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ECOLOGICAL EFFICIENCY OF COMPRESSION IGNITION ENGINE USING DIESEL, BIODIESEL AND HVO

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Abstract. *The energy ecological efficiency methodology possesses broad applicability to thermal systems. This approach incorporates multiple factors, including fuel combustion emissions, fuel calorific value, and engine thermal efficiency, enabling the assessment of potential human and environmental impacts, closely linked to the concept of CO₂ equivalent. In this research, we employed the ecological efficiency indicator to evaluate emissions resulting from the combustion of compression-ignition (CI) engines fueled by biodiesel, HVO, petroleum diesel, and their respective blends. The findings revealed that pure HVO demonstrated the highest ecological efficiency values, with biodiesel following closely at 0.63 and 0.55, respectively.*

Keywords: *HVO, energy ecological efficiency, carbon dioxide equivalent, pollutant emissions.*

1. INTRODUCTION

The study of atmospheric pollution has been extensively explored owing to its significant implications for the ecosystem and overall life dynamics. Pollution arises from diverse sources, comprising anthropogenic and natural origins, including volcanic emissions, among others. Notably, a substantial portion of pollution stems from human activities, predominantly attributed to various modes of transportation, whether terrestrial or otherwise, primarily reliant on petroleum-based fuels.

Globally, the transportation sector is responsible for approximately one-sixth of greenhouse gas (GHG) emissions, encompassing both indirect emissions, such as a small portion of electricity usage, and direct emissions resulting from the combustion of fossil fuels to facilitate transportation activities. Despite the allowance and even surpassing of necessary energy generation requirements, the utilization of fossil fuels carries adverse environmental consequences (LIMA et al., 2021). The production cycle of fossil fuels poses numerous challenges, including limited oil reserves, and raises concerns regarding national security, given the reliance on raw materials from politically unstable regions (BARMA, 2021). The escalating awareness of climate change has spurred initiatives aimed at environmental preservation, attributing much of the observed changes to the augmented concentration of polluting gases in the atmosphere (KOLOSZ et al., 2020; MULLIGAN et al., 2013).

In the progressive advancement of human civilization, the fundamental need to establish a reliable energy supply is of paramount significance, necessitating the exploration of alternatives that mitigate the repercussions associated with fossil fuel consumption. As the global population expands, urbanization progresses, and novel technologies emerge, the urgency to satisfy energy requirements for sustaining these activities and meeting daily demands becomes ever more critical (KAARSTAD, 1995). Consequently, to cater to the escalating energy demands, various alternative sources have been developed, including nuclear energy, renewable resources like wind and solar power, and biofuels (EPE, 2007). The latter, also known as agrofuels, distinguish themselves from fossil fuels due to their biological origin, relying on raw materials cultivated extensively in agricultural fields, thereby making agriculture a fundamental cornerstone of their production (AUSTIN; JONES; CLARK, 2022). Within the context of perpetually increasing energy demands, biofuels derived from biomass emerge as a promising and sustainable alternative (MÜLLER-LANGER; MAJER; KEEFFE, 2014).

In Brazil, the transport sector accounts for the highest consumption of diesel oil, comprising 41% of the total, with 94% of this consumption attributed to the road transport system. As per the projections of the “Plano Decenal de Energia 2031” (2022), it is anticipated that petroleum diesel will satisfy 51% of the transport sector's demand by 2031. Presently, the Brazilian market offers diesel ULSD (Ultra-low sulfur diesel) S10, with a maximum sulfur content of 10 mg/kg, specifically developed for light and heavy vehicles. Additionally, Diesel Oil S500 is available, with a maximum total sulfur content of 500 mg/kg, and Non-Road Diesel (S1800) with a maximum sulfur content of 1800 mg/kg, intended for applications in power generation (thermal power plants), rail transport, and open-pit mining (PETROBRAS, 2021). Table 1 displays the maximum allowable sulfur content of diesel oils presently sold in Brazil, along with the associated usage types.

Table 1. Diesel Oil Sold in Brazil: Sulfur Content and Application Classifications.

