



COB-2021-1768

LIFE CYCLE ANALYSIS AND EXPERIMENTAL TESTS ON DYNAMOMETER BENCH USING HVO COMPARED TO DIESEL.

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Abstract. *The search for renewable alternatives for the gradual replacement of fossil fuels is one of the great challenges of the contemporary world. Due to the intense use of fossil diesel emissions the development of new renewable fuels is a good practice nowadays. Hydrotreated vegetable oil (HVO) is an alternative to biofuels recently developed, with application in internal combustion engines has shown promising. In this way, a HVO from palm oil life cycle assessment was performed, when operated on an internal combustion engine with compression ignition. 200 l of HVO from NESTE Oil fuel were imported to carry out the experimental test at UNIFEI. For this purpose, experimental tests were carried out on a dynamometer bench in a specially designed with a single cylinder engine. With the tests, pollutant emission parameters were obtained and used in the life cycle assessment, using the software Simapro 9. Results have shown that HVO has the potential to reduce the Global Warming Potential up to 11,7%, the specific emission of NO_x up to 25%. Although, the acidification and eutrophication potential of HVO are higher when compared to fossil diesel, due to the input of compounds such as NPK, during the cultivation process of the raw material.*

Keywords: HVO, LCA, biofuel, GWP

1. INTRODUCTION

Most of the energy consumed, both in Brazil and in the world, comes mainly from nonrenewable sources like petroleum. According to EPE (2020) over 50% of the world's energy production is dependent on natural gas and petroleum. In Brazil, similarly, non-renewable resources also supply the energy demand. According to Ghesti (2009), due to the great polluting potential and the possibility of oil extraction reserves depletion, the alternative of using biofuels to meet the world's energy needs is considered. The biofuels are classified as follows, according to Soriano et al. (2018):

Biodiesel, which is composed of long-chain carboxylic acid alkyl esters, produced from the transesterification of animal or vegetable triglycerides;

Isoprenoids, which are compounds derived from isoprene (C₅H₈), and, as mentioned by Soto et al. (2019), farnesane, the most common fuel. Its Direct sugar to hydrocarbon (DSHC) production process begins with the fermentation of sugars derived from biomass by genetically modified microorganisms, obtaining a compound called Farnesene, which is later hydrogenated to generate Farnesane;

Alkane/olefin mixtures are paraffinic structures formed by compounds obtained by the hydrotreating process of vegetable oils. Singh et al. (2018) mentions that although raw materials may be similar to those used in biodiesel production, the hydrogenated vegetable oil (HVO) properties are closer to those of conventional diesel (generally with a higher cetane number and calorific power).

As expected, the impact caused to the environment by renewable fuels should be smaller compared to the harm caused by fossil fuels such as fossil diesel. Therefore, this article evaluates the cradle-to-grave life cycle of HVO, applied to an experimental bench with a dynamometer and single-cylinder compression ignition (IC) internal combustion engine (ICE).

Hydrotreated vegetable oil is a paraffinic oil produced from several types of vegetable oils, such as canola, sunflower, soybean and palm oil, in addition to animal fats. It can be used in conventional diesel engines, pure or mixed with fossil diesel. Recent studies indicate that HVO can directly replace conventional diesel or be mixed with it in any proportion, without modifying the ICE. (DIMITRIADIS et al., 2018). Some important properties of HVO are shown in Table 1. It is possible to observe that HVO has lower specific mass, viscosity and distillation point, which results in better outcomes for fuel injection and burning, compared to conventional diesel. In addition, HVO has an energy content similar to conventional diesel, but with a lower sulfur content, which results in a reduction in pollutant emissions. (SORIANO *et al.*, 2018). Furthermore, HVO has a high number of cetane and due to the lack of oxygen in its composition, the problem of oxidation does not occur when stored for long periods.

