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# LIFE CYCLE IMPACT ASSESSMENT OF DIFFERENT SCENARIOS FOR BIOGAS USE IN INTERNAL COMBUSTION ENGINE

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***Abstract.*** *Although biogas is an alternative to fossil fuels from an environmental, and economic social point of view, there are some challenges to incorporating it into the Brazilian context. Therefore, to increase the employability of the biogas obtained from cattle manure on a Brazilian farm, a Life Cycle Assessment (LCA) was carried out, adopting 1 MJ of energy as a functional unit. Three different scenarios including upgrading technologies are proposed: Scenario 1 – Pressure Swing Adsorption; Scenario 2 – Membrane Separation; Scenario 3 – High-Pressure Water Scrubbing. The Life Cycle Impact Assessment (LCIA) phase used the CML 2001 method, adopting the Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) impact categories. As a result, the PSA upgrade, used in scenario 1, has the most impact on GWP, considering that this technology has the highest $CO_2$ emissions. Overall, the technologies employed in scenarios 2 and 3 had similar environmental impacts in AP and EP. The biogas production phase played a significant role in all scenarios due to emissions associated with farming methods. However, different upgrade techniques have been shown to have even lesser impacts than using them to generate electricity, which is generally the most common application for biogas.*

***Keywords:*** *biogas, life cycle assessment, biomethane, upgrading technologies, environmental impacts.*

## 1. INTRODUCTION

The use of biofuels has been presented as an advantageous alternative for reducing the environmental impacts caused by excessive fossil fuel use. However, technological, economic and logistical challenges still hinder the transition from non-renewable sources to the production and use of these biofuels (Scholz et al., 2013).

Biogas is inserted in this context as an attractive option with chemical and combustible characteristics similar to natural gas (Atelge et al., 2021), and with a sustainable production process based on the anaerobic digestion of substrates such as animal manure (Ioannou-Ttofa et al., 2021), organic waste from different sources (Khandelwal et al., 2019; Patterson et al., 2013), and even energy crops (Cidades, 2016; Papong et al., 2014). Biogas production has significant importance for circular bioeconomy development because it is an efficient strategy for reducing environmental impacts and adds extra value to the products obtained (biogas and digestate) from waste utilization (Fagerström et al., 2018; Feng et al., 2023).

Depending on the raw material and the production technologies employed, biogas can be mainly composed of 50–75% methane ($CH_4$), 25–50% carbon dioxide ($CO_2$), and still presents around 1–2% of nitrogen oxides ($NO_X$), hydrogen (0–1%), hydrogen sulfide (0–2%) and oxygen (<1%) (Bragança et al., 2020; Francini et al., 2019). Its chemical composition enables a variety of practical applications for biogas, such as its use for cogeneration of electricity and heat (Wang et al., 2021), as an alternative to liquefied petroleum gas (LPG) (Garfí et al., 2019), or as a vehicle fuel (Natividad Pérez-Camacho et al., 2019), after undergoing a process to “upgrade”. After the upgrade, the methane content increases and the impurities are removed, allowing to use biogas as a biofuel in vehicles. The biomethane obtained has characteristics such as high methane ($CH_4$) concentration (97-99 $\%_{vol}$), a high octane rating, and high ignition temperature, making it an attractive option as a vehicular fuel, replacing the traditional fossil fuels commonly used for this application (da Costa et al., 2020; Yoon & Lee, 2011).

In Brazil, although the excellent development of biofuels, such as biodiesel and bioethanol, difficulties are still faced regarding biogas application. Brazil has a capacity of 417.20 MW of energy from biogas, from 811 plants, with an annual production of 2.83 billion $m^3$/year (CIBIOGAS, 2023; IRENA, 2021). Of the total number of existing biogas plants in Brazil, only 13 accounts with the upgrading techniques for biomethane production in 2023, producing the equivalent of 559.61 million $m^3$/year of biomethane, with the potential to replace the use of 405.23 thousand liters of diesel per day (CIBIOGAS, 2023). This low biomethane production becomes a significant barrier to popularizing biogas as a vehicular fuel, mainly due to the technologies involved in this system, as they are not widely available in Brazil.

