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Optimization of the manure/water ratio for maximum biogas production: Case of the FONSTI-CRDI digester in the East of Côte d'Ivoire

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Abstract

Effective waste management is crucial in addressing global environmental challenges. This study focuses on optimizing biogas production through anaerobic digestion of poultry manure, which is a significant agricultural waste in Côte d'Ivoire. The aim is to identify the optimal manure-to-water ratio to maximize biogas output using a FONSTI-CRDI digester with a capacity of 20 m^3. The study was conducted at the Brin Foundation poultry farm in Côte d'Ivoire. Three manure-to-water ratios (1:3, 1:2, and 1:1) were tested over 15-day cycles. A range of laboratory and field equipment, including pH meters and biogas analyzers, was employed to monitor digestion conditions and measure biogas production. Physicochemical properties of the manure, such as pH, total solids, and the carbon-to-nitrogen ratio, were also analyzed to understand their impact on biogas yield. The 1:3 ratio yielded an average biogas production of 4.1 m^3/day, with a methane content of 43%. The 1:2 ratio showed an improvement, achieving 5.3 m^3/day with 51% methane. The 1:1 ratio produced the highest biogas output at 6.23 m^3/day and 58% methane. However, operational challenges like digester blockages were observed at the 1:1 ratio. The digestate quality improved with lower water content, emitting less odor. The 1:2 manure-to-water ratio was

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determined to be the most effective for sustained biogas production, balancing high output and operational stability. This configuration supports renewable energy goals and sustainable agricultural practices, offering an efficient solution for managing poultry manure. Further research on co-substrates could enhance biogas yields and optimize the methanization process.

1. Introduction

Waste management is a major challenge in the current global context, characterized by growing climate urgency and the search for innovative solutions to preserve our planet. With the exponential increase in the volumes of waste generated by human activity, linked to industrialization, urbanization, and population growth, it has become imperative to rethink traditional waste management models [1, 2]. Conventional approaches, often centered on landfilling and incineration, have shown their limitations, particularly due to their environmental impact and the resources they mobilize without true value recovery. It is therefore essential to adopt more sustainable solutions, integrating principles of circular economy and aiming to reduce pressure on natural ecosystems [1, 2].

Among these solutions, waste valorization occupies a central role. It allows for the transformation of waste into valuable resources, offering multiple ecological, economic, and social benefits. Valorization not only helps reduce the ecological footprint of human activities but also creates new economic opportunities. It can, for example, reduce dependence on raw materials and foster innovation in sectors such as agriculture, energy, and construction. Public policies, technological advances, and local initiatives are now converging towards an integrated approach to waste management. This approach aims not only to limit the quantities of waste produced but also to mitigate their impact by reintegrating them into sustainable production cycles [3, 4].

In this context, renewable energies play a key role by offering viable alternatives to fossil fuels, which are responsible for a large share of global greenhouse gas emissions. Among these solutions, biogas production from organic waste stands out as an exemplary technology. This process relies on methanization, a biological technique that converts organic waste into biogas through the action of microorganisms in an anaerobic environment. The biogas produced can be used as a renewable energy source in the form of heat, electricity, or even fuel, while the digestate resulting from the process can be used as a natural fertilizer [5-8].

This approach offers significant environmental and economic benefits. By reducing methane emissions, a greenhouse gas with a much higher warming potential than carbon dioxide, methanization directly contributes to combating climate change. Furthermore, it helps reduce waste management costs while creating added value. In Europe, many countries have integrated biogas production into their energy and environmental strategies. For example, in France, waste management policies promote recycling, energy recovery, and the reduction of pollutant emissions in line with the global climate goals set by the European Union [3, 4].

Germany, often considered a model in this field, has demonstrated the full potential of organic waste valorization. Through an incentivizing regulatory framework and significant investments in infrastructure, the country has successfully transformed a large part of its organic waste, particularly agricultural waste, into biogas. This approach is part of a broader strategy aimed at strengthening energy security, reducing greenhouse gas emissions, and stimulating the local economy [5-8].

Animal manure, rich in organic matter and methane potential, is among the most exploited resources for this technology. In Germany, this valorization has significantly reduced dependence on fossil fuels while supporting the energy transition and creating jobs in waste management and renewable energy sectors [9-15].

Agricultural and agri-food operations thus represent a major opportunity in this dynamic. On average, a poultry farm produces several tons of manure each year, posing significant environmental challenges if these waste products are not properly managed. Poultry manure, when left untreated, can lead to soil and groundwater pollution, as well as the emission of harmful gases into the atmosphere. However, when these wastes are used in methanization systems, they are transformed into a valuable resource to produce energy and fertilize soils. The digestate from this process, rich in essential nutrients, offers a sustainable alternative to chemical fertilizers, thus contributing to environmentally friendly agriculture [16-17].

In the African context, where energy and environmental challenges are particularly pressing, the valorization of poultry manure appears to be an appropriate and promising solution. In Côte d'Ivoire, for example, the agricultural sector, which plays a central role in the economy, generates a large amount of organic waste that can be valorized. The biogas production project based on poultry manure, initiated by the Fund for Science, Technology, and Innovation (FONSTI), serves as a concrete example of this dynamic. Based at the Brin Foundation poultry farm in the Gontougo region, this project highlights the potential for technological innovation in the Ivorian agricultural sector.

