19th Brazilian Congress of Thermal Sciences and Engineering
November 06th-10th, 2022, Bento Gonçalves - RS - Brazil

ENC-2022-0485
LIFE CYCLE ASSESSMENT OF BIOGAS PRODUCTION FROM DAIRY COW MANURE ON A BRAZILIAN FARM

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Abstract. *The use of biogas can offer substantial savings in waste management due to its high energy potential. It shows the importance of delineating alternatives that enable the use of biogas in Brazilian territory. Therefore, a Life Cycle Assessment (LCA) of biogas from dairy cow manure was developed ainmed to map the enhancements in biogas utilization. This study uses a combination of primary and secondary data to model the biogas production processes, with a functional unit of 1 Nm^3 of compressed biogas ready for electricity generation or biomethane generation. The plant is supplied with 3160 kg of manure, yielding 186 Nm^3 of biogas. The production, management, pretreatment, anaerobic digestion, biogas cleaning, and manure compression were considered. So, the Life Cycle Inventory Analysis (LCIA) results show 0.281 kg Eq. of CO_2 for the Global Warming Potential category, 6.21E-4 kg Eq. of SO_2 for the Acidification Potential, and 8.23E-5 kg Eq. of Phosphate for the Eutrophication Potential. The processes of electricity supply and anaerobic digestion of manure strongly influence the LCIA results, indicating the requirement of alternatives to mitigate the impacts of these operations.*

Keywords: *life cycle assessment (LCA), biogas, manure, electricity.*

1. INTRODUCTION

Excessive use of non-renewable resources leads to negative impacts that affect the environment and directly contribute to greenhouse gas emissions (Esteves et al., 2019). It's a global problem that highlights the requirement to develop technologies that incentivize the utilization of renewable sources. The service and production of biofuels has proven to be an attractive alternatives, due to the reduced environmental impacts with the conventional use of fossil fuels.

Obtained by the anaerobic decomposition of organic matter, biogas is a biofuel with high energetic potential, becoming an environmental strategic that combines the use of waste and its application as an energy source. Of the several types of feedstocks for biogas production, the most common are animal manure, organic waste, sewage sludge, lignocellulosic materials, and energy crops (Parsaee et al., 2019).

Agricultural activities play an important economic and environmental role since the country is one of the largest exporters of animal protein, Brazil. However, there is still a necessity to correctly manage the residues of this production. The inclusion of anaerobic digestion of animal manure for biogas is a very promising path in terms of financial savings and the reduction of environmental impacts (Hollas et al., 2022).

For biogas generation, anaerobic bacteria decompose organic matter by the following stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The biogas produced is mainly composed of CH_4 (60%) and CO_2 (40%), also contains other components such as hydrogen (H_2), oxygen (O_2), ammonia (NH_3), hydrogen (H_2S), and other impurities depending on the feedstock (Aziz et al., 2019; Bragança et al., 2020).

Before being used as an energy resource, the biogas must be cleaned by filtration processes to remove excess humidity and other chemical components, such as H_2S. As the presence of such elements can cause damage to the biogas-to-energy conversion equipment (Wellinger et al., 2013). In addition, if the biogas is destined for use as vehicle fuel, it still has to go to a process called “upgrade” where the methane content is enhanced, and the carbon dioxide content is reduced (Starr et al., 2012). Among the different types of upgrade, the most discussed in the literature are based on chemical, physical and biological principles, with membrane and pressure swing adsorption units being the most frequently used (Angelidaki et al., 2018).

However, decisions concerning the sustainability of biogas production are challenging from an environmental and economic perspective, requiring specific mapping of each input and process involved. The reuse of biogas, and the estimation of its environmental impacts, are the principal challenge to solve to achieve its sustainability and insert it in the energy mix (Pérez-Camacho et al., 2019).

In this framework, the Life Cycle Assessment (LCA) methodology has been highlighted as an advantageous option to characterize how the environmental impacts of biogas production affect the quality of the environment. LCA is a methodology that focuses on describing the environmental aspects of a product's life cycle, using data from flows. of materials and resources needed to describe the processes involved in obtaining, even end-of-life (ISO, 2006a). It is organized into steps that provide an organized map of each piece of information relating to a production system. These steps are the definition of the purpose and scope of the product/system under analysis; the preparation of the Life Cycle Inventory (LCI); the Life Cycle Impact Assessment (LCIA), and the interpretation of the results (ISO, 2006b).

