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Towards Carbon-Neutral Diesel Engines: State-of-the-Art on Hydrotreated Vegetable Oil Blends with Multi-Source Fuels

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Abstract: The current issue related to pollution and the occurrence of extreme physical phenomena caused by global warming have forced society to search for diverse solutions and methods aimed at improving the quality of life on Earth. In response to the escalating problems of global warming and air pollution, international authorities have implemented several global measures, among which the "Paris Agreement" represents an initiative to limit the increase in temperature to 1.5°C by 2030. Among all the alternative fuels available now, hydrotreated vegetable oil - HVO is one of the best substitutes for fossil fuels. The paper will present the existing fuel blends between HVO, commercial diesel B7 and biodiesel used in internal combustion engines, as well as their experimental results created to reach the sustainability goal.
Keywords: pollution, sustainability, global warming, HVO, fuels.

INTRODUCTION

The current issue related to pollution and the occurrence of extreme physical phenomena caused by global warming have forced society to search for diverse solutions and methods aimed at improving the quality of life on Earth. Although the causes of global warming are numerous, attention is primarily directed toward areas where meaningful improvements can be achieved, most notably, the transportation sector. The impact of greenhouse gases extends significantly to human health. One concerning effect is the increasing resistance of microbes to antibiotics because of uncontrolled global warming and the resulting rise in ambient temperature. For instance, studies have shown that "Escherichia coli" and "Staphylococcus aureus" develop higher antibiotic resistance with increasing temperatures. Moreover, in aquatic environments, higher water temperatures promote the growth of antibiotic-resistant bacterial strains [1]. Additional health concerns have been reported regarding respiratory diseases (such as asthma and allergic rhinitis), as well as food allergies and allergic dermatitis, which have intensified over the years as a direct consequence of severe air pollution.[2]

Greenhouse gases are responsible for the rise in global temperature by trapping and storing heat within the Earth's atmosphere. The main chemical compounds that make up greenhouse gases include carbon dioxide, methane, nitrous oxides, and water vapor. Among these, carbon dioxide is one of the key contributors, primarily resulting from the combustion of fossil fuels. [3]

The European Union's objective is for the entire transport sector, including road transport, to achieve climate neutrality by 2050, as stated in the "European Green Deal." Launched in 2019, this initiative represents a key contribution of the EU to the Paris Agreement and brings together a set of policies designed to guide the Union along the path of ecological transition, with the goal of achieving climate neutrality by 2050 [4]. The amount of carbon dioxide present in GHG can be seen in the graph below and it is generally accepted that CO_2 contributes to three-quarters (~75–80%) of total anthropogenic GHG emissions. [5]

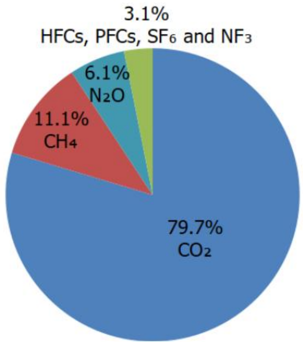

Figure 1. Overview of Greenhouse Gas Emissions

01.07.2025 Source : https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

From the perspective of road mobility, both scientific literature and numerous technical reports highlight the urgent need to implement alternative solutions in transportation that can contribute to reducing air pollution and greenhouse gas emissions. To facilitate a clearer understanding of the context of the paper, a graphical diagram was created. Below, the graphic example of the work:

