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EVALUATION OF THREE HEAT TRANSFER MODELS IN THE LCA OF BIOMETHANE, ETHANOL AND GASOLINE IN BRAZIL

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Abstract. *The use of biofuels has been listed as a priority by many governments in the fight against global warming and the search for alternatives to petroleum-based fuels. The primary motivation of this work is to assess the potential environmental impacts of different fuels for internal combustion engines. Additionally, the influences of heat transfer models on emissions are also estimated. The Life Cycle Assessment methodology is used from a well-to-pump perspective, which includes in system boundaries the stages of raw material extraction, fuel processing and distribution. The efficiency of the combustion process is analyzed in each scenario through a zerodimensional combustion model, where the heat transfer correlations of Hohenberg and Woschni are used. The three analyzed scenarios are conventional ICE fueled by gasoline, sugarcane ethanol, and biomethane. The standard functional unit assumed is 1.0 MJ of energy released by combustion. The LCA results are characterized in terms of global warming potential and human toxicity potential. The results show that the Hohenberg correlation has higher CO and NO emissions for ethanol and gasoline under high-speed conditions, while for biogas the Woschni correlation gives the best results. Moreover, biogas production shows better results with respect to the impact categories analyzed in the LCA method.*

Keywords: *Life cycle assessment, Heat transfer models, Internal combustion engine, Biofuels.*

1. INTRODUCTION

In wealthy Western countries, current energy policy is based on the premise that climate change poses an imminent "existential threat" to humanity. This threat is referred to as "climate change" and includes the effects of global warming caused by increasing concentrations of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Kalghatgi, 2022). In recent years, international climate policy discussions have attempted to limit the increase in global average temperature to 2°C relative to pre-industrial times, a figure that some believe represents a threshold beyond which climate impacts become "dangerous" (Zickfeld *et al.*, 2009). Figure 1 shows maps of surface temperature anomalies for the last month, the last three months, and the last 12 months, with July 2023 as the reference month.

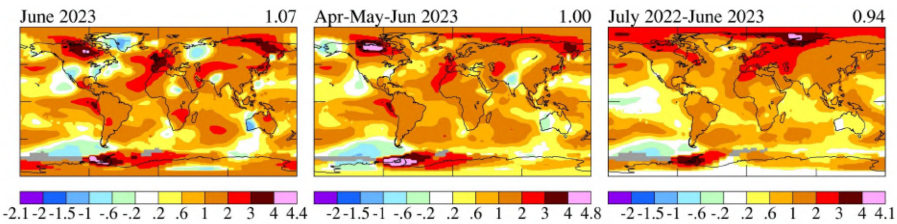


Figure 1. Surface temperature relative to 1951-1980 mean (°C) (Sato and Hansen, 2023).

The increase in global energy consumption is reflected in the relative increase in global temperature of 1.07°C, as the use of fossil fuels plays a major role in the increase in greenhouse gas emissions.

In this sense, the main objective of this work is to evaluate the heat transfer phenomena in combustion engine emissions using a phenomenological model written in MATLAB® by Mattos (2018), is based on classical thermodynamic submodels to simulate each process in the engine cycle and analyze the effects of Hohenberg and Woschni correlations on carbon monoxide (CO) and nitrogen monoxide (NO) emissions. To validate the model, a preliminary analysis was performed using parameters from the literature of a single-cylinder research engine (SCRE), wich is a naturally aspirated four stroke engine equipped with a port fuel injection (PFI) system.

Furthermore, the Life Cycle Assessment methodology is used to evaluate the potential environmental impacts involved in the production of gasoline, sugarcane ethanol, and biogas-derived biomethane produced through anaerobic digestion. The ReCiPe Midpoint method is used to characterize the environmental impacts of the studied systems. The impacts studied in the Life Cycle Impact Assessment (LCIA) are classified in terms of Global Warming Potential (GWP) and Human toxicity potential (HTP).

2. BIOFUELS

The intellectual development concerning climate change is summarized by the Intergovernmental Panel on Climate Change (IPCC), established in 1988 under the auspices of the United Nations. The IPCC details in its reports the consequences of increased greenhouse gas emissions in the world and proposes options to avoid climate collapse, as presented in Figure 2.

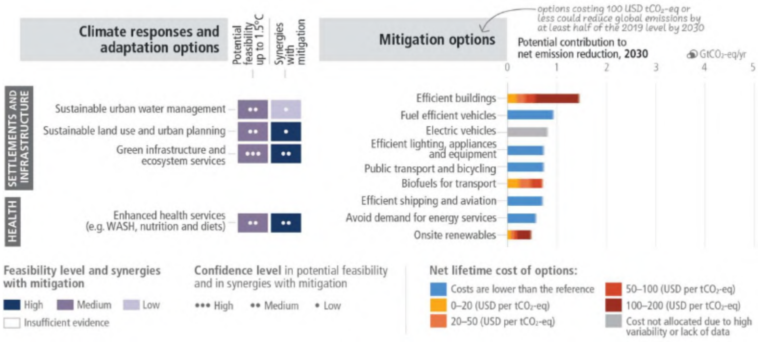


Figure 2. Feasibility of climate responses and adaptation, and potential near-term mitigation options (Lee *et al.*, 2023).

Among the proposed mitigation options, the use of biofuels for transportation stands out, which has been of utmost importance worldwide in promoting the growth of sustainability-based economies through the use of renewable resources (Moraes *et al.*, 2015). Reducing emissions directly affects the transportation sector, which accounts for one-third of the final energy consumption in Brazil, where the use of fossil fuels predominates (Bello *et al.*, 2023).