In biogas plants, LCA enables environmental analysis of the production system and the development of new strategies and technologies to increase production efficiency, encompassing product disposal and end-use. An intrinsic feature of LCA studies is the creation of alternative scenarios that allow comparisons between them, making it easy to identify aspects that interfere with environmental impacts. Based on this, scenario modeling can address, for example, the different ways of using biogas, covering the diversity of processes and inputs involved, motivating and allowing comparisons among such aspects (Klopffer & Grahl, 2014).

In the present study, a "cradle-to-grave" LCA of biogas production was performed on a farm with dairy cattle activities to describe and compare the environmental impacts of delivering 1 Nm³ of dry and desulfurized biogas. The development of the LCA was aimed at answering the following research questions: How can the production of 1 Nm³ of biogas from dairy cow manure on this farm impact the environment from the point of view of GHG emissions? Which production stages generate the most GHG emissions? What major improvements can be adopted to mitigate GHG emissions from on-farm biogas production?

2. METHODOLOGY

For the development of the Life Cycle Assessment (LCA) of biogas production on the farm, the recommendations provided by ISO 14040/14044 (ISO, 2006a, 2006b) were followed, covering the following steps: definition of objectives and scope, preparation the Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and, finally, the interpretation of the results. Based on these recommendations and using the GaBi Education software, version 9.2.1.68 (Thinkstep, 2022), the LCA phases of biogas production on a Brazilian farm were modeled. It is an attributional LCA that can provide data for decision-making policies and the Brazilian database.

2.1 Goal and scope definition

This study aims to carry out an LCIA of biogas production from cow manure in a dairy farm to characterize and identify points of improvement in biogas production and increase its application for energy purposes. The LCA was performed by combining primary data collected on a Brazilian dairy farm (Saia Velha farm, located in Luziânia, Goiás, Brazil) and secondary data collected from the available literature. The functional unit of the study was 1 Nm³ of cleaned biogas at the gate of the biogas plant. The system boundaries were adopted as illustrated in Figure 1.

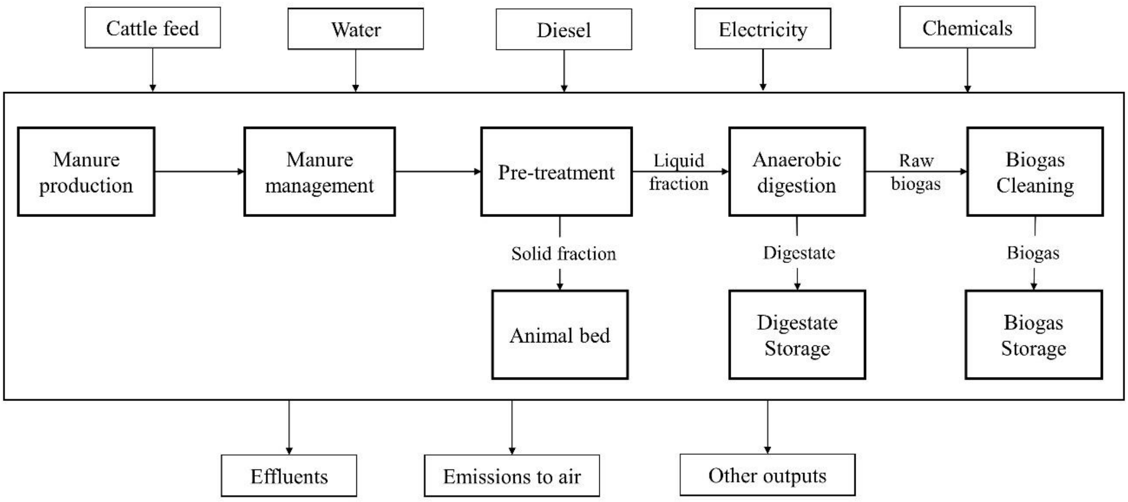

Figure 1 - Biogas production in Saia Velha farm flowchart

2.2 System description

Fazenda Saia Velha develops agricultural activities, with milk production being the main activity carried out on the farm. The herd comprises 93 dairy cows in confinement, producing about 34 kg of manure per animal daily. For biogas production, the farm has an anaerobic lagoon-type digester with agitation with a capacity of 1576 m³ of liquid and 771.1 m³ of biogas, with a hydraulic retention time of 40 days, and is supplied daily with dairy manure. Therefore, the daily production of biogas on the farm is 186 Nm³, with the main objective of reusing biogas to generate electricity, which will be used to supply some of the farm's dependencies, replacing that provided by the network.

