Generation of biogas and thermal energy at the Bolo das Oliveiras Agroindustry, Pombal, Paraíba, Brazil

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ABSTRACT: This study aimed to assess the potential for generation of thermal energy from biogas produced by a rural biodigester in the Bolo das Oliveiras Agroindustry, Pombal/PB, Brazil. The biodigester was fed every two days with 0.30 m^3 of biomass (mixture of water and bovine manure), retention time of 45 days. Affluent and effluent samples were collected every 15 days for 75 days. The affluent had a higher ($p < 0.05$) solids contents than the effluent. The highest dissolved oxygen concentration (6.67 mg L^{-1}) was observed in the affluent. The effluent had lower ($p < 0.05$) total alkalinity than the affluent at all sampling times. CH_4 values were higher than CO_2 values throughout the experiment. Biogas also contained trace proportions of H_2S and NH_3 (2/3 and 1/3 ppMV, respectively). CH_4 emissions were estimated at 10.58 m^3 day^{-1}. CH_4 was the major constituent of biogas, as indicated by flame combustion behavior. Generation of biogas and thermal energy at the Bolo das Oliveiras Agroindustry may be economically feasible, providing a minimum monthly savings of R$ 1,582.00.
Keywords: biodigester; effluent; methane.

Geração de biogás e energia térmica na agroindústria Bolo das Oliveiras, Pombal, Paraíba, Brasil

RESUMO: Este estudo teve como objetivo avaliar o potencial de geração de energia térmica a partir do biogás produzido por um biodigestor rural na Agroindústria Bolo das Oliveiras, Pombal/PB, Brasil. O biodigestor foi alimentado a cada dois dias com 0,30 m^3 de biomassa (mistura de água e esterco bovino), tempo de retenção hidráulica de 45 dias. Amostras de afluentes e efluentes foram coletadas a cada 15 dias durante 75 dias. O afluente apresentou teores de sólidos maiores ($p < 0,05$) do que o efluente. A maior concentração de oxigênio dissolvido (6,67 mg L^{-1}) foi observada no afluente. O efluente apresentou alcalinidade total menor ($p < 0,05$) do que o afluente em todos os tempos de amostragem. Os valores de CH_4 foram superiores aos valores de CO_2 durante todo o experimento. O biogás também continha traços de H_2S e NH_3 (2/3 e 1/3 ppMV, respectivamente). As emissões de CH_4 foram estimadas em 10,58 m^3 dia^{-1}. O CH_4 foi o principal constituinte do biogás, conforme indicado pelo comportamento da combustão da chama. A geração de biogás e energia térmica na Agroindústria Bolo das Oliveiras pode ser economicamente viável, proporcionando uma economia mensal mínima de R$ 1.582,00.
Palavras-chave: biodigestor; efluente; metano.

1. INTRODUCTION

In Brazil, cattle farming is one of the most economically important agricultural activities. The cattle population of Paraíba State increased by 1.6% in 2017, reaching about 1.25 million head (BRASIL, 2019). However, Brazilian agricultural enterprises generate high amounts of organic matter and have significant consequences on the environment (SAADY; MASSÉ, 2015).

In recent decades, the scientific community has shown great interest in the development of sustainable alternatives to minimize waste generation, promoting changes in the management of cattle waste (RIOS; KALTSCHMITT, 2016). As animal manure is mainly composed of carbon, hydrogen, nitrogen, and oxygen, it holds potential in thermal and

electric energy production (PIÑAS et al., 2018). There are, however, some drawbacks in the use of animal manure, such as low biodegradability resulting from its high content of lignocellulosic fibers (ANDRIAMANOHIARISOAMANANA et al., 2017).

Organic matter decomposition can be exploited to produce biogas and electric power, contributing to the reduction of unit costs in agricultural production. Some researchers investigated the feasibility of using biogas to meet daily cooking energy needs (SANTOS et al., 2018). An example of such a system has been implemented in the Bolo das Oliveiras Agroindustry, Pombal, Paraíba, Brazil, which had a monthly demand of 14 liquefied petroleum gas (LPG) cylinders (13 Kg each). To partially replace the use of LPG,

we developed a rural, sertanejo-type biodigester and a biogas purification system that is fed with cattle waste supplied by residents of the Várzea Comprida dos Oliveiras community.

