, thus contributing to the energy transition and the preservation of ecosystems in Guinea. Objective in study is to evaluate the energy potential of plantain substrates (leaves, stems and skins) for biogas production in the NZerekore prefecture.

2. MATERIAL AND METHODS

2.1. MATERIAL

2.1.1. Description of Study Area

The prefecture of NZerekore (**Figure 1**) (latitude between 7°32 and 8°22 North, longitude 9°04 West and 560 m altitude) is located in the south-east of Guinea. The climate type is Equatorial guinean with a rainy season extending from May to October and a dry season from November to April (**Kante, 2019 and Djossou et al., 2024**). The presence of abundant plantain plantations in the various sub-prefectures, such as N'Zérékoré, Bounouma, Yalenzou, Samôé, Gouécké, Koulé, Soulouta, offers strong potential for the production of biogas from its organic waste (stems, leaves, skins).

2.1.2. Material used for this study

Substrates such as plantain leaves, stems and skins collected from local farms. As for anaerobic digesters, the experiment is based on nine 20-litre digesters for the production of biogas by anaerobic fermentation. A gasometer stores the biogas, and a tank collects the condensed water. To do this, we used boots, valves, flexible hoses, clamps, liquid glue, Teflon, a pH meter, a K CHROMEL+ ALUMEL- temperature sensor, and a CL3020 multimeter. Furthermore, for the analysis of the physical and chemical parameters, we used gans, a muffle furnace, an oven, a desiccator, an incinerator, an electronic balance, a petri dish, metal tongs, porcelain crucibles, and an analytical balance.

2.1.3. Description of the experimental set-up

The experimental device consists of two main parts: batch type reactor and biogas volume measuring device. **Figure 2** shows the image of experimental set-up. The tests were carried out in a batch reactor. This is a very basic plastic laboratory model, designed to guarantee an anaerobic culture environment. The batch reactor consists of a 20-litre capacity plastic container, hermetically sealed to maintain anaerobic conditions. There are two openings in the lid. The first is used for sample collection, and the second facilitates the removal of the biogas produced. The latter is connected to the biogas volume measuring device. The reactor is immersed in a thermal control bath set at 37°C. Manual stirring is carried out every day (**Chana et al., 2002; Angélique, 2001**).

2.2. Preparation of anaerobic digestion substrate

In this study, samples of different substrates from plantain were prepared for biogas production, varying the amount of water added for each type of substrate. Banana leaves, stems, and skins were carefully weighed and mixed with specific amounts of water: 10 liters for 5 kg of leaves, 6 liters for 5 kg of stems, and 12 liters for 7 kg of skins. This preparation step aims to optimize the hydration of the substrates and to ensure good homogeneity under fermentation conditions, taking into account the absorption capacity and the nature of the organic materials.

The pH of the different substrates was measured during the loading time of the digesters. Monitoring pH is essential to assess the evolution of the acidity or alkalinity of the substrates, as it can directly influence the activity of the microorganisms involved in the anaerobic digestion process. A pH that is too acidic or too basic can inhibit biogas production, which is why it is crucial to monitor these variations. Since each substrate has a different chemical composition and structure, pH can behave differently in each case.

The results of these pH measurements can also provide information on the biochemical processes taking place in digesters. For example, a decreasing pH could indicate an accumulation of acidic compounds resulting from the degradation of organic substrates, while a stable or slightly basic pH could signal a good balance between the production and consumption of these compounds. These observations are crucial for adjusting the parameters of the digestion process and ensuring optimal biogas production.

Finally, analyzing these pH parameters over time provides a better understanding of how different substrates react to the anaerobic digestion process. This can also provide valuable insights into adjusting the formulation of substrate mixtures, particularly in terms of water/solid ratio, to improve biogas yields. By taking these variables into account, it becomes possible to maximize the efficiency of the process and choose the best conditions for the production of biogas from plantain waste.