Fuel	Maximum sulfur content (mg/kg)	Application
Diesel S10	10	Road use
Diesel S500	500	Road use
Diesel S1800	1800	Non-road use

Two biofuels widely produced in Brazil are ethanol and biodiesel, which are sold in the transport sector added to gasoline and diesel respectively. Currently, biodiesel production in Brazil is mostly based on soybean oil.

Biodiesel, chemically composed of long-chain monoalkyl esters and fatty acids derived from renewable sources like vegetable oils and animal fats, finds application in compression ignition engines and various thermal machines (ZHANG et al., 2003). Its production involves transesterification, wherein vegetable or animal fats or oils reacts with alcohol in the presence of a catalyst. Biodiesel offers numerous advantages, including its renewability, low sulfur and aromatic compounds content, high flash point, enhanced lubricity, higher cetane number, greater biodegradability, and also is a non-toxicity biofuel. Additionally, the presence of oxygen in the biodiesel molecule aids in the combustion process. However, certain limitations must be considered, such as higher viscosity, higher pour point, lower heating value, and reduced volatility compared to conventional diesel (CAVALCANTI et al., 2019; GIAKOUMIS; SARAKATSANIS, 2019). In Brazil, biodiesel is commercially available at filling stations blended with petroleum diesel. Presently, the sales proportion stands at 12% biodiesel and 88% diesel oil, with a planned increase to 20% by the year 2026 (DOU, 2023).

In the context of seeking alternatives to fossil-origin diesel oil, hydrotreated vegetable oil (HVO) also known as Renewable diesel, commonly referred to as green diesel, has emerged as another promising biofuel alongside the well-established biodiesel. HVO is characterized as a straight-chain paraffinic hydrocarbon, devoid of oxygen and sulfur, obtained through the hydrotreatment of triglycerides. Commercial implementation of HVO began in 2007, positioning it as a second-generation biofuel, boasting superior combustion properties compared to regular diesel. A key advantage lies in its seamless compatibility with conventional diesel engines, eliminating the need for engine modifications or exhaust gas after-treatment devices (LINDFORS, 2010; NESTE, 2009; NESTE CORPORATION, 2020; SONTALIA; KUMAR, 2019). HVO offers significant advantages over fossil diesel. These advantages encompass a higher cetane number and a narrow boiling range, aligned with the midpoint of the diesel range. Such characteristics facilitate quicker vaporization of HVO, leading to reduced ignition delay and enhanced combustion in compression ignition (CI) engines. Additionally, HVO exhibits lower volatility at room temperature. The utilization of HVO has been correlated with augmented thermal engine efficiency and diminished emissions of regulated pollutants (BORTEL et al., 2019 and PINTO et al., 2023). Table 2 provides an overview of some typical properties of S10 diesel, biodiesel produced from waste cooking oil, and HVO.

The use of fuels in MCI (Mobile Compression Ignition) engines generates atmospheric environmental impact, resulting in emissions of various gases in the exhaust, irrespective of whether the fuel used comes from biomass or not. One approach to assessing a fuel's environmental friendliness is by calculating its ecological efficiency. This methodology allows for evaluating the environmental impact caused by a fuel based on its low heating value (LHV), the efficiency of the heat engine employed, and the exhaust gases emitted during combustion, enabling the representation of the fuel's pollution level as a single value (CARNEIRO; GOMES, 2019).

The objective of this study is to evaluate the potential toxicity to human health and the impact on climate change resulting from the use of various fuels: fossil diesel oil, biodiesel, HVO (Hydrotreated Vegetable Oil), and their mixtures, by calculating the ecological efficiency " ϵ ". Pollutants emitted during fuel combustion are determined through an analysis of combustion stoichiometry. In the case of PM (Particulate Matter) and NO_x emissions, data were collected from experimental studies available in the literature.

Table 2. Typical diesel, biodiesel and HVO specifications.

