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Characterization of A Low-Cost Biodigester of Dairy Cattle Manure Installed in Southern Brazil

Fábio Nuernberg, Kátia Cilene Rodrigues Madruga and Elaine Virmond*

Federal University of Santa Catarina, Center of Sciences, Technologies and Health, Department of Energy and Sustainability, Campus Araranguá, Rodovia Governador Jorge Lacerda, 3201, Jardim das Avenidas, 88906-072, Araranguá, SC, Brasil

Abstract

The southern region of Brazil is currently one of the largest milk producers, an activity that contains great diversification in terms of its production system. The problem associated with the creation of dairy cattle is the high production of manure, which requires special care not to negatively affect the environment. One of the alternatives for the treatment of such waste is biodigestion, which promotes the reduction of the organic load present in the substrate, produces biogas and organic fertilizer. Biogas consists of a gas mixture (CH_4, CO_2, NH_3, H_2S, others) that can be used in different ways depending on the composition. The present work evaluated a low-cost biodigester of dairy cattle manure installed in a rural property located in Southern Brazil. For this, the substrate, organic fertilizer and biogas were characterized. In the substrate and in the organic fertilizer, the contents of total, volatile and fixed solids were evaluated to quantify the reduction of the content of volatile solids, which represents the decrease of the organic load present in the substrate. In the substrate the content of volatile solids found was 83.07±5.41%. After the biodigestion process, a concentration of 74.29±2.06% in the organic fertilizer was obtained, totaling a reduction of 10.28% of the organic load. The biogas chemical composition, energy content and the influence of temperature on its production were evaluated. The biogas produced had an average concentration of CH_4 of 72.9±8.6%, a *LHV* of 26.10 MJ/m³ and Wobbe Index of 25.72 MJ/m³, demonstrating that there is potential for replacement of LPG. The analysis carried out with the biogas showed a significant difference in the production during the spring when compared to the winter. In addition to these factors, it was estimated the amount of waste produced and the daily production of CH_4 within the property. The amount of waste treated nowadays is only 11% of the total available according to the estimative, what indicates that nine more biodigesters of the same model would be needed to treat all the waste produced and, as consequence, CH_4 production could be at least nine times higher.

1. Introduction

According to data from the Milk Yearbook [1], Brazil rose from fourth to third place in production and productivity of cow's milk in the world market in 2017, totaling a production of 33.5 billion liters.

The total milk production receives interference from factors such as the type of animal confinement, food offered, breed characteristics and animal health. In production systems there are two divisions: intensive and extensive system, the main differences between which are the type of food offered and the ability to recover waste (manure + urine) [2].

The manure produced by animals is often used as agricultural fertilizer, however, without a specific

* Corresponding author
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treatment they have a great potential to pollute soils, air by emitting acid and greenhouse gases, water by eutrophication of groundwater and also aquatic bodies [3]. According to Campos [4], the average daily production of manure from dairy breeds is 8% to 11% of the animal's weight.

One of the possible alternatives to treat and still reduce the amount of waste is biodigestion. According Colbella [5], this process reduces the polluting potential of waste, produces biogas and allows the use of the effluent as an organic fertilizer (biofertilizer or digestate) in a safe manner, and can be carried out by means of biodigesters.

Anaerobic digesters can be defined as a closed chamber fed with organic substrates that in the absence of oxygen are degraded by the action of microorganisms [6]. The most used models in Brazil are the Indian, the Chinese and the Canadian ones, each adapted to a reality and a need for organic fertilizer and biogas. They can be operated continuously (or intermittently) or discontinuously (batch) [7].

To assess the performance of the biodigestion process, the quality of the substrate, biogas and organic fertilizer must be determined. In the substrate, chemical parameters such as pH, solids content (total solids, volatile solids, fixed solids) must be analyzed. In relation to biogas, its chemical characterization, energy content, pressure and operating flow are important. The analysis of solids in organic fertilizer is also important to assess the reduction of solids. Nitrogen (N), phosphorus (P) and potassium (K) contents must also be analyzed for the correct use of fertilizer (application in agriculture).

The fraction of solids that make up the substrate can be divided into an organic portion, that of volatile solids (VS) and an inorganic portion, that of fixed solids (FS). The content of volatile solids is directly linked to the amount of biogas produced, so the higher the VS content, the greater the biogas production [8]. In addition, the total solids content (TS) is a parameter to determine the amount of dilution required in the substrate affluent to the biodigester, in the Indian model biodigesters the TS content at the entrance of the digester must be less than 8% to guarantee flow and decrease the chances of clogging [9].

Biogas consists of a gas mixture composed mainly of methane (CH_4) and carbon dioxide (CO_2). In lower concentrations, ammonia (NH_3), nitrogen (N_2) and hydrogen sulfide (H_2S) are also present [10]. The higher the percentage of CH_4, the greater its calorific value. From the calorific value, the equivalence of biogas with other combustible gases applicable to the intended use can be estimated through the Wobbe Index *(Iw)*, which represents the heat provided by the burning of combustible gases through an orifice subjected to constant pressures, upstream and downstream of that hole [11].

