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Setting Parameters and Evaluating Biogas Production from Several Organic Substrates in Chad

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Abstract

The study presented in this paper evaluates biogas production from six organic substrates (slaughterhouse waste, cattle and goat manure, banana peels, and mixtures) under anaerobic conditions in the city of N'Djamena (Chad). The tests, conducted over fifty-eight (58) days, measured the volumes of biogas produced, their gas composition (CH_4, CO_2, N_2, H_2S), and changes in physicochemical parameters (pH, temperature). The results show that slaughterhouse waste has the highest production yield, while plant substrates (banana peels) have low production and a highly acidic pH, which is unfavorable for methanization. The results show that slaughterhouse waste is the most effective for biogas production in the Sahelian context, while plant substrates require adjustments (pretreatment, co-digestion). The use of slaughterhouse waste can be a sustainable solution for a country like Chad, which has limited financial resources to provide its population with affordable domestic energy and where the management of slaughterhouse waste poses enormous problems for companies operating in this sector.

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Substrate, biogas, methanization, agricultural waste, renewable energy.

Introduction

Faced with growing demand for domestic energy and the challenges of sustainable organic waste management, methanization is emerging as a promising solution for converting biomass into biogas (Appels *et al.,* 2011).

According to projections by the International Renewable Energy Agency (IRENA, 2020), this technology could cover up to 20% of global energy needs by 2030. This prospect is particularly relevant for countries like Chad, where agri-food waste such as manure, crop residues, and slaughterhouse waste is abundant but still insufficiently recovered.

Recent advances in methanization have identified innovative methods to optimize the process. The work of Li *et al.,* (2022) demonstrated that microwave pretreatment of lignocellulosic substrates could increase methane production by 20 to 30%. Meanwhile, (Shakib. A, Lin. S, and al) showed that the addition of biochar as an additive significantly improved the stability of the anaerobic process while reducing inhibitions by volatile fatty acids (VFAs).

Research on specific substrates has revealed notable differences in methanogenic potential. A recent meta-analysis by Obaideen *et al.,* (2021) confirms that fat-rich slaughterhouse waste exhibits a particularly high yield

(0.6-0.8 m^3 CH_4/kg MV). Banana residues, on the other hand, show significant improvements in performance (up to 65% CH_4) when co-digested with sewage sludge (Kumar *et al.,* 2020). Regarding manures, studies by Achinas *et al.,* (2023) highlight a 15% higher yield for goat manure compared to cattle manure, attributed to its lower lignin content.

Several key parameters influence biogas production. The nature of the substrate plays a determining role, with protein-rich materials (such as animal waste) generally producing more CH_4 than fibrous substrates according to Weiland (2010). The carbon/nitrogen (C/N) ratio is another crucial parameter, with an optimal ratio of 20-30% promoting process stability (Kayhanian & Tchobanoglous, 1992).

Finally, according to Deublein and Steinhauser (2008), operating conditions, including a pH maintained between 6.5 and 7.5 and a mesophilic temperature of 35-37°C, are essential for efficient methanization.

Recent technological innovations are opening up new avenues of research. The development of IoT sensors for real-time monitoring of biogas production, tested by Sotirios, D (2025), notably makes it possible to reduce monitoring costs by approximately 40%.

These advances add to the knowledge established by previous studies on the optimization of methanization of different types of substrates carried out by Salminen & Rintala (2002); Møller *et al.,* (2004); Mata-Alvarez *et al.,* (2000).

In this context, the study aims to achieve three main objectives: first, to compare biogas production from six organic substrates that are commonly available in Chad; second, to conduct a detailed analysis of the gas composition and physicochemical parameters involved in the anaerobic digestion process; and third, to explore potential strategies for improving methanization efficiency under the specific environmental conditions of the Sahelian region. Through these objectives, the research seeks to enhance the energy recovery potential of agro-food waste, promote renewable energy generation, and address broader sustainable development challenges, particularly in regions facing energy scarcity and environmental degradation.

Materials and Methods

In this section, we present the materials used for the tests and the methods adopted according to the standards.

Materials: experimental device and instrumentation

The study was conducted in N'Djamena (Chad) for 58 days, from August 3 to October 1, 2024, under ambient temperature conditions ranging from 22.7°C to 31.8°C. Each experimental system consisted of a 1.5-liter PET (polyethylene) plastic bottle (see Fig. 1) used as an anaerobic reactor serving as a biodigester for the mixture (substrates and water).