In a cradle-to-gate approach, system boundaries comprise six main processes, illustrated in Figure 2: manure production, manure management, pre-treatment, anaerobic digestion and biogas cleaning. The main objective is the production of 1 Nm³ of compressed biogas at the farm gate to be used both to generate electricity and for other purposes.

Figure 2 – Installations where biogas is produced in Saia Velha farm: A) manure storage and collection yard; B) manure homogenization tank; C) pre-treatment with mechanical separator engine; and D) anaerobic lagoon biodigester.

The system boundaries do not cover the production of inputs related to cattle feeding, electricity, diesel, water, and chemical products. Both are auxiliary processes that were imported from the GaBi database. The machinery and transport carried out inside the plant, as well as the construction and installation phase of the plant, were also not considered, as they have an almost insignificant contribution to the environmental impacts of the plant's production, as shown in (Ioannou-Ttofa et al., 2021; Singh et al., 2020). Next, each of these steps will be described to better understand the processes developed and accounted for in the elaborated LCI.

2.2.1 Manure production

In the manure production process, it is considered that dairy cattle under confinement receive a feed consisting of pure corn, corn silage, soybean meal, vitamin concentrate, and water, modeled according to data available in the literature, focusing on the production of quality milk (Assunção, 2020; Campos, 2000). In this phase, CH_4 emissions related to the enteric fermentation process are considered and calculated following the Intergovernmental Panel on Climate Change Guidelines (IPCC, 2006). The main product of this phase is the manure generated by the cattle, which is stored in the cattle feeding yard until the manure management.

2.2.2 Manure management

This phase describes the first step on the farm, which the animal manure is considered as raw material for biogas production. Manure is collected by washing the yard with water jets with the aid of a 7.5 HP diesel tractor. The mixture is channeled and sent to the homogenizing tank, where it is mixed and pumped. This process is repeated until a considerable volume is reached in the homogenizer tank. The inputs in the LCI of this phase are the diesel used by the tractor, electricity used by homogenizing tank, and the water used to wash the yard comes from a stream lake close to the farm.

2.2.3 Pre-treatment

The pre-treatment process is the mechanical separation of the solid and liquid parts of the manure mixed with washing water. The solid part is used as an animal bed and the liquid part (slurry) is channelized and injected into the biodigester to produce biogas. Based on the literature (Hamelin et al., 2010), it was assumed that the separator motor is of the screw press type.

2.2.4 Anaerobic digestion

The biodigester receives the liquid fraction of the mixture, also called slurry, and besides specific conditions, the anaerobic bacteria produce biogas. Favorable conditions for biogas production are the mesophilic temperature (ranging from 35 to 42ºC) and pH of 6 to 7.5. On the farm, the anaerobic lagoon-type digester, with a hydraulic retention time of 40 days, receives the mixture and produces biogas and digestate. Table 1 listed the biogas chemical composition, and for modeling purposes, data from the literature were adopted (Ardolino et al., 2018; Hamelin et al., 2010).

Table 1. Biogas composition.

Raw biogas composition, % vol	
CH_4	50.83
CO_2	44.59
H_2S	0.01
N_2	0.38
O_2	0.10
NH_3	<0.01
H_2O	4.09
Properties	
Lower heating value	18.2 MJ/Nm³
Density	1.158 kg/Nm³

As biogas is not the only output of the process, digestate production was also considered. It is composed of nitrate, phosphorus, and potassium, which gives it the possibility of being reused as a field fertilizer. On the farm, the digestate is stored for a certain period is applied as field fertilizer. The environmental impacts of digestate use are not considered in the present LCA.

