Chapter 2
Hydrotreated Vegetable Oils for Compression Ignition Engines—The Way Toward a Sustainable Transport

Michele Pipicelli, Giuseppe Di Luca, and Roberto Ianniello

Abstract The COP26 goals rapidly accelerate the shift of road transport to electric vehicles (EVs). However, the global transition to EVs should be assessed carefully. A forced transition to electric mobility without tailored solutions for each case can increase greenhouse gas (GHG) emissions. In this context, low-carbon fuels can be considered a promising short-term solution to efficiently reach the carbon neutrality target. This manuscript aims to highlight the competitive advantages of hydrotreated vegetable oil (HVO) over commercial diesel fuel. Recent works on HVO are considered, ranging from exploring the production processes and spray evolution characteristics to the various engine strategies to highlighting the potential. Greater emphasis was placed on environmental impact assessment, considering the results available for Life Cycle Assessment (LCA) and Well-To-Wheel. The main characteristics and influences of HVO in CI engines are assessed on the combustion process, GHGs, and pollutants emissions. The results show the high potential of the HVO to reduce the impact of the road transport sector actively. It is highly compatible with existing engines and fueling systems while ensuring lower CO_2, CO, THC, PM emissions, and combustion noise levels with similar efficiency and fuel consumption. Additionally, the residual feedstock can assure up to 75% GHG over the whole life cycle. Therefore, sustainable fuels, such as HVO, combined with advanced technologies could not only support the reduction of tailpipe emissions but also benefit the overall CO_2 assessment.

Keywords Hydrotreated vegetable oils (HVO) · Renewable fuels · Compression ignition engine · Life cycle assessment · Greenhouse gas

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Abbreviations

APAC	Asia-Pacific
BEV	Battery Electric Vehicle
CI	Compression Ignition
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EGR	Exhaust Gas Recirculation
EMEA	Europe, Middle East, And Africa
EVO	Exhaust Valve Open
EVs	Electric Vehicles
FAME	Fatty Acid Methyl Ester
GHG	Greenhouse Gas
GWP	Global Warming Potential
HD	Heavy-Duty
HVO	Hydrotreated Vegetable Oils
ICEV	Internal Combustion Engine Vehicles
IMEP	Indicated Mean Effective Pressure
LATAM	Latin America
LCA	Life Cycle Assessment
LD	Light-Duty
LHV	Lower Heating Value
NAFTA	North America Free Trade Agreement
NOx	Nitrogen Oxides
PFAD	Palm Fatty Acid Distillate
PM	Particulate Matter
PN	Particulate Number
RED II	Renewable Energy Directive II
THC	Total unburned Hydrocarbon
WLTP	Worldwide Harmonized Light Duty Vehicles Test Procedure

2.1 Introduction

The COP26 global climate summit has defined ambitious goals to mitigate climate change. In particular, to secure global net zero carbon by mid-century, keeping global warming below 2 °C, the global emissions must be reduced by 45% by 2030 compared to 2010. Furthermore, to reach the COP26 targets, another objective is the progressive stop to coal use and coal-firing power plants founding (Arora and Mishra 2021). The prevention of further deforestation and the rise of funds for green and sustainable technologies are also non-negligible objectives. In this context, the transport sector is facing a radical transformation due to the almost worldwide carbon neutrality goal dictated by national and international regulations. In the period 1990–2019, the overall GHG emissions produced by this sector increased considerably, despite improvements in efficiency due to the higher demands. The time target to achieve the goal is for almost all the countries in the year 2050 (Arora and Mishra 2021; Hjelkrem et al. 2020). The main exception is China which has 2060 as the target. The transport sector is responsible for about 23% of the global CO_2 emission (Murdock et al. 2020), and its reduction toward global carbon neutrality is of great concern. The accepted solution for road transport, particularly passenger cars and light commercial vehicles, is the use of fully electric vehicles. However, although they are characterized by higher efficiency, their environmental impact is strictly related to two main factors: the battery pack and the electric energy production method. The tank-to-wheel efficiency of electric vehicles is roughly double that of gasoline and diesel engine-powered ones (Hjelkrem et al. 2020), making it a very attractive solution. However, their carbon intensity is strictly linked to the electric generation method. The GHG equivalent emissions factor related to electric energy production for different energy feedstocks is reported in Table 2.1. Very high variation between the most and the less carbon-intensive feedstock can be noticed with almost two orders of magnitude. The "Renewables 2020—Global status report" (Murdock et al. 2020) states that the transport sector is responsible for 32% of the total energy consumption, of which only 3.3% is from renewable sources. Globally only 11% of the total energy consumption is renewable.

Moreover, in the 2013–2018 period, an increase of 7% in total energy consumption was recorded, of which 15% was from renewable feedstock. On the other side, the full penetration of electric vehicles in the market will increase electric energy consumption by about 20–25%, according to different studies (Teixeira and Sodré 2018; Bellocchi et al. 2018). So in the following years, an increase in electric energy will probably be recorded with renewable energy that may not increase fast enough to follow the requirements.

Table 2.1 GHG emissions factor for various electric energy feedstock

Energy feedstock	Carbon intensity [gCO_2eq/kWh]
Coal	960–1060 (Varga 2013), 975 (Hondo 2005)
Natural gas	500–530 (Varga 2013), 518–608 (Hondo 2005)
Crude oil	620–750 (Varga 2013), 742 (Hondo 2005)
Geothermal	15 (Hondo 2005), 11–47 (Eberle et al. 2017)
Hydro	11 (Hondo 2005)
Wind	29 (Hondo 2005)
Photovoltaic	53 (Hondo 2005), 60 (Constantino et al. 2018)