However, despite its ambitions, this project faces technical and methodological challenges. One of the main issues is optimizing the manure-to-water ratio to maximize biogas production. Improper calibration of these parameters can limit the effectiveness of the biodigester, leading to suboptimal biogas production and reduced digestate quality. Furthermore, a better understanding of the specific characteristics of the raw materials, such as their chemical composition and dry matter content, is essential for adapting the processes to local realities.

The main objective of this study is therefore to fill these gaps by adopting a rigorous and methodical approach. The goal is to determine the optimal manure-to-water ratio for maximum biogas production with the FONSTI-CRDI digester, with a capacity of 20 m³. This research also includes characterizing the raw materials used, analyzing the composition of the produced biogas, and developing practical recommendations to improve methanization systems in Côte d'Ivoire. Through this approach, the study aims to strengthen the country's energy transition while contributing to the resilience of its agricultural sector in the face of environmental challenges.

2. Materials and Methods

2.1. Materials

The completion of this work required a variety of equipment, including laboratory, field, and computer tools. The laboratory materials mainly included glassware and reagents, which are essential for sample analysis and the determination of the raw materials' characteristic parameters. A Total Organic Carbon (TOC) analyzer was used to measure the concentration of organic carbon, a key indicator of the properties of the samples studied. Additionally, an electric furnace (Photo 1) and an oven (Photo 2) were used for drying, calcination, and mass characterization of the samples, thus preparing them for the various stages of analysis. These essential pieces of equipment ensured the accuracy and rigor of the experiments and were used complementarily to guarantee reliable and exploitable results.

The field equipment used for this study included essential tools for data collection and parameter monitoring during the methanization process. Measurement probes, including the HANNA HI 8424 pH probe (Photo 3) and the Testo 922 temperature probe (Photo 4), allowed monitoring of the pH and temperature of the digestion media, ensuring precise tracking of the experimental conditions. Storage tanks of various capacities

(1, 2, 5, and 10 m³) were used to collect and store the produced biogas, facilitating optimal management of the biogas (Photo 5). Finally, a BOSEAN biogas analyzer was used to assess the purity and composition of the biogas, providing reliable and detailed data on its quality (Photo 6). These tools, adapted to field requirements, played a central role in acquiring the data necessary for the study.

Photo 1. Electric furnace.

Photo 2. Oven.

Photo 3. The HANNA HI 8424 pH probe.

Photo 4. The Testo 922 temperature probe.

Photo 5. Storage tanks of various capacities.

Photo 6. BOSEAN biogas analyzer.

2.2. Description of the experimental site

This study was conducted at the poultry farm of the Brin Foundation, located in Yaokokoroko, a sub-prefecture of Tabagne, in the Gontougo region (Bondoukou) in the northeastern part of Côte d'Ivoire. Specializing in the marketing of eggs and poultry, the company operates two poultry farms that function alternately. Each farm has 45 rooms, with approximately 1,200 laying hens per room, totaling over 54,000 hens. Additionally, the company has a poultry feed production unit. The average production is 40 trays of eggs per room per day, amounting to about 12,600 trays per week. The farm generates approximately 500 kg of waste (chicken manure) daily, which poses a major environmental problem. To address this, a 20 m³ biogas digester was built by FONSTI-CRDI (Photo 7). The chicken manure serves as the organic substrate for the digester.

Photo 7. FONSTI-CRDI Biogas Digester at the Brin Foundation Poultry Farm.

2.3. Description and operating principle of the digester in the study

The anaerobic digestion technology used for biogas production in this study employs a specific digester. This digester operates continuously without agitation and is typically buried to stabilize its internal temperature. In these digesters, the produced biogas acts as a "micro-mix."

The digester studied has a volume of 20 m³ and is primarily composed of five compartments, as shown in Photo 7:

Water Tank: This compartment stores the water used to prepare the mixture.

Feed Tank: It first receives the raw material (chicken manure), which is then mixed with water before being fed into the biodigester.

Biodigester: This is the core of the system, comprising a fermenter where anaerobic digestion takes place, and a gasometer for storing raw biogas.

Expansion Pit: This receives the digestate (solid and liquid residue) from the biodigester.

Compost Room: This final compartment stores the digestate from the expansion pit.

2.4. Monitoring parameters of anaerobic digestion stability

The stability of anaerobic digestion depends on several parameters. However, pH and temperature are the stability parameters monitored in this study.

The pH of the digestate is determined daily using a pH meter. A sample of the digestate is first collected with a jar. The pH meter is then immersed in the sampled solution, and after 10 minutes, the pH is read on the device's screen. Before measuring the digestate's pH, the pH meter is calibrated in a solution with a known pH to ensure the accuracy of the readings.

Temperature monitoring was done using a probe thermometer. A probe connected to the thermometer by a wire (1) is immersed in the digester through a dedicated PVC pipe (3). The thermometer continuously displays the temperature inside the digester (Photo 8). The temperature was recorded daily for 15 days.