Another drawback to implement biogas as a in Brazil is due both to the lack of knowledge by society about the environmental and social benefits that biogas use may provide. Among the policies to provide incentives for the production of biogas in Brazil, the Fuel of the Future Program was recently instituted, proposed in April 2021 (Energia, 2021), with goals that encompass the integration of existing Brazilian public policies, such as Renovabio (Brasil, 2017), PROCONVE (Program of Air Pollution Control by Motor Vehicles) (Conselho Nacional do Meio Ambiente (COMANA, 2008) and Rota 2030 which deal with the use of biofuels with various aspects and recommendations.

In this context, the insertion of the Life Cycle Assessment (LCA) methodology, which includes in its system boundaries the production of biofuel until its combustion in a vehicle, is a relevant tool capable of identifying the environmental impacts of the processes involved. Moreover, LCA enables the comparison of environmental impacts of different alternatives to the production system, being a relevant source for strategic decision-making.

A common feature of LCA studies that address the production and use of biofuels is the creation of alternative scenarios, addressing the most diverse possibilities that can be adopted in the study system. These scenarios aim to compare the inclusion of some modifications in the system product or a process involved, focusing on reducing environmental impacts. In biogas to biomethane LCA studies, the modeling of these scenarios may vary, for example, regarding the divergent biogas practical applications (Ferreira et al., 2019; Patterson et al., 2013), different processes or innovations and the inputs that can be included or removed (Ioannou-Ttofa et al., 2021).

The upgrade processes are frequently discussed in the biomethane LCA literature, most of which are based on absorption, membrane separation, or cryogenic processes. Techniques such as pressure swing adsorption (Martín-Hernández et al., 2020), chemical amine scrubbing or high-pressure water scrubbing (Cozma et al., 2013), and the use of polymeric membrane separation (Scholz et al., 2013) are often reported as efficient techniques to upgrade biogas to biomethane from an environmental point of view. The upgrade technique called Pressure Swing Adsorption (PSA) works through the physical properties of the gas, that is, through the physical interaction between the gas molecules and the adsorbent material (activated carbon, natural and synthetic zeolites, titanosilicates, silica gel, and carbon molecular sieves, for example) in columns under relatively high pressure (Martín-Hernández et al., 2020). The upgrade Membrane Separation (MS) consists of a dense filter capable of removing impurities from the raw biogas based on the molecules' size, with the membrane permeability principle used to separate the undesirable compounds from raw biogas (Scholz et al., 2013). The upgrade of Water Scrubbing (WS) is based on diluting components, such as $CO_2$ and $H_2S$, in water, through high-pressurized columns (Bauer et al., 2013).

Comparisons concerning these processes (Florio et al., 2019), with each technique as an alternative scenario, indicate the membrane separation process shows the lowest environmental impact. However, comparing this scenario to the plant that uses biogas to cogenerate heat and power scenario, it offers significant savings in fossil fuels, mainly caused by electricity re-feeding to the biogas plant (Yang et al., 2014). In addition to the type of upgrade, LCA studies focused on using biomethane as a vehicle fuel. Also, they involved comparative scenarios of the use of biomethane in different vehicles, such as public transport buses (Shinde et al., 2021), trucks (Pérez-Camacho et al., 2019) and light vehicles (Ferreira et al., 2019). This allows the comparison of the use of biomethane with traditional fossil fuels, especially with gasoline C and diesel-powered vehicles, but also with electricity and heat generation applications such as Liquefied Petroleum Gas (LPG) on a small scale (Garfí et al., 2019; Wang et al., 2021).

In this study, the life cycle impacts of three different upgrade techniques were analyzed through life-cycle scenarios, where Scenario 1, the upgrade system is the Pressure Swing Adsorption (PSA), Scenario 2 is the Membrane Separation, and Scenario 3 is the Water Scrubbing technique. The LCA modeling in this study has system boundaries that begin with the biogas production phase from dairy cattle manure, extending to the biomethane use phase in a heavy-duty vehicle. Therefore, a medium-sized Brazilian biogas plant was used as a primary data source to propose upgrade scenarios as an option for this type of system.

## 2. METHODOLOGY

### 2.1 Goal and scope definition

This study aims to assess the environmental impacts from various biogas upgrading options to biomethane through life cycle analysis. The modeling is based on primary data from a medium-sized biogas plant in Luziânia, Goiás, Brazil. Accordingly, three alternative scenarios were established, each one incorporating a distinct technique for enhancing biogas to biomethane production. In the first scenario (SC 1), Pressure Swing Adsorption (PSA) upgrading is adopted, while in the second scenario (SC 2), Membrane Separation (MS) upgrading, and for the third scenario (SC 3), High Pressure Water Scrubbing (HPWS) upgrading is applied.