The general objective of this work was to characterize a biodigester located on a small rural property in São João do Sul, SC, Brazil, used for the treatment of bovine manure and biogas production. For that, the substrate, the organic fertilizer (digestate) and the biogas were characterized and the performance of the biodigester was evaluated.

2. Materials and Methods

This work was carried out in an Indian biodigester installed in a rural unit located in São João do Sul, Santa Catarina, Southern Brazil, with an area of approximately 18.5 ha. The property has a dairy cattle herd containing 34 cows weighing an average of 400 kg each, with two milking per day lasting between 1 and 2 hours totaling a production of 600 L/day of milk, adopting the intensive pasture production system.

The biodigester in question was built using low-cost materials, and has been operating continuously since 2017. The project of reference is contained in a booklet prepared by Diaconia Actaliança with the support of *Caixa Econômica Federal* "12 Steps to build a biodigester" [12]. The biodigester has the following components: inlet box, fermentation tank, gasometer, outlet box, water filter, steel wool filter and moisture drains, such as represented in Figure 1.

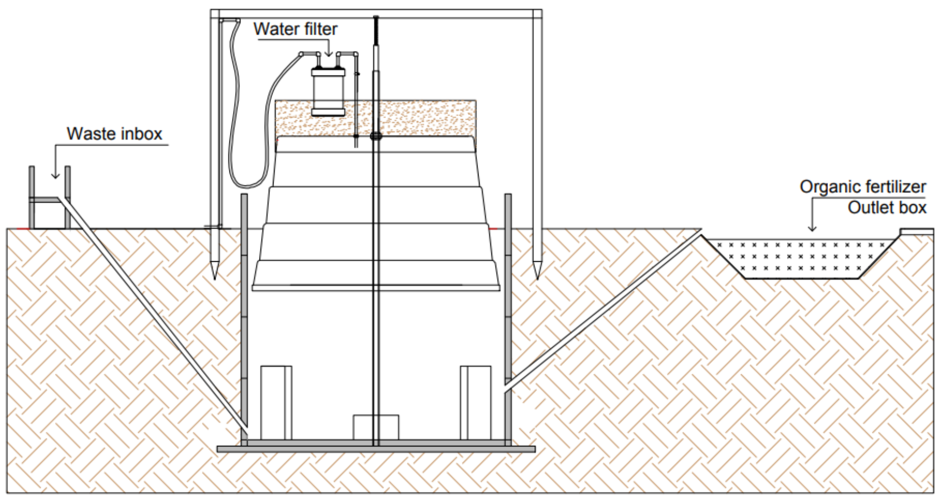

Figure 1. Practical scheme of the biodigester of the Indian type under study.

The analyses of this work took place in the winter (average temperatures between 13 ºC to 22 ºC) and spring (average temperatures between 16 ºC to 25 ºC), which were chosen to verify if there is a significant difference in the biogas composition due to the variation of room temperature and, consequently, biodigestion.

To use biogas, it is necessary to pressurize and filter it so that it reaches the point of consumption in good burning conditions. For this, the biodigester under study was wrapped with an aluminum belt (4.8 m x 0.5 m), covered with soil (approximately 0.26 m^3) and filters were installed to obtain a better biogas quality. A water filter (a tube with diameter of 200 mm and 35 cm of length) was located above the biodigester, as can be seen in Figure 1, which was responsible for reducing the content of ammonia (NH_3) and hydrogen sulfide (H_2S) just by forcing the biogas to pass through the water (approximately half of the volume of the filter filled with water). The second filter (a tube with diameter of 100 mm and 25 cm of length) was filled with steel wool filter (approximately 11.25 g), responsible for removing any residue of corrosive components, which could damage the biogas burner. In this filter, the biogas was forced through the steel wool. The disadvantage of using these filters is the head loss, which implies a considerable decrease in the pressure of the biogas in the pipeline to the point of consumption [12, 13, 14]. Between these two filters there were two drains in the biogas pipe, used to remove the remaining moisture in the biogas, which can condense in the pipe and end up accumulating inside the pipe, impairing its conduction. The drains were installed at the lowest points of the pipeline. There were derivations in the biogas line at the bottom that were submerged in a water tank to remove the condensate and not leak biogas. The distance between the biodigester and the point of consumption was approximately 55.4 m.

2.1. Production of substrate and digestate and quality of the substrate and digestate

The biodigester under study is fed intermittently, daily and only once a day, with a bucket of approximately 10 L of waste that is mixed with 10 L of water, following the ratio of mixture of waste and water of 1:1 in recommended volume by Cosmatri Filho [15] to ensure the normal flow of loading and unloading. To estimate the production of waste (MP, equation 1), the methodology of Campos [4] was used, where 8% to 11% of the animal's weight correspond to the production of waste per day. Due to the fact that the property's production system does not allow the recovery of all waste, equation 2 [16] was applied to obtain the hourly production of manure, relating the confinement time (*CT*) , number of animals (*N*) and hourly manure production (MP) to finally estimate the daily production of recoverable waste (*DPRW*) in the property.

$$MP = \frac{Average\ animal\ weight \times Average\ manure\ production\ per\ animal}{24} \quad (1)$$

$$DPRW = N \times CT \times MP \quad (2)$$

The production of organic fertilizer was estimated due to the biodigester feed, that is, the amount of waste that is added daily to the biodigester is equal to the amount of organic fertilizer that leaves it.