2.2.1. Criteria for establishing the material balance

The identification of dry matter (DM) and organic matter (OM) provides insight into the mass balance of anaerobic digestion. It also provides information on the efficiency of substrate decomposition during organic matter digestion, as well as the efficiency of converting organic matter into energy. The general formula used to establish this balance is:

- Balance of Dry Matter (DM) = DM_{input} - DM_{output}.
- Balance of Organic matter (OM) = OM_{input} - OM_{output}.

$$Degradation\ efficiency\ of\ OM\ (\%) = \frac{OM_{input} - OM_{output}}{OM_{input}} * 100 \qquad (1)$$

2.2.2. Determination of dry matter

Dry matter determination is a method used to quantify the amount of organic or mineral matter remaining in a sample after water has been removed. This measurement is crucial in many scientific fields, including agronomy, biotechnology, and biogas studies, to understand the composition of organic substrates before and after treatment. The principle of this method is based on drying the sample in a ventilated oven at a controlled temperature, usually 105°C, until a constant weight is reached. This process eliminates all moisture contained in the sample while preserving the stability of the solid components.

The measurement procedure begins by weighing the fresh sample, which is then placed in a ventilated oven where the temperature is maintained at 105°C. This temperature is high enough to evaporate free water and the water of constitution of the cellular structures without altering the chemical structure of the solids present. The sample is left in the oven for a period of 6 hours, which ensures complete moisture removal. It is important to note that this time may vary slightly depending on the specific properties of the sample, but generally, 6 hours is sufficient to achieve a constant weight.

Once the sample is dried, it is removed from the oven and weighed immediately after cooling in a desiccator to prevent any absorption of moisture from the ambient air. The weight obtained after drying is compared to the initial weight of the sample. The difference between these two weights gives the amount of water evaporated, and the remaining weight is the dry matter of the sample. This calculation thus makes it possible to determine the dry matter content, expressed as a percentage of the total weight of the fresh sample.

This method, described by **Nouha et al. (2015)**, is widely used in organic substance analyses, as it allows standardization of dry matter measurement and easy comparison of different samples. It offers high accuracy and reproducibility, making it essential for studies requiring assessment of material composition and properties before and after treatment, particularly in biogas production where dry matter will influence gas yield.

Operating mode

The procedure described involves determining the water content of a sample using a gravimetric method. First, three empty crucibles are accurately weighed, then a precise amount of sample, here 5 g, is introduced into each crucible. The crucibles containing the sample are then placed in an oven at a temperature of 105°C, a temperature sufficient to evaporate the water contained in the sample without altering its other components. Once the sample is heated, the water vaporizes, and the crucibles are removed from the oven and quickly transferred to a desiccator to prevent any moisture reabsorption by the sample during cooling. After the crucibles have cooled completely in the desiccator, they are weighed again. This process is repeated several times, each time after a heating and cooling cycle, until the successive weighings give a constant weight. This ensures that all volatile water has been removed from the sample. The water content (C_w) is then calculated using the following formula:

$$\boldsymbol{C_w}(\%) = \frac{\boldsymbol{W_i - W_f}}{\boldsymbol{W_i}} \times \mathbf{100} \qquad (2)$$

Where the initial weight (W_i) is that of the sample before heating, and the final weight (W_f) is that of the crucible after evaporation of the water. This method allows the moisture content of the sample to be precisely quantified by analyzing the loss of mass due to water evaporation.

2.2.3. Measurement of organic matter content

When a sample is incinerated at 550°C after being dried, the high heat causes the organic matter present to completely degrade. This incineration, often carried out in a temperature-controlled oven, volatilizes organic compounds such as lipids, proteins, and carbohydrates, which are then evaporated as gas. The process is called "carbonization" or "calcination" and eliminates all material that could decompose. The temperature of 550°C is particularly chosen because it is sufficient to ensure the destruction of the majority of organic matter while being low enough to prevent the oxidation of mineral elements present in the sample.

At the end of incineration, a residual material remains, composed of the mineral elements that were present in the sample before heat treatment. These residues consist mainly of ash, which may include metal oxides, salts, and other minerals that are not volatile at this temperature. This mineral, often analyzed to assess the ash or mineral content of a sample, allows the mineral composition of the original substance to be determined. This process is commonly used in routine analyses, such as those defined by the Association of Official Analytical Chemists (AOAC), to quantify the mineral fraction of a sample, thus providing crucial information on its chemical composition (See formula 3).

$$C_{OM}\,(\%) = \frac{\mathrm{m}_{Dry} - \mathrm{m}_{Calcined}}{m_{Dry}} \times 100 \quad (3)$$