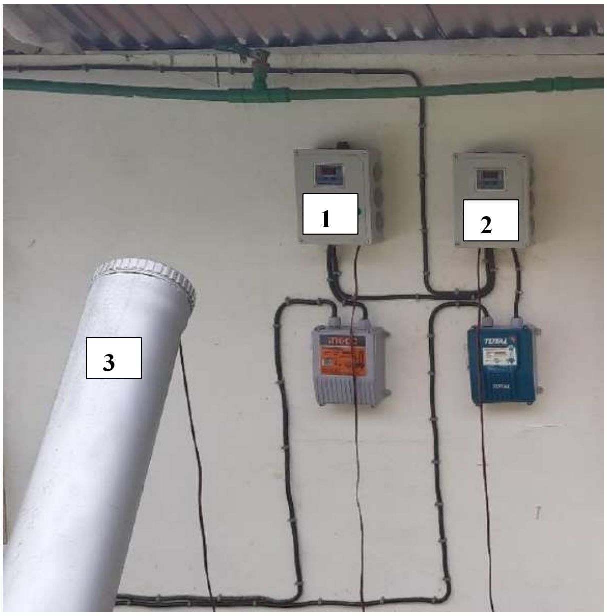

Photo 8. Dashboard for measuring the temperatures of the digester and digestate.

2.5. Determination of the physicochemical parameters of chicken manure

The Total Solid (TS) content was determined by drying in an oven at 105°C for 24 hours. The moisture percentage of the different samples was determined by the mass difference of the sample before and after drying, according to Formula 1 [18].

$$\% H = 100 \times (M0 - M1)/M0 \quad (1)$$

where:

% H = moisture percentage;

M0 = initial mass of the sample before drying;

M1 = final mass of the sample after drying.

The Total Solid content is then calculated as follows:

$$\% ST = 100 - \% H \quad (2)$$

where % TS represents the total solid content.

The Volatile Solid (VS) content was obtained by the mass difference between the dry waste mass (M1) and the mass of the waste calcined at 600°C (M2) for 6 hours [18].

$$\% \, SV = 100 \times (M1 - M2) / M1 \quad (3)$$

The pH of each waste sample was determined by dissolving the waste in a waste/distilled water ratio of 1:10. Thus, 5 g of waste was suspended in 50 mL of distilled water in a 250 mL plastic beaker under constant agitation for 5 minutes using a magnetic stirrer. The suspension was allowed to rest for 30 minutes before measuring the pH. The pH was measured using a HANNA HI 8424 pH meter [18].

The determination of organic carbon content and total nitrogen is performed by the Water Treatment Laboratory at INPHB on the poultry manure samples.

The C/N ratio is calculated. This calculation method is represented by the ratio of Organic Carbon (% TS) to Nitrogen (% TS). The result of the calculation is considered a constant value with no units [18].

$$\boldsymbol{TAC} = (\boldsymbol{V1} \times \boldsymbol{N} \times \boldsymbol{1000}) / \boldsymbol{V} \quad (4)$$

where:

V = volume in milliliters of the sample taken for testing

V1 = volume of acid (in milliliters) read from the burette until pH = 4.3;

N = normality of the acid solution

$$\boldsymbol{AP} = (\boldsymbol{V2} \times \boldsymbol{N} \times \boldsymbol{1000}) / \boldsymbol{V} \quad (5)$$

where:

V2 = volume of acid (in milliliters) read from the burette until pH = 5.75

$$AGV = TAC - AP. \quad (6)$$

2.6. Determination of the feed parameters for the biodigester

2.6.1. Determination of the feeding load

The digester used in this study is a fixed-dome digester with a volume of 20 m³, equivalent to 20,000 L (15,000 L for the fermentation chamber and 5,000 L for the gasometer) [19]. The daily waste production is estimated at 500 L. The time required for the poultry manure to release all of its biogas is estimated to be 15 days under the given methanization conditions. Therefore, it takes 15 days for the poultry manure to release the entire biogas within it. Thus, we have:

Vd = 15,000L; Tr = 15days;

Ch = (Vd/Tr)

where:

Vd = Useful volume of the digester,

Tr =Retention time,

Ch =Feeding load.

For proper sanitization of the digestate, the retention time can range from 15 to 30 days. Therefore, the daily feeding load is:

$$500<Ch<1000.$$

2.6.2. Determination of feeding ratios

Feeding the biodigester with waste requires the addition of an appropriate amount of water to promote the growth of the bacteria responsible for breaking down the material. A lack of water can inhibit the methanization process, while an excess of water can compromise biogas production. Therefore, in order to respect the permissible amounts of waste in the biodigester, the following selection was made:

For waste loads of 500 L, 600 L, 700 L, 800 L, and 1000 L per day, the addition of water must be carefully adjusted to maintain optimal moisture levels. Proper hydration is essential to maintain bacterial activity and ensure the effective degradation of organic matter. The amounts of water added must be proportional to the waste load to avoid imbalances in the biodigester.

The biodigester can accept waste quantities ranging from 500 L to 1000 L. By using different ratios of poultry manure and water, we can optimize the waste load introduced.