The organic fertilizer resulting from the digestion of the waste is sent to the storage tank, from where it is pumped for fertigation at a frequency of approximately once every two months, since the accumulated volume in that location varies with the occurrence of rains as it is open.

To evaluate the quality of the substrate and digestate samples of fresh manure (Sample 1), diluted manure (Sample 2) and organic fertilizer (Sample 3) were collected for further characterization in terms of total, volatile and fixed solids according to the methodology of Wilder et al. [17].

2.2. Biogas production, chemical and energetic characterization of biogas

The daily production of CH_4 (*PrM*) was estimated through the concentration of VS present in the samples of diluted waste, since it was the affluent substrate of the biodigester, multiplied by the amount of waste (*Q*) in kg/day and a conversion factor B_0 of 0.21 m³ of CH_4/kg of VS admitted in the study of Mito and collaborators [16] for dairy cattle manure, such as described in equation 3.

$$PrM = VS \times Q \times B_0 \quad (3)$$

To evaluate the pressure losses, speed and flow caused by the passage of the biogas through the water and steel wool filters, as well as the effects of the piping, a static Pitot tube (series 160, Dwyer Instruments Inc.) with 156 cm of total length, 19.5 cm long L-tip, with an outer tube diameter of 7.94 mm and tip with diameter of 3.18 mm, coupled to a Greenline MK2 flue gas analyzer (Eurotron Italiana S.r.l) was used. It determines the velocity of gases in ducts from the pressure differential measured. To do this, the instrument must be informed of the type of reference fuel among those contained in its database (natural gas was selected because it is the closest to biogas) and the density of the fuel. Three values of relative biogas density were considered: 1.03 kg/m³ (for composition of 75% CH_4 and 25% CO_2), 1.15 kg/m³ (for composition of 65% CH_4 and 35% CO_2) and 1.21 kg/m³ (for composition of 60% CH_4 and 40% CO_2), all values under normalized conditions of temperature and pressure (T=0 ºC and P=1 atm) [18]. The duct where the Pitot tube was inserted has an internal diameter of 15.87 mm and an external diameter of 20.87 mm. The measurements were performed in triplicate and at two different points: the first point of analysis was after passing through the water filter, located at the top of the biodigester (collection point A). The second collection point was located 4.5 m from the point of use of the biogas, which was 55.4 m from the biodigester (length of the pipe), where the steel wool filter (collection point B) was installed. The produced biogas is consumed in a four burner table top gas cooker, which operates with an adaptation in the burners (a bigger diameter of the hole through which flows the biogas due to the lower biogas pressure compared to the typical liquefied petroleum gas (LPG) pressure supplied by containers of 13 kg. The biogas flow was related to the average speed measured for the three biogas densities considered in the cross section of the duct (0.198 mm²) by Equation 4.

$$A = \frac{\pi D^2}{4} \quad (4)$$

The chemical characterization of biogas was obtained from the analysis carried out using a portable kit from Alfakit. The kit uses colorimetric indicator methods to determine the concentration of H_2S and NH_3 and a volumetric method to determine CO_2 and CH_4 concentrations. When the temperature at the time of analysis was different from 25 °C, the concentrations of NH_3 and H_2S were corrected according to the Alfakit manual. The Origin 6.1 software was used, one-way ANOVA function, with a significance level of 0.05 to statically analyze the results.

Biogas was characterized energetically in terms of Lower Heating Value (*LHV*) and Wobbe Index *(WI)*. The *LHV* of biogas was estimated from the stoichiometric combustion reaction (Reaction 1), as performed by Paim [19] from Hilsdorf [20], which is described in Equation 5.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (5)$$

$$LHV = hg \times \frac{G \times 1000}{22{,}4} \quad (6)$$

Where *LHV* is the Lower Heating Value (kJ/m³), *G* is the content of methane in the biogas in volume, *hg* is the enthalpy of combustion of methane (kJ/mol), this being equal to -802 kJ/mol at 25 °C and 1 atm [21]. The Wobbe index (*WI*) is defined by the quotient between the *LHV* and the square root of the gas density (ρ) and is expressed in (MJ/m³), as described in Equation 6.

$$WI = \frac{LHV}{\sqrt{\rho}} \quad (7)$$

2.3. Performance evaluation of the biodigester

In order to evaluate the performance in the operation of the biodigester under study, some parameters were analyzed to allow data comparison and also obtain information previously unknown for this model of biodigester. Thus, the following parameters were selected from Brasil [22].