The concept of biofuels in Brazil, especially bioethanol, was initially promoted by the National Alcohol Program (Proálcool), created in response to the crisis of high oil prices in the 1970s. However, the rise of bioethanol actually occurred in 2003 with the launch of the first flex-fuel vehicle in Brazil. Flex-fuel vehicles are designed to run on any mixture of gasoline and ethanol since they have lambda sensors in the exhaust system that identify the fuel composition and adjust the fuel-air ratio appropriately to ensure optimal combustion between gasoline, ethanol, or diesel, and oxygen.

Common ethanol, also known as hydrated ethanol, is composed of a maximum water content of 7.5% (ANP, 2022). On the other hand, anhydrous ethanol is subjected to a dehydration process to achieve at least 99% purity. In Brazil, the commercialized gasoline is composed of a mandatory blend of 27% anhydrous ethanol and pure gasoline. These regulations have encouraged the consumption of biofuels in the country while enabling the expansion of the energy matrix in a sustainable manner (Vidal, 2020). Ethanol represents a clean and renewable energy source, with significant importance for environmental sustainability, having avoided the emission of over 515 million tons of CO_2 into the atmosphere from 2003 to 2020 (UNICA, 2023).

In the 1970s, the oil crisis significantly raised the international energy prices. At that time, ensuring the basic energy supply became a matter of national sovereignty, leading to the emergence of several alternative energy programs, including the use of biogas in vehicles as a substitute for gasoline.

Biogas is considered one of the main sources of gaseous bioenergy, as it can be easily synthesized from a wide range of raw materials and can be continuously produced as long as organic matter is available. Biogas is a renewable energy source mainly composed of methane and produced through the anaerobic digestion of organic matter (Ferreira *et al.*, 2019). Anaerobic digestion, in turn, refers to the biological process of converting organic matter into CH_4 and carbon dioxide, carried out by different groups of bacteria and archaea. From the mid-1980s onwards, even with cases of conflicts in the Middle East caused by the 1991 war, the price of oil achieved relative stability, and once again, the use of petroleum derivatives became a priority. Consequently, there was a decrease in the development of alternative energy sources.

Currently, the primary use of biogas is for electricity generation. For biogas to be used as vehicle fuel, additional purification steps are necessary, such as the removal of oxygen (O_2), nitrogen (N_2), and carbon dioxide (CO_2). This purification process is called upgrading and results in the gas known as biomethane. The efficiency of biogas combustion is directly linked to the concentration of CH_4, as it is the main combustible element. Therefore, the presence of other elements results in less efficient combustion processes. Biogas upgrading allows increasing the concentration of CH_4, obtaining a fuel with calorific value equivalent to natural gas (Sinigaglia *et al.*, 2022).

The treatment of biogas for biometane consumption as a replacement for natural gas in the country is still in its early stages. However, the regulation of biometane is evolving to promote the use of this source (BRASIL, 2021). Currently, the country has 10 biogas purification units in operation, producing 435 Nm^3 daily, which is energetically equivalent to 378 liters of diesel (CIBiogás, 2022).

The importance of developing national solutions that fit into the global value chain of the automotive industry arises from the imperative of decarbonizing the sector. Local solutions that have enabled achieving low levels of greenhouse gas emissions in transportation, such as the widespread use of ethanol in flex-fuel vehicles, present apparent dilemmas in the face of the global strategies of the automotive industry, which increasingly emphasizes the introduction of electrification in its main markets.

2.1 Engines and Numerical Models

Until the 1960s, engines were developed and improved based solely on accumulated knowledge and experimental studies.With the invention of digital computers, the study of internal combustion engine operation through the use of detailed simulation models becomes possible, which is useful for predicting engine performance relatively quickly and inexpensively compared to experimental tests.

According to Heywood (1988), there are two basic types of simulation to model the behavior of a real engine: thermodynamics and fluid dynamics. Phenomenological models are based on the conservation of thermodynamic energy and are structured through a modular approach, where the engine cycle is divided into different blocks of sub-models, each representing a specific process, allowing an individual and precise analysis of each stage of the engine cycle.

2.1.1 Heat transfer models

An important analytical tool used to assist in understanding combustion phenomena is the heat release model. The burn rate directly affects indicated efficiency, power, emissions, lubrication, and engine cooling capacity (Gustavo *et al.*, 2017). For a homogeneous charge engine, the flame front is defined as a spherical sheet that divides the chamber into burned and unburned zones. In each of these two systems, heat transfer can then be calculated using an empirical convection coefficient and an approximate distribution of wall temperature, determined by the flame position. Thus, the unburned system will quickly approach zero mass if the calculated heat transfer is too high, otherwise, if the calculated heat transfer is too low, it can approach a different constant value other than zero. For a normally cooled engine, heat transfer reduces volumetric efficiency by about 3-4% under full load conditions (Borman and Nishiwaki, 1987).

However, heat transfer is not a phenomenon that can be numerically modeled in a simple manner. The variations in temperature and pressure to which the working fluid is subjected, as well as the three-dimensional, transient, and turbulent flow, give rise to the complexity of heat transfer to the surfaces of the cylinder, piston, and cylinder head—a phenomenon of non-stationary and three-dimensional nature.Furthermore, any detailed approach to the problem is extremely difficult due to the incessant variation of the thermophysical properties of the fluid, as well as the presence of moving boundaries and complicated geometries alongside the gases and cooling system.