1:1 Ratio: 250 kg of manure for 250 L of water, totaling 500 L of waste.

1:2 Ratio: 250 kg of manure for 500 L of water, totaling 750 L of waste.

1:3 Ratio: 250 kg of manure for 750 L of water, totaling 1000 L of waste.

Beyond 700 L of water, the total waste amount exceeds 1000 L. Additionally, when the amount of manure reaches 300 kg, a 1:3 ratio will exceed 1000 L, and with more than 350 kg of manure, a 1:2 ratio will also exceed this limit. Therefore, to maintain the permissible loads in the biodigester, it is appropriate to use 250 kg of poultry manure.

The poultry manure is cleared of solid waste such as stones and logs. These wastes are placed in the biodigester’s inlet in predefined quantities according to the adopted ratio. Water is added to these wastes in the defined proportion. The mixture is then stirred in the inlet until it forms a paste, which is then directed into the biodigester.

2.7. Analysis of the produced biogas

The analysis of the produced biogas was carried out through different stages to assess both the quantity and quality of the gas based on the feeding ratios. Over a period of 15 days, the biodigester was fed with a 1:3 ratio, and the produced biogas was analyzed daily using a biogas analyzer before being stored in balloons of various capacities. Once this phase was completed, the procedure was repeated with a 1:2 feeding ratio over the same 15-day period, followed by feeding with a 1:1 ratio, following the same protocol. The quantity of biogas produced at each ratio was meticulously measured and stored.

Furthermore, the quality of the gas was evaluated for each ratio by checking its flammability and observing the color of the flame during combustion—key indicators for determining the energy potential of the produced biogas. These combined analyses allowed for the characterization of the biodigester’s performance based on the different feeding ratios.

3. Results and Discussion

3.1. Physicochemical parameters of poultry manure

The analysis of the five samples submitted to the laboratory revealed precise results regarding the moisture content and the percentage of dry matter. The average moisture content observed was 65.19%, with a standard deviation of ±0.81, indicating a certain homogeneity among the samples. Furthermore, the percentage of dry matter was 34.81%, with a standard deviation of ±0.73, showing consistency in the analyzed samples. These moisture and dry matter values fall within the same range as those defined by Elasri et al., who conducted similar studies on poultry manure from local breeds [20]. The significance of these results lies in their indication of the fermentation process. According to Shapovalov et al., a dry matter percentage between 20% and 50% is characteristic of both wet and dry fermentation [21]. Thus, the values obtained in this analysis confirm that the samples exhibit the ideal conditions for this type of fermentation. This information is crucial for agricultural and environmental applications, where effective organic waste management can contribute to more sustainable and ecological practices.

The pH of the poultry manure after analysis ranged between 7.50 and 8.45. This value is close to that reported by Elasri et al., where the pH of poultry manure is 8.54, indicating an alkalinity in the manure [20]. These pH values are important because they provide information about the chemical nature of the manure and its potential behavior in various biological and chemical processes. An alkaline pH, such as the one observed, can have significant implications for biodigestion. For example, an alkaline pH may influence the decomposition of organic materials and the production of gases like methane in biodigestion systems. Moreover, knowledge of the manure's pH is essential for organic waste management. A pH that is too high or too low could inhibit certain essential microbial processes, thus affecting the quality and efficiency of the biogas produced.

When characterizing waste for methanization, the carbon-to-nitrogen (C/N) ratio is a crucial parameter. The analyses revealed a total organic carbon (TOC) level of 80.55 mg/L and a nitrogen level of 8.94 mg/L, resulting in a C/N ratio of 9.004. According to Elasri et al., the optimal C/N ratio is between 10 and 30. However, Shapovalov et al. indicate that the C/N ratio should be between 20 and 30 [21]. Similarly, Elasri et al. present a C/N ratio of 9.04 and emphasize that the ideal ratio for good fermentation is between 20 and 30 [20]. It is important to note that, despite a C/N ratio of 9, fermentation is still possible.

The results of this characterization show that poultry manure has physicochemical properties favorable to methanization, despite a C/N ratio lower than the optimal recommended values. The high volatile solids content and the alkaline pH are positive indicators for methane production. However, to maximize the efficiency of the methanogenic fermentation, adjustments such as adding co-substrates to improve the C/N ratio may be necessary. These modifications could optimize the methanization process and increase biogas production.

3.2. Biogas production analysis

3.2.1. Feeding the digester with a 1/3 ratio

Over the course of one month, 1000 L of waste were introduced into the biodigester. Daily production was measured over a 15-day period. Table 1 presents the results of this production, as well as the stability parameters of the biodigester. From the analysis of Table 1, it is evident that the daily production ranges from 3 m³ to 5 m³. The temperature inside the biodigester remains between 34°C and 37°C, which indicates an environment conducive to bacterial growth. However, the pH values fluctuate between 5.0 and 6.4, which is considered acidic for a biodigester. This acidity can be attributed to an excessive organic load in the biodigester. According to Nuhu et al., this could also be due to the amount of water used, which promotes the acidogenic phase. Figure 1 illustrates the variations in production [22]. This figure shows a progressive increase in biogas production from the first to the sixth day. This rise in production can be attributed to the initial adaptation of the methanogenic bacteria to the conditions within the digester, allowing them to effectively break down organic matter and produce biogas [19]. The peak in production reached on the sixth day suggests that the biodigester has reached an optimal performance point, where internal conditions, such as temperature and pH, are favorable for maximum bacterial activity. After the sixth day, production stabilizes around 4.1 m³ per day. This stabilization indicates that the biodigester is operating at a steady state, with balanced internal conditions allowing for sustained biogas production.