The applied organic load (AOL), which corresponds to the mass of organic matter (VS) available per unit of time (kg/day). It is obtained by the product of the mass flow (Q) in (kg/day) by the concentration of organic matter present in the affluent substrate (S_0) in (kg/kg), according to Equation 7.

$$AOL = Q \ x \ S_0 \quad (8)$$

The biogas yield (A_{biogas}) corresponds to the amount of biogas generated from the available organic matter, given in m³/kg, which relates the daily flow of biogas (Q_{biogas}) in m³/day with the AOL in (kg/day) using the Equation 8.

$$A_{biogas} = \frac{Q_{biogas}}{AOL} \quad (9)$$

The biogas productivity (P_{biogas}) expresses the amount of biogas produced (Q_{biogas}) by the volume of the bioreactor (V_R) in m³, such as described by Equation 9. The biogas productivity is a comparative parameter for biodigesters.

$$P_{biogas} = \frac{Q_{biogas}}{V_R} \tag{10}$$

The efficiency in converting the available organic matter inside the biodigester can be described by Equation 10.

$$\eta_{Sub} = \frac{AOL_{in} - AOL_{out}}{AOL_{in}} \; x \; 100 \tag{11}$$

The available power expresses the amount of thermal or electrical energy available from the amount of biogas produced daily and its quality in terms of CH_4 quantity and lower calorific value, analyzed using Equation 11.

$$P_d = Q_{biogas} \times C_{CH4} \times LHV \tag{12}$$

3. Results and Discussion

3.1. Substrate and digestate production and substrate and digestate quality

Considering that the cows of the studied property have an average weight of 400 kg, the daily production of manure (manure + urine) was estimated to be 32-44 kg per animal per day, totaling a daily production of 1,088 kg to 1,496 kg. Considering the animals confinement time, the estimate of recoverable waste on the property is shown in Table 1.

Table 1. Estimate of the fraction of recoverable waste for different milking times and specific production.

Milking time	Milking number / day	Estimated waste with PE (8%)	Estimated waste with PE (11%)
1 h	2	90.66 kg	124.66 kg
2 h	2	181.33 kg	249.33 kg

In the property the daily feed of the biodigester is approximately 10 kg per day added to 10 kg of water, using the waste density for this work equivalent to that of water (approximately 1000 kg/m³), so only 11% were treated of the total waste produced during milking, considering the minimum value of 90.66 kg.

To treat the estimated minimum amount of waste (90.66 kg), at least eight more digesters of the same model and volume would be required, with the said efficiency, or another biodigester with greater capacity (of this or another model). However, in order to validate such estimates under study and for a precise determination, it is recommended to quantify the production of recoverable waste on the property and to deepen the studies carried out in this work.

The production of organic fertilizer in this work was estimated considering the biodigester feed, that is, the amount of waste added per day. The production of organic fertilizer approaches the value of the added substrate, a total of 20 L/day that are used in the fertigation of the pasture. This estimated value can vary due to the fact that the biodigestion process decreases the density of the substrate, resulting the digestate.

The analysis of the TS content in the substrate (Sample 1 and Sample 2) and digestate (Sample 3) was performed in triplicate and, and the analysis of the VS and FS content was performed in duplicate. The data obtained, mean and standard deviation (SD), can be seen in Table 2. The samples were collected in the spring season.

Table 2. Results of the analysis of total solids (TS), volatile solids (VS) and fixed solids (FS) of the samples of fresh manure, diluted manure 1:1 and organic fertilizer.

Identification	Parameter	Repetition			Mean and standard deviation
		1	2	3	
Sample 1 (fresh manure)	TS (%)	15.25	14.49	14.86	14.87 ± 0.38
	VS (%)	82.79	82.84	n.d.*	82.81 ± 0.04
	FS (%)	17.21	17.16	n.d.	17.19 ± 0.04
Sample 2 (diluted manure 1:1)	TS (%)	5.52	5.70	5.79	5.67 ± 0.14
	VS (%)	86.89	79.24	n.d.	83.07 ± 5.41
	FS (%)	13.11	20.76	n.d.	16.93 ± 5.41
Sample 3 (digestate)	TS (%)	1.36	1.48	1.61	1.48 ± 0.13
	VS (%)	75.74	72.83	n.d.	74.29 ± 2.06
	FS (%)	24.26	27.17	n.d.	25.71 ± 2.06

*n.d.: not determined

The content of TS found for the fresh manure was 14.87±0.38%, value close to the one reported by Brasil [23], 12.9% for dairy cattle manure with average weight of 450 kg. It is noticed that as the manure is diluted, the TS content decreases which explains the lower percentage of TS in the samples 2 and 3. Deganutti et al. [9] recomended TS content in the substrate lower than 8% for Indian type biodigesters. Given that the TS content found in Sample 2 was 5.67%, it is accordingly.

In the present study, the average VS content for the fresh (Sample 1) and diluted manure (Sample 1) were very close (82.81±0.04% and 83.07±5.41%, respectively) because it was the same sample, only the dilution was made in one of them. These values agree with the literature, given that Brasil [23] reported 80% of VS for dairy cattle manure and Comastri Filho [15] verified that the VS fraction in cattle manure varies from 80% to 85% in weight. To know the VS content of the substrate becomes essential to assess the potential of biogas production since it corresponds approximately to the fraction which undergoes fermentation. The reduction of the VS fraction indicates that the organic fraction of the biomass is being degraded during the biodigestion process [27], and the degree of conversion of the organic matter defines the efficiency of the process.

The biodigester under study showed a reduction in the VS content of 10.28%, being below the levels found in the literature (18.18% to 39.19%) [24, 25, 26] due to the constructive characteristics of the biodigester that do not favor the flow of organic matter within it. In Indian-type models, it is common to have a dividing wall in the fermentation tank to force a flow of organic matter inside the biodigester, however, the implementation of such wall did not occur in the construction of the biodigester under study, which may be the cause of little digested organic matter to leave the biodigester.