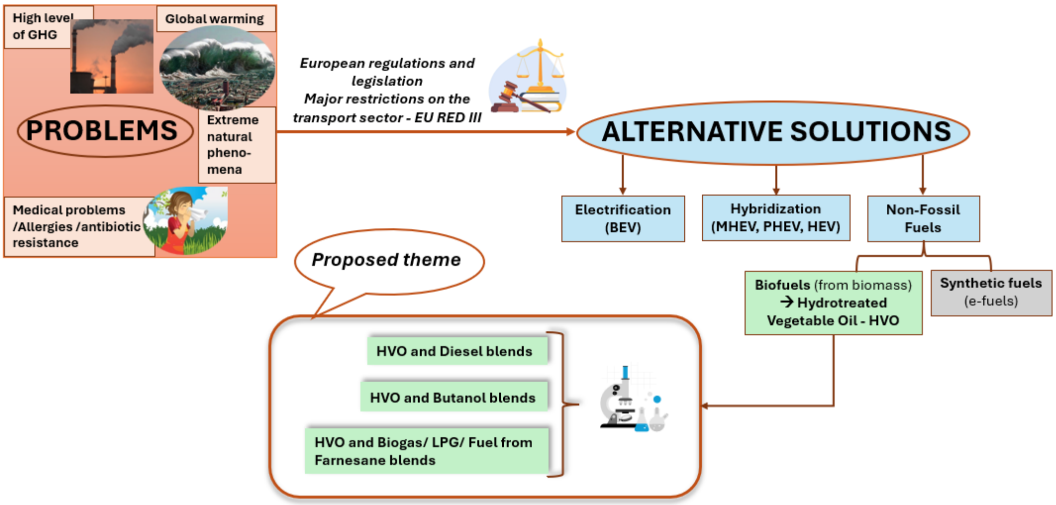

Figure 2. Logical context diagram of paperwork

ALTERNATIVE SOLUTIONS

The transition towards a sustainable energy sector has become one of the major global challenges, driven by the depletion of fossil resources and increasingly stringent greenhouse gas emission targets.
The transportation sector, heavily dependent on conventional diesel fuel, remains a significant contributor to CO_2, NO_x, and particulate emissions. This situation has stimulated intensive research

efforts aimed at developing alternative fuels that can lower the environmental impact while maintaining compatibility with existing internal combustion engines. In this context, liquid biofuels have emerged as a promising pathway to decarbonize the transport sector without requiring major structural modifications to diesel engines.

Based on rough estimates, EVs (battery electric + plug-in hybrid) represent about 4–5 % of all passenger cars, meaning roughly 95–96 % of cars on the road are ICE right now [6],[7]. EU-wide binding goal of at least 42.5 % renewable energy in total energy consumption by 2030 (with an ambition to reach 45 %). Until full climate neutrality is achieved in the road transport sector, current efforts focus on decarbonization through the application of these available alternative technologies. In the present research, the accent is placed on biofuels and their blends with fossil fuels, evaluating their quality and performance when used in internal combustion engines. Two major research directions have been defined as: synthetic fuels and biofuels:

Synthetic fuels (also called e-fuels when produced with electricity) are artificially manufactured liquid or gaseous fuels, with properties like fossil fuels, but produced through controlled chemical processes, usually from:

- CO_2 captured from the atmosphere
- Hydrogen obtained by electrolysis of water (ideally with renewable energy) [8],[9]

The cost of electricity is what substantially influences the production costs of synthetic fuels. Also, the high cost of obtaining hydrogen contributes to the increase in the final price of these fuels [10]. Low-cost hydrogen production technologies exist, but they must reach an acceptable level of maturity to be implemented on a large scale [11]. The lowest cost of obtaining hydrogen is through the steam reforming of methane. Solar-powered water electrolysis is about ten times more expensive, wind-powered electrolysis is about six times more expensive, and biomass gasification with carbon capture and storage is about three times more expensive [12].

In conclusion, even though the price of synthetic fuels is currently higher than that of fossil fuels, substantial investment is needed in this area. If all measures are not taken to limit greenhouse gas emissions, climatic conditions and vital resources such as water and food will become incompatible with human life on Earth. At that point, money will no longer have any value.

Biofuels are fuels obtained from biological raw materials (biomass), i.e. from renewable resources such as plants, algae or organic waste. These fuels are an alternative to fossil fuels, with the potential to reduce greenhouse gas emissions and support the transition to more sustainable energy sources.

There are four categories of biofuels of different generations, depending on the source of the raw material. First-generation biofuels are represented by food sources, which can compete with food production. The raw material for the second generation is grass, wood, waste straw, i.e. lignocellulosic biomass. The energy obtained from this generation is much more favorable than that from the first generation.