Table 1. Daily production and stability of the biodigester based on the 1/3 ratio.

Days	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Production 1/3 (m³)	3.0	3.5	4.0	4.5	4.5	5.0	4.5	4.5	4.0	4.5	4.0	3.5	3.5	4.5	4.0
Temp (°C)	36	35	34	35	36	35	36	37	38	37	36	35	36	37	37
pH	5.1	5.0	5.3	5.5	5.8	6.0	6.1	5.0	5.3	6.0	6.1	6.4	6.0	5.2	5.5

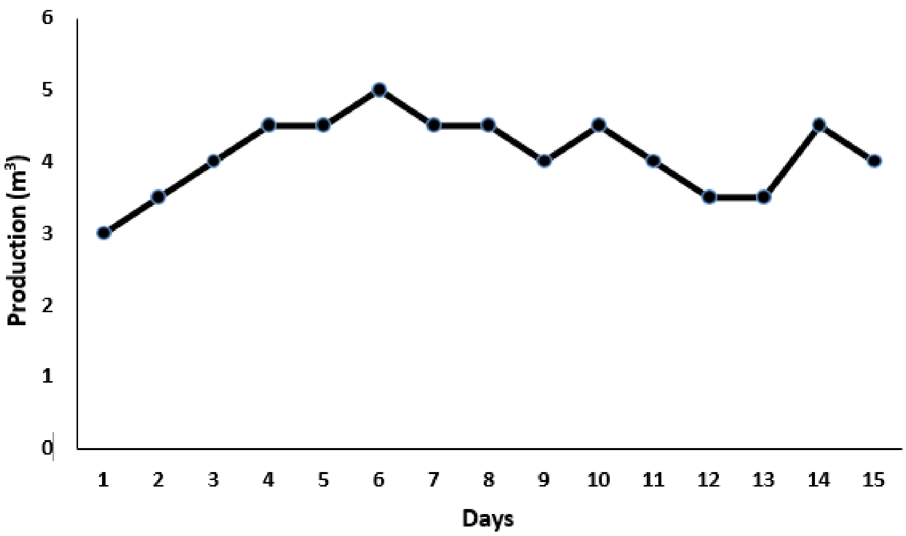

Figure 1. Daily biogas production at a 1/3 ratio.

3.2.2. Feeding the digester with a 1/2 ratio

During the second month, the biodigester was fed with 750 liters of waste. Daily production was measured over 15 days. Table 2 presents the results of this production as well as the stability parameters of the biodigester. The analysis of Table 2 reveals that daily production values, ranging between 4.5 m³ and 6 m³ with an average of 5.3 m³ per day, indicate a relatively stable and efficient biogas production. This stability is a strong indicator of the biodigester's performance, suggesting that the system's internal conditions are well-controlled and optimized for effective methanization. Additionally, the internal temperature of the biodigester, maintained between 34°C and 37°C, falls within the ideal range for the growth of methanogenic microorganisms [19]. This thermal consistency is crucial as it ensures optimal bacterial activity, which is essential for continuous and regular biogas production. This stability also indicates that environmental conditions are well-managed, contributing to the overall performance of the biodigester. Furthermore, the pH, ranging from 5.8 to 7.1, shows a trend toward stabilization within the optimal range for methanogenic bacteria. This pH stabilization is vital for creating an environment conducive to the development of bacteria responsible for methanization. A stable pH supports the efficient decomposition of organic matter and maximizes biogas production. The initial pH shift toward a more neutral range indicates system adaptation and progressive improvement of the biodigester's internal conditions.

Figure 2 illustrates the evolution of daily biogas production over a 15-day period. From the first to the ninth day, biogas production fluctuates slightly but remains generally stable, with values ranging between 4.5 m^3 and 5.5 m^3. This stability suggests that the biodigester is operating consistently and efficiently during this period. A slight increase is observed between days 10 and 12, with production peaking at 6 m^3. This rise may indicate an improvement in the internal conditions of the biodigester or a greater adaptation of methanogenic bacteria to the treatment conditions. After day 12, biogas production returns to more stable values, fluctuating between 5 m^3 and 5.5 m^3. This new phase of stability demonstrates that the system has reached a new equilibrium following the slight increase in production.

Table 2. Daily production and stability of the biodigester based on the 1/2 ratio.