3.2. Biogas production, chemical and energetic characterization of biogas

The estimated production of CH_4 (*PrM*) with the current feeding routine in the biodigester was 0.20 m³ of CH_4 (equivalent to 202 L of CH_4). If the minimum amount of waste estimated (90.66 kg + 90.66 kg of water) was disposed of in the biodigestion system, the estimated production of CH_4 (*PrM*) would be 1.83 m³, equivalent to 1831.4 L of CH_4, an amount nine times greater than that estimated for the current routine, however, the biodigester under study would not process all this amount of waste.

The results of determining the pressure differential, speed and flow of biogas can be seen in Table 3, in terms of mean and standard deviation (SD), where ID A (first column) corresponds to the biogas sampling point located after the water filter located on the top of the biodigester and ID B corresponds to the second sampling point (B) located after the second filter, the steel wool filter, located about 4.5 m the point of biogas consumption.

Table 3. Results of pressure differential, speed and flow of biogas.

ID*	Density (kg/m³)	Parameter	1	2	3	Mean and standard deviation	Flow (m³/s)
A	1.03	ΔP (mmHg)	0.52	0.54	0.55	0.54 ± 0.02	0.0020
		Speed (m/s)	10.1	10.3	10.4	10.27 ± 0.15	
	1.15	ΔP (mmHg)	0.46	0.45	0.42	0.44 ± 0.02	0.0017
		Speed (m/s)	8.9	8.8	8.4	8.70 ± 0.26	
	1.21	ΔP (mmHg)	0.55	0.56	0.56	0.56 ± 0.01	0.0019
		Speed (m/s)	9.7	9.7	9.6	9.67 ± 0.06	
B	1.03	ΔP (mmHg)	0.18	0.19	0.2	0.19 ± 0.01	0.0012
		Speed (m/s)	6	6.1	6.3	6.13 ± 0.15	
	1.15	ΔP (mmHg)	0.17	0.19	0.19	0.18 ± 0.01	0.0011
		Speed (m/s)	5.6	5.8	5.8	5.73 ± 0.12	
	1.21	ΔP (mmHg)	0.19	0.17	0.16	0.17 ± 0.02	0.0011
		Speed (m/s)	5.5	5.3	5.2	5.33 ± 0.15	

ID* = measurement point identification

From the results shown in Table 3, it was clear the influence of of the biogas filters and of the length of the pipeline from the biodigester to the point of end use. A reduction of more than 50% in the differential pressure between points A and B was observed, from an average of 0.51 mmHg to 0.18 mmHg. Similarly, the biogas speed and flow also droped both approximately 60%.

However, it is clear that despite the significant reduction in pressure, speed and flow, this did not prevent the end use of the biogas, as the owner of the biodigester removed a pressure and flow reducer in two of the four burners in his table top gas cooker, which is needed when LPG is used.

The first biogas analysis took place in winter, with an average temperature of 18.5 °C, and the second in spring, with an average temperature of 27 °C, being carried out in triplicate. According to the temperature on the days of analysis, the concentrations of NH_3 and H_2S were corrected as a function of temperature according to the instructions of the analytical method applied. The results of the CO_2 and CH_4 concentrations remained reported at room temperature, but considering that in a same day the temperature varied due to the time of execution of the analyzes that was around 2 hours for each sampling point. In winter, samples identified as "A" were analyzed at a temperature of 16 °C, while samples "B" at 21 °C. In the spring, the temperature recorded for samples “A” was 26 °C, and for samples “B”, 28 °C.

Table 4 presents the results (mean and standard deviation) of the analysis of the biogas collected immediately after the water filter - samples A1, A2 and A3 - and the biogas collected after passing through the water filter and the steel wool filter - samples B1, B2 and B3.

Table 4. Results of biogas chemical characterization.

Identification	Sample	NH_3 [ppmV] at 25 °C	H_2S [ppmV] at 25 °C	CH_4 [%] at RT*	CO_2 [%] at RT
T_A = 16 ºC	A1	0	750	67.5	32.5
	A2	0	750	65	35
	A3	0	750	67.5	32.5
Winter	Mean and standard deviation	0 ± 0	750 ± 0	66.7 ± 1.4	33.3 ± 1.4
T_B = 21 ºC	B1	0	122.5	77.5	22.5
	B2	0	120	65	35
	B3	0	60	60	40
	Mean and standard deviation	0 ± 0	100.8 ± 35.4	67.5 ± 9.0	32.5 ± 9.0
T_A = 26 ºC	A1	0	152	75	25
	A2	0	152	70	30
	A3	0	230	77.5	22.5
Spring	Mean and standard deviation	0 ± 0	178 ± 96.3	74.2 ± 3.8	25.8 ± 3.8
T_B = 28 ºC	B1	15	235	75	25
	B2	0	235	80	20
	B3	0	310	80	20
	Mean and standard deviation	5 ± 8.7	260 ± 43.3	78.3 ± 2.9	21.7 ± 2.9

*RT: Room temperature

The average temperatures during the winter analyses were 18.5 °C and 27 °C in spring. The ideal range for the operation of a biodigester is between 30 °C to 35 °C, however, above 10 °C the biodigestion process already takes place, with biogas production [28].