Therefore, the heat transfer modeling follows an approach that involves the use of simple correlations derived from experimental data capable of determining the heat transfer coefficient. Such correlations take into account the properties of the fluid, engine dimensions, hydrodynamics of the flow in the cylinder, and specific characteristics of the combustion process, assuming that the thermal boundary layer is extremely thin with negligible thermal capacity. This assumption allows adopting the hypothesis that the heat flow at the wall is proportional to the temperature difference between the gas and the fluid.

Despite being frequently cited in the literature, the correlation proposed by Woschni requires knowledge of many parameters (Heywood, 1988). Therefore, through a review of Woschni's work, Hohenberg eliminated the need to estimate the cylinder pressure with the engine without combustion, and by using other dimensional groups, developed the correlation presented by Eq. (1). Hohenberg's correlation for the instantaneous heat transfer coefficient truly considers the current conditions in a direct injection engine. This correlation is based on extensive experiments conducted on direct injection diesel engines (Lakshminarayanan and Aghav, 2010).

$$\mathbf{h_h} = 130\mathbf{p}^{0.8}(\mathbf{S_p} + 1.4)^{0.8}\mathbf{V}^{-0.06}\mathbf{T}^{-0.4} \tag{1}$$

where $\mathbf{h_h}$ is the heat transfer coefficient [W m^{-2} K^{-1}], $\mathbf{p}$ is the absolute pressure in the cylinder [kPa], $\mathbf{S_p}$ is the average piston velocity [m/s], $\mathbf{V}$ is the displaced volume (displacement) [m^3], and $\mathbf{T}$ is the fluid temperature [K].

3. LIFE CYCLE ASSESSMENT (LCA)

The first studies related to LCA (Life Cycle Assessment) concerning automotive systems were initiated in the 1970s with the purpose of reducing dependence on crude oil derivatives. Since then, the growing interest in eco-efficiency and sustainable products has driven the advancement of studies in the development and application of the LCA methodology (de Souza *et al.*, 2018).

Life Cycle Assessment (LCA) is a methodology used to measure resources consumed and evaluate environmental aspects associated with goods and processes throughout their life cycle (Souza, 2021). Internationally standardized by the International Organization for Standardization (ISO) (ISO, 2006a,b), LCA quantifies the environmental impacts associated with goods and services by utilizing data on inputs, energy, and environmental emissions (de Souza, 2015). Environmental product declarations can be based on LCA studies, as well as the integration of environmental aspects in product design and development (Coltro *et al.*, 2007).

3.1 Previous studies

The use of LCA is recommended to identify environmental impacts throughout the complete life cycle of products. In this regard, Table (1) summarizes a recent literature review on the use of LCA in the transportation sector.

Table 1. Previous LCA studies available in literature.

Functional Unit (km)	**Goal and Scope**	**Powertrains configurations/fuels**	**Analyzed Environmental Impact Categories and Main Results**	**Reference**
1.0	Assess the environmental impacts of both types of ICEVs and BEVs	ICEVs and BEVs	ADP, GWP and FWT	Chroma and Ugaya (2014)
1.0	LCA of a passenger car, including the battery system, the glider, and the powertrain, comparing advanced vehicles to conventional vehicles.	ICEVd, BEV, HEVd (30%), HEVd (60%), PHEV	ADP, FDP, ACP, ETP, GWP, HTP, ODP, POP, FETP, METP, TEP from CML 2001 baseline. ICEVd showed the highest contribution to GWP, mainly in the use phase.	Tagliaferri et al. (2016)
1.0	Evaluate and compare the environmental impacts of vehicles in the Brazilian context.	ICEVg, ICEVf, ICEVe, PHEV, BEV	ODP, ADP, FDP, GWP, HTP, POP, ACP, and ETP	Souza et al. (2018)
1.0	Comparative LCA of typical small European vehicles, including vehicle production, use phase and EOL together with supply chains.	EV Li-NCM, EV Li-FePO4, ICEVg, ICEVd	GWP, ACP, POP, HTP, ETP, ADP, FDP, PMF, FETP, TEP.	Hawkins et al. (2012)

It has been described in the literature that most of the environmental impacts of vehicle manufacturers are associated with the vehicle use phase, mainly due to greenhouse gas emissions and energy demand (fuel consumption). For this reason, LCA in this field are crucial, and the results are an important contribution to vehicle designers and manufacturers, fuel producers and distributors, as well as policy makers, to make informed decisions regarding the environment and consequences throughout the production and supply chain, especially when the novelty is extreme or high in relation to the state of the art.

3.2 Life Cycle

All products and services can be represented through systems that describe the respective stages of their execution. In the LCA methodology, these stages are referred to as the product life cycle and are typically assessed from a cradle-to-grave perspective.

The life cycle can be approached from different perspectives, with the most common ones being:

- **Cradle-to-grave:** Considers all stages of the life cycle, from the extraction of natural resources to the final disposal.
- **Cradle-to-gate:** Includes only the extraction of raw materials and manufacturing, excluding all subsequent stages.
- **Well-to-wheels:** Similar to the cradle-to-grave process, but it investigates the life cycle of fuels, from the extraction of natural resources to their use in vehicles. The well-to-wheels approach can also be divided into the stages of "well-to-pump" and "pump-to-wheels."

Figure 3 shows the typical product life cycle, which begins with the acquisition of the necessary resources for manufacturing, whether they are materials or energy, usually extracted from nature. The resources then proceed to manufacturing, followed by distribution and use. After fulfilling their function, products can be reused, recycled, or disposed of, returning to the environment.