Property	DIESEL	BIODIESEL	HVO
Appearance at 25°C	Yellowish transparent	Light yellow to orange	Clear and transparent
C (% mass)	84.61	76.88	84.75
H (% mass)	15.39	11.46	15.39
O (% mass)	0.00	11.64	0.00
S (% mass)	0.001	0.00	0.00
Approximate molecular formula	C ₁₂ H ₂₆	C _{12.82} H _{22.76} O _{1.46}	C ₁₄ H ₃₀
H/C ratio	1.84	1.77	2.14
LHV (MJ/kg)	41.03	39.26	44.10
<i>A/Fest</i>	14.92	12.19	14.89
Specific mass at 20°C (kg/m ³)	846.6	880	780
Kinematic viscosity at 40°C (mm ² /s)	2.88	4.5	2.82
Distillation rank (°C)	250-360	350-370	180-320
Total aromatics (% mass)	30	0	0
Cetane number	50.5	50	70
Lubricity at 60°C (µm)	543.5	194.5	≈ 680
Stability storage	Good	Challenging	Good

Source: (DA COSTA, 2021; DA COSTA et al., 2022; GARRAÍN et al., 2014; MATTOS, 2012).

2. EMISSIONS

The main sources of pollutant emissions are the gases released during the combustion process in devices that harness the thermal energy generated (CARVALHO JR; LACAVA, 2003). It is crucial to analyze the combustion byproducts when studying internal combustion fuels and engines. Exhaust gases from compression-ignition engines contain nitrogen oxides, commonly known as NO_x (consisting of nitric oxide, NO, and small amounts of nitrogen dioxide, NO₂), organic compounds (unburned or partially burned hydrocarbons - HC), particulate matter (PM), carbon monoxide (CO), and sulfur oxides if the fuel contains sulfur in its composition (HEYWOOD, 2018; MOLLENHAUER; TSCHOEKE, 2010).

The reduction of smoke emissions (particulate matter), carbon monoxide, and unburned hydrocarbons can be achieved by enhancing the processes of air/fuel mixture formation and combustion, thereby contributing to improved engine performance and efficiency (HEYWOOD, 2018). Internal combustion engine projects must aim to strike a balance that meets the emission limits of pollutants while achieving satisfactory engine efficiency levels. An alternative to modifying the design of a specific engine is improving the fuel to be used, which can be achieved by adopting biofuels or their blends.

2.1 Energy ecological efficiency (ϵ)

The ecological efficiency parameter (ϵ) was originally developed by researchers (CÂRDU; BAICA, 1999a) as a method for estimating the overall ecological impact of coal-fired power plants. The energy ecological efficiency methodology was initially designed to provide a single indicator capable of assessing the environmental cleanliness of a fuel for a specific application, where higher values of ecological efficiency indicate a cleaner fuel and vice versa (CARNEIRO; GOMES, 2019). The energy ecological efficiency has been applied in various energy conversion technologies and has undergone modifications by both its creators and other researchers to suit the requirements of specific case studies (ANCONA et al., 2021; CARNEIRO; GOMES, 2019; CORONADO et al., 2009; LAMAS et al., 2013; SANTOS et al., 2014; SOARES et al., 2022).

The concept of carbon dioxide equivalent (CO_{2eq}) was introduced by Cardu and Baica (1999a). CO_{2eq} serves as an auxiliary virtual pollutant encompassing the harmful effects of the exhaust gases of interest. The value of the maximum permissible concentration of CO₂ (10000 mg/m³, approximately 5160 ppm) is divided by the maximum permissible concentration for the most important harmful components of flue gases in the workplace atmosphere, following the

respective industry labor protection standards (CORONADO et al., 2014a; LORA; SALOMON, 2005). This results in equation (1), where CO_2 , SO_2 , and PM represent the emissions resulting from burning one kilogram of fuel.

$$CO_{2\ eq} = CO_2 + 80(SO_2) + 50(NO_2) + 67(PM) \quad (1)$$

The emission values of CO_2 , SO_2 , NO_2 , and PM pollutants can be determined through stoichiometry of the reaction using the elemental composition of the fuel (for CO_2 and SO_2), assuming complete oxidation of all carbon and sulfur present. Additionally, fuel composition can be utilized to calculate particulate emissions using the ash content (SOTOMONTE, 2009). Table 3 presents the maximum allowable limits of the pollutants considered in the calculated carbon equivalent and their respective multiplication factors.

Table 3. Maximum concentrations of CO_2 , SO_2 and NO_x , and respective multiplication factors.