Days	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Production 1/2 (m^3)	4.5	5.0	5.5	5.5	5.0	5.5	5.0	5.5	5.0	5.5	6.0	6.0	5.0	5.5	5.0
Temp (°C)	35	35	36	34	35	36	37	34	36	35	36	34	36	34	35
pH	5.8	6.1	6.1	6.5	6.7	6.6	6.7	6.8	6.6	6.8	7.0	6.8	7.1	7.0	7.1

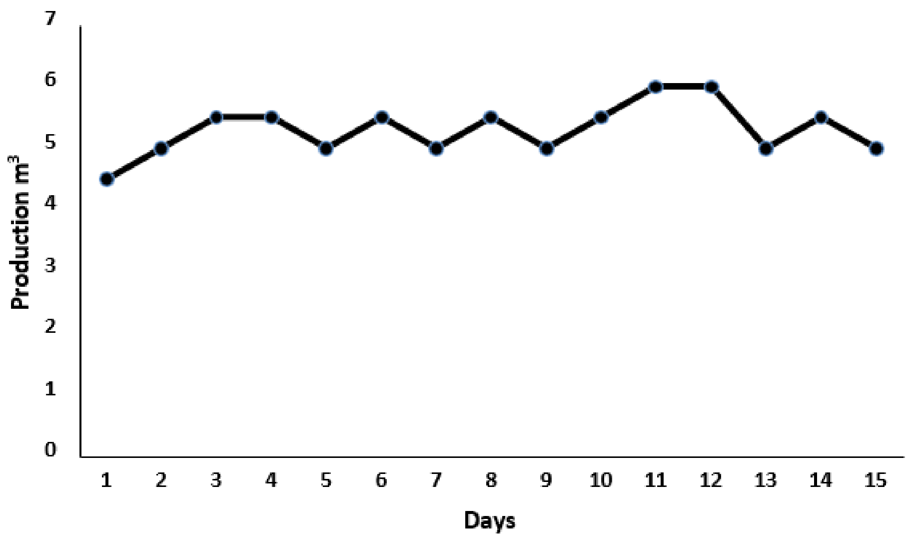

Figure 2. Daily biogas production at a 1/2 ratio.

3.2.3. Feeding the digester with a 1/1 ratio

In the third month, the feeding of the digester was adjusted from 750 liters of waste to 500 liters per day, maintaining a 1/1 ratio between waste and water. During this month, daily production was measured over a 15-day period to evaluate the system's performance. The obtained values are presented in Table 3. The daily biogas production ranges from 5.0 m^3 to 7.0 m^3, with an increasing trend over the days. Notably, production peaks at 7.0 m^3, indicating improved efficiency of the biodigester after the adjustment in feeding. Additionally, the temperature inside the biodigester remains generally between 34°C and 37°C, an ideal range for the development of methanogenic microorganisms [31]. This thermal stability is essential for ensuring optimal bacterial activity.

Furthermore, the pH evolves from 6.4 to 7.8 over the 15 days. It is noteworthy that the pH reaches levels close to neutrality, then stabilizes between 7.3 and 7.8, which is favorable for methanization [23]. This pH stabilization indicates an environment conducive to the activity of methanogenic bacteria [23]. The curve in Figure 3 below illustrates the variations in production. In this graph, biogas production shows growth from 5 m^3 to 7 m^3 between the first and seventh days. After this period, the production remains almost constant. According to Le Hyaric et al., good pH stability can promote the proper progress of methanization. This favorable production kinetics at the 1/1 ratio is also identified in the studies by [24].

Table 3. Daily production and stability of the biodigester at a 1/1 ratio.

Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Production 1/1 (m^3)	5.0	5.5	6.0	5.5	6.0	6.5	7.0	6.0	6.5	6.5	6.5	7.0	6	6.5	7.0
Temp (°C)	36	35	36	35	35	34	35	36	37	37	36	34	36	35	37
pH	6.4	6.5	6.5	6.6	6.8	6.9	7.4	7.5	7.7	7.8	7.6	7.5	7.4	7.4	7.3

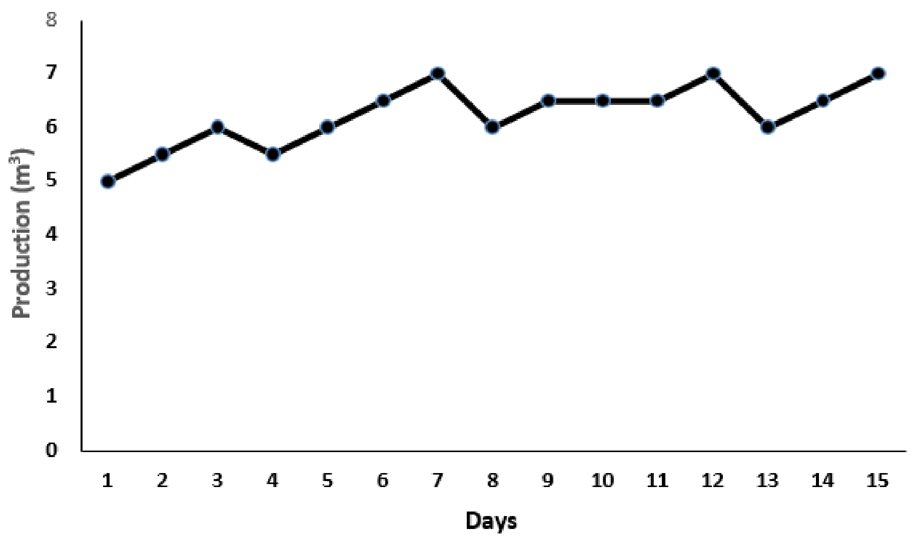

Figure 3. Daily biogas production at a 1/1 ratio.