Looking for an alternative source to reduce the conflict with food production, it has come to the use of algae as a new renewable source, known as the third generation. Between 2000 and 2020, the fourth generation was developed [13]. Among the wide range of biofuels, Hydrotreated Vegetable Oil (HVO) has gained considerable attention over the past decade due to its favorable properties compared with conventional biodiesel. HVO is an oxygen-free, paraffinic fuel characterized by excellent chemical stability, very low sulfur and aromatic content, and a high cetane number that ensures efficient combustion. Nevertheless, HVO also presents certain drawbacks, such as reduced lubricity and poor cold-flow performance, which can be mitigated through blending with fossil diesel or by using suitable additives. Recent studies have therefore focused on identifying optimal HVO–diesel blending ratios and examining their influence on injection behavior, autoignition characteristics, combustion efficiency, and pollutant formation. As a liquid fuel, HVO is typically distributed in small blends with fossil diesel fuel through fuel distribution companies filling stations. HVO stands out as an attractive alternative fuel because it has chemical equivalence to conventional diesel fuel and can be run in diesel engines without the blending limits or modifications required for biodiesel. [14] HVO has physicochemical compatibility with fossil diesel, which means that no additional investment in new transportation or distribution systems is necessary, and it does not require changes in the physical structure of internal combustion engines.[15] Talking about the chemical structure, HVO and fossil diesel are the same at the base: Cn H2n+2, both being hydrocarbons consisting entirely of hydrogen (H) and carbon (C) atoms. Advantages of HVO compared to fossil Diesel:

- The absence of aromatics in HVO → fewer particulate emissions and NO_x
- Uniform paraffinic chains → higher combustion efficiency
- Higher cetane number in HVO → better ignition in diesel engines
- Better cold flow properties than Diesel (CFPP + CP).

As for disadvantages of HVO compared to fossil diesel:

- Higher costs: Production requires energy-intensive, high-pressure hydrogenation, making it 10-15% more expensive than conventional diesel.
- Limited availability: Compared to conventional diesel, the supply chain is less established, and it is not widely available in all markets.
- Sustainability risks: If sourced improperly, such as from palm oil, HVO production can contribute to deforestation and carbon emissions.
- Low lubricity when using 100% HVO without blending.

The use of HVO gives the engine increased performance considering its physicochemical properties. However, the use of 100% HVO leads to high costs resulting from the raw material used and from the need for slight modifications to the engine.

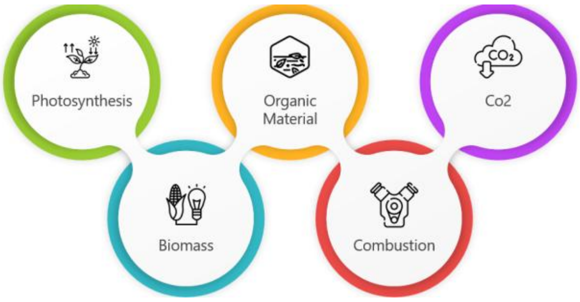

Figure 3. Biomass cycle

LITERATURE REVIEW – Blends of HVO and other fuels

The purpose of this scientific report is to provide a critical review of the current scientific literature on the use of HVO–diesel blends in internal combustion engines, with particular emphasis on engine performance, combustion characteristics, and emission behavior. The most relevant findings reported by various researchers are synthesized and discussed to highlight common trends, methodological differences, and knowledge gaps.

This analysis aims to present a coherent overview of the potential integration of HVO into conventional diesel propulsion systems and to identify the key areas where further research is needed. In the literature review below, a brief comparative analysis between different types of blends will be presented, focusing on the type of fuel used in the blend, the testing method and the results obtained. At the same time, the science gap and the need for further research will be highlighted.

Several studies have investigated the effects of HVO–diesel blends on engine performance, but their conclusions differ significantly depending on the blend ratio and test conditions tested in internal combustion engines. The main emphasis is on mixtures of HVO and diesel, but in the specialized literature it seems that tests have been carried out with various additives such as butanol, biogas, farnesane, etc.

HVO and fossil Diesel blends

Diesel blends with Hydrotreated Vegetable Oil represent one of the most practical pathways for reducing emissions in compression-ignition engines without modifying existing engines.

In the scientific paperwork [16] Suarez-Bertoa and collaborators investigated the impact of HVO blends on emissions from Euro 6b diesel passenger cars, both under laboratory conditions (WLTP at 23°C and −7°C) and during real-world driving. The study compared pure HVO, blends with 30% and 7% HVO, fossil diesel, and commercial B7 diesel. It was demonstrated that HVO100 consistently reduced CO_2 emissions by approximately 4% compared to fossil diesel and B7. Under cold conditions, most emissions increased significantly, regardless of fuel type. For unregulated pollutants, differences were mainly due to catalyst operation. Nevertheless, HVO100 recorded the lowest formaldehyde levels. On-road tests confirmed that the HVO proportion did not influence NOx or CO emissions, but HVO100 achieved significant CO_2 reductions.