3. RESULTS AND DISCUSSION

3.1. Analysis of banana plantain substrates

Figure 3 shows the substrates from plantain banana, particularly plantain banana leaves, stems and peels. The parameters analyzed are humidity (H%), dry matter (DM%), organic matter (OM%) and organic carbon (OC%). The plantain stem has the highest moisture content (93.22%), followed by the leaf (83.42%) and the skin (83.5%). In fact, the plantain leaf has a higher proportion of dry matter (16.58%), while the stem has the lowest (6.78%), indicating a higher humidity level. Furthermore, the leaves have the highest content (90.7%), followed by the stem (84.53%) and the peel (73.88%). Finally, the plantain peel has the highest proportion of organic carbon (26.11%), followed by the stem (15.46%) and the leaf (9.29%). These results indicate that the different plantain substrates have distinct physicochemical characteristics that influence their potential use in applications such as biogas production, composting and recovery in organic amendments. According to **González et al. (2017)**, banana residues have an average moisture content of 80 to 95%, in agreement with our results for the stem and leaf of plantain. **N'Dri et al. (2019)** showed that banana peel has an organic carbon richness varying between 20 and 30%, which corresponds to our observations (26.11%). **Jiménez et al. (2020)** indicate that substrates rich in organic matter and carbon (>70%) are favorable for composting and the production of organic amendments, which suggests a potential valorization of the substrates analyzed. Analysis of plantain substrates reveals high moisture content, richness in organic matter and variability in organic carbon depending on the parts analyzed. These results are consistent with those in the literature and suggest several potential applications, particularly in organic waste management, composting and biogas production.

3.2. Average daily production of banana waste

Figure 4 shows the daily production quantity (kg/d) of different types of banana residues (leaves, stems and skins). Analysis of banana waste shows significant production of banana leaves (363.525 kg/d), followed by stems (7.975 kg/d) and skins (0.5 kg/d). This distribution highlights the importance of leaves in the total biomass of the banana plant. These results are consistent with those reported by **Smith et al. (2020)**, who indicate that leaves represent more than 80% of the biomass of banana plants in tropical areas. As for **Martínez et al. (2019)** observed similar values in Mexico, where banana leaves contribute 85% of the plant's residues.

In contrast, our results diverge slightly from those of **Koffi et al. (2021)**, who found that stems represented a larger proportion of waste due to local agricultural harvesting practices. The low quantity of banana peels is explained by their partial consumption by animals and their transformation into compost, as **González et al. (2022)** points out in a study on the recovery of agricultural waste.

3.3. Evolution of temperatures in digesters

Figure 5 shows the temperature evolution for three data series (TFB, TTB and TPB) over the period from January 18, 2023 to February 25, 2023. In this figure, we observe a general trend towards increasing temperatures with some marked variations. Indeed, the TFB (blue curve) shows fluctuations with a notable drop around 02/07/2023. Additionally, the TTB (orange curve) follows a similar trend, but with sharper peaks around 02/10/2023 and 02/25/2023. Furthermore, the TPB (grey curve) is more stable but also experiences variations at the same periods.

These temperature variations are a key factor in biogas production, as temperature directly influences the microbial activity involved in the anaerobic digestion process. Indeed, according to **Ahn et al. (2010)**, methane production is optimal in a temperature range between 35 and 55°C (mesophilic and thermophilic regimes). Large temperature variations, such as those observed in our data, can lead to fluctuations in the activity of methanogenic microorganisms, thereby reducing the efficiency of biogas production. Furthermore, **Weiland (2010)** showed that seasonal temperature variations have a direct impact on the stability of anaerobic digesters, particularly in tropical climates. Our results, which show sudden temperature increases, suggest that adjustments to fermentation conditions may be necessary to maintain stable biogas yield. Finally, **Liu et al. (2009)** studied the effect of thermal variations on the degradation of organic matter and found that unstable temperature slows down the hydrolysis of solid substrates, which can reduce biogas production. Thus, the fluctuations observed in our data could also have implications for the efficiency of biodegradation of organic substrates in an anaerobic digester.

3.4. Daily production kinetics

Figure 6 illustrates the normal daily production of three categories (FB, TB, PB) over a period from 01/20/2023 to 02/25/2023. Indeed, the FB (blue curve) has a significant fluctuation with marked peaks around 01/26/2023, 02/05/2023 and 02/13/2023. This variability suggests influential factors that may affect production. However, the TB (orange curve) has low and stable production, suggesting a limited yield. Furthermore, the PB (grey curve) is practically non-existent, indicating either an absence of production or conditions unfavourable to this category. Furthermore, a general decline in production is observed after 02/17/2023, which may be linked to a depletion of raw materials, unfavorable environmental conditions or technical constraints.