2.2.5 Biogas cleaning and compression

Before the biogas is sent to its destination, the amounts of H_2S and H_2O in raw biogas must be removed to avoid problems such as corrosion and damage to equipment for biogas reuse. In addition, the presence of some components in excess can result in unwanted emissions from the combustion of biogas in engines (Wellinger et al., 2013). Therefore, an activated carbon-based filter was modeled based on literature data (Jungbluth & Chudacoff, 2007), that removed 100% of water and 95% of the H_2S present in the raw biogas. After removing these impurities, the biogas is compressed and piped, ready to be sent to the chosen purpose, either directly in the cogeneration engine or for the upgrading process.

2.3 Life Cycle Impact Assessment

In the Life Cycle Impact Assessment (LCIA), the main objective is the classification of the environmental impacts of each process described in the product system's LCI. To characterize the environmental impacts of biogas production, focusing mainly on the estimative of greenhouse gas emissions, the CML 2001 software (January 2016) was used in the GaBi software as a method for the LCIA. According to ISO 14044, the mandatory steps in an LCIA are selecting the impact categories and characterization methods, classification of the results in impact categories, and results from calculation with indicators factors. In this regard, the present study evaluated the following impact categories: global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP).

2.4 Life Cycle Inventory

The life cycle inventory (LCI) comprises the elementary flows of mass and energy that are used as inputs and outputs of the processes involved in the life cycle of a product (ISO, 2006a). The data source can be of primary or secondary sources, and the data obtained in this phase of the LCA will be the basis for the next step, the LCIA. Table 12 shows the LCI of biogas production on Saia Velha farm.

Table 2. Life Cycle Inventory of biogas production. Data for 1 Nm³ functional unit of filtered biogas.

	Unit	**Quantity**	**Origin**	**Source**
Process 1 – Manure production				
Inputs				
Corn silage	kg	4.70	Literature	(Assunção, 2020)
Corn pure	kg	1.00	Literature	(Assunção, 2020)
Soybean meal	kg	0.64	Literature	(Assunção, 2020)
Vitamin concentrate	kg	0.08	Literature	(Assunção, 2020)
Water	kg	10.67	Literature	(Campos, 2000)
Outputs				
Manure	kg	17.00	Measured	-
Emissions to air				
CH_4	kg	0.09	Literature	(IPCC, 2006)
Process 2 – Manure management				
Inputs				
Manure	kg	17.00	Measured	-
Electricity	kWh	0.02	Measured	
Diesel	kg	0.05	Measured	
Water	kg	43	Measured	
Outputs				
Dry manure	kg	60.03	Measured	
Emissions to air				
CH_4	kg	0.002	Literature	(IPCC, 2006)
Process 3 – Pre-treatment				
Inputs				
Dry manure	kg	60	Measured	
Diesel	kg	0.007	Measured	
Electricity	kWh	0.016	Literature	(Hamelin et al., 2010)
Outputs				
Animal bed	kg	6.007	Measured	
Slurry	kg	54	Measured	
Process 4 – Anaerobic digestion				
Inputs				
Slurry	kg	54	Measured	
Electricity	kWh	0.0081	Measured	
Outputs				
Raw biogas	Nm³	1.05	Calculated	

Digestate	kg	52.7	Calculated	
Emissions to air				
CH_4 emissions	kg	0.0038	Literature	(Hamelin et al., 2010)
CO_2 emissions	kg	0.0054	Literature	(Hamelin et al., 2010)
Process 5 – Biogas cleaning				
Inputs				
Raw biogas	Nm³	1.05	Calculated	
Activated carbon	kg	0.001	Literature	(Jungbluth & Chudacoff, 2007)
Electricity	kWh	0.0027	Literature	
Outputs				
Biogas	Nm³	1	Measured	
Wastewater	kg	0.765	Literature	(Ardolino et al., 2018)
H_sS removed	kg	0.00177	Literature	(Ardolino et al., 2018)
Process 6 – Biogas Compression				
Inputs				
Biogas	Nm³	1	Measured	
Electricity	kWh	0.23	Literature	(Shinde et al., 2021)
Outputs				
Compressed biogas	Nm³	1	Measured	

In the first process, manure production, the environmental impacts related to the production of the cattle feed inputs were not considered. For simplification purposes, it was assumed that the entire amount of feed consumed by the cattle was transformed into manure. Therefore, the only environmental impacts considered are methane emissions from the enteric fermentation process, which, as well as methane emissions from manure management, were calculated according to the IPCC methodology (IPCC, 2006).