Table 1. Comparison between chemical and physical properties of EN 590 fossil diesel and HVO [Arvidsson (2011)]

Property	EN 590 Diesel	HVO
Density at 15°C, kg/m ³	835	775-785
Viscosity at 40°C, mm ² /s	3,5	2,9-3,5
Distillation 90% vol, °C	350	295-300
Lower heating value, MJ/kg	43	44
Sulfur content, mg/kg	<10	~0
Oxygen content, wt-%	0	0
Cetane number	53	84-99

Some companies such as Neste Oil Corporation and Universal Oil Products (UOP) produce hydrotreated vegetable oils. The Neste Oil fuel has the trade name NExBTL and the UOP fuel is known as Green Diesel.

2. GOAL AND SCOPE

A life cycle assessment of HVO from two different types of raw material was developed with the aim of quantifying the environmental impacts from the raw material cultivation, through the stages of vegetable oil extraction, hydrotreatment, transport and end use in an ICE. Previous studies on the life cycle of Green Diesel have already been developed, such as Sunde, Brekke and Solberg (2011) that compared the life cycle of three types of green fuels: biodiesel, HVO and BTL (biomass to liquid) produced from wood. The analysis ranked the environmental performance, the raw material and fuel production costs. The results indicated that HVO produced from waste cooking oil is more advantageous than biodiesel and BTL both in production costs and environmental impacts. However, the raw material availability for HVO production from waste cooking oil is limited and other raw materials should be used to support this green fuel. The authors also claim that the biofuel production from vegetable raw material is extremely important in the sector, even though the energy consumption for converting raw material into the final product requires high energy. Arvidsson et al. (2011) who performed a life cycle analysis of HVO from canola, palm and jatropha vegetable oil, operating in an ICE for power generation, comparing to conventional fossil diesel, where it was inserted that HVO has lower global warming potential than conventional diesel, for any raw materials used. The main contribution to the global warming potential is due to the nitrous oxide emission from the soil. Nitrogen oxides and ammonia emissions from the soil are responsible for almost the entire eutrophication potential of the HVO life cycle and contribute significantly to the acidification potential. Garraín, Lechón and Santamaría (2016) evaluated from an economic point of view, the environmental consequences of an HVO biofuel obtained from palm oil in the Spanish scenario. The results were compared with two counterparts: a fossil diesel with low sulfur content (<10 ppm) and another palm oil biofuel obtained by transesterification using the FAME method (fatty acids methyl esters). The evaluation concluded that FAME and HVO would have a worse environmental performance when compared to diesel due to increased nitrogen oxides, small particles and ammonia emissions. According to the authors, these emissions cannot be offset by reductions of other pollutants emissions, such as sulfur dioxides and greenhouse gases. Soam and Hillman (2019) analyzed the factors influencing environmental sustainability and the HVO growth in Sweden, comparing production from palm and canola oil with vegetable oil residues. The LCA studies revealed that the cultivated feedstock (palm and canola) has greater GHG emissions throughout the life cycle than the residual feedstock. However, due to the limited supply of residual raw material, it is necessary to become more dependent on sustainable resources.

Considering these studies results, it is not possible to affirm that the use of Green Diesel is capable of producing only positive results, as with any technology, there are pros and cons to its application. Life cycle assessment plays a fundamental role in understanding the different impact categories caused by the HVO application. Thus, this LCA aimed to evaluate the different types of environmental impacts caused by the use of hydrotreated renewable diesel operated in a

single-cylinder compression-ignition internal combustion engine on a bench with a dynamometer, operating in a power generation cycle on a small scale in the Brazilian scenario. The assessment was carried out using the Simapro 9 software, which is an important tool for measuring the environmental impacts of different processes. In addition, Ecoinvent 3 and Agro-footprin databases were used as complementary inventory and ReCiPe 2016 Midpoint (E) were used as basic method. The engine has a maximum power of 7.1 kW @ 3600 rpm and a maximum torque of 27 Nm @ 2800 rpm. The vegetable oil used in the operation was considered to be produced from palm oil, which is one of the raw materials used by Neste Oil, and cultivated in the Brazilian state of Pará. The hydrotreatment was considered to be carried out by Neste Oil, in Porvoo, Finland. Figure 1 shows the LCA delimitation, identifying the process stages, their material and energy inputs and their outputs. The impact categories considered in this study were global warming potential (GWP) and acidification potential (AP).