Pollutant emission	Maximum limit	Multiplication factor
CO_2	10000 mg/m ³	1
SO_2	15 mg/m ³	80
NO_x	10 mg/m ³	50
PM	45 mg/m ³	67

Source: CORONADO et al., 2014 (modified).

In the initial proposal by Cardu and Baica (1999b), nitrogen oxides (NO_x), carbon dioxide (CO_2), and sulfur dioxide (SO_2) were considered as the most important harmful components of fuel combustion gases. Later, Villela and Silveira (2007) introduced new pollutants to be considered, such as PM , and CO , H_2S , SO_2 , and N_2O were also added later by Diniz Filho et al. (2013).

After calculating the $CO_{2\ eq}$, the pollution indicator (Π) is calculated, taking into account the carbon equivalent as well as the lower heating value of the fuel (LHV), according to Equation 2.

$$\Pi = \frac{CO_{2\ eq}}{LHV} \quad (2)$$

In this study, the lower calorific value (LHV) is expressed in MJ/kg, while the carbon dioxide equivalent ($CO_{2\ eq}$) is measured in kg of CO_2 per kg of fuel burned (kg/kg). The pollution indicator (Π) is quantified in kg/MJ, wherein "kg" denotes the mass of $CO_{2\ eq}$. It becomes evident that a fuel exhibits superior ecological characteristics when Π is smaller, as this signifies a reduced production of $CO_{2\ eq}$ when generating a unit of useful energy.

The initial methodology of energy ecological efficiency, pioneered by Cardu and Baica (1999a), was marred by the drawback of not encompassing the synergistic or global impact of pollutant gases on the health and well-being of ecosystems, wildlife, and particularly, human beings. This limitation was effectively addressed by Carneiro and Gomes (2019) through the introduction of weighted methodology, which considers human toxicity and global warming potential factors tailored to each specific type of polluting gas.

3. METHODOLOGY

In this work, the modified methodology of energy ecological efficiency developed by Carneiro e Gomes, (2019) will be used. Their methodology divides the pollution indicator (Π) into two components: one that considers the effects on climate change or global warming, denoted as Π_{GW} , and another that accounts for emissions contributing to toxicity in humans, denoted as Π_{HT} . (Carneiro & Gomes, 2019). These components are mathematically expressed in equations (3) and (4), respectively.

$$\Pi_{GW} = \frac{CO_2 + 28CH_4 + 265N_2O}{LHV} \quad (3)$$

$$\Pi_{HT} = \frac{4.54SO_2 + 56.71NO_x + 38.75MP}{LHV} \quad (4)$$

Parallel to the concept of carbon dioxide equivalent ($CO_{2\ eq}$) Carneiro e Gomes, (2019) introduced the 1,4-dichlorobenzene equivalent ($1,4DCB_{2\ eq}$) as a reference substance for calculating human toxicity potentials, a parameter

commonly employed in life cycle analyses (HUIJBREGTS et al., 2000). The effects of 1,4-dichlorobenzene are quantified in kg of 1,4DCB_{2 eq} per 1 inhabitant.

With this approach, Π_{GW} and Π_{HT} measure the potential to cause damage to ecosystem quality and human health, respectively (CARNEIRO and GOMES, 2019). The total emissions pollution indicator is expressed as a single value, which integrates climate change and human toxicity through weights according to Equation (5). Hofstetter et al., (1999) proposed to correlate damage indicators using relative weights based on the "number of premature deaths per million European inhabitants per year," derived from data from European emissions inventories. Hofstetter et al., (1999) divided a total of annual European environmental damage into damage to human health and damage to ecosystem quality, with 74.2% associated with damage to human health and the remaining 25.8% as damage to ecosystem quality.

$$\Pi_T = 0.742\Pi_{HT} + 0.258\Pi_{GW} \quad (5)$$

The factors influencing the magnitude of the environmental impact associated with a particular unit include fuel composition, combustion technology, pollution indicator, and thermodynamic efficiency, as outlined by Coronado et al. (2014). The parameter " ε " is directly related to the thermodynamic efficiency (η), inversely related to the pollution indicator (Π_T), and falls within the range of 0 to 1, along with the thermoelectric efficiency. The aforementioned correlation is denoted mathematically by Equation 6.

$$\varepsilon = \left[c * \frac{\eta}{\eta + \Pi_T} * \ln(K - \Pi_T) \right]^z \quad (6)$$

In ecological terms, a situation where the ecological efficiency parameter (ε) equals 0 for any value of thermodynamic efficiency (η) is considered ecologically unsatisfactory, while a situation where ε equals 1, and Π equals 0, signifies an ideal condition in terms of ecological efficiency.