In the pre-treatment phase, emissions related to this process were not considered due to the unavailability of such data. In the modeling of the anaerobic digestion process, the calculation of emissions to air was according to the methane composition of the biogas produced, as described in (Hamelin et al., 2010), in which it is 1% of the CH_4 content existing in biogas is emitted into the air, that is, as fugitive methane. The CO_2 emission is also calculated using a ratio of 1.47 kg of CO_2 per kg of CH_4 emitted. In modeling, the H_2O and H_2S removal from biogas, the data from the literature were used to estimate the amount of activated carbon used in the process and its removal efficiency (Ardolino et al., 2018; Jungbluth & Chudacoff, 2007). Finally, the compression of biogas ready to be sent for use was accounted for, also counting on electricity data extracted from the literature (Shinde et al., 2021).

3. RESULTS AND DISCUSSION

3.1 Overview of LCIA

The LCIA results of biogas production are listed in Table 3 for each selected impact category and according to each process. Among the distribution of environmental impacts referring to some processes involved in the LCA of biogas production, some impacts were associated with the supply of inputs such as electricity, diesel, water, activated carbon, and wastewater treatment. Therefore, it was chosen to express the environmental impacts in terms of the supply of these inputs, except for some processes. Therefore, the environmental impacts of these processes will be described through the provision of these inputs and the processes mentioned as available parts of the LCIA carried out.

In general, the adoption of anaerobic digestion as a waste management option in agricultural production had low environmental impacts compared to other management options, such as incineration and storage. The values found are similar to those shown in related literature (Garfí et al., 2019; Ramírez-Arpide et al., 2018), confirming that biogas production is an environmentally friendly alternative.

Significant reductions in environmental impacts are demonstrated when biogas production systems are implemented on small farms, with up to 5 times smaller reductions in emissions, comparing scenarios where only waste incineration occurs (Garfí et al., 2019). This is mainly because by anaerobic digestion, the waste is transformed into two value-added by-products (biogas and digestate), in addition to causing reductions in GHG emissions (Hollas et al., 2022) Among the sources of environmental impacts described in biogas plants, the most frequent are the open storage of manure, transport carried out during production, the use of electricity, and fugitive methane emissions (Tonini et al., 2016). In the present case, it was no different, where the GWP impact category was the one where the environmental impacts were much higher compared to the AP and EP categories, with EP having the lowest value among the three. The majority of sources of environmental impacts from biogas production are attributed to CH_4 emissions, resulting from the anaerobic digestion of manure and the use of electricity, the latter being the process that most contributed to the environmental impacts of the farm.

Table 3. LCIA results for biogas production in Saia Velha farm for 1 Nm³ of compressed biogas produced.

Process	GWP (kg de CO_2 Eq.)	GWP (%)	AP (kg de SO_2 Eq.)	AP (%)	EP (kg de Phosphate Eq.)	EP (%)
Electricity supply	0.091	32.39 %	5.19E-4	83%	5.23E-5	64%
Manure management	0.061	21.83 %	-	-	-	-
Diesel supply	0.009	3.37 %	9.6E-5	15.83%	2,04E-5	29%
Anaerobic digestion	0.111	39.80 %	-	-	-	-
Carbon black use	0.002	0.84%	5.14E-6	0.82%	1,86E-7	0,23%
Waste water treatment	-	-	3.01E-8	0.0048%	1,99E-7	0,24%
Water use	0.004	1.76%	7.26E-6	1.16%	5,57E-6	7%

3.2 Global Warming Potential

The Global Warming Potential (GWP) reflects and translates air emissions of gases such as CH_4, CO_2, N_2O to the environment, in which the characterization of these emissions is done with the factor of equivalence of kg CO_2 Eq. Thus, the environmental impacts from the emission of these gases are quantified on a time scale of 100 years, representing the impact that such emissions can have on climate change. Figure 3 shows the distribution of the GWP according to the processes involved in biogas production at Saia Velha Farm.