Measurement uncertainties were calculated following the methodology presented in Da Costa et al. (2021), by dividing the analysis into uncertainty due to the records repeatability (type A) and the uncertainty due to the instrument accuracy (type B).

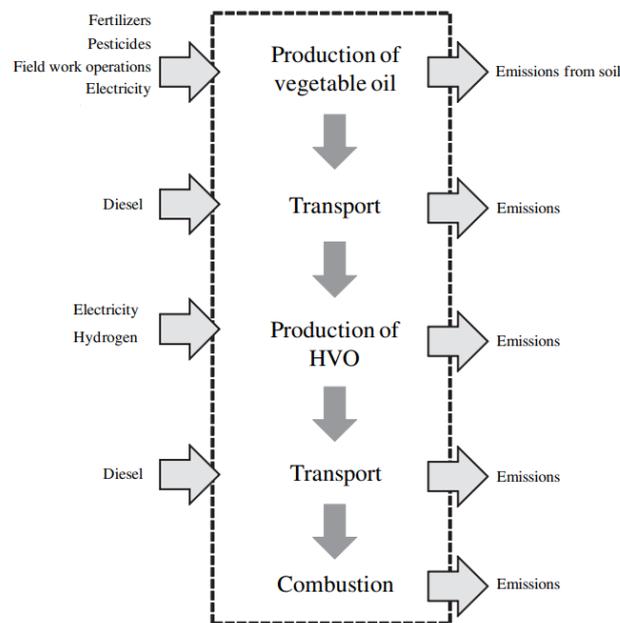


Figure 1. Process tree describing the HVO life cycle. [Arvidsson (2011)]

3. INVENTORY

3.1 Vegetable Oil Production

The data used for the palm oil planting and cultivating stage were used mainly from Mekhilef, Siga E Saidur (2011), Carvalho (2015), Costa (2007) and EPE (2005). According to Mekhilef, Siga E Saidur (2011), palm oil is one of the raw materials for biofuels production with greater prospective, compared to other oilseeds. Palm oil has a higher production yield and less fertilizer, water and pesticides are needed for planting. Palm oil production requires less sunlight, in terms of the energy balance to produce one unit of oil, as it produces more oil per hectare. According to EPE (2005), the estimated palm lifetime is 27 years. The average annual productivity is 15 tons of bunches per hectare per year and fruit production takes place within four years after planting. Costa (2007) mentions that after harvesting, the fruits are transported to the processing plant, where they will be sterilized and cooked. Then, the fruits are macerated and pressed in a digester, where the oil from the bunch's fleshy mesocarp is removed. Crude oil obtained from pressing is transferred to a deaerator, where heavy particles are removed and then clarified to remove moisture and impurities. The palm fruit almonds are broken and laminated by a laminator roller. The paste produced in the lamination is cooked and pressed. The crude oil (palm kernel) is filtered in the filter press and then transferred to the storage tank, extracted mechanically or by solvent. According to Arvidsson (2011), it is possible to obtain 4220 kg/ha of vegetable oil from palm cultivation. For motorized equipment in cultivation, such as tractors and trucks, fossil diesel was considered as fuel.

3.2 Vegetable Oil Transport

The vegetable oil cultivation and extraction stage were considered to be carried out in the Brazilian state of Pará, the largest country's palm producer and where Abrapalma, the largest palm oil producer in Brazil, is located. Transport on land to the Belém Port by heavy duty trucks with trailers, using an operating cycle based on the European Euro IV emissions standard. The total gross load of each vehicle is 40 ton and the diesel consumption considered is 4.9 l per 10 km. The distance is approximately 200km. At the port, the oil is transferred to the cargo ship and transported to Porvoo, Finland, where the HVO production will take place, with a distance of 9820km. Transport from the port to the Neste Oil industrial complex is via pipelines.