In 2021 according to the International Energy Agency, a +6% of coal consumption was recorded with an increasing forecast to 2024. So the transition to electric-powered vehicles, if not regulated, can further worsen GHG emissions. Life cycle assessment regarding battery electric vehicles, considering various mixes, shows that the variation in terms of gCO_2/km for a battery electric vehicle (BEV) is so significant that it also comprises conventional vehicles (Faria et al. 2013). This applies to the Polish energy mix, which is based on coal at about 90%. So attention should be paid to the transition period to fully electric vehicles, which can last for decades. In this transition period is essential to search for solutions rapidly disposable to reduce the carbon intensity of the road transport sector. Different analyses have reported that a forced transition to EV in a short time can be counterproductive to fulfilling carbon neutrality and environmental goals. Andersson and Börjesson from the LCA analysis concluded that renewable fuels, including HVO, ethanol, methanol, and other renewable fuels, are a key element to meeting the climate goals in the automotive sector (Andersson and Börjesson 2021), considering the slow rate at which the EU carbon intensity is reduced and the slow substitution rate of the older vehicles. Similar conclusions are given by Ternel et al. (2021), for which biofuels are quick and efficient solutions to reduce GHG emissions of the global transport fleet. However, they should be viewed as complementary to electrification to quickly reach the carbon neutrality target, together with other technologies such as energy management strategies (Beatrice et al. 2022; Giardiello et al. 2022), eco-efficient advanced driving assistance systems (Musa et al. 2021), and vehicular connectivity (Michel et al. 2016). So, renewable fuels can play a crucial role in the decarbonization of the transport sector. Different potential renewable fuels are analysed in the literature for both SI and CI engines. For the latter different fuel families such as alcohols (Pipicelli et al. 2022; Luca et al. 2022; Ianniello et al. 2021; Sahu et al. 2022), ethers (Styring et al. 2021), and esters (Rajasekar and Selvi 2014) were tested in many works. An overview of the fuel classification is reported in Fig. 2.1. In particular, on the left panel is shown a one based on chemical composition and on the right panel, a one based on feedstock. The HVO is a fuel composed of alkanes and belongs to the second generation of renewable fuels. In the figure, a light grey shadowed zone has been used to highlight these classes.

The Fatty Acid Methyl Ester (FAME), a first-generation biofuel, has been commercially available since the 1990s but suffers from many problems such as fuel injection system clogging, cold start problem, crankcase oil dilution, and material compatibility, which limits its use pure (Szeto and Leung 2022). For these reasons, it is usually blended in fossil diesel at 5 or 7% v/v and it is not used in its pure form. The search for new renewable fuel formulations has found in HVO good properties with a potential full substitution ratio to fossil fuel in CI engines. This manuscript analyses the hydrotreated vegetable oils (HVO) capability to decarbonize since its similar properties to diesel fuel assures good retrofitting capabilities. As shown in Fig. 2.1, the HVO is an actual state-of-art sustainable fuel and is already commercially available. Research on HVO fuelled engines is still ongoing. Indeed, being characterized by greater reactivity and a narrower molecular structure, it guarantees a different response to the combustion control parameters than diesel. Therefore,

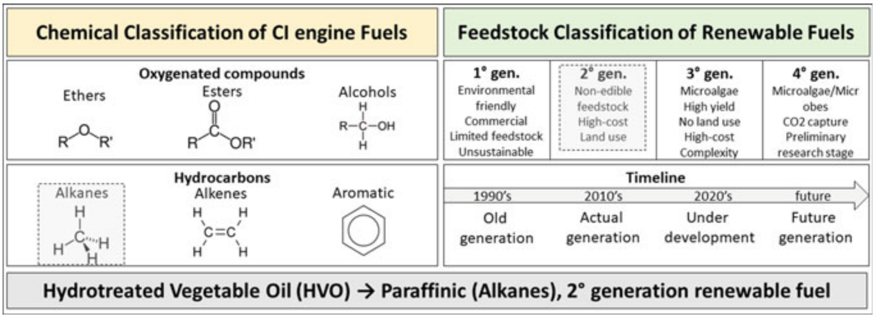

Fig. 2.1 An overview of the classification of fuels. On the left a chemical classification, and on the right one based on feedstocks

although considered a suitable fuel for efficient, low-emission PPCI combustion mode (Hunicz et al. 2022), the following study will focus more on fuel analysis in drop-in mode, using standard engine-control maps, or adopting different recalibration strategies to take further advantage of fuel properties. Synergistic application of alternative and sustainable fuels coupled with advanced combustion architectures (Belgiorno et al. 2020) and injection systems (Beatrice et al. 2019; Blasio et al. 2019), in internal combustion engines has the potential to bring significant benefits also to efficiency, pollutant, and CO_2 emissions (Zhang et al. 2020).

A meta-analysis of the available literature is done using some post-elaboration based on the exported database from Scopus. The search was based on the combination of logic operators (AND, OR, and NOT) and some keywords inside titles and abstracts. In particular, the following research was used: "engine" OR "vehicle" OR "lca" OR "life cycle analysis" AND "hvo" OR "hydrotreated vegetable oil" AND "fuel" AND NOT "hvof". The main synthetic data from the analysis are reported in Fig. 2.2. The first study on HVO is from 2007, with increasing scientific interest starting from 2011, reaching about 30 yearly manuscripts in the last three years. For a fair comparison, 2022 is not considered as it is actually ongoing. A consistent number of citations ranging from 200 to 350 shows the interest of HVO in the renewable fuel field.

Moreover, the manuscripts were grouped into commercial areas: EMEA (Europe, Middle East, and Africa), APAC (Asia-Pacific), LATAM (Latin America), and NAFTA (North America Free Trade Agreement). It is worth to highlight that EMEA is the main commercial area whose research on HVO (about 54% of the total manuscripts) is followed by NAFTA (about 30%). On the other hand, the LATAM shows almost no interest in HVO since its national and international policies focus on bioethanol and Fatty Acid Methyl Ester (FAME) as renewable fuels (Geraldes Castanheira et al. 2014; Renewable Fuels Association Focus Forward 2020).

The following manuscript is structured as follows. First, a brief introduction to HVO chemical-physical properties and production methods are presented. Then, an analysis of the life cycle analysis available in the literature is done. Finally, HVO effects on spray behavior and engine operation, including combustion and emission

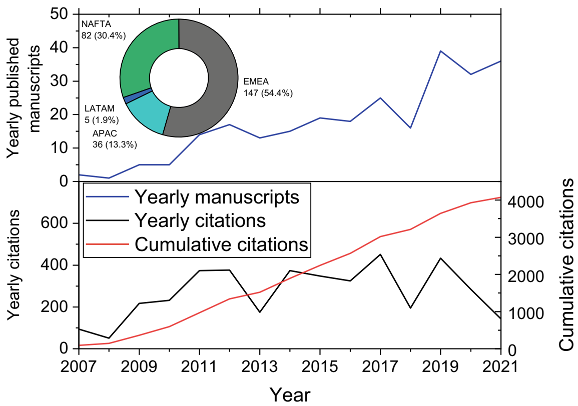

Fig. 2.2 Meta-analysis of the literature on HVO: division of manuscripts based on commercial area, yearly published manuscript on the topic, yearly citation and cumulative citation. *Source data* Scopus database

formation, are discussed. The structural presentation and the data plotting method adopted in the manuscript are intended to conceptualize the HVO effect on the performance and emissions in CI engines and its environmental impact assessment. Most previous reviews and research articles focused on the HVO effects on CI engine performance and emissions characteristics. The manuscript purpose is to provide a snapshot of all aspects related to the environmental impact of HVO regarding both the production process and aspects related to on-road and off-road propulsion.