It was observed that in the samples B1, B2 and B3 collected in the spring season, the production of CH_4 was higher, since at higher temperatures the speed of the biological reactions of the microorganisms is higher, resulting in a more efficient operation and a shorter detention time. The biodigestion process also occurs at lower temperatures, however, the efficiency decreases considerably, as can be seen in the samples obtained in the winter, when the temperature was below the value considered ideal, on average of 18.5 °C.

The concentration of CH_4 analyzed in the two seasons showed a significant difference when comparing the samples A and B collected in winter to the samples A and B collected in spring (F=10.52174 and p=0.00881), for significance <0.05. Likewise, the CO_2 concentration showed a significant difference (F=10.51174 and p=0.00881) between the different seasons, with reduced concentration as the temperature and the CH_4 concentration increased. Being methane the most energetic biogas component, a higher percentage of it is desired for greater calorific power and greater biogas application potential.

The concentrations of H_2S obtained during winter and spring did not differ significantly from each other (value of F=1.95891 and value of p=0.19188), not being influenced by the temperature. The H_2S concentrations varied greatly, which is believed to be due to the low accuracy of the applied method since wide ranges of concentration are used (colorimetric chart), and may have incurred wrong interpretations during the analysis. Although the values did not show a pattern, they are still within the limit range of 0 to 10,000 ppmV reported by Canever [13]. However, a new study with other analytical methods is suggested to obtain a more precise concentration for this biogas component. The concentration of NH_3 measured in this work was close to zero for all samples. Still according to Canever [13], concentrations higher than 100 ppmV would not be expected given the high solubility of NH3 in water, thus, being removed in the water filter.

To obtain the *LHV* value, a methane concentration of 72.9% (v/v) was used (average value between type B samples) as it corresponds to the measurement closest to the point of use (Point B). A *LHV* of 26.10 MJ/m³, equivalent to 6,238.95 kcal/m³ (at T=25 ºC and P=1 atm) was found in this study. The *LHV* can vary from 5,000 kcal/m³ to 7,000 kcal/m³ depending on the percentage of methane present in the biogas [29]. It was noticed that the biogas analyzed in this study had a *LHV* 43.7% lower than that of LPG (11,100 kcal/kg), therefore, a greater amount of biogas is needed to supply the demand met by LPG.

In this work, a Wobbe index of 25.72 MJ/m³ was obtained from Equation 6 when applying the LHV estimated and biogas density of 1.03 kg/m³ (for 75% v/v of CH_4 and 25% v/v of CO_2 at T=0 ºC and P=1 atm, according to Zilotti [18]. Combustible gases with the same Wobbe index will have the same energy performance, providing the same rate of heat transfer or energy power. Comparatively, the characteristics of LPG are observed, which is the most used in homes and is also used as backup gas in the property where the biodigester in study was installed, that the Wobbe index is about 2.8 to 3.4 times higher than in the biogas evaluated in this work. The negative point of this difference in the Wobbe index between these two combustible gases is that flaring equipment is adjusted only to the energy value of LPG, so the use of biogas is dependent on changes in flaring equipment, such as replacement of injectors, regulator pressure, registers, other components of the gas circuit and regulation of primary air intake, to keep the device's performance unchanged [30]. In the table top gas cooker used in the rural property of study, only the change in the nozzle was necessary.

3.3. Performance evaluation of the biodigester

The applied organic load (*AOL*) was found using Equation 7 and was obtained from the average amount of VS present in the analyzed samples of the affluent manure (diluted manure 1: 1) to the biodigester. The applied organic load was 0.94 kg of VS/day.

The biogas yield (A_{biogas}) was calculated using Equation 8 through the ratio between the estimated biogas flow for 30 minutes of daily use (Q_{biogas}=1.98 m³/day) and the applied organic load (*AOL*=0.94 kg of VS/day), resulting 2.10 m³/kg of applied VS. The estimated bioreactor volume (V_R) was 6.93 m³. The biogas productivity estimated using Equation 9 was 0.29 m³ of biogas/m³ of biodigester per day, equivalent to 0.21 m³ of CH_4/m³ of biodigester, a much higher value of productivity given that the estimate of CH_4 production carried based on the amount of manure currently treated was 0.20 m³ CH_4 per day, therefore the estimated biogas productivity would be 0.03 m³ CH_4/m³ of biodigester per day. In order to compare, the productivity value was multiplied by the average CH_4 content (72.9% v/v) found in the produced biogas to obtain the CH_4 productivity per kg of VS. The yield value obtained was 1.53 m³ of CH_4/kg of applied VS, a very high yield value when compared to the conversion factor (B_0) reported by Mito et al. [16] and used to estimate the CH_4 production, which was 0.21 m³ CH_4/kg of VS.

In order to calculate the fraction of degraded substrate described in Equation 10, in addition to the organic load applied to the biodigester (AOL_{in}), it was also necessary to estimate the organic load present in the effluent (AOL_{out}). The AOL_{in} and AOL_{out} data were taken from the waste characterization results, so that a substrate degradation percentage achieved was 76.65%.