3.3. Comparison of different feeding ratios

Over the months of experimentation, it was possible to evaluate the daily biogas production for each feeding ratio. The feeding ratio of 1/3 generated an average production of 4.1 m^3/day, with a minimum of 3 m^3 and a maximum of 5 m^3. At a ratio of 1/2, the average production increased to 5.3 m^3/day, ranging from 4.5 m^3 to 6 m^3. The highest average production was observed with the 1/1 ratio, reaching 6.23 m^3/day, with a minimum of 5 m^3 and a maximum of 7 m^3. Figure 4 illustrates the production trends for each feeding ratio, clearly showing that daily biogas production with the 1/1 ratio is superior to that of the 1/2 and 1/3 ratios. The lower production observed with the 1/3 ratio can be attributed to the acidification of the medium, favoring the acidogenesis phase, which requires a significant amount of water. Studies [18] show that during the conversion of organic acids into acetic acid, a substantial quantity of water is essential to ensure proper hydrolysis and acetogenesis, which produce acetic acid.

With the 1/1 ratio, optimal production conditions are achieved rapidly. The 1/2 ratio serves as an intermediate phase between the 1/3 and 1/1 ratios. For short-term continuous feeding, the biogas production at the 1/1 ratio is significantly higher than at the 1/2 and 1/3 ratios, as shown in Figure 5. The cumulative biogas production over 15 days for each ratio is as follows: 1/1 Ratio: 93.5 m^3; 1/2 Ratio: 79.5 m^3; 1/3 Ratio: 61.5 m^3. Previous studies on animal waste biogas potential, such as cow dung and poultry droppings, have shown that: a 1/5 ratio produces more biogas than a 1/3 ratio [19]. For cow manure, a 1/3 ratio yields more gas than the 1/1 and 1/2 ratios [20]. This synthesis of studies highlights that the daily production kinetics of ratios with a large amount of water are slower compared to ratios with less water. However, the cumulative production for water-intensive ratios is higher due to the essential role of water in hydrolysis and acetogenesis, which lead to acetic acid production. The acidic environment resulting from water-intensive ratios can slightly inhibit methanogenic bacterial activity, which explains the lower daily production. Conversely, ratios with less water show higher daily kinetics but limited cumulative production due to substrate depletion and insufficient water for methanogenic bacteria. In this study, continuous feeding was implemented to achieve rapid and large-scale production for industrial use, such as heating chicks. This requirement led to the selection of a water-intensive feeding ratio, specifically the 1/2 ratio, to ensure faster and higher biogas production. In addition to digester volume and daily waste input, it is essential to allow sufficient retention time for waste to deodorize and for the digestate to stabilize.

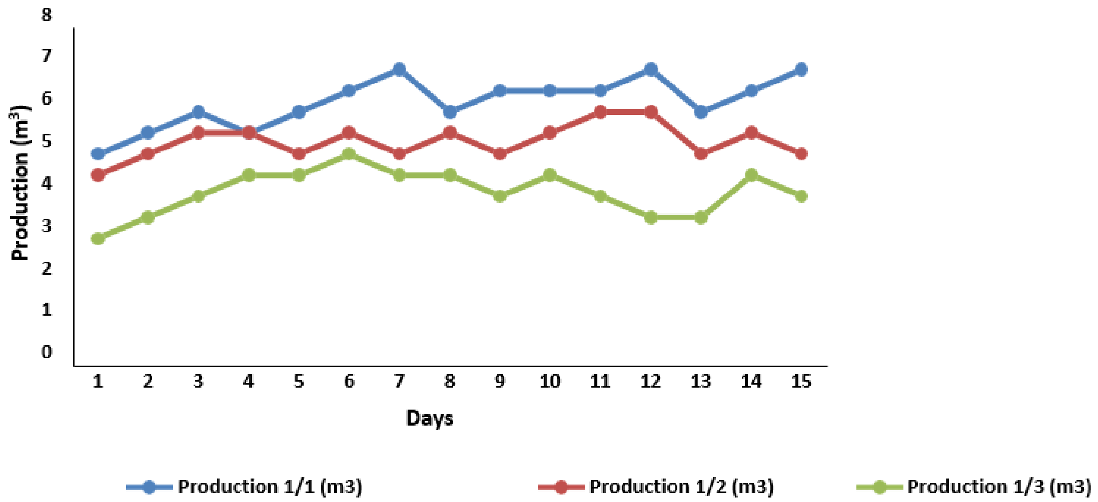

Figure 4. Comparison of daily biogas production for different ratios (1/1, 1/2, and 1/3).