2.2 Production and Properties of HVO

The term HVO emerged in the last decade when only vegetable oils (e.g. rapeseed, soybean, and corn oil) were used as feedstocks. Nowadays, non-edible feedstocks are preferred for HVO production, such as industrial waste (tall oil and fats) and used cooking oils (Engman et al. 2016). Furthermore, alternative non-food oils such as jatropha, algae, and palm oil are gaining attention to avoid vegetable feedstocks competition with food production due to the scarcity of edible oils (Brahma et al. 2022). For these reasons, the name HVO is no longer accurate in properly describing the fuel origins. Currently, it is common to call HVO with the terms “renewable diesel” and/or “green diesel”, with both the terms often used interchangeably (Knothe 2010). However, these terms are not scientifically accurate as they can also refer to other fuels, such as the FAME. Moreover, the original name cannot be easily changed since it is common in the European regulation, fuel standards and biofuel quality recommendations.

The HVO production process can be summarised as reported in Fig. 2.3.

The first stage, the hydrotreatment, takes place in a reactor in a pressure range of 300–500 bar at 300–400 °C. In this first step, hydrogen is added to the liquid feedstock to break down the feedstock triglycerides into various intermediates species, mainly

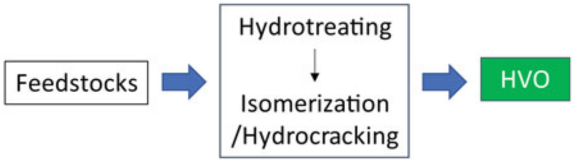

Fig. 2.3 Synthetic description of the production process of the HVO fuel

carboxylic acids, monoglycerides, and diglycerides. The conversion of these intermediate species into alkanes is obtained via three intermediate processes (Šimáček et al. 2010):

- Hydrogenation.
- Hydrodeoxygenation, which results in the removal of oxygen atoms from carboxylic groups in the form of water.
- Hydrodecarbonylation, which leads to the elimination of the carboxylic group in the form of carbon dioxide.

Initially, hydrogen saturates any double bonds of the triglycerides, followed by cleavage to fatty acids and the hydrogenation (hydrogen removes the acid group oxygen as H_2O) of glycerol to propane and water. Finally, the fatty acids are processed through hydrogenation or decarboxylation (the acid group oxygen leaves as CO_2). The split reaction depends on the catalyst used and operating conditions (https://www.etipbioenergy.eu/value-chains/conversion-technologies/conventional-technologies/hydrotreatment-to-hvo). During the process, carbon monoxide, carbon dioxide, water, and propane are obtained as side products (No 2014). The isomerization and hydrocracking process of the alkanes depend on the desired fuel products. For example, the isomerization process is used to improve the low-temperature properties of the final product. Then, the distillation process separates the various desired hydrocarbons products fractions, including HVO, diesel, gasoline, and others (https://www.etipbioenergy.eu/value-chains/conversion-technologies/conventional-technologies/hydrotreatment-to-hvo).

Several industries are involved in HVO production around the world, such as Universal Oil Products (UOP)-Eni (UK, Italy), Neste Oil (Finland), Syntroleum (United States), SK energy (Korea), ConocoPhillips (United States, Ireland), and Nippon Oil (Japan). Each of them uses a different commercial name to indicate their product, e.g. the NExBTL, acronym for "next-generation bio-to-liquid", is the trade name of the product obtained by Neste Oil Corporation (Engman et al. 2016), while for UOP/Eni Ecofining process the trade name is "Green Diesel" (https://www.eni.com/it-IT/attivita/biocarburanti-sostenibili-ecofining-tm.html). The HVO produced by SK energy was referred to as hydrogen-treating biodiesel (No 2014).

As a final product, HVO can be used pure or blended in the existing CI engines due to its similar chemical composition to the reference diesel fossil fuel. As paraffinic fuel, HVO meets the EN 15,940:2016 standard, which regulates HVO and Fischer-Tropsh GTL up to 7.0% in volume of FAME. For higher HVO-diesel blend ratios, the final composition meets the diesel fuel regulations, such as EN590 and ASTM D975. Furthermore, for HVO, the FAME regulations cannot be applicable. Since 2011, with an update of ASTM D7566-14, the HVO has also been approved for the aviation sector, allowing up to 50% of HVO in conventional jet fuel (ETIP Bioenergy—European Technology and Innovation Platform 2020). It demonstrates the potential of HVO also in the non-road transport sector.

Table 2.2 depicts the main characteristic of HVO compared to conventional diesel fuel. From a chemical point of view, the HVO is a paraffinic bio-based liquid composed mainly of paraffin and ISO-paraffin in the range C15–C18 and is free of sulfur and aromatic compounds. These are one of the main polycyclic aromatic hydrocarbons (PAH) precursors (Zubel et al. 2016). Thus HVO can potentially help reduce the particulate matter from its combustion due to lower soot precursors.

The increased amount of paraffinic components in HVO fuel and the absence of aromatics lead to a high cetane number (CN), which indicates a superior fuel ignition quality (Bhardwaj et al. 2013). In addition, the HVO, since it does not contain oxygen, has high oxidation stability, resulting in excellent storage behavior similar to fossil fuel and better than diesel with FAME (Dimitriadis et al. 2018).

The lower boiling point promotes better evaporation of HVO, while the different distillation curves lead to a reduced spray liquid length (Fajri et al. 2022). So an improvement of the air-fuel mixture can be expected to promote lower PM, total hydrocarbons (THC), and CO while slightly higher NO_x.