To exemplify this parameter, we consider the classification of two virtual fuels: pure hydrogen, which would result in an environmental impact of 0% (considering that all hydrogen reacts solely to form water, without considering the potential formation of NO_x due to high temperatures in combustion equipment), and sulfur, which would cause an impact of 100% (CÂRDU; BAICA, 1999b, 1999a; CORONADO et al., 2014a). The ecological efficiency value (ε) varies between zero and one, where $\varepsilon = 1$ represents the ideal value and is attained when using fuels with zero pollution indicators ($\Pi = 0$), regardless of the efficiency (η) of the thermal machine. In contrast, the unsatisfactory value $\varepsilon = 0$ is obtained when using fuels with pollution indicators similar to sulfur, regardless of the efficiency value (CORONADO et al., 2014a; SOTOMONTE, 2009).

The following conditions apply in the calculation of constants c , K , and z (CÂRDU; BAICA, 1999a):

1. K shall be set according to the value of the total emission pollution indicator Π_T for sulfur. For this fuel, the lowest ecological efficiency must be zero for any value of η .

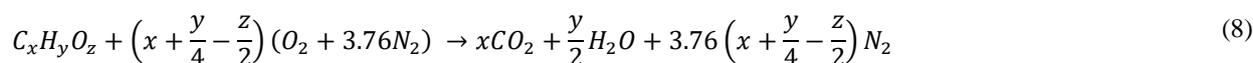
2. Once the value of K is determined, the constant c is calculated from the combustion of hydrogen, which, as previously mentioned, is the ideal fuel when considering water as the only product of combustion. For this fuel, the highest efficiency ($\varepsilon = 1$) must be achieved for any value of η .

3. Petroleum diesel has a total pollution indicator value ($\Pi_T = 0.06$). To calculate constant z , the diesel ecological efficiency value is set to 50% ($\varepsilon = 0.5$), for an engine efficiency of 35%. The value obtained for z was 3.2.

The presented formula incorporates the updated values of constants c , K , and z , enabling the assessment of the ecological impact of diesel, biodiesel, and HVO under specific working conditions, as expressed in Equation 7.

$$\varepsilon = \left[2 * \frac{\eta}{\eta + \Pi_T} * \ln(1.65 - \Pi_T) \right]^{3.2} \quad (7)$$

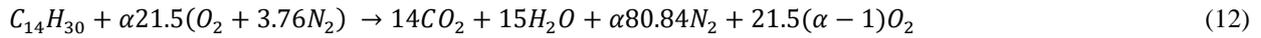
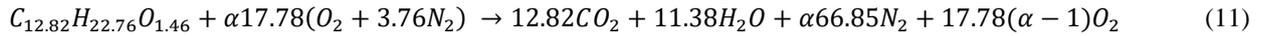
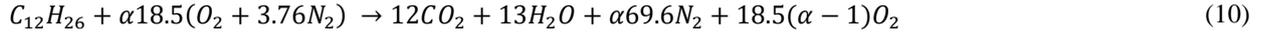
Ecological efficiency values are estimated for internal combustion engines using blends of diesel, biodiesel and HVO. The chemical composition of reagents and products will be used to analyze petroleum diesel, biodiesel and HVO. An excess air ratio of 40% will be considered. An analysis of the stoichiometry of fuel combustion was carried out, using an approach based on the principle of mass conservation of each chemical element of the reactants and on the molecular composition of the fuels. (BEJAN, 2016; HEYWOOD, 2018; TURNS, 2000):



Where " $C_xH_yO_z$ " is the generalized molecular formula of the fuel. The determination of the coefficients x , y and z allows the calculation of the stoichiometric air/fuel ratio (A/F_{est}), according to Equation (9):

$$A/F_{est} = \frac{\left(x + \frac{y}{4} - \frac{z}{2}\right) + (M_{O_2} + 3.76M_{N_2})}{(12.01x + 1y + 16z)} \quad (9)$$