In other paperwork [17] D'Ambrosio, Mancarella, and Marello analyzed the performance and emissions of a 2.3-liter Euro 6 diesel engine used in light commercial vehicles when fueled with HVO compared to conventional B7 diesel. The study evaluated HVO both without ECU calibration changes and with dedicated calibration. The methodology included dynamometer tests at five operating points, measuring in-cylinder pressure, specific fuel consumption, thermal efficiency, and engine emissions under both warm and cold conditions. Additionally, for the dedicated calibration case, parameters such as injection timing, rail pressure, and EGR values were optimized. Results showed that HVO, compared with B7, reduced soot emissions (up to 67%) and HC and CO (up to 40%), with no variation in NOx emissions.

As a parallel between [16] and [17], the test methods of the mixtures differed. HVO does not seem to have influenced NOx emissions but reduced significantly HC, CO and CO_2 emissions.

The paper [18] analyzes the impact of renewable fuels (pure HVO and HVO/biodiesel blends) on the emissions and toxicological properties of particles from an older off-road diesel engine (without SCR and DPF systems). Tests were conducted on a 4.5L John Deere engine.

Tested fuels: ULSD diesel (reference), HVO 100%, HVO/biodiesel blends 65/35 and 50/50. Measurements: NOx, CO, CO_2, PM, particle size distributions, organic/elemental carbon, metals, carbonyl compounds. Results were like: For Nox - pure HVO reduced emissions by about 5% compared to diesel, while biodiesel blends increased NOx (up to +4%). PM mass and particle number decreased significantly for all biofuels (reductions between 27–63% in PM mass). Biodiesel in the blend provided even greater reductions than pure HVO. However, the increase in NOx emissions for biodiesel highlights an important trade-off that must be managed in real applications.

In the paperwork [19] Hunicz analyzed HVO combustion performance compared with diesel and a HVO50 blend in a single-cylinder diesel engine, using multiple injection strategies and high exhaust gas recirculation (EGR). The tests focused on partially premixed combustion, measuring in-cylinder pressures, thermal efficiency, and both regulated and unregulated emissions. Results showed that HVO had superior tolerance to high EGR, maintained stable ignition, and improved combustion phasing, achieving a thermal efficiency of 43.2% (about 1.5 points higher than diesel). NOx emissions decreased considerably, particulate emissions were reduced, and aldehyde and aromatic compound levels were lowest for HVO.

To conclude this sub-chapter, can be seen the variety and innovation in the field of HVO blends alongside biodiesel and fossil diesel. It is difficult to draw a single conclusion on the specialized works, because all the tested blends and the testing methods differ. What can be clearly said is that NOx emission has a similar trend in all the works analyzed in the sub-chapter of HVO and diesel blends, namely it is not considerably reduced or improved, as in the case with HC and CO2 when using HVO versus fossil diesel. From what is observed in the specialized literature, the proportions of fuels used in the blends matter a lot. When additives or biodiesel are added along with HVO and fossil diesel, the trend of pollutant emissions also changes.

When combining HVO with diesel, it is worth noting that the properties of the mixture are visibly improved due to their similar chemical paraffinic structure. Also, in addition to the trend in pollutant emissions, many improvements appear in the performance of the internal combustion engine, in order, depending on the testing method, an impact is seen on thermal efficiency, in-cylinder pressure, specific fuel consumption and so on. Therefore, it is good to see that for future work, it can compare this variety of scientific work in the field of fuel blends.

HVO and Butanol blends

The use of butanol as a blending component is widely documented in the literature, especially in the context of HVO–diesel fuel blends. There is interest in using butanol, especially n-butanol as a biofuel or fuel blend because it has higher energy density than ethanol and is less corrosive / easier to handle in existing infrastructure.

Interest in butanol production has increased because it serves both as an important industrial chemical and a potential biofuel alternative [20],[21]. Generally, butanol can be produced through two primary pathways: biochemical and thermochemical (also known as petrochemical) processes. The biochemical route mainly relies on fermentation, while the thermochemical route primarily utilizes oxo synthesis as its key method.