The HVO density does not meet the European standard EN 590 adopted for diesel fuel, so it can only be used in its pure form on specifically designed vehicles (Murtonen et al. 2009). The regulations usually define fuel density limits since this

Table 2.2 Physical and chemical properties of the selected fuels (Pipicelli et al. 2022; Ping et al. 1996; Hunicz et al. 2020)

Properties	Diesel	HVO
Cetane number [−]	≥51	75
Molar mass [g/mol]	~170	224
Carbon number [−]	12–20	15–18
H/C [−]	1.8	2.17
O/C [−]	0	0
LHV [MJ/kg]	43.0	44.35
(A/F)s [−]	14.5	15.2
Viscosity (@40 °C) [cSt]	2.72	2–4.5
Lubricity (µm corrected wear scar)	315	460
Density (@15 °C) [kg/m^3]	820–845	770–790
Boiling point [°C]	120–400	313
Cloud point [°C]	−5	−5.4
Sulfur content [mg/kg]	6.5	<5
Oxygen content [%wt]	0.77	0
Carbon content [%wt]	87.2	84.6
Hydrogen content [%wt]	12.2	15.4
Aromatics content [%v/v]	23	0

value is coded in the engine control units, and a significant deviation from the nominal value can lead to engine non-optimal operation with higher emissions (Lapuerta et al. 2010). However, a blend of up to 30% of HVO meets the EN 590 requirements, and different fuel with 15% v/v or more is commercially available in Europe (Bohl et al. 2018). Due to the lower density, HVO is characterized by a lower volumetric heating value than market diesel. HVO, thanks to its higher H/C ratio, has a higher heating value per mass unit compared to market diesel.

The lubricity of neat HVO is borderline with common acceptable values of <460 μm, which should assure adequate wear protection for the fuel injection system (Barbour et al. 2000). Some additives should be used to improve its lubricity; however, the same additive adopted for standard winter-grade diesel can be used, which is currently available for oil companies (Hartikka et al. 2012). Moreover, material compatibility is similar to fossil diesel and requires no particular attention for fuel system design and retrofitting (Pellegrini et al. 2015).

As mentioned above, there are different patented production methods of HVO which can be produced from different feedstocks. In the next section, several LCA studies have been reported to appreciate the HVO impact with a cradle-to-grave approach.

2.3 Environmental Impact of HVO

This section discusses the main environmental impact of HVO through an LCA and a well-to-wheel analysis based on the available literature data. In particular, the section focuses on GHG and the related Global Warming Potential (GWP), which represent one of the most relevant problems for which the regulations pose ever-increasing limitations.

The LCA is one of the more adopted techniques for assessing the environmental impact of a product or a process. The European Union, with its Renewable Energy Directive (RED II), had legislated that a life-cycle assessment should address the potential GHG saving of biofuels compared to fossil fuels.

It usually uses different metrics to assess different types of environmental impacts, such as human toxicity, eco-toxicity, loss of biodiversity, and climate change (Keoleian et al. 2006).

The LCA requires defining the process flow, its inputs and outputs, and system boundaries. The main input for the considered process is the fuel feedstock, which can be various for the HVO. The first distinction of the feedstock for the HVO production is between on-purpose and residual ones, which the latter usually shows lower GHG emissions due to neglecting the cultivation phase (Soam and Hillman 2019). Moreover, a further division can be addressed based on edible and not-edible feedstock. The use of edible feedstock such as rapeseed and palm oil is of great concern since the ever-increasing food and biofuels requests, possibly leading to socio-economical implications (Balat 2011). Thus, non-edible sources, such as jatropha oils, are greatly interested (Arvidsson et al. 2011). A general flow process of HVO production is

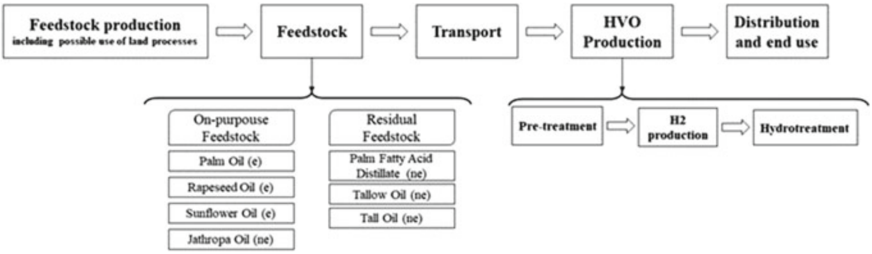

Fig. 2.4 Typical process flow diagram assumed in the literature for HVO LCA. Typical feedstocks are reported, indicating with (e) the edible ones while with (ne) the non-edible ones

depicted in Fig. 2.4. Using residual feedstock can shift the system boundaries of the LCA, avoiding the feedstock production part. The system boundaries should be carefully assessed since they can significantly influence the LCA results, mainly when a feedstock produces more than one product. The inclusion or exclusion of some subprocess is sometimes subjective and can lead to system boundary problems and mismatch (Suh et al. 2004).

In this context, the discussion will be focused only on climate change which is often measured as equivalent carbon dioxide emissions for the functional unit of the product. For fuel, the functional units often used in the literature are the mass of fuel burned, the energy released by combustion, brake energy, and vehicular distance travelled. All the available data reported have been converted in gCO_2eq/MJ of chemical energy of the fuel to avoid dependency on assumed vehicle efficiency, test driving cycle, combustion efficiency, or lower heating value (LHV). These data are shown in Fig. 2.5, where the diesel fuel was added for comparison. The standard diesel fuel GHG emissions vary between 75 and 100 gCO_2eq/MJ, while the HVO shows a most significant variation ranging between 5 and 80 gCO_2eq/MJ. Residual feedstocks such as Palm Fatty Acid Distillate (PFAD), waste and tall oil assure the lowest GHG. Reasoning in terms of mean values, the HVO from residual feedstock assures around −75% of GHG emissions compared to fossil diesel fuel, potentially leading to low carbon transport.