The purpose of this study was to assess the potential for generation of biogas and thermal energy of the biodigester developed for the Bolo das Oliveiras Agroindustry. We investigated the physical and chemical characteristics of the influent and effluent at different sampling times, evaluated biogas quality in terms of its composition, flame color, combustion characteristics, and CH_4 emission, and estimated the potential savings obtained from thermal energy generation.

2. MATERIAL AND METHODS
2.1. Location of the experiment
The research project was developed in the Bolo das Oliveiras Agroindustry (Figures 1A), located in the rural community of Várzea Comprida dos Oliveiras, Pombal, Paraíba, Brazil. According to the 2019 census, Pombal has 32,801 inhabitants and an area of 889 km² (IBGE, 2019). The rural community is 9.81 km away from the Center for Agrofood Sciences and Technology (CCTA) of the Federal University of Campina Grande (UFCG), Pombal campus,

Paraíba, Brazil, where the laboratory analyses were performed. Geographical coordinates for the site were determined using a global positioning system (GPS) device (Garmin®, model 010-01199-10) and are given in UTM (Universal Transverse Mercator) format based on the rectangular coordinate system: 625653 m E and 9252998 m S.

A biodigester (Figure 1B) and biogas purification system was installed at the Bolo das Oliveiras Agroindustry. According to Ribeiro Filho et al. (2017), the region has hot semi-arid climate.

2.2. Biodigester features
The biodigester has a total volume of 14.8 m³. The system consists of (I) a 0.25 m³ feed tank, (II) a fermenting chamber with a total capacity of 14.8 m³, (III) a 5 m³ gas holder, (IV) a pressure adapter, (V) a primary water filter, and (VI) a 0.38 m³ overflow tank (Figure 2).

2.3. Purification system features
The biogas purification system comprises three treatment columns (Table 1). The system also includes a compressor that delivers the gas to an adapted oven through a 38 m long line, operating at a pressure of about 110 lbf in⁻².

Figure 2. Bolo das Oliveiras Agroindustry in Pombal, PB, Brazil (A) and area of implantation of the biodigester in the countryside (B).
Figura 2. Agroindústria Bolo das Oliveiras em Pombal, PB, Brasil (A) e área de implantação do biodigestor no interior (B).
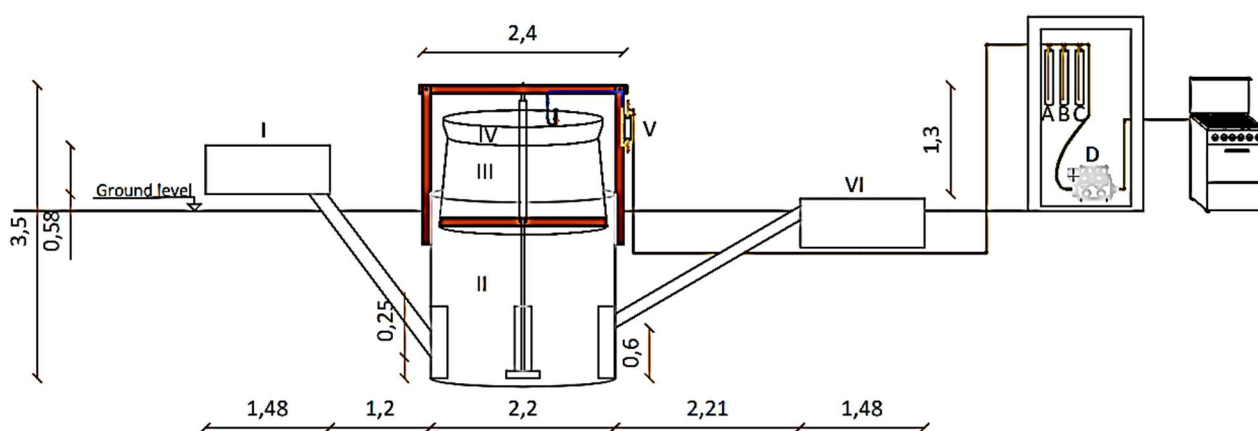