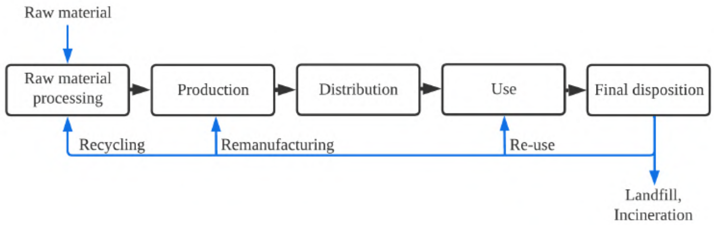


Figure 3. Life cycle stages.

4. METHODOLOGY

The processes governing the engine's performance and emissions can be addressed through two basic types of simulation: thermodynamics and fluid dynamics (Heywood, 1988). In this study, the emission analysis is conducted using the phenomenological model proposed by Mattos (2018), written in MATLAB® language. The program is developed based on classical thermodynamic submodels and involves the use of a system of ordinary differential equations associated with a series of models that simulate each process of the engine cycle. The main considerations of the model are as follows: Air is modeled as: Ar, N_2, CO_2, H_2O, O_2; Port fuel injection (PFI) engine; Two-zone phenomenological model; 12 species in the combustion products; Fuels: Hydrated Ethanol, Anhydrous Ethanol, Gasoline C, and Gasoline; Wiebe Combustion model; Heat transfer models are Hohenberg (open phase) and Nishiwaki (closed phase); Detonation model; and Prediction model for NO_x and CO emissions.

4.1 Implementations in Mattos model

4.1.1 Woschni's correlation

The instantaneous heat transfer modeling present in the Mattos (2018) model considers the correlation of Hohenberg (1979) for the closed phase, given by Eq. (1). The open phase is based on the Nishiwaki *et al.* (1979) model. In order to assess the behavior of CO and NO emissions as a function of heat transfer models, the correlation proposed by Woschni (1967) was implemented in the numerical model, where the heat transfer coefficient is calculated by Eq. (2).

$$\mathbf{h_w} = 3.26\mathbf{D}^{-0.2}\mathbf{p}^{0.8}\mathbf{T}^{-0.55}\mathbf{v_g}^{0.8} \tag{2}$$

where $\mathbf{h_w}$ is the heat transfer coefficient [W m^{-2} K^{-1}], $\mathbf{D}$ is the diameter of the cylinder [m], $\mathbf{p}$ is the absolute pressure in the cylinder [kPa], $\mathbf{T}$ is the fluid temperature [K], and $\mathbf{v_g}$ is the characteristic velocity of the gas admitted into the chamber [m/s], the latter calculated using Eq. (3), described below.

$$\mathbf{v_g} = 2.28\mathbf{S_p} + 0.00324(\mathbf{p} - \mathbf{p_0})\mathbf{V_d}\frac{\mathbf{T_1}}{\mathbf{p_1 V_1}} \tag{3}$$

where $\mathbf{S_p}$ is the average piston speed [m/s], $\mathbf{p}$ is the absolute pressure in the cylinder [kPa], $\mathbf{p_0}$ is the pressure inside the chamber during compression without combustion [kPa], $\mathbf{V_d}$ is the displaced volume (displacement) [m^3], and $\mathbf{T_1}$, $\mathbf{p_1}$, and $\mathbf{V_1}$ are the temperature [K], pressure [kPa], and volume [m^3] at the closing angle of the intake valve.

4.1.2 Biomethane

With the aim of describing the phenomena related to CO and NO emissions concerning the use of biogas fuel, a polynomial was implemented in the numerical model to calculate the specific heat properties. The polynomial was developed based on tabulated data of the specific heat (Cp) as a function of temperature for biometane, researched by Barin and Platzki (1995) and presented in the study by González (2010). The data was used in a Lagrange interpolating polynomial, which, due to its complexity and to ensure result accuracy, was calculated using MATLAB® software. Equation (4) presents the polynomial obtained for the temperature range of 300 to 2000 K.

$$\begin{aligned}\mathbf{C}_{\mathbf{p},\mathrm{CH4}} =& \mathbf{aT^{17}} + \mathbf{bT^{16}} + \mathbf{cT^{15}} + \mathbf{dT^{14}} + \mathbf{eT^{13}} + \mathbf{fT^{12}} + \mathbf{gT^{11}} + \mathbf{hT^{10}} + \mathbf{iT^{9}} + \mathbf{j}T^{8} + \mathbf{k}T^{7} + \mathbf{lT^{6}} + \\ & \mathbf{mT^{5}} + \mathbf{nT^{4}} + \mathbf{oT^{3}} + \mathbf{pT^{2}} + \mathbf{qT} + \mathbf{r}\end{aligned} \tag{4}$$

where $\mathbf{C}_{\mathbf{p},\mathrm{CH4}}$ is the specific heat [$\frac{J}{mol \cdot K}$], and $\mathbf{T}$ is the temperature [K].
Table 2 presents the coefficients for the specific heat polynomial of the biomethane model.

Table 2. Polynomial coefficients $C_{p,CH4}(i)$.

Coefficient	Value	Coefficient	Value
a	-5.866×10^{-14}	j	3.216
b	1.158×10^{-11}	k	-25.878
c	-1.061×10^{-9}	l	162.357
d	5.996×10^{-8}	m	-783.748
e	-2.338×10^{-6}	n	2847.063
f	6.668×10^{-5}	o	-7508.321
g	-0.00144	p	13532.974
h	0.0240	q	-14866.436
i	-0.314	r	7516.056

4.2 Biofuels simulation

The phenomenological model was calibrated with the experimental values of the biofuels stipulated based on the study by Berlini (2017), and the values for gasohol were adopted. Table 3 presents the data on the fuels used in the simulation.