Finally, the potential for thermal energy generation from biogas, estimated by Equation 11 when considering the biogas flow rate (Q=0.0011 m³/s), the CH_4 concentration (72.9% v/v=0.729) and the *LHV* (26.10 MJ/m³), an available power of 20.93 kW per day was obtained.

It is noteworthy that the fraction of substrate degradation of 76.65% is high when compared to the reduction in the content of volatile solids, which was 10.27%, due to the constructive characteristics of the biodigester as previously mentioned, which do not favor the flow of matter inside the biodigestion chamber. Thus, the digestate leaves the biodigester with lower *ST* content compared to the feed, however, with low reduction of organic matter (*VS*). Thus, to better treat the amount of waste inserted in the biodigester daily (10 L + 10 L of water), constructive improvements would be necessary to make the biodigestion process more efficient.

In order to treat the minimum amount of the dairy manure production estimated (90.66 kg), at least eight more digesters of the same model and volume would be needed, with the referred efficiency, or another biodigester with greater capacity (of this or another model). However, in order to validate such estimates under study and for a precise determination, it is recommended to quantify the production of recoverable waste on the property and to deepen the studies carried out in this work.

4. Conclusions

This piece of work becomes important in the context of decentralized bioenergy generation in the agricultural sector, especially in Brazil, where most of the agricultural and animal production comes from small properties. In fact, the demand for implementation of biodigestion systems is huge, however, many operational constraints still limit the biodigestion technology success and dissemination. And this may be related to the low level of monitoring and control of the biodigestion systems. Evaluating the results of the characterization of the samples of fresh manure, diluted manure and organic fertilizer performed in a rural property located in Southern Brazil, a reduction of around 10.28% in the VS content was obtained, proving that the organic fraction of the biomass was minimally degraded inside the biodigester.

From the assessment of the total amount of waste produced in the property, it was estimated that only 11% of the waste was treated via biodigestion. Thus, there is potential to increase the production of biogas if more waste goes through biodigestion. The biodigester currently has an estimated CH_4 production of 202 L/day. If more dairy manure was treated, this amount would be up to nine times higher, totaling 1,831.4 L/day of CH_4. The authors suggest, to confirm this estimate, a quantification of the waste in the study site for a more accurate analysis of the real need for the use of more biodigesters and a later proposition to complement the current biodigestion system.

The chemical characterization of biogas in different climatic seasons showed a significant difference in the concentration of CH_4, indicating that at higher temperatures, biogas production with higher energy content occurs. Although the biogas *LHV* was within the ideal range recommended by the literature, it was 43.7% lower than the liquefied petroleum gas *LHV*, representing a lower performance in its combustion.

Due to the constructive characteristics of the biodigester, its performance was considered inefficient. However, it produced biogas with a good chemical composition, making it possible to use it almost intermittently, with few changes in the domestic stove. There is also the possibility of converting biogas into bioelectricity to supply all or part of the demand of the rural property in question, especially considering the potential shown to increase current biogas production. However, a broader analysis must be carried out in this context, constituting an object of study for future works.

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References

[1] Embrapa, Anuário Leite 2019, Brasil, 2019.

[2] C. Bondan, Fatores que afetam a composição do leite bovino em rebanho sob controle leiteiro: enfoque epidemiológico e metabólico (PhD thesis), Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil, 2015.

[3] M. Y. Hirano and C. L da Silva, Análise da viabilidade do uso de biogás gerado a partir de dejetos bovinos em microturbinas para fins de geração, cogeração e trigeração de energia, X Fórum Ambiental da Alta Paulista, Bauru, Brasil, 2014.

[4] A. T. de Campos, Análise da viabilidade da reciclagem de dejetos de bovinos com tratamento biológico, em sistema intensivo de produção de leite (PhD thesis), Universidade Estadual Paulista, Botucatu, 1997.

[5] A. Colbella, Viabilidade do uso do biogás da bovinocultura e suinocultura para geração de energia elétrica e irrigação em propriedades rurais (MSc thesis), Universidade Estadual do Oeste do Paraná,

Cascavel, 2006.

[6] A. S. Reis, Tratamento de resíduos sólidos orgânicos em biodigestor anaeróbio (MSc), Universidade Federal do Pernambuco, Caruaru, 2012.

[7] D. S. Castanho and H. J. Arruda, Biodigestores, VI Semana de Tecnologia em Alimentos, Ponta Grossa, Brasil, maio, 2008.

[8] O. Konrad et al., Avaliação da produção de biogás e geração de metano a partir do lodo de estação de tratamento de efluentes e glicerina residual, Revista Destaques Acadêmicos, vol 4(2), pp. 49-55, 2010.

[9] R. Deganutti et al., Biodigestores rurais: modelo indiano, chinês e batelada, Encontro de energia no meio rural, Campinas, Brasil, 2002.

[10] Brasil. Cibiogás, Centro Internacional de Energias Renováveis. Sobre o biogás, 2019.

[11] A. R. Fonseca, Eficiência energética e a queima de combustíveis limpos (MSc), Instituto Superior de Engenharia do Porto, Porto, Portugal, 2009.

[12] Diaconia. 12 passos para construir um biodigestor, fundo Socioambiental Caixa, 2013.

[13] V. B. Canever, Estudo de filtragem do biogás para fins energéticos utilizando como método de filtragem lavador de gases de baixo custo (MSc thesis), Universidade Estadual do Oeste do Paraná, Cascavel, Brasil, 2017.