3.3 HVO Production

The HVO production goes through different stages, where the main ones are the production of hydrogen used in the hydrotreatment, the triglycerides hydrotreatment, isomerization of the paraffinic chains obtained and the combustion of the propane obtained in the process. Hydrogen production is usually carried out in a steam reformer, where water and natural gas are mixed and react to form hydrogen and carbon monoxide, as explained by Nikander (2008). Then there is the hydrotreatment, stage in which the production of biofuel HVO occurs. To produce 1000kg of green diesel, 1191kg of vegetable oil and 42kg of hydrogen are needed.

According to Lorenzi et al. (2020), the hydrotreatment reactions must often occur between 300 and 450°C and the hydrogen must be in a pressure condition between 3 and 20MPpa. The reaction takes place in some main steps, which are decarboxylation, decarbonylation and deoxygenation. Figure 2 exemplifies the hydrotreatment process for the triolein molecule, which is one of the present compounds in palm oil.

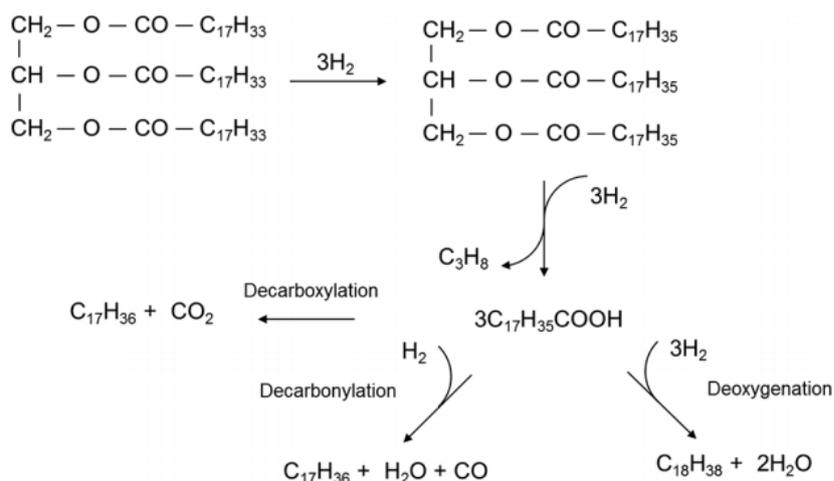


Figure 2 – Hydrotreatment process for the triolein molecule producing heptadecane, octadecane, propane, water, carbon monoxide and carbon dioxide [Lorenzi *et al.* (2020)]

3.4 HVO Transport

From the production plant in Porvoo, the HVO is transported by pipeline to the port and transported by ship to the Port of Santos, Brazil, covering a distance of 11371km. The cargo will then be transferred to heavy duty trucks, using an operating cycle based on the European Euro IV emissions standard. The total gross load of each vehicle is 40 ton and the diesel consumption considered is 4.9 l per 10 km. The distance to the final destination is considered 350km.

3.5 HVO Combustion

The emissions originating from the biofuel combustion were obtained by tests on a four-stroke single-cylinder internal combustion engine with ignition compression, operating as a power generation regime, located in the Thermal Machines Laboratory (LMT) of the Federal University of Itajubá (UNIFEI) shown in Figure 3. Following the guidelines of the ISO 8178 standard, which regulates emissions tests on diesel engines in power generation applications, engine operation was adopted at 1800 rpm and operating load of 10Nm 50% of the maximum load for the selected speed. The rotation was chosen due to the fact that the frequency of electrical energy available in the Brazilian grid is 60 Hz and thus, the coupling of the engine with the generator can be done directly. Furthermore, the HVO mass injected was 0,61 kg/h, considering a

Static start of injection (SOI) of $22^{\circ} \pm 1^{\circ}$ before TDC and a constant injection pressure of 19.6 MPa. The diesel mass injected was 0,701 kg/h and the injection conditions remained the same due to the mechanical injection system.