The scope of the study encompassed all the necessary processes and inputs, including the production phase of raw biogas on the farm, the processes required for biogas upgrading to biomethane, and the use of the generated biomethane, which involves its combustion in a cargo vehicle.

The functional unit (FU) was 1 MJ of biomethane resulting from the adopted upgrading process, according to the established scenarios. The main reason for adopting this functional unit is to highlight the energy potential of biomethane as a vehicular fuel, considering that its use in Brazil is still not widespread. Additionally, this unit facilitates the comparison of life cycle impacts with traditional fossil fuels that could be replaced by biomethane.

The Life Cycle Assessment (LCA) developed follows the recommendations of ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b), which provide the constituent elements of a comprehensive LCA. For the Life Cycle Inventory (LCI) phase, primary data were used for the biogas production stage, collected through questionnaires applied during on-site visits to the farm, which, combined with literature data, resulted in the LCI previously disclosed in previous work. In scenarios modeling literature data were used in conjunction with data made available in the GaBi software database, version 9.7.2, and also from Ecoinvent database version 3.8 (Ecoinvent, 2021).

To estimate the environmental impacts of the analysis scenarios, the CML 2001 impact assessment methodology was employed, considering the impact categories of Global Warming Potential (expressed in kg of $CO_2$ Eq.), Acidification Potential (expressed in kg of $SO_2$ Eq.), and Eutrophication Potential (expressed in kg of $PO_4$ Eq.). The chose categories were motivated by the impacts of these gases on the greenhouse effect and to facilitate comparisons with similar systems.

Figure 1 illustrates the system boundaries established and the processes applied in the study scenarios. Following a well-to-wheels approach, the system boundaries begin with the production of biogas, which then undergoes an upgrading process to purify its methane content and remove impurities, resulting in biomethane used as fuel in a heavy-duty vehicle. In the life cycle modeling of the different upgrade techniques, inputs such as water, electricity, and air emissions resulting from the process are considered. At the same time, the environmental impacts of equipment assembly and final disposal are excluded.

Regarding the combustion of biomethane in the cargo vehicle, it was assumed that the vehicle covers a distance of 100 km and carries a load proportional to its capacity in all life cycle scenarios. Another process considered in all scenarios is the compression of biomethane after leaving the upgrading process, which is necessary for its insertion into the vehicle, like the Compressed Natural Gas (CNG) process.