[14] G. S. Pereira, Implantação de um biodigestor de baixo custo em uma propriedade com criação de gado leiteiro (Undergraduate final project), Universidade Federal de Santa Catarina, Araranguá, Brasil, 2018.

[15] J. A. Cosmatri Filho, Biogás: independência energética do pantanal mato-grossense, Corumbá, Brasil, 1981.

[16] J. Y. L. Mito et al., Metodologia para estimar o potencial de biogás e biometano a partir de plantéis suínos e bovinos no Brasil, 2018.

[17] B. H. Wilder et al., 2540 Solids, In: Standard methods for the examination of water and wastewater, [s.l: s.n.]. pp. 55-61, 1997.

[18] H. A. R. Zilotti, Potencial de produção de biogás em uma estação de tratamento de esgoto de Cascavel para a geração de energia elétrica (MSc thesis), Universidade Estadual do Oeste do Paraná, Paraná, Brasil, 2012.

[19] J. V. Paim, Aplicação do biogás produzido a partir de dejetos de gado leiteiro como fonte alternativa de energia em uma queijaria (Undergraduate final project), Universidade Federal de Santa Catarina, Araranguá, Brasil, 2018.

[20] J. W. Hilsdorf, Química tecnológica (1st ed.), Cengage learning, São Paulo, Brasil, 2015.

[21] Universidade de São Paulo, Laboratório de química ambiental, combustão e energia, 2006. Available at:<http://www.usp.br/qambiental/combustao_energia.html>. Last accessed: 7 ago. 2019.

[22] Brasil, Secretaria Nacional de Saneamento Ambiental. Probiogás. Conceitos para o licenciamento ambiental de usinas de biogás / Probiogás; organizadores, Ministério das Cidades, Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ); autores, Felipe Correa de Souza Pereira Gomes [et al.]. - Brasília, DF: Ministério das Cidades, pp. 147, 2016.

[23] Brasil, Ministério da Agricultura, Pecuária e Abastecimento. Pecuária de baixa emissão de carbono: Tecnologias de produção mais limpa e aproveitamento econômico dos resíduos da produção de bovinos de corte e leite em sistemas confinados. Secretaria de Mobilidade Social, do Produtor Rural e Cooperativismo. 2018.

[24] C. M. C. Amaral et al., Biodigestão anaeróbia de dejetos de bovinos leiteiros submetidos a diferentes tempos de retenção hidráulica. Ciência Rural, Santa Maria, vol 34(6), pp. 1897-1902, dez. 2004.

[25] C. F. Matos, Produção de biogás e biofertilizante a partir de dejetos de bovinos, sob sistema orgânico e convencional de produção (MSc Thesis), Universidade Federal Rural do Rio de Janeiro, Seropédica, Brasil, 2016.

[26] A. J. Fernandes, Variáveis microbiológicas e físico-químicas em biodigestores anaeróbios escala piloto alimentados com dejetos de bovinos leiteiros e suínos (MSc thesis), Universidade Federal Juiz de Fora, Juiz de Fora, Brasil, 2016.

[27] S. L. C. D. Junqueira, Geração de energia através de biogás proveniente de esterco bovino: estudo de caso na fazenda aterrado (Undergraduate final project), Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brasil, 2014.

[28] L. A. H. Nogueira, Biodigestão: a alternativa energética, Nobel, São Paulo, Brasil, 1986.

[29] R. D. Oliveira, Geração de energia elétrica a partir do biogás produzido pela fermentação anaeróbia de dejetos em abatedouro e as possibilidades no mercado de carbono, Universidade de São Paulo, São Carlos, Brasil, 2009.

[30] Associação Brasileira de Normas Técnicas, NBR 13723: aparelho doméstico de cocção a gás. parte 1: desempenho e segurança. Rio de Janeiro: ABNT, pp. 58, 2003.

Biographical information

Fábio Nuernberg is a graduate student in the Energy Engineering course at the Federal University of Santa Catarina, Brazil. Participated in projects of the Association Technique without Borders Brazil (TsF) for two years, working in the study group on low cost biodigesters.

Kátia Cilene Rodrigues Madruga has Doctorate in Business Administration with focus on social and environmental issues (University of Bremen, Germany), developed post-doctorate projects with the Hohenheim University, Stuttgart, Germany and the Institute of Energy Economics and Rational Energy Use of the University of Stuttgart. She is currently a Lecturer at the Federal University of Santa Catarina, Brazil, working at the Department of Energy and Sustainability, Energy Engineering course and director of Association Technique without Borders Brazil (TsF), Araranguá-SC-Brazil group.

Elaine Virmond is a Food Engineer with a Master and a Doctorate in Chemical Engineering. She has spent five months working with the "Combustion, Gasification and CO_2 capture group", Department of Chemical Engineering and Chemical Technology, Imperial College, London, doing research as part of her doctorate. She has worked for Embrapa Agroenergy, the energy section of the Brazilian Agricultural Research Corporation - Embrapa (November 2010 to July 2013) and is currently a Lecturer at the Federal University of Santa Catarina, Brazil, working at the Department of Energy and Sustainability, Energy Engineering course.