Several authors have studied the variability of biogas production depending on the raw materials used, environmental conditions and technical factors. According to **Weiland (2010)**, the nature of the substrates used significantly influences the biogas yield. Organic waste rich in fermentable matter, such as agricultural residues and livestock effluents, offers high potential. In our study, the variability of FB production could be due to the fluctuation of raw material supply or differences in their composition. As for **Nasir et al. (2012)** demonstrated that temperature and pH strongly influence the efficiency of the methanization process. A decrease in temperature or pH variations may explain the decrease in production after 02/17/2023. According to **Appels et al. (2011)**, the hydraulic retention time and the C/N (Carbon/Nitrogen) ratio must be optimized to ensure stable yield. The low production of TB and PB could be related to imbalances in these parameters or to poor adaptation of the digester to the specific substrates used. However, **Nizami and Murphy (2010)** studied production stoppages due to technical malfunctions, such as digester fouling and accumulation of volatile acids inhibiting methanization. A possible explanation for the decrease after 17/02/2023 could be system saturation or accumulation of toxic by-products.

3.5. Kinetics of cumulative biogas production

Figure 7 shows the cumulative daily production for three categories (FB, TB, PB) between 01/20/2023 and 02/25/2023. The FB (blue curve) shows continuous growth with several plateaus, indicating periods of irregular but overall increasing production. After 02/17/2023, production appears to reach a plateau. TB (orange curve), gradual but more limited increase compared to FB. After 02/10/2023, production becomes stable, suggesting a lack of additional substrate input or a decrease in process efficiency. Furthermore, the PB (grey curve) shows very little progression, indicating almost no production over the entire period. These results suggest that FB has a better biogas yield, while TB and PB appear to be limited by biological, chemical or technical factors.

The variations observed in cumulative production can be explained by the nature of the organic materials used. **Weiland (2010)** showed that carbon-rich substrates (such as agricultural residues) produce more biogas than nitrogen-rich ones (such as sewage sludge). The superiority of FB could be due to a substrate more suitable for anaerobic digestion. According to **Appels et al. (2011)**, the main factors influencing cumulative biogas production are Hydraulic Retention Time (HRT), C/N ratio and temperature. Too short a HRT can limit the production of TB and PB, explaining their stagnation after a certain threshold. According to **Nasir et al. (2012)**, the stability of production after a period of increase can be linked to: a decrease in the yield of methanogenic bacteria due to an accumulation of volatile acids; excessive exploitation of the available substrate, leaving no more organic matter to degrade; technical problems linked to the maintenance of the digester. In their study, **Nizami and Murphy (2010)** showed that optimizing digestion conditions can prolong the production phase and avoid a premature plateau. They recommend adjusting the organic loading and using co-substrates to maintain continuous production.

3.6. Biogas combustion test

The figure 8 shows the image of a combustibility test of biogas produced from the anaerobic fermentation of plantain leaves. The presence of an intense and stable flame upon ignition confirms that the biogas contains a significant proportion of methane (CH_4), the main combustible gas. Plantain leaves are an effective substrate for biogas production. The methanization allowed for adequate decomposition of organic matter, generating biogas rich enough in CH_4 for domestic or energy use. The absence of black smoke indicates a low content of impurities such as CO_2 and H_2S, which could impair combustion efficiency. These results demonstrate that plantain leaves are a viable source of biogas.

Conclusion

In this work, we studied the energy potential of plantain (Musa paradisiaca) substrates. The results obtained are as follows:

- Analysis of the physicochemical parameters of substrates from plantain bananas highlights significant differences between leaves, stems and skins. The stem had the highest moisture content (93.22%), followed by the leaves (83.42%) and the skins (83.5%). Therefore, dry matter is more abundant in the leaves (16.58%), while the stem contains the least (6.78%). Regarding organic matter, the leaves record the highest content (90.7%), followed by the stem (84.53%) and the skins (73.88%). Organic carbon is particularly concentrated in the skin (26.11%), compared to 15.46% in the stem and 9.29% in the leaves. These characteristics directly influence their potential for recovery in methanization.