The molar mass of oxygen (M_{O_2}) is 32 g/mol, and the molar mass of nitrogen (M_{N_2}) is 28.02 g/mol. Given that diesel engines generally operate with an air-fuel ratio higher than the stoichiometric one, resulting in an excess of air (lean air-fuel ratio) (HEYWOOD, 2018), the combustion of diesel S10, which contains 10 ppm of sulfur, it will be considered that it reacts completely with oxygen forming sulfur dioxide (SO_2). The combustion of each fuel was analyzed separately using equations (10 - 12) for diesel, biodiesel, and HVO respectively, and subsequently, the mixture proportion of each fuel was applied.



Using equations (10 - 12) and considering an excess of 40% air ($\alpha = 1.4$), the combustion products of diesel, biodiesel, and HVO were individually computed. The calculated products are presented in Table 4. For S10 diesel oil, with a maximum sulfur content of 10 mg/kg representing 0.001% of the fuel's sulfur mass fraction, this corresponds to $5.31e-5$ moles of sulfur in its composition. This amount of sulfur has the capability to contribute a mass fraction of 0.0001% of SO_2 in the products, resulting in 19.98 mg of SO_2 for every kilogram of diesel combusted. Table 4 displays the quantities in metric tons (t) of the products generated from the combustion of 1 m^3 of each fuel, with the calculation considering the density of each fuel.

Table 4. Combustion products.

Product	Diesel*		Biodiesel		HVO	
	% mass	t/m ³	% mass	t/m ³	% mass	t/m ³
CO ₂	14.170	2.62	15.59	2.48	14.22	2.42
H ₂ O	6.286	1.16	5.67	0.90	6.24	1.06
N ₂	73.190	13.56	72.45	11.2	73.18	12.46
O ₂	6.354	1.18	6.29	1.00	6.35	1.08

*1 m³ of burned S10 diesel has the capacity to generate 16.95 gr SO₂ (16.95gr/ m³).

In a study conducted by Bortel et al., (2019), experiments were performed using a 0.5 L single-cylinder research engine without an exhaust gas after-treatment system. The fuels examined included pure diesel oil, a blend of 70% diesel oil and 30% HVO, and pure HVO. Similarly, Da Costa et al., (2022) conducted tests using a single-cylinder, naturally aspirated engine, where the fuels analyzed were HVO and S10 Diesel, a brazilian fuel mixture comprising 90% diesel and 10% biodiesel by volume and with a maximum sulfur content of 10 mg/kg. The experiments conducted by Da Costa et al., (2022) were performed at constant pressure conditions, without the use of an exhaust gas after-treatment system.

The experimental data on exhaust gas emissions from both studies (DA COSTA et al., 2022) (BORTEL et al., 2019) were compiled in Table 5 and were utilized to support the calculation of the ecological efficiency (ϵ). For biodiesel, the particulate matter (PM) and nitrogen oxides (NO_x) values were calculated based on proportions of 105% and 35%, respectively, compared to the corresponding values found in petroleum diesel, as established in the study by Coronado et al., (2009).

Table 5. LHV and exhaust gases in compression ignition engines with diesel, biodiesel, HVO and their mixtures.

Pollutant	Diesel*	HVO30*	HVO*	Biodiesel**
CO ₂ (kg/kg)	3.1231	3.1241	3.1533	-
NO _x (kg/kg)	0.0379	0.0372	0.0380	0.0398
PM (kg/kg)	0.0006	0.0003	0.0001	0.0002
LHV (MJ/kg)	42.7	43.1	44.0	-

Source: Derived from: *Bortel et al., (2019) and **Coronado et al., (2009).