Table 3. Experimental fuel data

Fuel	Load	Speed [RPM]	Ignition timing [°]	AFr [λ]	PI [kPa]	PE [kPa]	TI [K]	TE [K]
Biomethane	100%	1800	-24	1	97	110	301.15	845.15
Biomethane	100%	3600	-31.1	1	97	68	301.15	947.15
Ethanol	100%	1800	-12.4	0.99	96	116	306.15	865.11
Ethanol	100%	3600	-14.5	1	96	88	307.15	973.15
Gasohol	100%	1800	-20	1	97	110	301.15	845.15
Gasohol	100%	3600	-20	1	97	110	301.15	845.15

AFr: Air-Fuel relation, PI: Pressure in intake, PE: Pressure in exhaust, TI: Temperature in intake, TE: Temperature in exhaust.

4.3 Engine simulation

Experimental data from a single-cylinder research engine studied by Berlini (2017) were used, and its specifications are presented in Tables 4 and 5.

Table 4. AVL SCRE Model specifications.

Parameter	Value
Type	Single cylinder
Cylinder diameter	82 mm
Stroke length	86 mm
Displacement volume	454.17 cm^3
Compression ratio	13.6:1
Number of valves	4
Type of injection	PFI

Table 5. Valve timing specifications.

Valve timing - Intake	Value
Valve diameter	31 mm
Valve opening time	220°
Intake valve opening	10°
Valve timing - Exhaust	**Value**
Valve diameter	28 mm
Valve opening time	236°
Exhaust valve opening	-242°

4.4 Study boundaries of the LCA methodology

The first phase of LCA is to define the objective, which in this study is the comparison of the environmental performance of gasoline, sugarcane ethanol, and biomethane produced from biogas originating from anaerobic digestion. The functional unit used for comparison is 1 MJ of produced fuel, normalized based on the amount of fuel produced (AFP) relative to the lower heating value (LHV). Inventory data for the conversion routes of the investigated fuels, as well as their properties, are described in Table 6.

In this study, the well-to-pump perspective is used, involving the stages of cultivation (for ethanol and biogas), production of (bio)fuels, and distribution. Figure 4 presents the system boundaries for gasoline (A), ethanol (B), and biogas (C) scenarios.

Table 6. Experimental fuel data

Fuel	Composition	LHV[Mj/kg]	AFP	Inventory data source
Biogas	65% methane and 35% carbon dioxide	22.00	20.79 m^3	Aziz and Hanafiah (2020)
Ethanol	94% ethyl alcohol and 6% water	28.36	69.3 kg	Cavalett *et al.* (2013)
Gasohol C	27% ethanol and 73% gasohol A	43.20	1 kg	Borges and Silva (2004)

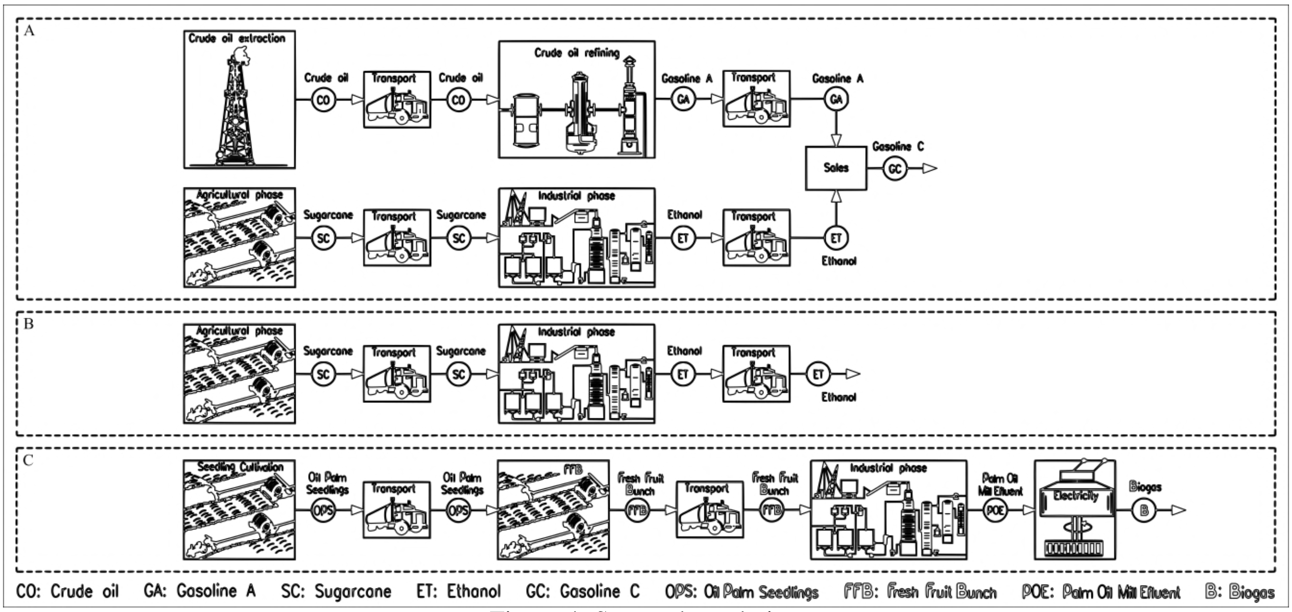


Figure 4. System boundaries.