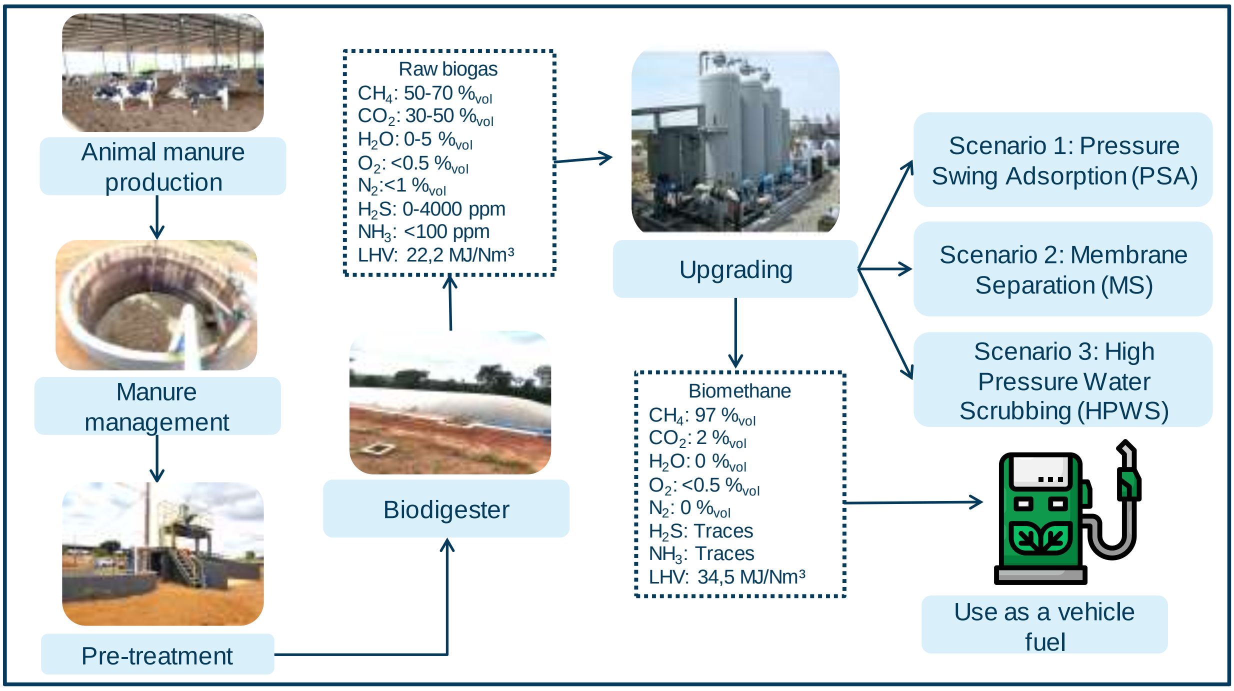



Figure 1 - System boundaries of the study.

## 2.2 Life Cycle Inventory

The data used to model the Life Cycle Inventory (LCI) of each upgrade process is shown in Table 1, calculated for the functional unit of 1 MJ of biomethane generated by the upgrade processes. The PSA upgrading process was modeled according to the Ecoinvent database (Jungbluth & Chudacoff, 2007) version 3.4., while the MS and HPWS processes were modeled according to literature data adapted from Florio et al. (Florio et al., 2019) and Ardolino et al. (Ardolino et al., 2018). These represent examples of techniques could be adopted to facilitate the implementation of this route of use in biogas Brazilian plants, the economic viability is a common issue in this regard (da Costa et al., 2020). However, from the environmental point of view, it is still essential to know and compare how they can be inserted in the Brazilian agricultural context, as will be demonstrated below.

Although these techniques that enable the delivery of biomethane in biogas production systems are widely reported in the literature, there is still difficult to find systems that employ these techniques in Brazilian territory. Therefore, in using biogas as biomethane, all data considered in the Life Cycle Inventory (LCI) were collected from related literature combined with the database from the software.

Table 1. The LCI for the upgrading process involved in Scenarios 1, 2, and 3, taking FU as 1 MJ of biomethane.

| | | | **Upgrading** | |
|---|---|---|---|---|
| **Flows** | **Unit** | **PSA** | **MS** | **HPWS** |
| **Inputs** | | | | |
| Electricity | kWh | 0.0230 | 0.0240 | 0.0240 |
| Raw Biogas | Nm³ | 0.0461 | 0.0461 | 0.0461 |
| Water | kg | - | - | 0.1840 |
| **Outputs** | | | | |
| Biomethane | MJ | 1 | 1 | 1 |
| **Emissions to air** | | | | |
| $CH_4$, biogenic | kg | 5.99E-04 | - | - |
| CO | kg | - | 0.0168 | 0.0249 |
| $CO_2$ | kg | 0.0309 | - | - |
| $H_2S$ | kg | 1.01E-07 | - | - |
| $NH_3$ | kg | - | 1.70E-05 | 1.70E-05 |
| NMVOC [(1)] | kg | - | 6.91E-04 | 6.91E-04 |
| Acetaldehydes | kg | - | 1.07E-07 | 1.06E-07 |
| $SO_2$ | kg | 2.4E-05 | - | - |
| Waste heat | MJ | 0.0522 | - | - |
| Wastewater | kg | - | - | 0.1840 |

[(1)] NMVOC: Non-Methane Volatile Compound.

Additionally, the compression processes applied to biomethane were also adopted, and a biomethane cargo vehicle operation was in sequence. The vehicle is medium-sized, with a fuel-specific consumption of 22.2 Nm³/100km, carrying a relatively small load, only representative of a biomethane cargo vehicle, as demonstrated in similar literature (Ardolino et al., 2018; Ricardo-AEA, 2015). The LCI of the compression processes and the operational phase of a biomethane vehicle are shown in Table 2.