3.1 The particularity of carbon in biofuels

The Earth's atmosphere maintains a state of equilibrium with various components constituting its composition. Among these components, carbon exists in the form of carbon dioxide (CO₂). Over the course of the last two centuries, the concentration of CO₂ in the atmosphere has experienced a 27 percent increase due to human activities such as the combustion of fossil fuels, deforestation, and land use changes (PACHECO; HELENE, 1990). The burning of fossil fuels results in the oxidation of stored carbon, leading to the release of CO₂ into the atmosphere. Conversely, biofuels derived from biomass play a role in mitigating atmospheric carbon by engaging in a relatively rapid biological cycle. During photosynthesis, terrestrial plants utilize atmospheric CO₂ to construct their tissues, establishing a cyclic exchange of CO₂ with the atmosphere. Additionally, the adoption of biofuels as alternatives to fossil fuels contributes to reducing atmospheric carbon emissions. The combustion of fossil fuels releases carbon that has been sequestered over vast geological time frames, accentuating the significance of biofuels, such as biodiesel and HVO, in mitigating greenhouse gas emissions, particularly CO₂, in comparison to traditional fossil fuels (CORONADO et al., 2014; PACHECO; HELENE, 1990).

The life cycle analysis conducted by Sheehan et al., (1998) on biodiesel revealed a notable reduction of 78% in net CO₂ emissions compared to petroleum-derived diesel. Similarly, Xu; Lee and Wang, (2020) investigated the life cycle analysis of palm oil-based hydrotreated vegetable oil (HVO) and found a substantial reduction in greenhouse gas (GHG) emissions ranging from 85% to 84% relative to petroleum diesel. Moreover, Kalnes et al., (2009) observed significant savings in fossil emissions between 66% and 84% when comparing green diesel to petroleum diesel. Based on these previously published life cycle analysis studies, the use of pure biodiesel results in approximately 0.577 ton of CO₂ per m³ of fuel burned. Similarly, in the case of pure HVO, under the most favorable conditions, approximately 0.393 ton of CO₂ per m³ of fuel burned will be generated.

In the calculation of ecological efficiency, different fuel blends were considered, including pure diesel oil (D), biodiesel (BD), and HVO (HVO), as well as blends of diesel with biofuels: B10 (90% diesel and 10% biodiesel), B20 (80% diesel and 20% biodiesel), and HVO20 (80% diesel and 20% HVO). Experimental values from previous works by Bortel et al., (2019) were used to determine emissions of PM and NO_x, while CH₄ and N₂O emissions were considered negligible.

Table 6 presents the emissions of pollutants resulting from the combustion of pure diesel oil (D), biodiesel (BD), and HVO (HVO), as well as blends of diesel with biofuels, where B represents biodiesel. The number after the biofuel designation represents its proportion in the blend, with B10 indicating a blend with 90% diesel fossil and 10% biodiesel, and so on.

Table 6. Comparison of Pollutants Emitted from Studied Fuels and Their Blends.

Pollutant	D	B10	HVO10	B20	HVO20	B30	HVO30	B	HVO
CO ₂ (kg/kg)	3,10057	2,85873	2,83703	2,61689	2,57348	2,37504	2,30993	0,68213	0,46509
SO ₂ (kg/kg)	0,00002	0,00002	0,00002	0,00002	0,00002	0,00001	0,00001	0,00000	0,00000
NO _x (kg/kg)	0,03789	0,03808	0,03790	0,03827	0,03791	0,03845	0,03792	0,03978	0,03801
PM (kg/kg)	0,00057	0,00051	0,00051	0,00046	0,00046	0,00040	0,00040	0,00020	0,00012

4. RESULTS AND CONCLUSIONS

Energy ecological efficiency values were computed for diesel, biodiesel, HVO, and their respective mixtures: B10, HVO10, B20, HVO20, B30 and HVO30. The resulting ecological efficiency values (ϵ), pollution factors related to global warming (Π_{GW}), human toxicity (Π_{HT}), and the overall total Π_T are listed in Table 7.

Table 7. Parameters of ecological efficiency values for the studied fuels.