4.5 Life cycle inventory analysis

The analysis stage of the life cycle inventory, as established by ISO 14040, involves data collection and procedures used to quantify inputs (material and energy flows) and outputs (atmospheric emissions, liquid effluents, and solid waste). The life cycle inventory was developed using the OpenLCA® software based on literature data (Table (6)).

In this study, adapting data closer to Brazilian reality was considered a quality requirement since the database in OpenLCA® is based on the North American context. Figure 5 presents the final stage in the production flowchart of (bio)fuels with their respective system inputs and outputs.

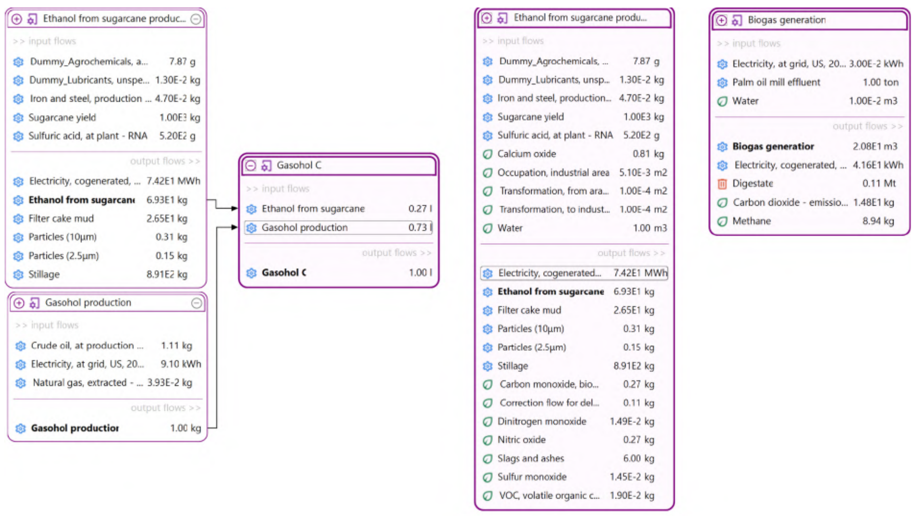


Figure 5. Last stage of the (bio)fuels production life cycle.

4.6 Life cycle impact assessment

The LCIA (Life Cycle Impact Assessment) stage was carried out following the ISO 14044 standard (ISO, 2006b). The method applied in this study is ReCiPe 2016, developed by Huijbregts *et al.* (2017). ReCiPe 2016 assesses 17 different impact categories at the midpoint level and has a stronger relationship with environmental flows as well as lower parameter uncertainty. The impact categories evaluated in this study and their indicators at the midpoint level are summarized in Table (7). The software OpenLCA® was used to perform the study.

Table 7. Overview of the midpoint impact categories and related indicators.

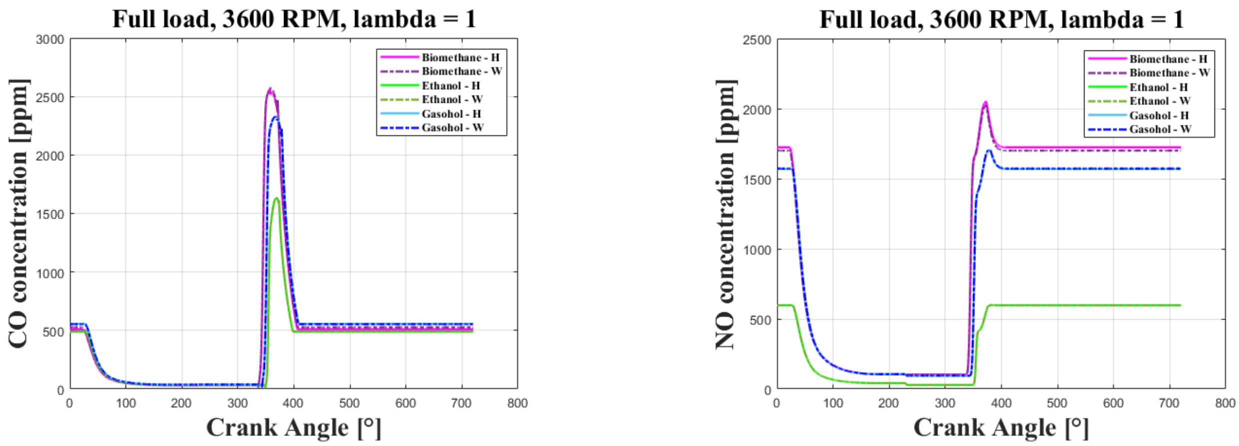
Midpoint impact category	Indicator	CFm	Unit	Key references
Climate change	Infrared radiative forcing increase	Global warming potential (GWP)	kg CO2-eq to air	Lee *et al.* (2023)
Human toxicity: cancer	Risk increase of cancer disease incidence	Human toxicity potential (HTP)	kg 1.4-DCB-eq to urban air	WMO (2011)

CF_m: Characterisation factors.

5. RESULTS AND DISCUSSION

5.1 Results of heat transfer correlations

Concerning emissions, the Hohenberg correlation exhibited remarkable superiority in 75% of the cases for CO emissions and 66.67% for NO emissions. Conversely, the Woschni correlation demonstrates lower emission rates solely during engine operation at high speed (3600 rpm), utilizing either ethanol or gasoline as fuels. The influence of the Hohenberg and Woschni correlations for each fuel is presented in Figure 6a for CO emissions and Figure 6b for NO emissions.



(a) CO formation at 3600 rpm.

(b) NO formation at 3600 rpm.

Figure 6. Influence of heat transfer models on emissions at 3600 rpm.