- Daily production of banana waste reveals a significant quantity of leaves (363.525 kg/d), while the production of stems (7.975 kg/d) and skins (0.5 kg/d) remains more limited. This distribution highlights the importance of leaves in the total biomass of the banana tree and their strong potential as a substrate for biogas production.
- Temperature variations show a general upward trend, although marked by fluctuations. The TFB curve (blue) records decreases around 07/02/2023, while the TTB curve (orange) shows peaks around 10/02/2023 and 25/02/2023. The TPB curve (grey) remains more stable but follows similar variations.
- The study of daily production indicates that the FB curve (blue) undergoes significant fluctuations, with notable peaks around 01/26/2023, 02/05/2023 and 02/13/2023. The TB curve (orange) is more stable but shows limited yield, while the PB curve (grey) shows almost no production, suggesting unfavourable conditions. A general decline in production after 02/17/2023 may be linked to substrate depletion or unfavourable environmental conditions.
- The evolution of the cumulative daily production reveals a continuous growth of the FB with several levels, reflecting an irregular but generally increasing production. The TB increases gradually, but reaches stability after 02/10/2023, indicating a limited supply of substrate. The PB remains very low, confirming an almost non-existent production. These results show that the FB has a better biogas yield, while the TB and PB are limited by biological, chemical or technical factors.
- Finally, the combustibility test of biogas from the anaerobic fermentation of plantain leaves demonstrates an intense and stable flame, confirming a significant proportion of methane (CH_4). The absence of black smoke indicates a low impurity content, reinforcing the interest of this substrate for the production of biogas for domestic or energy use.

Thus, plantain leaves appear to be a viable and promising source for energy recovery through methanization, offering a sustainable alternative to conventional energy sources while contributing to organic waste management.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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FIGURES