Parameter	D	B10	HVO10	B20	HVO20	B30	HVO30	B	HVO
CO _{2eq} (kg/kg)	3,10	2,86	2,84	2,62	2,57	2,38	2,31	0,68	0,47
Π_{GW} (kg/MJ)	0,08	0,07	0,07	0,06	0,06	0,06	0,06	0,02	0,01
1.4DCB _{2eq} (kg/kg)	2,17	2,18	2,14	2,19	2,10	2,20	2,07	2,26	2,01
Π_{HT} (kg/MJ)	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,06	0,05
Π_T (kg/MJ)	0,06	0,06	0,06	0,06	0,05	0,06	0,05	0,05	0,04
ϵ	0,48	0,49	0,50	0,49	0,51	0,50	0,53	0,55	0,63

In the case of pure diesel oil, the ecological efficiency (ϵ) was found to be the lowest among all the studied fuels ($\epsilon = 0.48$). Conversely, pure HVO and pure biodiesel exhibited the highest ϵ values, measuring 0.63 and 0.55, respectively. These ecological efficiency values align with the net CO₂ emissions of these biofuels, wherein lower CO₂ emissions correspond to higher ϵ , as observed in the case of HVO, followed by biodiesel. Notably, HVO demonstrated a more pronounced increasing linear trend in ϵ concerning its proportion in blends with diesel oil, in comparison to the linear trend observed in biodiesel mixtures with petroleum diesel, as depicted in Figure 1.

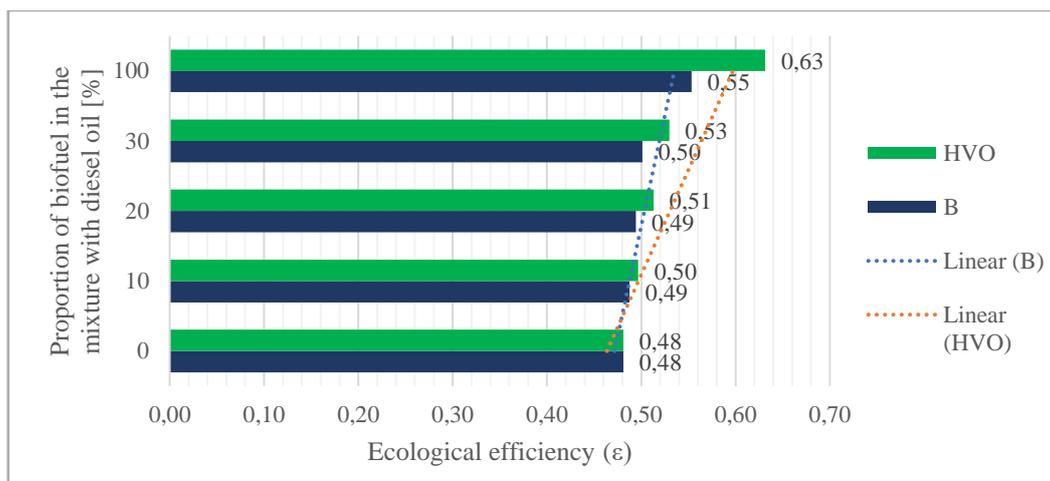


Figure 1. Comparative Analysis of Ecological Efficiency in Diesel, Biodiesel, Hydrotreated Vegetable Oil (HVO), and Their Blends.

Energy ecological efficiency was computed using experimental emissions data from the studies conducted by Bortel et al., (2019). This was done as a means of comparison with the results obtained from stoichiometric calculations. The corresponding values are provided in Table 8.

Table 8. Ecological Efficiency Results Based on Published Experimental Data.

Ecological Efficiency	Diesel	HVO30	HVO
ϵ	0.493	0.502	0.504

Source: prepared by the authors using data from Bortel et al., (2019).

In the process of conducting a comparative assessment of the efficiency values between HVO and diesel oil, derived from the experimental exhaust gas data published in the study by Bortel et al. (2019), HVO exhibited an increase of 1.83% in energy ecological efficiency compared to diesel oil. The energy ecological efficiency analysis proves to be a versatile tool for evaluating various fuels, providing a single value that encompasses their effects on human health and the environment. Based on the energy ecological efficiency stoichiometric values obtained for the fuels under investigation, it is evident that renewable fuels, such as biodiesel from residual oil and HVO, exhibit a lower environmental impact when compared to the damage caused by petroleum diesel when utilized in an internal combustion engine.

In the context of the Brazilian energy scenario, which endeavors to enhance the presence of biofuels in the road fleet, the energy ecological efficiency analysis of HVO suggests its potential in attaining the target of a 20% biofuel share in the blend with petroleum diesel by the year 2026.

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