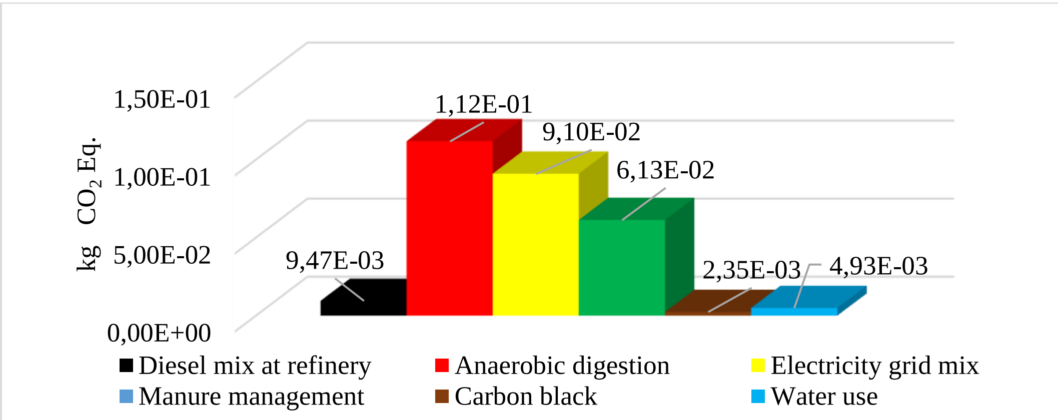

Figure 3 – Global Warming Potential impact of biogas production on Saia Velha Farm.

The processes that most contribute to GWP are anaerobic digestion, electricity use, and manure management, processes in which CH_4 emissions to are accounted for. In the anaerobic digestion process, 0.106 kg of CH_4 /Nm³ of filtered biogas is emitted together with CO_2 emissions also from the process represent 39.8% of GWP emissions. The main reason for such values is the fugitive emissions of CH_4 that occur during biogas formation and must be accounted for using average values, which in the present case was 1%. The high environmental impact associated with electricity use, which mostly corresponds to the CO_2 emissions that occur during the production of electricity in the Brazilian mix. It should be noted that the database provides the electricity supply process according to the various sources in the country, which mostly come from non-renewable resources.

3.3 Acidification Potential

The emissions that most influence the Acidification Potential category are gases such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which cause environmental effects, mainly acid rain. The characterization factor used to quantify the environmental impacts generated by the emission of these gases is the kg of SO_2 Eq. In the LCA of biogas production, the distribution of impacts caused in each inventoried process is shown in Figure 4.

The total AP impact for biogas production on the farm is 6.27E-04 of SO_2 Eq./Nm³ of biogas produced, where the processes that contributed the most were the supply of electricity and diesel, which correspond to 93% of the total impacts in this category. Electricity consumption stands out as the major source of AP impacts, mainly due to SO_x emissions from the burning of fossil fuels for electricity generation, which correspond to the principal source of electricity in the Brazilian mix. In short, the high contribution to the AP category reported in similar studies is due to the open storage of manure, which causes an increase in ammonia (NH_3), methane (CH_4,) and nitrous oxide (N_2O) emissions to the air, that is, the adoption inadequate waste management techniques (Gopal et al., 2020; Hamelin et al., 2011).

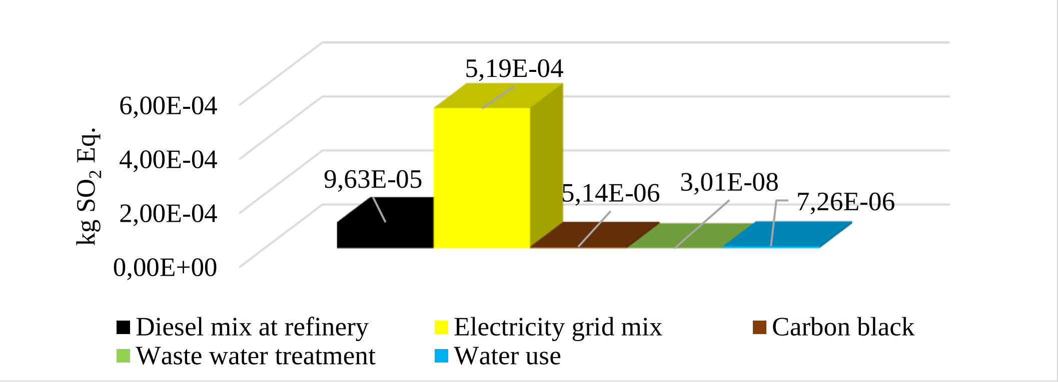

Figure 4 – Acidification Potential impact of biogas production on Saia Velha Farm.