(a) PE foam tank used to collect and store the biogas generated in the digester, (b) PVC (Polyvinyl Chloride) tubing with leak-proof fittings, used to connect the digester to the storage tank equipped with an adjustment knob. The latter ensures safe transfer of biogas while preventing leaks and (c) PET bottle.

The instrumentation installed for monitoring biogas production includes a set of measuring devices shown in Figure 2.

(a) A probe pH meter, with an accuracy of ±0.01, is used to determine the pH of liquids, particularly that of the substrates before and after fermentation. This parameter is a key parameter for controlling the acidity and alkalinity of the digestive medium and assessing the progress of the digestion process.

(b) An S316 gas detector, equipped with a suction pump and an integrated alarm, can detect and quantify with an accuracy of ±2% the concentrations of methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) present in the biogas. This device also plays a crucial role in the safety of the experiment by alerting in case of high levels of flammable gases.

(c) Temperature is another important factor, and an INRIGOROUS digital probe thermometer, with an accuracy of ±0.1°C, is used to measure both the ambient temperature and the internal temperature of the digester, thus optimizing biogas production.

(d) Finally, a KERN electronic balance, with an accuracy of ±0.01 g and a digital display, is essential for accurately measuring the masses of the substrates before their introduction into the digester, thus ensuring the quantification of the proportions of the materials used.

Substrate parameterization

The substrates used for the experiments included cattle, goat, and pig manure, banana peels, and slaughterhouse waste. The resulting biogas was characterized based on on-site experimental analyses. These substrates were characterized using different approaches:

Humidity

Humidity was obtained using the NF EN 15934 standard and is expressed by (equation 1):

$$\%H = \frac{(m_h - m_s)}{m_h} \times 100$$

Where:

m_h = wet mass;

m_s = dry mass (105°C for 24 hours).

C/N Ratio (Kjeldahl Method)

The C/N ratio is obtained using the Kjeldahl method and is expressed as:

$$C/N = \frac{\%C_{total}}{\%N_{Kjeldahl}}$$

Theoretical Methanogenic Potential

The methanogenic potential is calculated using the Boyle equation given below:

$$B_0 = 0{,}415 \times \%Proteins + 0{,}496 \times \%Fat + 0{,}298 \times \%Carbohydrates$$

Biogas Volume

The biogas volume is measured daily by water displacement in a graduated system, corrected for temperature and pressure.

Temperature (Daily Measurement)

The temperature is recorded daily using a probe thermometer to monitor thermal variations that influence microbial activity.

Gas Composition (CH_4, CO_2, H_2S)

The gas composition is determined weekly by gas chromatography (GC).

pH

The pH is measured with a calibrated pH meter to detect potential acid-base imbalances.

Methane Yield

The methane yield (%CH_4) was calculated to assess the quality of the biogas produced. It allows us to determine the energy-recoverable proportion of the biogas. The following formula was applied (equation 4):

Where:

V_{CH4} = Volume of methane produced.
V_{total} = Total volume of biogas collected.

Operating Protocol

Loading the Digesters

The digesters were loaded with 1 kg of previously ground and homogenized substrate, mixed with 750 ml of distilled water to ensure optimal fluidity.

The COD/N/P ratio was maintained at 100/5/liter to ensure a nutrient balance favorable to methanogenic microorganisms. The initial pH was adjusted to 7.0 ± 0.2 using 1M NaOH solutions (in case of acidity) or 1M HCl (in case of excessive alkalinity) to create conditions conducive to anaerobic digestion.

Operating Conditions

The experiment was conducted over a period of 58 days, corresponding to the hydraulic retention time (HRT) required for complete degradation of the substrates. The organic load applied was 1.5 kg of volatile matter (VS) per m³ per day to find a compromise between productivity and process stability. Daily manual stirring was carried out to homogenize the medium and prevent the formation of surface crusts, while limiting stress on anaerobic bacteria.

Results and Discussion

Biogas Production and Gas Composition Results for Different Substrates

This section presents the volumes of biogas produced for each substrate tested. The data reveal marked differences between animal and plant substrates in terms of the quantity of biogas produced.

Kinetic analysis provides insight into the temporal dynamics of biogas production for each substrate. Figure 3 shows the evolution of biogas production for different substrates.

The following key findings emerge from Figures 3 and 4:

• For slaughterhouse waste: maximum production is 2.142 L at D58, with a CH_4 rate of 68.1% (Figure 3A), confirming its status as an optimal substrate. The excellent performance of slaughterhouse waste can be explained by its high protein and lipid content, which are easily degradable (Salminen & Rintala, 2002).