Figure 2. Longitudinal section of the sertanejo-type biodigester and purification system. A, chemical solution; B, hydrogen sulfide (H2S) gas filter; C, water column; D, gas compressor.
Figura 2. Corte longitudinal do biodigestor tipo sertanejo e sistema de purificação. A, solução química; B, filtro de gás sulfureto de hidrogénio (H2S); C, coluna de água; D, compressor de gás.

Table 1. Description of treatment columns of the biogas purification system.
Tabela 1. Descrição das colunas de tratamento do sistema de purificação de biogás.

Column	Description
A	Contains sodium hydroxide (NaOH) and removes carbon dioxide (CO_2).
B	Lined internally with iron filings for removal of hydrogen sulfide (H_2S) from the biogas mixture.
C	Contains artisanal well water and removes CO_2, H_2S, ammonia (NH_3), and other gases. A safety seal prevents the reflux of gas to the biodigester.

2.4. Methods

During the study period, the digestion chamber was fed every two days with 0.30 m^3 of biomass (a mixture of 200 L of water and 100 Kg of bovine manure). The water used was from an artesian well and a simple effluent treatment system installed at the agroindustry. Bovine manure was collected from a herd of about 40 animals raised in a semi-feedlot system, most of which were lactating cows. The amount of manure generated by the cattle is equivalent to that produced by five feedlot animals (10 Kg of manure per day), according to data from Sganzerla (1983) adapted by Colatto; Langer (2012). A hydraulic retention time of 45 days was adopted. Influent and effluent samples were collected every 15 days for 75 days.

2.5. Physical and chemical analyses

Physical and chemical analyses were performed in five replications, according to the recommendations of Baird et al. (2023). Fixed solids (FS, combustion in a muffle furnace at 550 °C for 1 h), total solids (TS, combustion in a muffle furnace at 550 °C for 1 h, followed by oven-drying at 105 °C for 24 h), and volatile solids (VS) were calculated according to Eqs. (1), (2), and (3), respectively. Electrical conductivity (direct electrode reading), dissolved oxygen (measured using a portable oxygen meter under controlled aerobic conditions at 20 °C for 5 days), pH (measured using a pH meter calibrated with pH 4.0, 7.0, and 10.0 buffer solutions), and total alkalinity (TA, volumetric determination using a standardized solution of sulfuric acid and calculated using Eq. 4) were also determined.

$$FS\ (mg\ L^{-1}) = \frac{(W_2 - W_0) \times 10^6}{V_s} \quad (01)$$
$$TS\ (mg\ L^{-1}) = \frac{(W_1 - W_0) \times 10^6}{V_s} \quad (02)$$
$$VS\ (mg\ L^{-1}) = \frac{(W_1 - W_2) \times 10^6}{V_s} \quad (03)$$
$$TA\ (mg\ HCO_3\ L^{-1}) = \frac{V \times M \times 61000}{V_s} \quad (04)$$

where: W_0 is the initial weight; W_1 the dry weight; W_2 the final weight; V_s the sample volume; V the volume of base used for titration; M the base molarity; and 61000 the mass of HCO_3 expressed in milligrams.

2.6. Biogas qualification and economy estimate

The proportion and composition of gases (CH_4, CO_2, H_2S, and NH_3) in biogas was determined on-site at the time of sampling using a kit developed by Kunz; Sulzbach (2007). Flame color and combustion behavior were analyzed in a biogas stove and oven. CH_4 production, expressed in m^3, was calculated using Eqs. (5) and (6) and applied to estimate the economic savings of thermal energy generation.

$$CH_4\ (m^3\ day^{-1}) = \frac{M_t \times t \times N_a \times P_b \times C}{V_e} \quad (05)$$
$$d = \frac{m}{V} \quad (06)$$

where: M_t is the total amount of manure fed to each biodigester unit (Kg day^{-1}), t is the sampling time (days); N_a is the number of animals producing waste, P_b is the biogas production (Kg biogas Kg^{-1} manure); C is the CH_4 content of biogas; V_e is the specific volume of CH_4 (0.67 Kg m^{-3}); d is the density of CH_4 (0.72 Kg m^{-3}; m is the mass of CH_4, and V is the volume of CH_4.