Table 2. The LCI for compression and vehicle operations used in Scenarios, taking FU as 1 MJ of biomethane.

| | | **Process – Biomethane compression** | | |
|---|---|---|---|---|
| **Flows** | **Unit** | **Quantity** | **Origin** | **Ref.** |
| **Inputs** | | | | |
| Biomethane | MJ | 1.00 | Functional unit | - |
| Electricity | MJ | 8,28E-02 | Literature | (Patterson et al., 2013) |
| **Outputs** | | | | |
| Compressed biomethane | MJ | 1 | Calculated | - |
| | | **Process – Biomethane Heavy-duty vehicle operation** | | |
| **Inputs** | | | | |
| Compressed biomethane | MJ | 1.00 | Literature | (Patterson et al., 2013) |
| Cargo | kg | 1.31E-01 | Estimated | |
| **Outputs** | | | | |
| Cargo | kg | 1.31E-01 | Estimated | |
| **Emissions to air** | | | | |
| $CH_4$, biogenic | kg | 1.63E-02 | Literature | (Ardolino et al., 2018) |
| CO, non-fossil | kg | 4.58E-03 | Literature | (Ardolino et al., 2018) |
| $N_2O$ | kg | 1.43E-03 | Literature | (Ardolino et al., 2018) |
| HC | kg | 6.30E-02 | Literature | (Ardolino et al., 2018) |
| $NO_x$ | kg | 3.80E-03 | Literature | (Ardolino et al., 2018) |
| Particulates < 2.5 mm | kg | 1.69E-04 | Literature | (Ardolino et al., 2018) |

The compression process of biomethane in cylinders is crucial for its integration into vehicles, meeting the specific pressure requirements when used as a substitute for natural gas (Scholz et al., 2013). Regarding the emissions associated with the upgrade processes, it is important to note the inclusion of the $CH_4$ exhaust amount inherent in these processes, which was found to vary around 0.69% of the resulting biomethane (Ardolino et al., 2018). This value is added to the $CH_4$ emissions in the LCI.

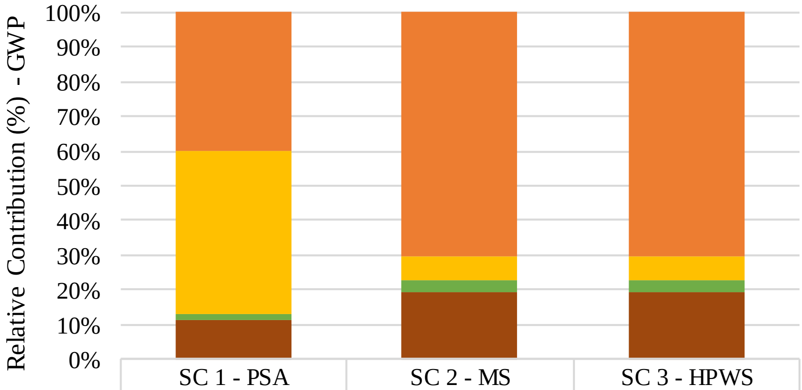
The modeling of the biomethane vehicle fueling process was based on literature (Ardolino et al., 2018; Ricardo-AEA, 2015), which the emission factors were selected based on the distance traveled by the vehicle. The load used in the modeling was determined using vehicle models available in the GaBi software database (Thinkstep, 2022).

### 2.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) was conducted using the CML 2001 characterization methodology through the GaBi software database, version 9.2.1.68 (Thinkstep, 2022). Therefore, the following impact categories were considered: Global Warming Potential (GWP - kg $CO_2$ Eq.), Acidification Potential (PA - kg $SO_2$ Eq.), and Eutrophication Potential (PE - kg $PO_4$ Eq.).