Based on the literature, a general consideration can be drawn regarding the well-to-wheel analysis. Firstly, there is a break-even point in vehicle mileage from which a fully electric vehicle is more sustainable than an internal combustion engine vehicle (ICEV) (including hybrid solutions). The break-even point varies as a function of many factors but among all: electricity production method, fuel and battery technology. Nordelöf et al. (2019) compared through LCA in a heavy-duty application (city buses) various powertrain configurations spacing from full electric to ICEV fueled by diesel and HVO considering 12 years. The results show that the electric bus has the best potential in terms of GHG reduction, up to −90%, in a hypothetical scenario where electricity production has zero carbon intensity. It is also confirmed by Lyng and Brekke (2019). Hoverer in this work it also showed that HVO-fuelled ICEV has less impact than electric if the grid mix GHG intensity is greater than 280 gCO_2eq/kWh. This threshold is further reduced to 200 gCO_2eq/kWh

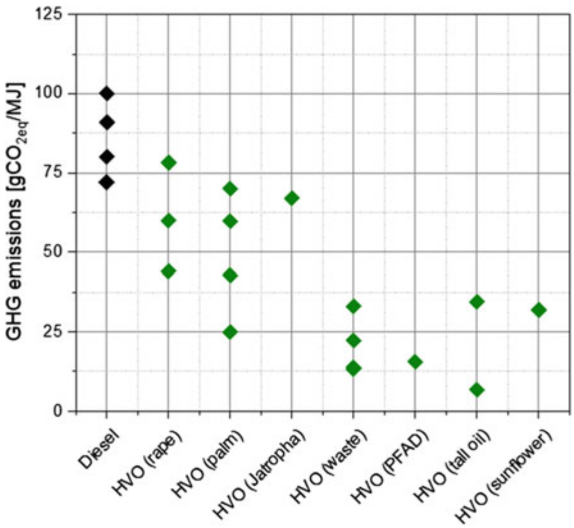

Fig. 2.5 GHG emissions for HVO and diesel fuels by literature LCA data. *Source data* Soam and Hillman (2019), Arvidsson et al. (2011), Källmén et al. (2019), Lyng and Brekke (2019), Liu et al. (2020), Prussi et al. (2020), Benavides et al. (2017), Marek et al. (2016)

if a hybrid powertrain fueled with HVO is assumed. Similarly, assuming a service life of 390,000 km and 10 years, Lyng and Brekke (2019) found that HVO from waste cooking oil can reduce the Global Warming Potential (GWP) by about 70% with respect to fossil fuel and electric vehicles with coal produced electricity.

In general, the HVO assures a reduction in the range of 4–8% (Murtonen et al. 2009; Blasio et al. 2022) of tank-to-wheel GHG emissions compared to diesel, with a reduction of THC, CO, and PM emissions, as detailed in the following section.

The results show that the GHG emissions reduction of HVO can reach 70%, which is still lower than electric vehicles powered by a carbon-intensive electricity mix. The HVO potential reduction shows high variability among feedstock, production process, and different studies. Therefore, there is a need for regulations and governance control to regulate the production process and guarantee the lowest carbon-intensive processes to maximize the potential benefits of HVO. In particular, these highly environmentally friendly results are linked to residual feedstocks, which have limited availability of their nature. Turkey produces 25e3 tons/year of tall oil and a diesel consumption of 15e6 tons/year (Altıparmak et al. 2007). The biofuel yield from tall oil is high, as it can be above 95%, and for a rough calculation, it can be assumed as an ideal 100% (https://www.mdpi.com/2673-4079/2/1/12). Also, considering that all the tall oil produced will be used for HVO production, it can fulfil only about 0.2% of the diesel request. Considering PFAD, according to Neste, there are about 2.5e6 tons/year available globally (PFAD residue from palm oil refining 2020), while only the EU has a demand of about 240e6 tons/year of diesel fuel. The biodiesel yield from PFAD is usually lower (about 80–85%), which leads that the global available PFAD can be used to fulfil less than 1% of the EU demands.

Regarding waste cooking oil, in the EU in 2020, there were potentially 1.15e6 tons available (Ershov et al. 2022), corresponding to about 0.5% of the diesel requirement. Moreover, obvious gathering difficulties and constraints, which require ad-hoc infrastructures, should be considered a constraint to a fully circular economy. So, the mass-production potential of HVO from these feedstocks should be carefully assessed. It is worth highlighting that only a few works treat this problem. Besides the fuel availability, with an associated problem of demand and supply balance, also the economic feasibility should be analysed. In particular, the economic profitability of the HVO can act as a prime mover to its diffusion. The production cost of HVO, about 1800–2200 $/year (Squadrin 2021), is about 3 or 4 times the one of diesel. Some studies foresee a reduction in the production costs of HVO in the next years (Syauqi et al. 2022). However, the production cost of diesel fuel ranges in Europe between 30 and 50% of the retail price (https://www.fuelseurope.eu/knowledge/refining-in-europe/economics-of-refining/fuel-price-breakdown/). In this context, regulations play a crucial role. The EU RED II directive provides a differentiation in fuel taxes, which should promote the use of renewable fuels at the expense of fossil ones (Ershov et al. 2022). Moreover, the HVO should be considered not as a complete substitute for fossil fuels in the actual transport sector but as a more sustainable fuel for the transition to electric mobility in developed countries, long-term solutions for developing countries, and applications less prone to electrification (heavy-duty, off-road, aviation, etc.).

2.4 Application of HVO to CI Engines

HVO can be used in compression ignition engines as a pure fuel, a blended one with traditional fuel, or a blending agent with additives. The research activities for alternative fuels are usually related to a study on the spray characteristics, combustion process, and emissions. This section will first discuss the spray evolution characteristics and then evaluate the fuel properties' effect on the combustion and emissions process for pure HVO.

2.4.1 Spray Characteristics

The evolution of the spray in the combustion chamber strongly influences the combustion process and, consequently, the formation of pollutants (Cardone et al. 2021). Therefore, the characteristics of the spray, in liquid and vapor phases, are fundamental aspects of evaluating the fuel quality. A limited number of manuscripts are available in the literature analyzing the behavior of the HVO spray at engine-like conditions.