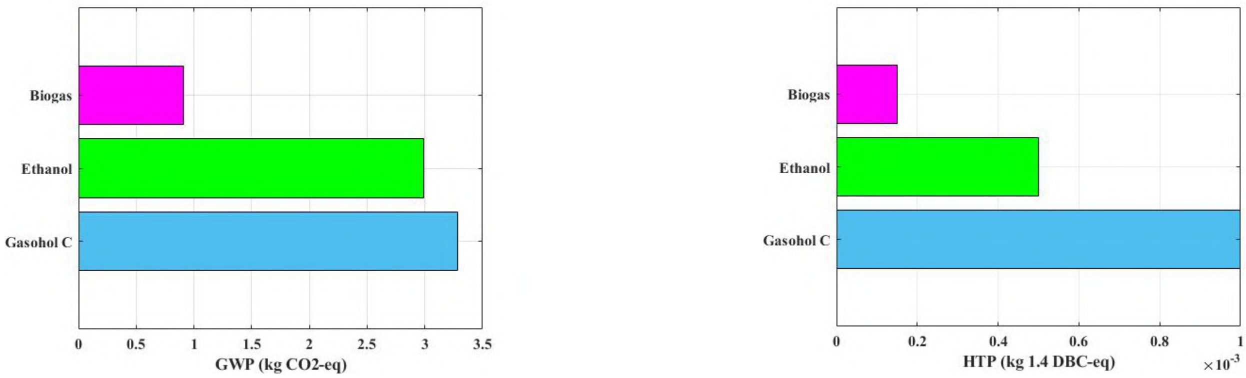
5.2 Results of LCA

The GWP category determines the potential impacts on climate change in terms of kg CO2-eq, where GHG emissions are converted into carbon dioxide equivalents based on their global warming potential. Figure 7a presents the environmental performance of the GWP impact category for the production of (bio)fuels. Regarding GWP, gasoline production represented the worst scenario (3,283 kg CO2-eq), followed by ethanol production (2,988 kg CO2-eq). Biogas production showed the best environmental outcome for the GWP impact category (0.91 kg CO2-eq).

Figure 7b shows the potential impacts of fuel production on HTP in terms of kg 1.4-dichlorobenzene-equivalents (1.4DCB-eq), which represents potential impacts on human health due to toxic emissions to the atmosphere of benzene, ethylene, butadiene, phenols, dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), non-methane volatile organic compounds (NMVOCs), heavy metals, and particulate matter.

Biogas production showed the best environmental result for the HTP impact category (0.15E-03 kg 1.4 DBC-eq), followed by ethanol production (0.50E-03 kg 1.4 DBC-eq). Regarding HTP, the worst case is represented by gasoline production (1.0E-03 kg 1.4 DBC-eq).

Ethanol production contributes significantly to this impact category due to the use of herbicides, pesticides, and fertilizers in agricultural activities.



(a) GWP impacts for the production of (bio)fuels.

(b) HTP impacts for the production of (bio)fuels.

Figure 7. LCA results to GWP and HTP impact categories.

6. CONCLUSION

In this study, the environmental impact in the GWP (Global Warming Potential) and HTP (Human Toxicity Potential) categories of gasoline, sugarcane ethanol, and biomethane from biogas production routes was assessed using the LCA (Life Cycle Assessment) method. Considering the concern about the increase in greenhouse gas emissions from ICE engines, the results show the importance of looking for alternatives to commonly used fuels. Biomethane produced from biogas proves to be more environmentally friendly compared to the production of sugarcane ethanol and gasoline C.

However, the evaluation of the influences of the Hohenberg and Woschni correlations on emissions showed that the use of ethanol reduces NO emissions by about one-third and CO emissions by 40% compared to the use of biomethane and gasoline C. As can be seen from the obtained plots, the Hohenberg correlation shows higher CO and NO emissions for ethanol and gasoline under high speed conditions (3600 RPM), while for biomethane the use of Woschni correlation is superior. Since the presented results were obtained by numerical simulations, further experimental data on different fuels as well as specific engine data are needed to draw comprehensive conclusions regarding the efficiency of these models.

In this context, the potential of biofuels for promoting sustainable economies through the use of renewable resources becomes clear. The growth of sustainability economies can be stimulated by harnessing the potential of biofuels.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

ANP, 2022. “Resolução nº 907, de 18 de novembro de 2022”.

Aziz, N.I.H.A. and Hanafiah, M.M., 2020. “Life cycle analysis of biogas production from anaerobic digestion of palm oil mill effluent”. *Renewable Energy*, Vol. 145, pp. 847–857.

Barin, I. and Platzki, G., 1995. *Thermochemical Data of Pure Substances*. VCH, Weinheim; New York, 2003rd edition.

Bello, A., Lyro, B., Paiva, G., zalez, G., Araújo, G., Lima, H., Sampaio, L., Guimarães, P., Guedes, R., Moraes, T., Telles, Y., Szklo, A., Império, M., Poggio, M. and Schaeffer, R., 2023. “Neutralidade de carbono até 2050: Cenários para uma transição eficiente no brasil”. URL `www.cebri.org`.

Berlini, R.R., 2017. “Estudo experimental da tecnologia dual-fuel em motor de combustão interna utilizando biogás, gnv e etanol”.

Borges, F.J. and Silva, G.A.d., 2004. *Inventário do ciclo de vida do PVC produzido no Brasil*. Master’s thesis, Universidade de São Paulo.