## 3. RESULTS AND DISCUSSION

The GWP impact category allows analyzing how emissions arising from the processes involved in each scenario can influence climate change and the greenhouse effect, where different weights are given to $CO_2$, $CH_4$, $N_2O$, and hydrofluorocarbons (HFCs) emissions. As the study's central objective is linked to identifying the environmental impacts of the different options for upgrading from biogas to biomethane, the absolute values for the other processes remained the same, showing differences only for the types of upgrades adopted in each scenario. Figure 2 demonstrates the relative contribution and the absolute values obtained for the three modeled scenarios, distributed among the processes involved for the GWP impact category, concerning the functional unit of 1 MJ of biomethane.




| | SC 1 - PSA | SC 2 - MS | SC 3 - HPWS |
|---|---|---|---|
| Biogas Production | 3.99E-02 | 3.99E-02 | 3.99E-02 |
| Upgrade | 4.70E-02 | 4.14E-03 | 4.16E-03 |
| Compression | 1.86E-03 | 1.86E-03 | 1.86E-03 |
| Vehicle operation | 1.10E-02 | 1.10E-02 | 1.10E-02 |
| Total | 9.99E-02 | 5.70E-02 | 5.70E-02 |

Figure 2 – Relative contribution of the processes involved in each modeled scenario, for the GWP category, concerning the 1 MJ of biomethane. SC 1: Upgrade – Pressure Swing Adsorption (PSA); SC 2: Upgrade - Membrane Separation; SC 3: Upgrade – High-Pressure Water Scrubbing.

Overall, the total contribution of the PSA-type upgrade adopted in SC 1 was the one with the highest contribution to the Global Warming Potential (GWP), accounting for 46.7% of the total contributions in this impact category. Both scenarios SC 2 and SC 3 had contributions equivalent to 26.6% in the GWP, which present significant technical differences, despite being practically identical. This means that, for this category, both scenarios have the same environmental impacts and are more advantageous than the upgrade technique adopted in SC 1.

The impacts obtained in SC 1 reflect the participation of the PSA-type upgrade, which represents 47.05% of the total contribution of the mapped processes in this scenario. As reported by (Starr et al., 2012), the electricity consumption inherent in the technique was one of the determining factors, along with $CO_2$ and $CH_4$ emissions, which were accounted for in the process's Life Cycle Impact Assessment (LCIA). The other processes that constitute SC 1 also demonstrated significant contributions to this category, such as biogas production, which represented 39.94% of the total impacts, followed by vehicle operation, which accounted for 11.01%, and lastly, compression, with a 1.86% share.

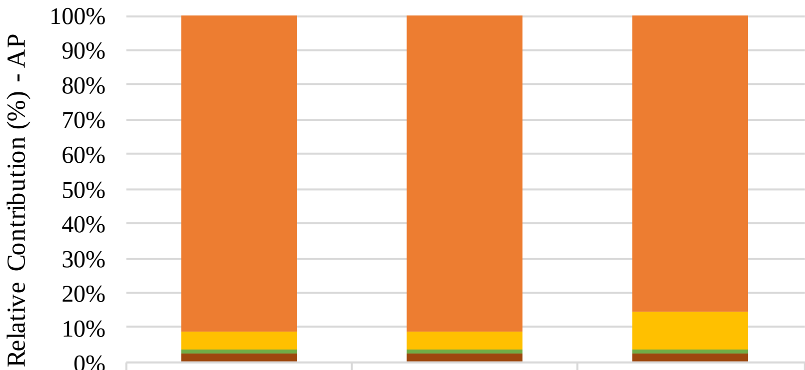
Previous studies (Ardolino et al., 2018; Ferreira et al., 2019; Florio et al., 2019; Patterson et al., 2013) confirm similar contributions from such processes, where, despite using different functional units, both report electricity consumption as the most significant influence on the environmental impacts of the compared techniques. It is also important to note that even though these environmental impacts have been demonstrated, adopting biogas-to-biomethane upgrade techniques in biogas production chains shows lower environmental impacts compared to scenarios that employ biogas production for electricity (IRENA, 2021).

Regarding scenarios 2 and 3, the upgrade's contribution is 7.30% of the total impacts, where the impacts from other processes, such as biogas production (70%) and vehicle operation (19.30%), and a small portion for compression (3.2%), were higher for this category. This demonstrates that the MS and HPWS upgrade processes are more environmentally friendly than the PSA technique and other processes accounted for in scenarios 2 and 3.

The contribution of the biogas production phase in all scenarios for GWP proves to be relevant, considering the higher emissions resulting from the production methods employed on the farm, highlighting the need to adopt measures involving the reduction of these impacts. As previously reported in previous work (Hamelin et al., 2011), the impacts of manure production and open-air management contribute to higher emissions of greenhouse gases, thus being identified as hotspots for reducing environmental impacts in this phase.