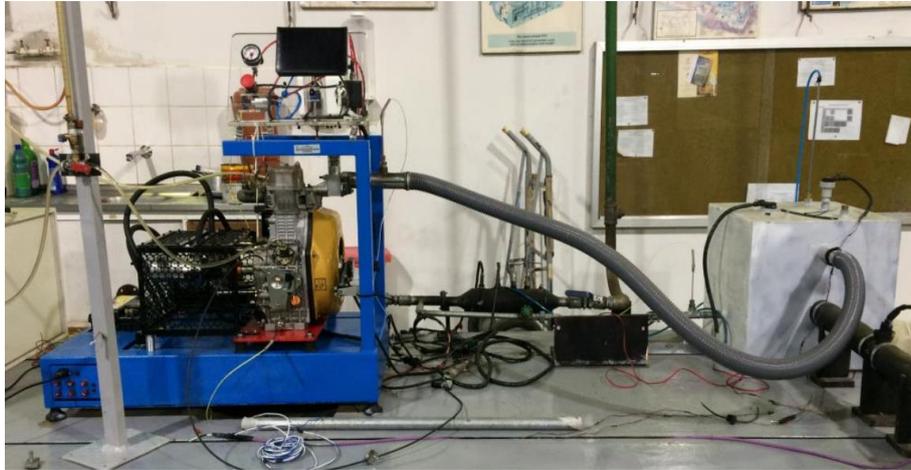


Figure 3. Experimental test bench developed at LMT – UNIFEI

4. RESULTS

4.1 Global Warming Potential

Figure 3 shows the impacts caused by each step of the HVO production process, considering its production from palm oil. Initially, it is possible to notice that the largest portion of contribution to the global warming potential in the process is given to the palm oil cultivation and extraction stage. A large part of the contribution of this stage is due to the modifications made to the soil, mainly related to the deforestation generated by the removal of the pre-existing forest at the cultivation site. Although the cultivation of biomass reinserts the vegetation at the planting site, this modification must be taken into account and contributes to the process. The contribution of the other process steps is mainly due to the use of non-renewable fossil resources in the process, for example, during the hydrogen production step, when natural gas is used as a raw material. Similarly, other steps in the process also end up using non-renewable resources, such as the fossil diesel consumed in the transportation stage.

An important feature of the use of renewable fuels is in the consideration of the biogenic cycle of carbon dioxide production. As mentioned by Head (2021), it is possible to assume, over the life cycle of a biomass, that all carbon dioxide emitted directly from the processing of renewable raw material is absorbed back into nature. Thus, it was considered in this study that all carbon dioxide produced in the combustion of HVO is reabsorbed, thus causing a zero global warming potential for this stage of the biofuel's life.

The Figure 4 compares the characterization of each process step obtained in this study with that obtained by Arvidsson et al. (2011). It is noted that biofuel produced from the feedstock in Brazil presents a greater share of GWP, mainly due to longer distances traveled, for the most part by sea, during the transport of both raw material and fuel. The hydrotreatment process has a similar GWP in both cases, as is to be expected, since the production plant is the same in both studies.