Borman, G. and Nishiwaki, K., 1987. “Internal-combustion engine heat transfer”. *Progress in Energy and Combustion Science*, Vol. 13, pp. 1–46. ISSN 0360-1285.

BRASIL, 2021. “Dispõe sobre a política nacional de biocombustíveis (renovabio) e dá outras providências.”

Cavalett, O., Chagas, M.F., Seabra, J.E. and Bonomi, A., 2013. “Comparative lca of ethanol versus gasoline in brazil using different lcia methods”. *International Journal of Life Cycle Assessment*, Vol. 18, pp. 647–658. ISSN 16147502.

CIBiogás, 2022. “Panorama do biogás no brasil 2021”. pp. 17–17.

Coltro, L., Mourad, A., Garcia, E.E.C., Queiroz, G.C., Gatti, J. and Balan, S., 2007. “Avaliação do ciclo de vida como instrumento de gestão”.

de Souza, L.L.P., 2015. “Avaliação do ciclo de vida do sistema veículo/combustível no brasil”.

de Souza, L.L.P., Lora, E.E.S., Palacio, J.C.E., Rocha, M.H., Renó, M.L.G. and Venturini, O.J., 2018. "Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in brazil". *Journal of Cleaner Production*, Vol. 203, pp. 444–468. ISSN 09596526.

Ferreira, S.F., Buller, L.S., Berni, M. and Forster-Carneiro, T., 2019. "Environmental impact assessment of end-uses of biomethane". *Journal of Cleaner Production*, Vol. 230, pp. 613–621. ISSN 0959-6526.

González, F.O.C., 2010. "Avaliação do desempenho de um sistema integrado motor ciclo otto/gaseificador co-corrente utilizando modelagem matemática".

Gustavo, P., Nunes, K., Luiz, W. and Gallo, R., 2017. "Investigations of effects of timing injection in four-stroke direct-injection diesel engine performance".

Heywood, J., 1988. *Internal Combustion Engines Fundamentals.* (A. D. Morris, Ed.) McGraw-Hill.

Hohenberg, G.F., 1979. "Advanced approaches for heat transfer calculations". *SAE International Off-Highway and Powerplant Congress and Exposition*, , No. 0148-7191, p. 19.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A. and van Zelm, R., 2017. "Recipe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level". *The International Journal of Life Cycle Assessment*, Vol. 22, No. 2, pp. 138–147. ISSN 1614-7502.

ISO, 2006a. "Iso 14040 environmental management-life cycle assessment-principles and framework management environnemental-analyse du cycle de vie-principes et cadre".

ISO, 2006b. "Iso 14044 environmental management-life cycle assessment-requirements and guidelines management environnemental-analyse du cycle de vie-exigences et lignes directrices".

Kalghatgi, G., 2022. "Is it the end of combustion and engine combustion research? should it be?" *Transportation Engineering*, Vol. 10, p. 100142.

Lakshminarayanan, P.A. and Aghav, Y.V., 2010. *Modelling Diesel Combustion*. Springer.

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C. and Romero, J., 2023. "Synthesis report of the ipcc sixth assessment report (ar6)".

Mattos, A.P., 2018. "Estudo do desempenho de um motor turbo alimentado a etanol empregando egr para redução de emissões de nox e controle de detonação."

Moraes, B.S., Zaiat, M. and Bonomi, A., 2015. "Anaerobic digestion of vinasse from sugarcane ethanol production in brazil: Challenges and perspectives". *Renewable and Sustainable Energy Reviews*, Vol. 44, pp. 888–903. ISSN 18790690.

Nishiwaki, K., Shimamoto, Y. and Miake, K., 1979. "Average heat transfer coefficients on a cylinder wall in the intake and exhaust process of motoring test". *Bulletin of the JSME*, Vol. 22, No. 174.

Sato, M. and Hansen, J., 2023. "Updating the climate science".

Sinigaglia, T., Freitag, T.E., Machado, A., Pedrozo, V.B., Rovai, F.F., Guilherme, R.T.G., Lanzanova, T.D.M., Nora, M.D. and Martins, M.E.S., 2022. "Current scenario and outlook for biogas and natural gas businesses in the mobility sector in brazil". *International Journal of Hydrogen Energy*, Vol. 47, pp. 12074–12095. ISSN 03603199.

Souza, L.L.P.D., 2021. "Análise do ciclo de vida consequencial da maximização das fontes renováveis em cenários futuros da matriz elétrica no brasil análise do ciclo de vida consequencial da maximização das fontes renováveis em cenários futuros da matriz elétrica no brasil". p. 194.

UNICA, 2023. "UNICA works cited: Renovabio avoids the emission of 94.5 million tons of co_2 (in portuguese) (web publications)". União da Indústria de Cana-de-Açúcar e Bioenergia, https://unica.com.br/noticias/renovabio-evita-emissao-de-945-mi-de-toneladas-de-co2/. Accessed 11 Jun 2023.

Vidal, F., 2020. "Produção e mercado de etanol". *Caderno Setorial ETENE*, Vol. 121.

WMO, 2011. "Scientific assessment of ozone depletion: 2010". Technical report, Global Ozone Research and Monitoring Project-report no.52. World Meteorological Organization, Geneva.

Woschni, G., 1967. "A universally applicable equation for the instantaneous heat transfer coefficient in the internal combustion engine". *SAE transactions*, Vol. 76.

Zickfeld, K., Eby, M., Matthews, H.D. and Weaver, A.J., 2009. "Setting cumulative emissions targets to reduce the risk of dangerous climate change". *Proceedings of the National Academy of Sciences*, Vol. 106, No. 38, pp. 16129–16134.

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