Regarding vehicle operation, which showed a significant contribution to GWP in scenarios 2 and 3, it was observed that $N_2O$ and biotic $CH_4$ emissions were the main contributors compared to other emissions obtained. Although similar studies (Alamia et al., 2016; Ferreira et al., 2019) that also account for the operation of vehicles using biomethane in environmental impacts highlight that the substitution of fossil fuels such as diesel and gasoline-C proposes a reduction in environmental impacts, the impacts reported here refer to the comparative context of these processes within the system boundaries

Figure 3 illustrates the contribution of each process to the total impacts obtained in the Acidification Potential, considering a functional unit of 1 MJ of produced biomethane. In this category, gas emissions such as $SO_2$, $NO_X$, $NH_3$, and volatile organic compounds (VOCs) are quantified to assess their ability to contribute to the acidification of the environment, resulting in effects such as acid rain, soil, and water acidification.




| | SC 1 - PSA | SC 2 - MS | SC 3 - HPWS |
|---|---|---|---|
| Biogas Production | 9.10E-04 | 9.10E-04 | 9.10E-04 |
| Upgrade | 5.00E-05 | 5.00E-05 | 1.20E-04 |
| Compression | 1.01E-05 | 1.01E-05 | 1.01E-05 |
| Vehicle operation | 2.53E-05 | 2.53E-05 | 2.53E-05 |
| Total | 9.95E-04 | 9.95E-04 | 1.07E-03 |

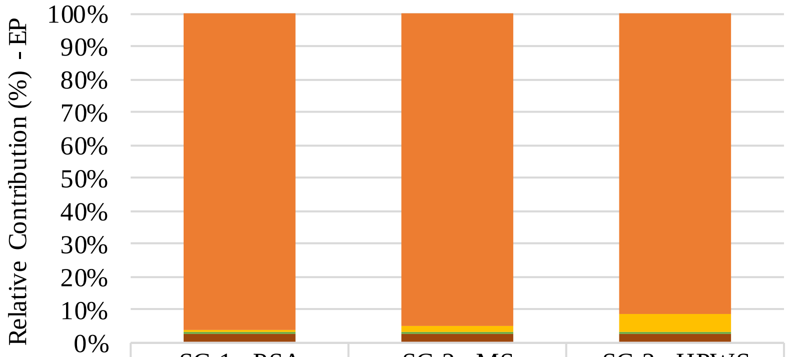
Figure 3 - Relative contribution of the processes involved in each modeled scenario, for the AP category, concerning the 1 MJ of biomethane. SC 1: Upgrade – Pressure Swing Adsorption (PSA); SC 2: Upgrade - Membrane Separation; SC 3: Upgrade – High-Pressure Water Scrubbing.

Of the mapped processes, the impacts of biogas production were also the majority in the AP category. This is justified by the emissions from manure production and management processes, where higher $NH_3$ emissions were recorded. These emissions result from the excretion of manure by cattle in the collection yard before washing to send the residues to the management stage, as demonstrated in a previous study (Ravina & Genon, 2015). The other $NH_3$ emissions from the management process are due to outdoor storage in the homogenization tank, which could be a tipping point for plant operators.

As for the updating processes adopted, a greater contribution is observed in AP for SC 3 (11.26%), against 5.02% for SC 1 and for SC 2, which were practically identical from the point of view of AP. Once again, $NH_3$ emissions also justify the differences obtained, arising from the use of water necessary for the HPWS upgrade, which does not occur in the other processes, which use only electrical energy. Studies demonstrate that this technique can be beneficial because it is adaptable to the capacity of the biomethane plant and because it is an automated technique (Bauer et al., 2013).

Although the environmental impacts are greater for scenarios 1 and 2, when compared to scenarios in which biogas plants are not used, for example (Battini et al., 2014), a significant reduction in impacts results from implementing the biogas plant for electricity generation. In addition, reusing the heat generated in the cogeneration process within the production chain is one of the strategies that can be employed for even smaller environmental impacts in systems of this type (Bacenetti et al., 2016). It is important to point out that among the adopted modernization processes, the different emission sources in the case of the AP were the $SO_2$ emissions in scenarios 1 and 2, caused by the use of electricity for its implementation.