Biogas production was determined using the energy conversion value for cattle recommended by the National Biomass Reference Center (CENBIO), as adapted by Colatto; Langer (2011).

2.7. Statistical analysis

The Shapiro-Wilk Test was applied to assess the normality of the data. Physical and chemical data were subjected to analysis of variance in a completely randomized design using Assistat software version 7.7 beta (SILVA; AZEVEDO, 2016). Means were compared by Tukey's test at the 5% significance level ($p < 0.05$).

3. RESULTS
3.1. Physical analyses

Table 2 describes the physical characteristics of influent and effluent from the biodigester after 45, 60, and 75 days of digestion.

The TS (3407.23–3446.67 mg L^{-1}) and VS (3399.25–3434.58 mg L^{-1}) of effluents at 45 and 60 days of digestion did not differ ($p > 0.05$) from each other, nor did the FS content (6.96–7.98 mg L^{-1}) of effluents at 60 and 75 days. Effluent EC remained significantly higher ($p < 0.05$) than influent, with no differences ($p > 0.05$) between effluents collected at different times.

Table 2. Physical characteristics of the affluent and effluent of a sertanejo-type biodigester after 45, 60, and 75 days of digestion.
Tabela 2. Características físicas do afluente e efluente de um biodigestor do tipo sertanejo após 45, 60 e 75 dias de digestão.

Sample	Time (days)	TS (mg L^{-1})	FS (mg L^{-1})	VS (mg L^{-1})	EC (mS cm^{-1})
Affluent	-	3672.17 ± 1.02 [a]	14.52 ± 0.28 [a]	3657.64 ± 0.74 [a]	3.76 ± 0.04 [b]
Effluent	45	3446.67 ± 0.92 [b]	12.09 ± 0.81 [b]	3434.58 ± 0.82 [b]	4.01 ± 0.04 [a]
	60	3407.23 ± 0.87 [b]	7.98 ± 0.50 [c]	3399.25 ± 0.51 [b]	3.95 ± 0.10 [a]
	75	3190.85 ± 0.80 [c]	6.96 ± 0.05 [c]	3183.89 ± 0.81 [c]	3.96 ± 0.05 [a]
CV (%)		1.70	4.82	1.72	1.60
p-value		<0.0001	<0.0001	<0.0001	0.0059

Values are presented as the mean ± standard deviation. Means in a column followed by the same letter are not significantly different at $p < 0.05$ by Tukey's test. -, relative to all sampling periods; TS, total solids; FS, fixed solids; VS, volatile solids; EC, electrical conductivity; CV, coefficient of variation.

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3.2. Chemical analyses

The chemical characteristics of influent and effluents at 45, 60, and 75 days are presented in Table 3. DO values differed significantly from each other ($p < 0.05$). As expected, the influent had the highest DO content (6.67 mg L^{-1}). Nevertheless, digester effluents had high DO concentrations at all sampling times.

A relationship was observed between effluent pH values, which did not differ ($p > 0.05$) from those of the influent only on days 45 and 60. Effluents had lower TA than the influent at all sampling times, with significant differences between effluent samples ($p < 0.05$).

Table 3. Chemical characteristics of the affluent and effluent of a sertanejo-type biodigester after 45, 60, and 75 days of digestion.
Tabela 3. Características químicas do afluente e efluente de um biodigestor do tipo sertanejo após 45, 60 e 75 dias de digestão.