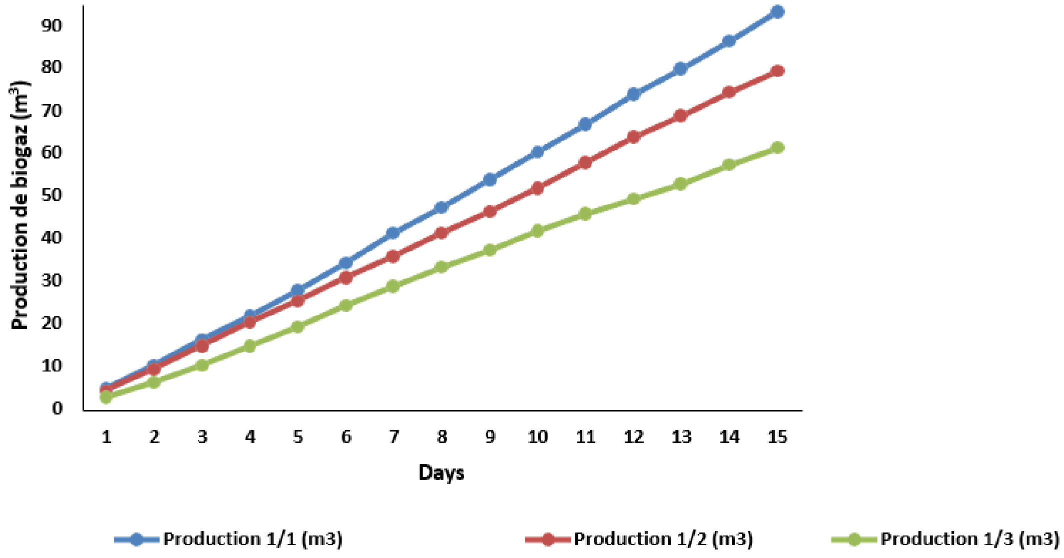

Figure 5. Cumulative daily biogas production based on ratios 1/1, 1/2, and 1/3.

3.4. Digestate quality

During feeding, the digestate was in liquid form, and its odor varied depending on the feeding ratio used.

Ratio 1/3: The digestate emitted a particularly strong odor. This strong odor could be due to the short retention time required for this ratio, which involved 1000 liters of waste, given the digester's volume. Additionally, the acidification of the medium, which hinders the proper development of methanogenic bacteria, may also be a contributing factor.

Ratio 1/1: The digestate produced with this ratio had a relatively mild odor. This can likely be attributed to its longer residence time in the digester, which could extend up to 30 days.

Ratio 1/2: The digestate from this ratio emitted an odor that was less strong compared to the 1/3 ratio but more pronounced than the 1/1 ratio.

These observations suggest that the olfactory quality of the digestate is influenced by both the feeding ratio and the retention time in the digester [23]. A longer residence time and a more balanced feeding ratio appear to support better development of methanogenic bacteria, which helps to reduce the odor of the digestate.

3.5. Biogas quality

Using a biogas analyzer, the quality of biogas produced with the different feeding ratios was assessed. The results are presented in Table 4.

Ratio 1/1: Produced the highest quality biogas, with a methane (CH_4) concentration of 58%.

Ratio 1/2: Delivered slightly lower performance, with a CH_4 concentration of 51%, still within an acceptable range.

Ratio 1/3: Produced the lowest quality biogas, with only 43% CH_4.

These results indicate that the feeding ratio significantly affects the quality of the biogas produced. A more balanced ratio, such as 1/1, promotes the production of biogas with a higher methane content, resulting in better energy efficiency.

Table 4. Biogas analysis by feeding ratios.

Feeding ratio	Methane (CH_4) %	Carbon dioxide (CO_2) %	Other gases %
1/1	58	40	2
1/2	51	46	3
1/3	43	54	3

3.6. Selection of the poultry droppings/water ratio

The selection of the poultry droppings-to-water ratio is a crucial factor in optimizing biogas production in a biodigester. In conclusion, the 1/2 ratio (250 kg of droppings to 500 liters of water) proved to be the most optimal for this study. This ratio strikes a balance between high biogas productions, stable internal conditions within the digester, and good biogas quality. By maintaining this ratio, the system achieves:

Maximized biogas production,

Stable conditions for anaerobic digestion processes, and

Efficient energy generation through high methane content in the biogas.

Overall, this configuration demonstrates its effectiveness for similar applications and contributes to the optimal utilization of poultry droppings. It promotes sustainable waste management and efficient renewable energy production.

4. Conclusion

This study optimized the poultry droppings-to-water ratio to maximize biogas production using the FONSTI-CRDI digester in eastern Côte d'Ivoire. Experimental results demonstrated that the 1/2 ratio (250 kg of droppings to 500 liters of water) was the most effective, achieving an average daily production of 5.3 m³ of biogas under optimal temperature and pH conditions. Compared to the 1/3 ratio, which resulted in lower production due to excessive acidification, the 1/2 ratio showed superior and stable production. While the 1/1 ratio yielded even more impressive results than the 1/2 ratio, it posed operational challenges as it caused blockages in the digester's feeding channels. The quality of the biogas was confirmed by its flammability and high methane content, while thermal stability; maintaining digester temperatures between 34°C and 37°C; ensured efficient methanization.

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Conflict of Interest

The authors declare no conflict of interest.

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