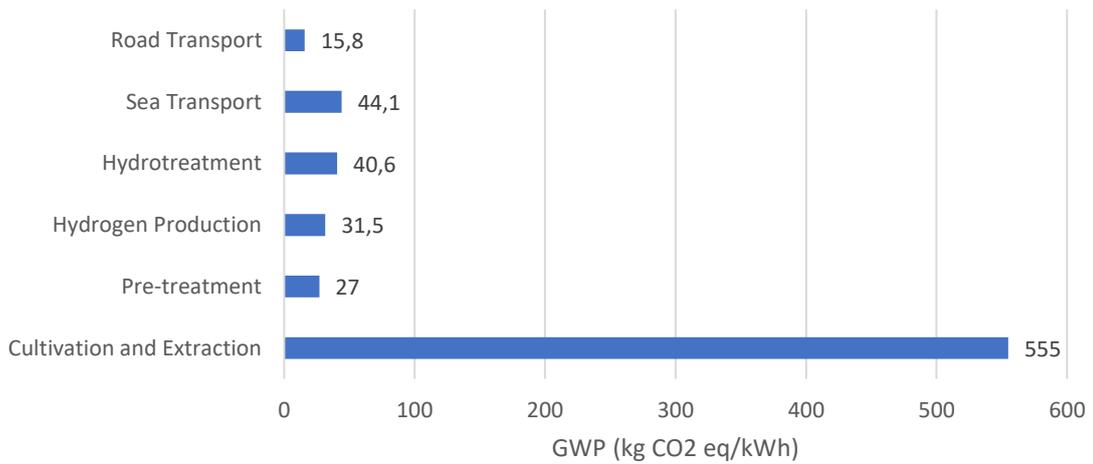


Figure 4 – Global Warming Potential of Palm Oil HVO

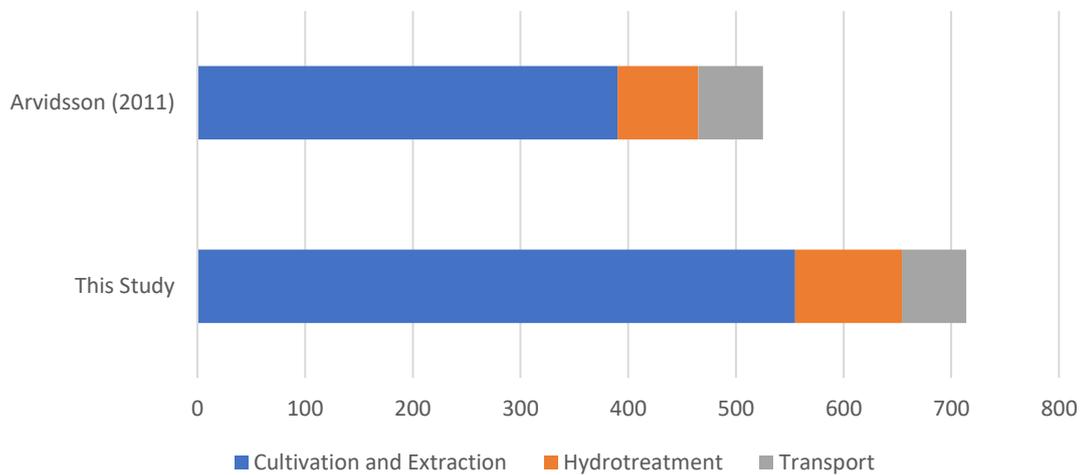


Figure 5 – Characterization of the Global Warming Potential of HVO produced from palm oil compared to Arvidsson et al. (2011)

4.2 Acidification Potential

It is possible to say that the emissions with the main role in increasing acidification are sulfur dioxide (SO₂), nitrogen oxides (NO_x) and ammonia (NH₃). This statement can be confirmed by observing Figure 5, since the stages that contained some form of combustion (Combustion, Marine Transport and Cultivation and Extraction) were the ones that most added to the acidification potential. This can be justified due to the fuel sulfur content, since there are acids formations at the time of combustion that can be deposited in water or soil, causing an increase in acidity. In addition, it is necessary to consider the NH₃ and NO_x emissions from the soil itself, which makes cultivation and extraction the phase with the greatest potential for acidification.