Sample	Time (days)	Parameter		
		DO (mg L^{-1})	pH	TA (mg HCO$_3$ L^{-1})
Affluent	-	6.67 ± 0.06 [a]	6.67 ± 0.12 [b]	1259.67 ± 0.58 [a]
Effluent	45	4.83 ± 0.06 [b]	6.89 ± 0.06 [ab]	1258.67 ± 0.58 [a]
	60	4.00 ± 0.10 [c]	6.92 ± 0.06 [ab]	1250.67 ± 0.58 [b]
	75	3.60 ± 0.10 [d]	7.12 ± 0.17 [a]	1233.67 ± 0.58 [c]
CV (%)		1.71	1.58	0.05
p-value		<0.0001	0.007	<0.0001

Values are presented as the mean ± standard deviation. Means in a column followed by the same letter are not significantly different at p < 0.05 by Tukey's test. -, relative to all sampling times; DO, dissolved oxygen; TA, total alkalinity; HCO$_3$, hydrogen carbonate; CV, coefficient of variation.

3.3. Biogas qualification and economy estimate

Figure 3A and B shows the results of biogas quality testing, indicating the concentrations of CH$_4$ and CO$_2$, as well as the proportions of H$_2$S and NH$_3$.

CH$_4$ levels were higher than those of CO$_2$ throughout the experiment (Figure 3A). In the current study, the highest CH$_4$ concentration in biogas (78%) was observed at 60 days after digestion, not differing from those observed at 45 and 75 days (76%). The proportions of H$_2$S and NH$_3$ remained stable throughout the experimental period (2/3 H$_2$S and 1/3 NH$_3$ ppMV). Figure 4 show photograph of the biogas flame.

The predominantly light blue color of the biogas flame indicated a high concentration of CH$_4$. We estimated that CH$_4$ was produced at a rate of 10.58 m^3 day^{-1} or 317.26 m^3 month^{-1} (30 days) under the current experimental conditions. A CH$_4$ volume of 317.26 m^3 is equivalent, in terms of energy, to 17–18 LPG cylinders of 13 Kg.
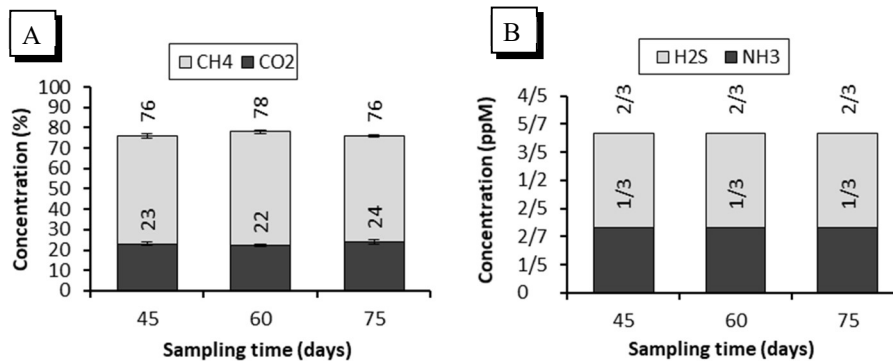
Figure 3. Concentrations of methane (CH$_4$) and carbon dioxide (CO$_2$) (A), and proportions of hydrogen sulfide (H$_2$S) and ammonia (NH$_3$) (B) in biodigester effluents collected after 45, 60, and 75 days of digestion.
Figura 3. Concentrações de metano (CH$_4$) e dióxido de carbono (CO$_2$) (A), e proporções de sulfeto de hidrogênio (H$_2$S) e amônia (NH$_3$) (B) em efluentes de biodigestores coletados após 45, 60 e 75 dias de digestão.

Figure 4. Photograph of the biogas flame on a stove top.
Figura 4. Fotografia da chama de biogás em cima de um fogão.

4. DISCUSSION

Solids determination is important, as it provides a characterization of biodegradable matter, which directly influences the efficiency of anaerobic digestion. Organic matter is consumed and transformed into biogas through the action of microorganisms; thus, the higher the amount of biodegradable matter, the higher the biogas production potential (HASSANEEN et al., 2020). The values of TS, FS, and VS throughout the experimental period can be associated with substrate degradation (Table 2). The solids contents of the influent were significantly higher ($p < 0.05$) than those of the effluents, as is expected for biogas generation, according to Xiao et al. (2018).