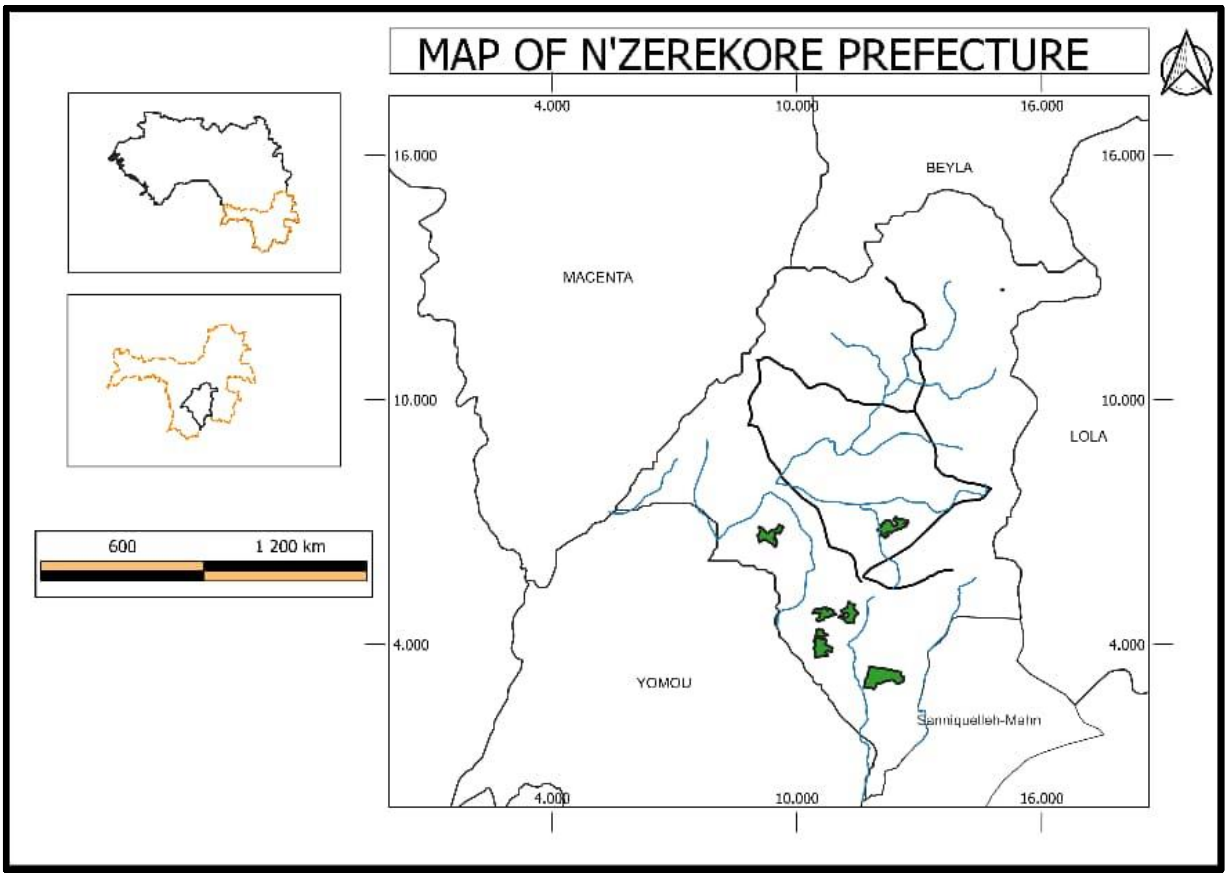

Figure 1 : Map of NZerekore prefecture

Figure 2 : Image of Experimental set-up

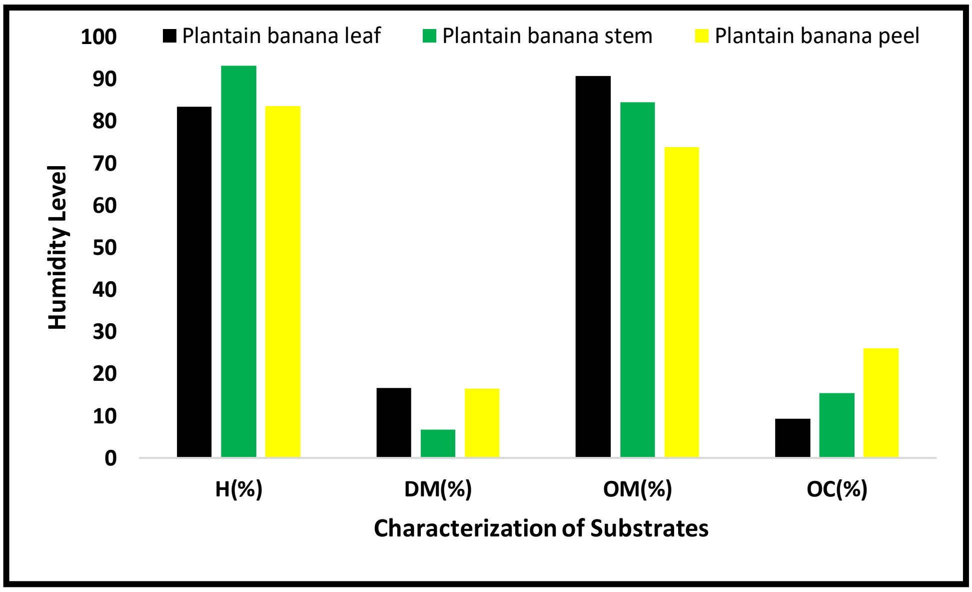

Figure 3: Characterization of plantain substrates