Despite the impacts associated with the supply of electricity to the operation of the plant, the AP values obtained here were significantly lower when compared with similar systems (Tian et al., 2021), where 0.0046 kg of SO_2 Eq./Nm³ of biogas, compared to 6.27E-04 kg of SO_2 Eq./Nm³ of biogas obtained in the present study. The main difference between the two studies is that consider the environmental impacts of the use of digestate as a biofertilizer on the soil, which also contributes to this impact category (Tian et al., 2021).

3.4 Eutrophication Potential

The EP impact category is the one where the effects of nitrification on the environment will be represented, in which the emissions of gases such as nitrogen dioxide (N_2O), ammonia (NH_3), and nitrogen oxides (NO_x) will be shown. Generally, these emissions come from atmospheric pollution, wastewater, and inorganic fertilizers use and are calculated in kg of Phosphate Eq. Figure 5 demonstrates how the LCA processes of producing 1 Nm³ of biogas influence this impact category.

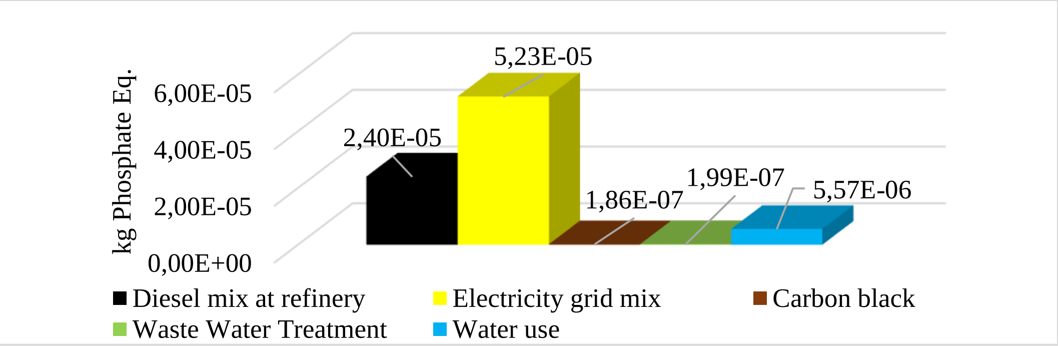

Figure 5 – Environmental impacts of biogas production on Saia Velha Farm, according to the Eutrophication Potential category.

The total impact referring to the EP category is 8.23E-05 kg of Phosphate Eq./Nm³ of biogas produced, which is mainly due to the diesel and electricity use in the plant's processes. As in the AP, the low values obtained for EP indicate biogas production as advantageous from an environmental impact perspective. When evaluating the environmental impacts of the operational phase of a small plant similar to the present study (Ioannou-Ttofa et al., 2021) obtained for the EP impact category 6.56E-4 kg of Phosphate Eq./Nm³ of biogas, which is mainly due to the production of manure. At this phase, the environmental impacts of the production of inputs necessary for cattle feeding, such as fertilizers and pesticides, which are items that directly impact this impact category, are accounted for. Additionally, a plant item that could have high environmental impacts in EP and AP would be the applying the digestate to the soil as a biofertilizer, that is, considering it as a use of the effluents of biogas production (Tian et al., 2021).

4. CONCLUSIONS

The biogas production was proved by LCA to be an environmentally friendly technique, given the values of environmental impacts obtained in each category analyzed. Among the life cycle phases that most contributed to the impact categories, the anaerobic digestion phase was the one with the highest values, due to fugitive methane emissions, in the GWP category. Another particularity of the process that strongly impacted the results in all impact categories was the supply of electricity by the Brazilian mix because its products are derived from fossil sources, causing emissions that directly influence the impacts of the greenhouse effect. To improve GHG emissions it is proposed to add the environmental impacts related to the use of digestate as a biofertilizer and its application in the soil, and mainly, to add the process of generating electricity from the biogas as an alternative to mitigate the plant's electricity supply.

5. ACKNOWLEDGMENTS

The authors thank to the Saia Velha farm, Luziânia/GO/Brazil for providing their data to carry out this study, to CNPq and Fundação de Desenvolvimento da Pesquisa – FUNDEP Rota 2030/Linha V *27192.01.01/2020.06-00* for financial support.

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