• For camel manure (analysis carried out at the Biogaz planET laboratory), the yield of 178 m³ CH_4/t shows interesting potential despite its fiber content. Although camel manure performs well in the laboratory, it shows lower than expected yields on site, probably due to the climatic conditions in the Sahel.

• As for banana skins, late production (starting on day 37) and low CH_4 content (28.3% on day 50) highlight their limitations for mono-digestion methanization. Fiber-rich substrates (bananas, manure) have slower kinetics, consistent with the observations of Battimelli *et al.,* (2017). This representation is crucial for correctly sizing retention times in large-scale facilities.

• The evolution of pH and the production of volatile fatty acids explain the differences in yield between substrates. Goat manure (pH 6.8) is stable because it is within the optimal range for methanogenesis. The marked acidification of banana peels (final pH = 3.95) creates unfavorable conditions. The excessive acidification observed with plant substrates (pH < 4.0) clearly inhibits the activity of methanogens (Deublein & Steinhauser, 2008). These results require pH control, possibly by adding buffers such as biochar (Wang *et al.,* 2023). Thus, banana peels confirm their need to be co-digested to improve their biodegradability (Kumar *et al.,* 2020).

Other results of substrates analyzed in the laboratory

Other relevant substrate parameters were analyzed, including dry matter (DM), organic matter (OM), total nitrogen, and the methanogenic potential of the substrates, specifically camel, pig, and chicken manure, which were analyzed by the Biogaz PlanET France laboratory. These substrates were analyzed according to the NF EN 15934 and ISO 11734 protocols. Table 1 provides the values of some relevant substrate parameters and the methanogenic potential.

Table.1 Methanogenic potential tests carried out at 37°C for 30 days

Parameter	Camel manure	Pig manure	Chicken manure
Dry matter (%)	95.50	96.8	96.4
Organic matter (%)	81.0	38.6	42.8
Total nitrogen (kg/t)	19.6	22.1	24.6
Potential CH_4 (m^3/t)	178	78	86

Figure.1 Biodigester

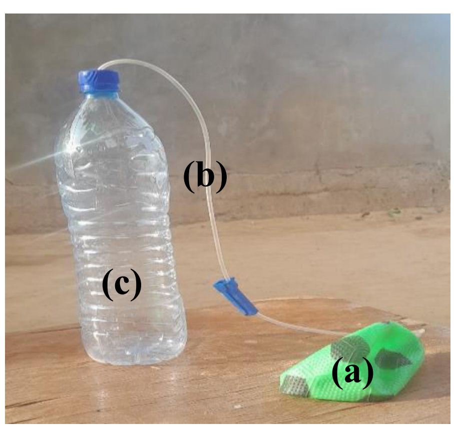


Figure.2 Measuring instruments

(a)

(b)

(c)

(d)