The biodegradation rate of organic matter and, consequently, the rate of biogas production depend on

substrate composition and nutrient content, biomass/water ratio, inoculum source, and process conditions, such as pH, temperature, and hydraulic retention time (MONLAU et al., 2015). As discussed by Simm et al. (2016), biodegradation rate can also be influenced by digester configuration, such as by the use of mechanical stirring and post-fermentation.

It is likely that EC values (Table 2) were associated with the physicochemical characteristics of water from artesian wells, as previously observed by Farhat et al. (2018). Artesian well water was used to dilute bovine manure before feeding the biodigester, possibly increasing the salt content of the organic material. No study has investigated the correlation between substrate salt concentration and biogas production. McVoitte et al. (2019), however, identified that substrate pretreatment may influence biogas yield and quality. Furthermore, Arelli et al. (2018) reported that biofertilizers with high salt concentrations obtained by digestion may damage the soil and water bodies if used without pretreatment.

The DO results (Table 3) suggest the occurrence of microbial multiplication, indicating the need for post-treatment to avoid pollution or contamination of water bodies, soil, and air when using the effluent as an organic fertilizer (ORRICO et al. 2016). TA, volatile fatty acids, and pH are crucial to assess the level of substrate stability in the digester and prevent system souring (GUIMARÃES et al., 2018; JANKE et al., 2018). All pH values were within the optimal range suggested for anaerobic digestion (pH 6.0–8.0) by previous studies (GARDONI; AZEVEDO 2019), obviating the need for pH correction.

According to Rosli et al. (2016), the TA below the affluent (Table 3) is indicative of an expressive buffering capacity, considered positive for anaerobic digestion. TA levels greater than 1000 mg HCO_3 L^{-1} are recommended to maintain a neutral pH. Normally, TA ranges from 1000 to 5000 mg HCO_3 L^{-1} in anaerobic processes (PANYAPING; MOONTEE, 2017).

Similarly, Simm et al. (2016) found high CH_4 concentrations in biogas obtained by anaerobic digestion of crude glycerin. Campos et al. (2013) reported CH_4 concentrations of 48.60 to 68.14% in unpurified biogas during 86 days of anaerobic digestion of coffee wastewater. According to Piñas et al. (2018), biogas composition may be influenced by substrate type and animal diet. Leite et al. (2015), in studying dense sludge samples, observed that the proportions of H_2S and NH_3 vary according to the type of organic matter used for anaerobic digestion. The light of the biogas flame (Figure 4) in agreement with the findings of Mario et al. (2015). Calza et al. (2015) highlighted that the calorific value of biogas varies according to the amount of CH_4 in the gaseous compound.

Considering that a conventional LPG cylinder of 13 Kg costs R$ 113.00, we estimated that biogas generation afforded a monthly savings of R$ 1,582.00 for the Bolo das Oliveiras Agroindustry. As the agroindustry consumes only 14 cylinders per month, biogas generation provides a surplus of four cylinders (R$ 452.00). Assuming the installation costs of the biodigester to be R$ 9500.00, it is estimated that the time for a return on investment is 6 months. This shows that the *sertanejo*-type biodigester can be an economically feasible investment with a short payback period.

5. CONCLUSIONS

The results of this experiment demonstrate that the solids contents of biodigester effluents are influenced by organic matter biodegradation rate. Substrate pretreatment was recommended for higher biogas production and quality. Chemical analysis underscored the importance of effluent post-treatment to minimize environmental impacts. The biogas had a high CH_4 concentration, as evidenced by the predominantly blue flame. The use of biogas for generation of thermal energy in the Bolo das Oliveiras Agroindustry seems to be economically feasible, capable of affording minimum monthly savings of R$ 1,582.00. Biogas plants are an efficient solution to improve manure management, mitigate environmental impacts, and stimulate investment in renewable energy. However, further studies are needed to improve the efficiency, monitoring, and savings of biogas generation.

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