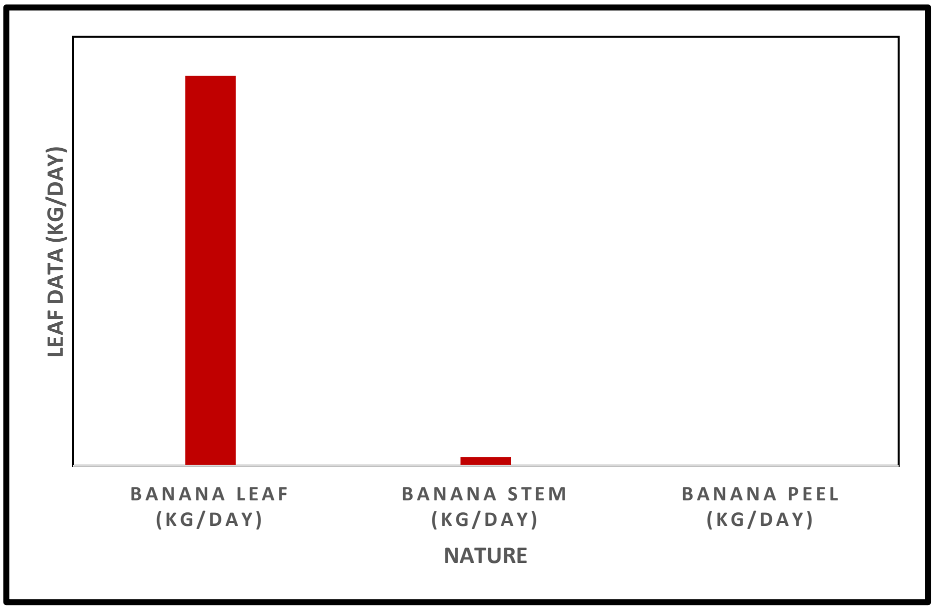

Figure 4: Average daily production of banana waste

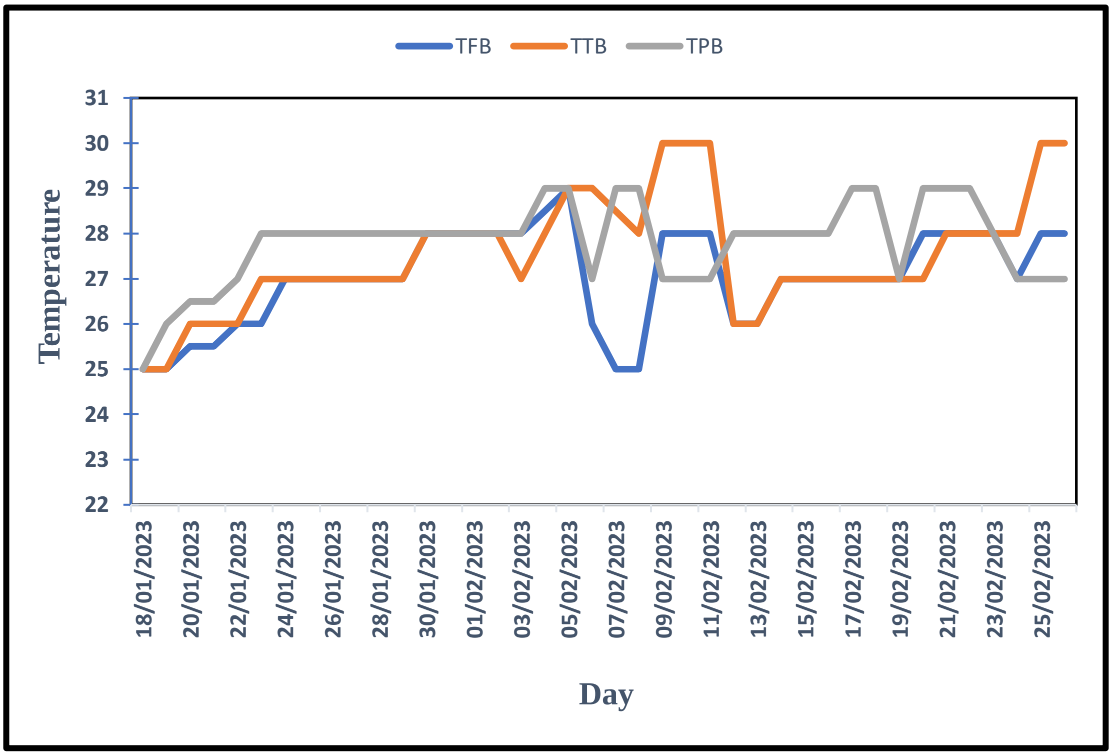

Figure 5: Temperature variation curves

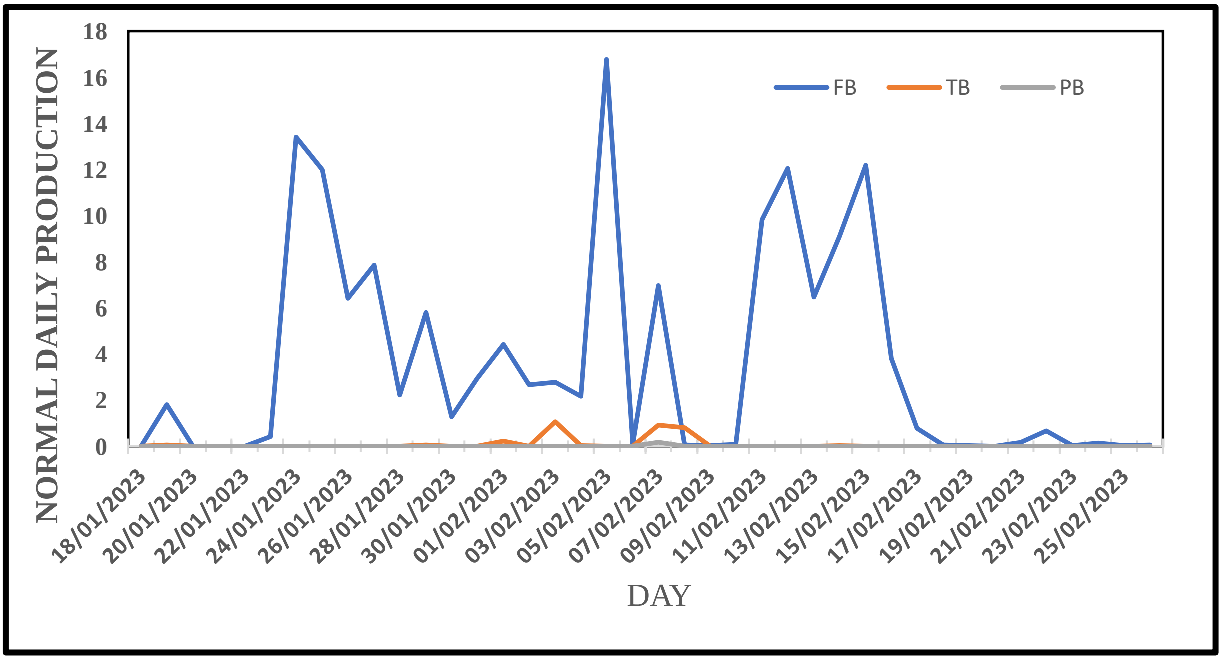

Figure 6: Daily production kinetics