Figure.3 Evolution of biogas production for different substrates

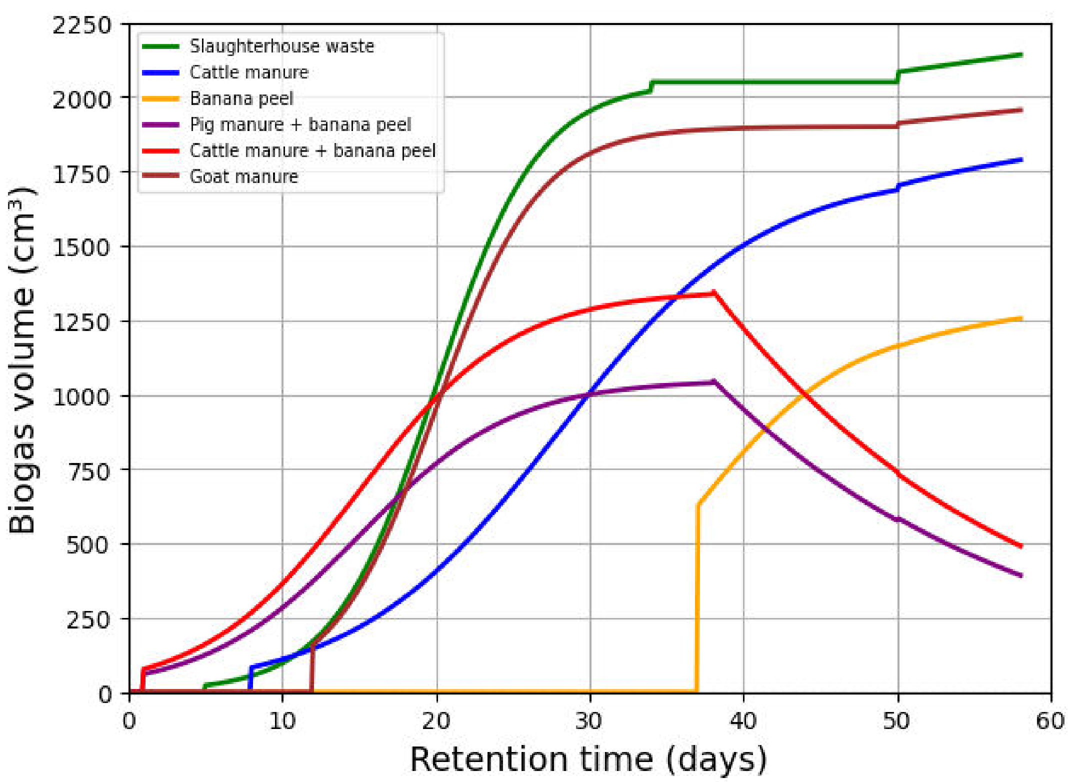
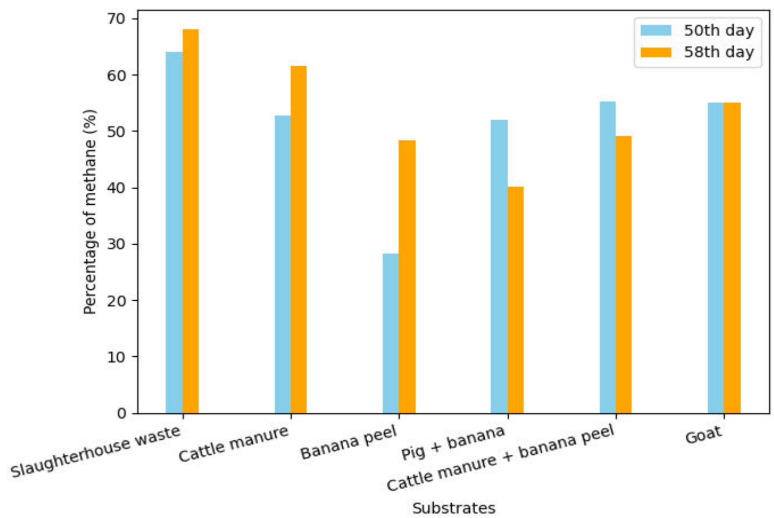


Figure.4 Methane levels measured during two different substrate tests



Due to the high DM content of these three samples, they have a strong drying effect when used in a continuous liquid process and may need to be diluted with a large amount of slurry. The discontinuous dry process could also be considered in this case.

The high nitrogen and sulfur contents of these inputs can cause problems with biogas quality (presence of H2S and NH3), making its recovery more difficult. These manures may need to be combined with other inputs to improve biogas quality.

The nitrogen contained in fuels is the source of most nitrogen oxide (NOx) emissions resulting from biomass combustion. A lower nitrogen content helps reduce NOx emissions. In our case, camel manure is better in this regard. It should also be noted that the quantities analyzed were low and that, given the appearance of the samples, the organic matter in the samples was judged to be of low quality. Finally, there is experience with camel manure in the literature and it is possible that there is a slight uncertainty in the estimation of methanogenic potential.

In conclusion, we demonstrated that slaughterhouse waste is the most efficient substrate for biogas production in the Sahelian context, with a yield of 1.459 m^3 CH_4/t and a methane content of up to 68.1%. Animal manures (cattle, goat, camel) exhibit lower but stable yields, while plant substrates (banana peels) require co-digestion to compensate for their excessive acidity (pH < 4) and their low methane production (28.3%, see Fig. 4). Analyses conducted by the Biogaz PlanET France laboratory on reference manures (camel, pig, chicken) confirmed the robustness of our protocols and identified avenues for optimization, particularly for fiber-rich substrates. This study demonstrates that local substrates (slaughterhouse waste, cattle/goat manure) outperform laboratory references (pig/chicken manure) in CH_4 yield. PlanET Biogas analyses validated the methodology and identified areas for optimization (e.g., pH management).

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Author Contributions

Al-Hafiz Abdoulaye Affadine, Abdel-hakim Boukar - Conceived the original idea and designed the model and wrote the manuscript.
Ali Ahmat Younous, Abdallah Dan-nah Mahamat - Designed the model and the computational framework and analysed the data.

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