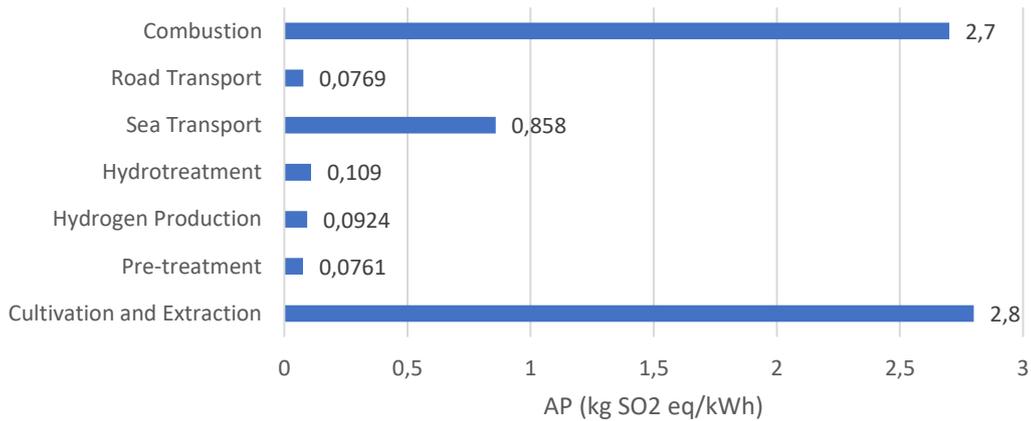


Figure 6 – Acidification Potential of HVO produced from palm oil.

In comparison with the study by Arvidsson et al. (2011), the Figure 6 presents that the stage with the highest potential for acidification was transportation, which can be explained by the long distance traveled to import palm oil from Malaysia. In addition, there is the fact that Arvidsson et al. (2011) considered the destination of solid waste from oil extraction (empty bunches and palm kernel press cake). Thus, it is possible to validate the impact of the transport step in the stages of the life cycle of the HVO when it comes to acidification potential.

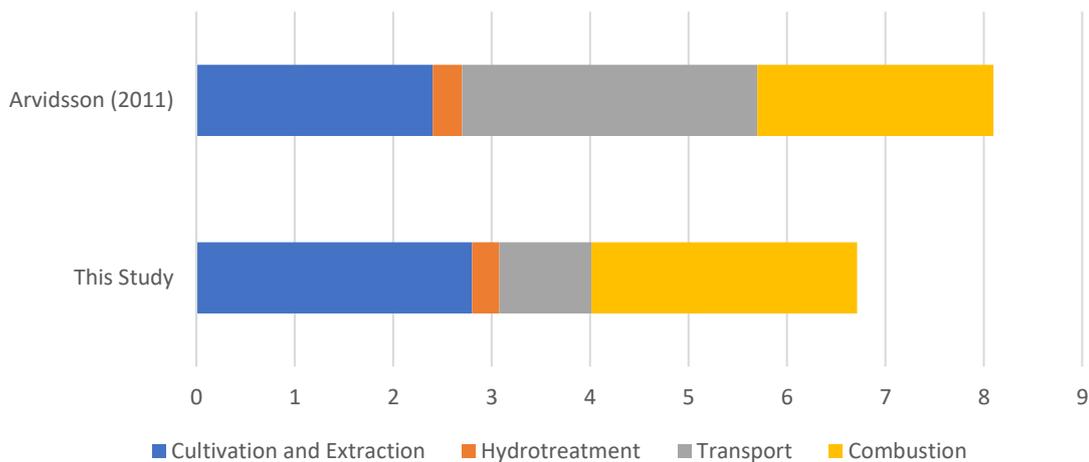


Figure 7 – Characterization of the Acidification Potential of HVO produced from palm oil compared to Arvidsson et al. (2011).

4.3 Diesel and HVO Emissions Comparison

From the tests performed on the internal combustion engine, gas emission parameters into the atmosphere were calculated. The Table 2 relates the engine performance data with the emission of pollutant gases, for the application of diesel and HVO as fuels. It is noted that HVO has better performance in all measured parameters. A highlight is the increase in engine efficiency with the use of HVO, in view of the fact that less mass of biofuel is needed to generate 1 kWh of electric energy under the same conditions with fossil fuel. In addition, there is a significant reduction in particulate matter emission and NO_x emission. One factor contributing to reduction in the nitrogen oxides emission is the lower combustion temperature of the renewable fuel.

The fossil diesel production process is widely known and has a consolidated inventory in literature, and is detailed in Ferreira and Carvas (2014). Knowing this process, the life cycle analysis presented the following characterization of the total environmental impacts of petrodiesel compared to biofuel. For the petrodiesel production inventory, the ECOINVENT 3 database was used, available in SIMAPRO, which considers the production process from extraction to fuel commercialization. The comparison of the results is shown in Table 3.