The comparison between macroscopic quantities of the spray, such as spray tip penetration and spray cone angle between HVO and diesel, was carried out by Cheng et al. (Zubel et al. 2016). They evaluated the air density effect on spray evolution through the diffusive back-illumination technique in a combustion vessel under non-evaporative conditions. There were no evident differences in spray tip penetration, cone angle, and air-fuel mixing between the two fuels. The results agreed with Sugiyama (Dimitriadis et al. 2018) and Hulkkonen et al. (Bhardwaj et al. 2013), who performed a spray characterization using two different nozzle hole diameters, 0.08 and 0.12 mm and three rail pressures, 450, 1000, and 1980 bar at non-evaporative conditions. In addition, by numerical investigations, Fajri et al. (2022) assessed the effect of HVO properties on spray behavior in non-evaporating and evaporating conditions. HVO and diesel showed very similar behavior even under evaporating conditions. In the evaporating condition, only the droplet sizes for HVO are slightly smaller, justified by the higher vapor concentration due to the lower evaporation temperature, viscosity, and surface tension than diesel. These results are also in agreement with Chen (Murtonen et al. 2009).

Regarding the macroscopic spray characterization of the HVO, however, Bohl et al. (2018) found that the HVO led to a slight increase in the cone angle and lower spray tip penetration due to the lower density, in disagreement with the previous analyses. Also, Fajri et al. showed that HVO has lower maximum liquid penetration compared to diesel fuel (Fajri et al. 2022). It is due to faster evaporation and mixture formation, which can improve engine thermodynamic efficiency, useful for CO_2 reduction. These apparent contrasts are probably the results of different test conditions and nozzle geometry, which can highlight or confuse the different fuel properties (Pastor et al. 2021).

Bjørgen et al. (2020) have characterized the combustion process and in-flame soot phase with HVO and diesel fuel in a compression ignition engine with optical access. The results show a reduction of ignition delay of HVO than diesel according to the fuel cetane number. However, regarding the lift-of-length, no trend was observed in agreement with the ignition delay. A possible reason for this contradiction is the evaporative cooling differences between diesel and HVO since greater evaporation cools down the air-fuel mixture, which leads to a lengthening lift-of-length. Regarding the in-flame soot analysis, the HVO guarantees a soot reduction amount of about 3–6 times compared to diesel fuel, thanks to the absence of aromatics, despite the number of carbon bonds being similar between the two fuels.

In general, all the manuscripts considered conclude that the differences between diesel and HVO, in terms of spray evolution, are insignificant concerning the net effect on the combustion process.

2.5 Combustion and Emissions Characteristics

Although in the literature there are numerous studies regarding HVO, used as a blending agent, mixture, or pure fuel, the following section will report the results in emissions and combustion, referring only to the case of HVO employed as neat fuel.

Based on spray results illustrated in the previous section, the HVO can have the potential to directly replace diesel without any modification to CI engines (Hartikka et al. 2012). This allows its use as a drop-in fuel. However, further improvement in CI engine performances in terms of both emissions, efficiency, and combustion can be achieved with proper recalibration (Blasio et al. 2022; Dimitriadis et al. 2020).

Numerous studies have shown that HVO, characterized by a high cetane number, strongly influences the combustion process, especially at low loads. The high cetane number guarantees a reduction of ignition delay with consequent reduction of soot and benefits in terms of combustion noise. At high and full load, the high in-cylinder temperature has a dominant effect on the combustion process, and the CN effect is negligible, as reported by Bohl et al. (2018) for an HD engine in which virtually identical ignition delay and HRR are obtained for diesel and HVO.

Bhardwaj et al. (2013), through an experimental campaign on a light-duty single-cylinder engine, showed a reduction of particulate matter in the range of 50–65%. Similar results were also observed by Di Blasio et al. (2022) compared the effect of HVO with the same SOI of diesel fuel calibration, the same CA50 and similar HR to the one of the diesel in a single-cylinder research CI engine. They observed that the most effective strategy is dependent on the engine operating point at partial load. Overall, the HVO shows better global performances for all test points. Furthermore, a smoke gain of up to 50% was achieved, proportional to the PN reductions, as confirmed by Dimitriadis et al. (2020), Kuronen et al. 2007).

The PM reduction is also consistent at medium and high loads thanks to the aromatic free fuel composition (Bhardwaj et al. 2013), while the effect of the cetane number is less evident due to the high bulk gas temperatures (Hartikka et al. 2012). Omari et al. (Soam and Hillman 2019) also confirmed the same aspect, who observed an increased tendency of PM at lower loads and a decrease at higher loads. The PM reduction ranges from 25 to 30% using an HVO drop-in strategy at higher loads during the WLTP test cycle. Indeed, not only it generate less PM, but its particles can be oxidized at lower temperatures in the DPF than diesel, as it is free of aromatics and building blocks for the more thermally stable graphite-like material (Szeto and Leung 2022). These advantages lead to a lengthening of the DPF regeneration interval, with further benefits on fuel consumption (Ianniello et al. 2020).

Usually, lower combustion noise can be expected using HVO compared to diesel fuel because of the shorter ignition delay and lower adiabatic flame temperature thanks to the free aromatic and higher CN of HVO. Indeed a shorter ignition delay allows more fuel to be injected during the mixing controlled combustion phase. This implies a more gradual heat release rate and a premixed combination phase peak reduction. It ensures a combustion noise reduction and a lower combustion temperature peak (Liang et al. 2019). Bhardwaj et al. (2013) found a reduction in combustion noise of about 1.5–2.0 dBA reduction in engine noise intensity compared to diesel fuel. Also, Di Blasio et al. (2022) also found at partial load a reduction of combustion noise in the range 1–3 dBA adopting a drop-in calibration strategy. This is also confirmed by Omari et al. in a four-cylinder LD engine (Omari et al. 2017). The indicated thermal efficiency for HVO has a similar value to base diesel fuel. It is supported for both LD and HD engines by Preuß et al. (2021). In addition, Shepel

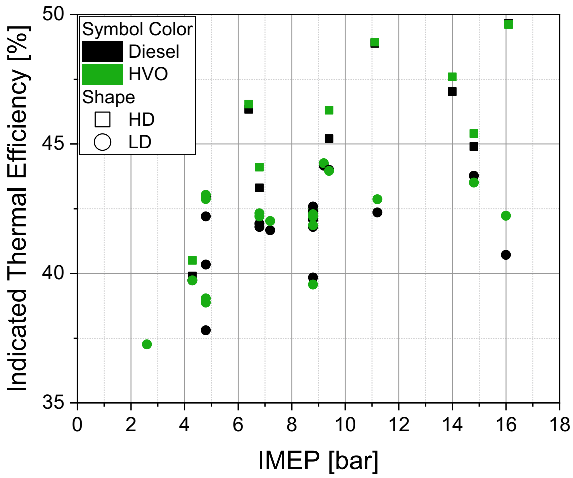

Fig. 2.6 Indicated thermal efficiency for different loads and engines operating conditions. *Source data* Zubel et al. (2016), Hunicz et al. (2020), Di Blasio et al. (2022); Preuß et al. (2021), Preuss et al. (2021)

et al. reported a slight increase in brake thermal efficiency of +0.5% (Shepel et al. 2021), which is confirmed at various loads by Rimkus et al. (Rimkus et al. 2019). The HVO does not give great concern regarding combustion stability. Many works reported values of coefficient of variation of IMEP perfectly in line with the diesel fuel (Blasio et al. 2022; Costa et al. 2022).