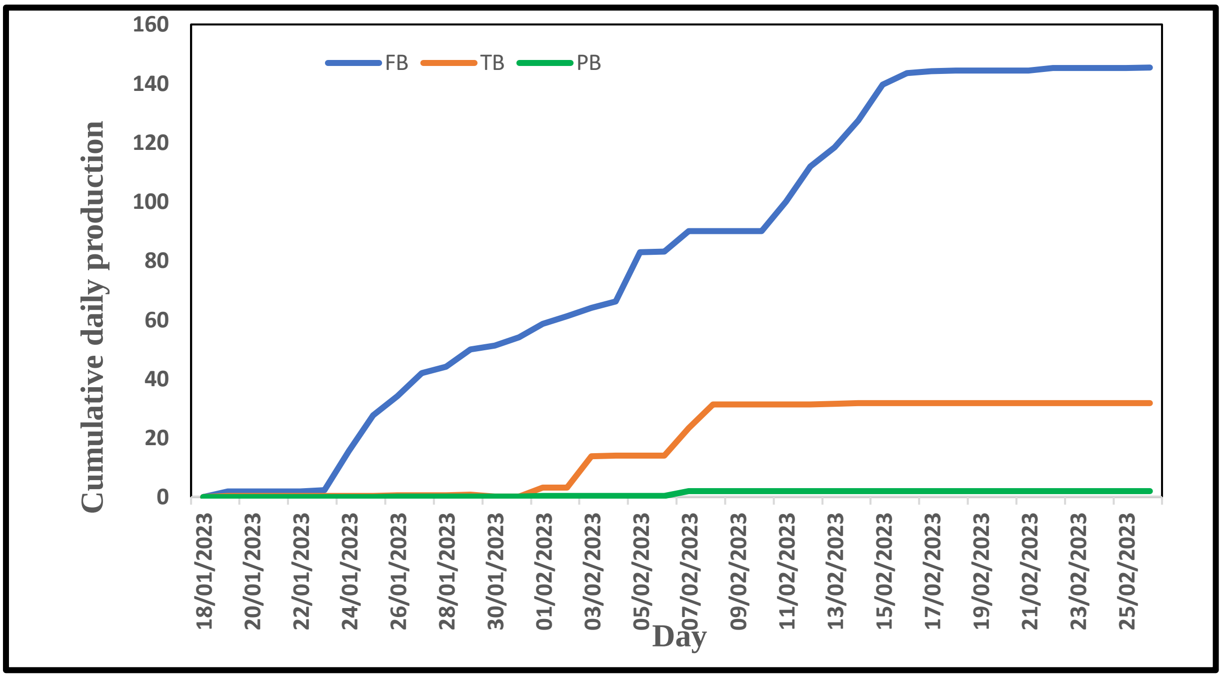

Figure 7: Kinetics of cumulative biogas production

Figure 8: The image of a combustibility test of biogas produced from the anaerobic fermentation of plantain leaves.