Table 2. Comparison between consumption data and specific emissions for diesel and HVO in compression-ignition internal combustion engine, operating at 1800rpm and 10Nm load

Parameter	Diesel	HVO
Specific fuel consumption, g/kWh	373,1 ± 5,5	327,6 ± 4,7
CO, g/kWh	10,75 ± 0,54	2,12 ± 0,35
CO ₂ , g/kWh	664,1 ± 20,5	621,2 ± 19,8
NO _x , g/kWh	10,6 ± 0,4	7,95 ± 0,4
HC, g/kWh	0,88 ± 0,01	0,22 ± 0,01
PM, g/kWh	6,36 ± 0,14	2,97 ± 0,10

It is noted that the GWP of HVO is lower compared to diesel. This is, as mentioned earlier, due to the reabsorption of all carbon emitted in HVO combustion during the biofuel production. In addition, since the NO_x emission from the fuel is lower, there is less ozone formation in the lower layers of the atmosphere as a result, which is harmful to human health. On the other hand, as Ferreira and Carvas (2014) point out, there is an increase in acidification and eutrophication impacts on both freshwater and seawater. The accentuated acidification in HVO life cycle is especially due to the transportation steps of raw materials and inputs for biofuel production, caused by the fossil fuel consumption. The freshwater eutrophication refers to the excessive growth of aquatic plants or algal blooms, mainly on rivers and lakes while the marine eutrophication refers to the reaction of a marine ecosystem to an excessive availability of a nutrients, commonly nitrogen. The accentuated eutrophication occurs mainly due to the use of inputs in the agricultural phase, such as NPK, which has high amounts of nitrogen and phosphor.

Table 3. Comparison between environmental impact categories for diesel and HVO in a compression-ignition internal combustion engine, operating at 1800rpm and 10Nm load

Impact	Diesel	HVO
Global Warming, kg CO ₂ eq/kWh	808 ± 11	714 ± 12
Ozone Formation, kg NO _x eq/kWh	11,327 ± 0,169	9,7498 ± 0,164
Acidification, kg SO ₂ eq/kWh	5,1 ± 0,2	6,5124 ± 0,2
Marine Eutrophication, g N eq/kWh	1,31 ± 0,03	8,78 ± 0,07
Freshwater Eutrophication, g P eq/kWh	13,7 ± 0,2	101 ± 1,7

5. CONCLUSIONS

This paper evaluated the global warming potential (GWP) and acidification potential (AP) of palm oil HVO biofuel applied to a single-cylinder, compression-ignition internal combustion engine in small-scale power generation application. Specific pollutant emission performances and environmental impact categories were also compared between HVO and fossil diesel, both with the objective of producing 1 kWh of energy.

It was found that the global warming potential along the HVO production process occurs mainly in the palm oil cultivation and extraction stage, due to the need of deforestation for the cultivation of the raw material. In terms of GWP, it is considered that the CO₂ emission in the combustion process is of the biogenic type and, therefore, does not affect the environment with global warming potential. Similarly, the greatest potential for acidification occurs in the cultivation and extraction of vegetable oil, due to the gases emitted by the soil and the use of motorized equipment, intended for the cultivation and extraction phase, powered by diesel.

When applied to an internal combustion engine and compared to fossil diesel, a reduction in specific emissions of all measured pollutant gases was observed, in addition to a lower specific fuel consumption. However, when evaluating the environmental impact, it is clear that despite the reduced impact on ozone formation and global warming, HVO has a greater environmental impact in terms of acidification and eutrophication, mainly due to the need to add inputs during the cultivation of raw materials such as NPK. Thus, it is observed that despite being a renewable fuel, there are disadvantages from the environmental point of view of using HVO when considering some impact categories.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge Thermal Machines Laboratory (LMT e UNIFEI); Combustion and Biofuels Laboratory (LC-BIO e UNIFEI); IEM e UNIFEI and Fundação de Desenvolvimento da Pesquisa e Fundep Rota 2030/Linha V (Proc. N° 27192*5) for supporting the development of this research.

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