The indicated thermal efficiency for HVO has a similar value to base diesel fuel, as reported in Fig. 2.6. The HVO effect on thermal efficiency is strictly linked to the adopted test methodology, such as drop-in, recalibration and optimization, and combustion systems. Negligible differences are found for both LD and HD engines by Preuß (Preuß et al. 2021). In addition, Shepel et al. reported a slight increase in brake thermal efficiency of +0.5% (Shepel et al. 2021), which is confirmed at various loads by Rimkus et al. (2019). The HVO does not give great concern regarding combustion stability. Many works reported values of coefficient of variation of IMEP perfectly in line with the diesel fuel (Di Blasio et al. 2022; Costa et al. 2022).

Regarding NO_x emissions, thanks to the wide availability in the literature, it can be observed that light-duty engines show a slight or negligible reduction (Kousoulidou et al. 2014; Lapuerta et al. 2012) compared to heavy-duty ones (Happonen 2012). The NO_x reduction, as well as for the PN, is mainly due to the CN effect, which strongly influences the ignition delay. It involves a heat release reduction during the premixed phase of the combustion process, with a consequent decrease in combustion temperature and peak firing pressure, conditions unfavorable to the formation of NO_x (Huang et al. 2008). According to Sugiyama et al. (Sugiyama et al. 2011), the benefits of NO_x are more significant in adopting a single injection pulse. It is mainly due to the cetane number, which does not influence the ignition delay reduction in the case of the addition of pilot injection since the gas temperature in the combustion chamber is already very high with the only main one.

However, despite the slight influence on NO_x emissions, the great potential of HVO can be highlighted in overcoming the traditional PM-NO_x trade-off of CI engines. A proper engine recalibration setting for light-duty engines can lead to significant benefits in terms of emissions.

Dimitriadis et al. (2020) investigated the pilot and main injection timings and rail pressure effects, finding that an optimal calibration is to retard the main injection pulse of about 2° CA. Di Blasio et al. (2022) confirmed the substantial reduction in PM with higher EGR levels at ultra-low NO_x, demonstrating that the use of oxygenating fuel would probably provide more margin to the EGR use to reduce emissions further. Aatola et al. (2008) evaluated the combustion timing effect on a heavy-duty engine using pure HVO. Compared to the drop-in condition, further benefits were obtained on NO_x and PM by optimizing the injection times. Omari et al. (2017), thanks to the soot reduction and advanced combustion phasing at medium and high loads, it was possible to optimize the engine calibration setting through an increase in rail pressure, reducing the pilot quantity and the dwell time between the two pulses. This adjustment led to further benefits in emissions by not exceeding the diesel threshold values, emissions, and combustion noise.

In Fig. 2.7, some available data from the literature concerning PM-NO_x trade-offs are reported. LD and HD engine data are shown, and the same line style is used for the same engines and operating points. It is possible to notice that, especially for LD engines, shifting the whole trade-off curve in the ultra-low emissions zone. Figure 2.7 shows that the PM reduction can be exploited to optimize the ERG strategy further. Supposed, on the one side, the reduction of PM guarantees an extension of the DPF regeneration intervals, with consequent reduction of fuel consumption and CO_2 (Omari et al. 2017); on the other one, it can be exploited to reduce NO_x further. The figure shows that it is possible to reduce the NO_x emissions not exceeding the diesel threshold values. This effect is most evident in heavy-duty engines, for which there is a more significant difference between the two fuels in the ultra-low NO_x zone.

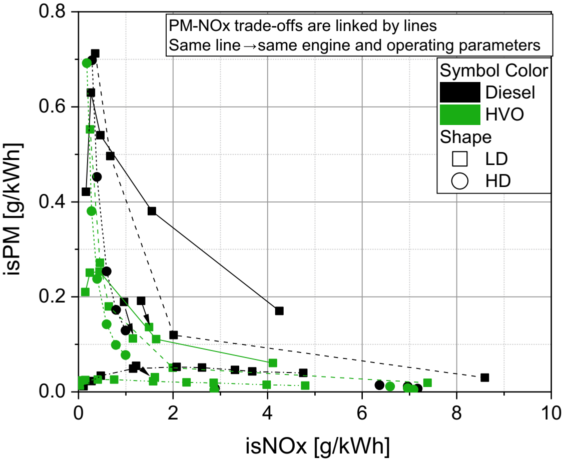

Fig. 2.7 NO_x-PM trade-off for different engines and operating conditions. *Source data* Di Blasio et al. (2022), Dimitriadis et al. (2020), Preuß et al. (2021), Shepel et al. (2021)

Total Hydrocarbons (THC) and Carbon monoxide (CO) do not represent problematic emission components as well as PM and NO_x for CI engines. Thanks to the high cetane number, lower boiling point, and absence of aromatics influence, the HVO favors the reduction of CO and THC, both regarding light and heavy-duty engines. A drop in both indicates an improvement in combustion efficiency (Aatola et al. 2008). Pflaum et al. (2010), through an experimental activity using a four-cylinder diesel engine fuelled with neat HVO, showed a reduction of up to 50% in both CO and THC emissions to diesel. Based on steady-state experimental data, Dimitriadis et al. (Hartikka et al. 2012) found an aligned result: lower THC emissions by up to 45%. A reduction of THC and CO emissions, in the range of approximately 65–70%, was noted over the entire speed load range for HVO due to its shorter ignition delay, as observed with the drop-in condition. Omari et al. (2017), adopting a drop-in HVO strategy, showed a similar THC and CO reduction interval. This unburned emissions reduction was used to optimize the EGR strategy to reduce the NO_x level further.