Figure 3 represents the contribution of each process to the total impacts obtained in Eutrophication Potential, considering 1 MJ of biomethane obtained as a functional unit.




| | SC 1 - PSA | SC 2 - MS | SC 3 - HPWS |
|---|---|---|---|
| Biogas Production | 3.90E-04 | 3.90E-04 | 3.90E-04 |
| Upgrade | 2.75E-06 | 8.44E-06 | 2.45E-05 |
| Compression | 1.27E-06 | 1.27E-06 | 1.27E-06 |
| Vehicle operation | 1.17E-05 | 1.17E-05 | 1.17E-05 |
| Total | 4.06E-04 | 4.11E-04 | 4.27E-04 |

Figure 4 - Relative contribution of the processes involved in each modeled scenario, for the EP category, concerning the 1 MJ of biomethane. SC 1: Upgrade – Pressure Swing Adsorption (PSA); SC 2: Upgrade - Membrane Separation; SC 3: Upgrade – High-Pressure Water Scrubbing.

In addition to the participation of the biogas production phase as a protagonist for PE, another similarity that can be observed is the contribution of SC 3, which was greater than the total found for this category (34%). However, when comparing the impacts obtained for the different upgrade techniques adopted, it can be seen that the PSA technique in SC 1 presented 0.68% of the total impacts of the scenario in EP, compared to 2.75% and 5.03 % for SC 2 and SC, respectively. This factor highlights that for PE, the best option is SC 1, given the low impacts obtained compared to the other techniques.

In SC 3, the HPWS technique showed greater contributions, which is explained by nitrogenous emissions ($NO_X$ and $N_2O$) resulting mainly from the use of water and electricity to supply the modernization process, followed by emissions already accounted for by the technique itself. The other processes accounted for in the scenarios had little influence on this impact category, except for the production of biogas, which in all cases corresponds to most of the impacts obtained.

## 4. CONCLUSIONS

Analysis of the different scenarios (SC 1, SC 2, and SC 3) regarding their contributions to the impact categories provides valuable insights. Firstly, SC 1, which employed the upgrade technique known as PSA, exhibited the highest GWP contribution among the scenarios. Electricity consumption, $CO_2$ emissions, and $CH_4$ emissions primarily influenced this. However, the other processes, including biogas production and vehicle operation, also demonstrated significant impacts.

On the other hand, SC 2 and SC 3, which used different upgrade processes (MS and HPWS), showed similar contributions to GWP. These scenarios were more environmentally favorable than the PSA technique in SC 1. The upgrade processes in SC 2 and SC 3 were more environmentally friendly, with higher contributions from biogas production and vehicle operation.

It is important to note that the biogas production phase performed significantly in all scenarios, contributing to the GWP due to the emissions associated with farming methods. Measures to reduce the environmental impacts of manure production and open-air management were noted as crucial to mitigate these emissions.

In addition, the operation of vehicles using biomethane, as shown in scenarios 2 and 3, has established a relevant contribution to GWP. While replacing fossil fuels with biomethane can reduce environmental impacts, the effects reported must be considered in a comparative context within system boundaries.

Most of the impacts of the acidification potential (AP) category are attributed to the biogas production processes. This is mainly due to manure production and management emissions, with higher levels of $NH_3$ emissions resulting from livestock excretion and outdoor storage. The choice of upgrading technique also influences the AP, where SC 3 shows a higher contribution due to water use in the HPWS upgrading process. This technique offers advantages in terms of adaptability and automation, as highlighted in previous studies.

For Potential Eutrophication (EP), the biogas production phase performs a prominent role. SC 3 shows the highest contribution compared to the total impacts in this category. However, when comparing the impacts of the different upgrading technologies, the PSA technology in SC 1 shows lower impacts on EP compared to SC 2 and SC 3. SC 3, with the HPWS technique, shows higher contributions to the EP, mainly due to nitrogen emissions from the use of water and electricity in the upgrading process.

In general, biogas production and the choice of upgrading technology significantly influence the environmental impacts of biogas production systems. The choice of upgrading technique and the efficient management of biogas production processes can significantly reduce environmental impacts, particularly in terms of GWP. Measures to mitigate $NH_3$ and nitrogen emissions should be prioritized to minimize impacts on PA and PE. These results highlight the importance of adopting sustainable practices and considering the entire life cycle of biogas production to minimize its overall environmental footprint.

## 5. ACKNOWLEDGMENTS

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