Below are the NO_x-THC (left panel of Fig. 2.8) and NO_x–CO (right panel of Fig. 2.8) trade-offs to further demonstrate the HVO potential for both engine sizes. As seen previously in Fig. 2.7, further optimizing EGR can reduce NO_x engine out by not exceeding the diesel target. The following graphs show how this optimization does not significantly impact unburnt emissions. For both CO and THC, regardless of the engine, a reasonably constant gap is observed for the entire range considered, particularly for low unburned emissions values.

However, this section discusses combustion-related CO_2, which should not be confused with well-to-wheel or LCA CO_2 emissions. CO_2 reduction is confirmed in the literature in a broad range of conditions. The CO_2 emissions, in general, are reduced thanks to its lower carbon to hydrogen atom ratio (C/H) and increased LHV compared to conventional diesel. The lower C/H ratio shifts the production ratio towards water instead of CO_2, while the increased LHV helps to reduce the quantity

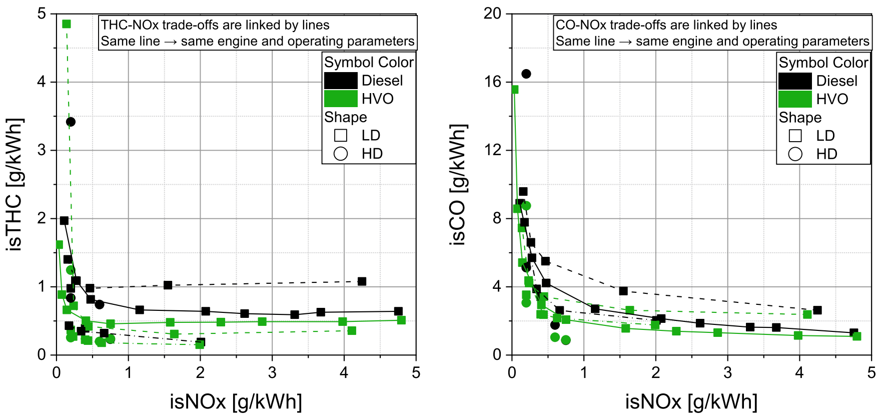

Fig. 2.8 NO_x-THC (on the left) and NO_x–CO (on the right) trade-offs for different engines and operating conditions. *Source data* Zubel et al. (2016), Bhardwaj et al. (2013), Hunicz et al. (2020), Di Blasio et al. (2022)

of fuel used, even considering a lower HVO density. Valeika et al. (2021) found a reduction of CO_2 emission in the range of 3.5–6.7% at a constant engine speed of 2000 rpm and different engine loads. Similar values are reported in Costa et al. (2022) of about 6% for an LD engine, in the range of 4–6% for passenger cars on WLTP driving cycle by Suarez-Bertoa et al. (2019) and up to 4% with 2 HD vehicles by Karavalakis et al. (2016).

Unregulated emissions are rarely investigated in the literature. However, some of the main findings of HVO on these pollutants are briefly listed below. Westphal et al. (2013) found that HVO reduces the PAH while slightly increasing carbonyl emissions are observed, especially for aldehydes, compared to diesel fuel in an HD engine. Hunicz et al. (2020) analyzed the unregulated emissions varying EGR rate in an LD engine. Formaldehydes and acetaldehydes are slightly lower, from without EGR to moderate one (about 17% v/v of O_2 at intake manifold). The differences became greatest at higher EGR levels. For aromatic compounds, until moderate EGR level, the emissions are under 0.02 g/kWh, with a rapid increase proportional to the EGR rate. It is due to the lack of oxygen, which can prevent the oxidation of intermediate combustion species before the Exhaust Valve Open (EVO). McCaffery et al. (2022), testing an HD engine with two different transient test cycles found that carbonyl species strongly depend on test cycles with HVO emission sometimes higher and other times lower than diesel. However, they confirmed the lower PAH emissions for HVO, thanks to the lack of aromatic compounds in fuel formulation.

2.6 Conclusions

In this chapter, an assessment of HVO fuel applied to CI engines is carried out. The work assesses the most important chemical and physical fuel properties with their influence on spray, combustion, and emission production in CI engines. Moreover, an evaluation of the environmental impact from the available scientific literature is carried out. The main outcomes are listed below:

- The HVO has the potential to become an important player in the transition phase to electric passenger vehicles and a suitable substitute for fossil fuels for road and non-road applications. However, the national and international regulations should be revised to exploit the full fuel potential. It can be seen as one of the promising solutions to sustainable mobility, not only for passenger cars but also the long-haul transportation, in order to achieve carbon neutrality in emissions by 2050.
- The GWP of the HVO in the whole life cycle strongly depends on the feedstock. Substantial benefits in terms of gCO_2eq/MJ are obtained using residual feedstock, which results in −75% GHG to fossil diesel. Therefore, the availability of these feedstocks for the mass production of HVO should be addressed.
- In general, no differences in spray evolution are observed between the two fuels; only the droplet sizes for HVO are slightly smaller, thanks to the higher vapor

concentration due to the lower evaporation temperature, viscosity, and surface tension compared to diesel. It demonstrates that HVO can potentially replace diesel directly without any modification to CI engines.

- HVO is a fuel superior to fossil diesel in terms of engine-out emissions (particulate matter, HC, CO, and NO_x), noise, and thermal efficiency for CI engines. The reported benefits mainly derive from its typical basic characteristics, including the absence of cycloalkanes (only n-and ISO-alkanes) and aromatics contents, free of sulfur and other ashes, and less dispersed molecular weights.
- In general, lower combustion noise is obtained thanks to a higher cetane number and the absence of aromatics, which strongly influence the combustion process. Thermal efficiency benefits are not always guaranteed because of strictly depend on engine calibrations.
- At the same operating conditions, slight differences in NO_x emissions can be expected but with lower PM (up to 65%) due to the higher cetane number and lack of aromatic compounds, allowing to overcome the traditional PM-NO_x trade-off.
- Lower THC and CO levels are usually achieved, in the range from 40 to 70%, thanks to the high cetane number, lower boiling point, and absence of aromatics. It allows for further optimize EGR and NO_x emissions.
- Few studies on unregulated emissions have been published so far. However, based on the literature results, the HVO has the potential to reduce the PAH significantly.

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