In the paperwork [22] were used reference fuels and blends like neat diesel (B0), biodiesel (B100), hydrotreated vegetable oil (HVO100). Blends with diesel: B30 (30biodiesel), HVO30 (30HVO). Blends with butanol: nBu30 (30 n-butanol + 70 HVO), iBu30 (30 isobutanol + 70HVO). Experiments were carried out on a 6-cylinder Iveco diesel engine without exhaust. HVO–butanol blends successfully combined the benefits of both components - clean combustion and high cetane number from HVO. While blending butanol into diesel fuel has been reported to increase the ignition delay and the production of PAHs, blending of either n-butanol or isobutanol at 30% into HVO has resulted in lower emissions of total particle mass, elemental carbon, and polyaromatic hydrocarbons both with respect to neat HVO and with respect to diesel fuel. Butanol-HVO blends have resulted in a 75–78% reduction in elemental carbon, a substantially higher reduction compared to both neat HVO and neat biodiesel.

In the paperwork [23] diesel was mixed with n-butanol at different mixtures like: B10 (10% butanol, 90% diesel), B20 (20% butanol, 80% diesel), B30 (30% butanol, 70% diesel), B40 (40% butanol, 60% diesel). Tests were done in a single-cylinder compression ignition engine across variable operating conditions, and it results that B20 (20 butanol, 80 diesel) is the optimal blend, combining efficiency and significant emission reductions without requiring engine modifications. Key performance indicators, including brake thermal efficiency (BTE), mechanical and volumetric efficiency, along with oxide of nitrogen (NO_x), smoke, and unburned hydrocarbon (HC) emissions, were measured. Results showed a slight reduction in BTE with increased butanol concentration due to its lower calorific value. However, B20 offered an ideal compromise, achieving reductions in NO_x (up to 32%), smoke (77%), and HC emissions (35%).

When Butanol is introduced into blends with HVO and Diesel, an improvement in smoke and carbon reduction is observed. Although, in work [22], when mixing fossil diesel with butanol there is an increase ignition delay of the mixture, while HVO with butanol (be it n-butanol or iso) confers multiple benefits on pollutant emissions. The main advantage of butanol is that butanol contains built-in oxygen ($C_4H_{10}O$), and this oxygen makes the air–fuel mixture more oxidizing so this contributes to complete fuel combustion.

HVO and Biogas/ LPG/ Farnesane blends

In the paperwork [24] author study demonstrates that HVO and farnesane can effectively replace diesel in thermal engines, particularly when used in dual-fuel mode with biogas or CNG, significantly reducing NOx and PM emissions and supporting renewable, low-carbon energy goals — with only minor efficiency penalties. The tests were done with conventional diesel (10% biodiesel); HVO (Neste Renewable Diesel); Farnesane (Amyris Biotechnology). Combinations between those were: Diesel–CNG, Diesel–Biogas; HVO–CNG, HVO–Biogas; Farnesane–CNG, Farnesane–Biogas. Results said that both HVO and farnesane are viable green diesel alternatives, offering better combustion efficiency. Lower NOx, CO, CO_2, and PM emissions comparable or slightly better thermal efficiency than fossil diesel. Dual-fuel operation (especially with biogas) further reduces NOx and PM but slightly worsens efficiency and increases CO/HC. Farnesane $C_{15}H_{32}$ is an oil used to obtain synthetic renewable hydrocarbon fuel — a bio-based diesel substitutes that mimics the chemical and physical properties of fossil diesel but is produced from plant or microbial sources instead of petroleum. This biofuel is made from sugar via microbial fermentation and hydrogenation. It behaves like conventional diesel but burns cleaner and supports decarbonization goals in transport and power generation. This biofuel is used mainly in aviation as a certified SAF (SAF is a drop-in or synthetic fuel for aircraft) component, helping meet EU RED III decarbonization targets with significant greenhouse-gas reductions. [26],[27]

In scientific work [25], the study explores how LPG can be blended with HVO or diesel to create cleaner fuels for heavy-duty diesel engines while reducing CO2 and particulate emissions. The test was done in a Constant-Volume Combustion Chamber built in-house, simulating diesel engine condition. Tested fuels: Diesel, HVO, LPG (33.7% propane, 28.3% iso-butane, 38% n-butane). Blends tested: 25LPG–75HVO; 50LPG–50HVO; 75LPG–25HVO; Each contained 150 ppm lubricity additive. Optimal blends 25LPG–75HVO → performs well without injection changes. 50LPG–50HVO → best compromise with advanced injection. Main results: LPG-HVO blends can significantly reduce GHG (Green House Gases) emissions while maintaining good autoignition behavior. Temperature dominates ignition behavior; pressure has a secondary role. Pilot and split-pilot injections are essential to shorten ignition delay, especially at low load/cold conditions. When it comes to blends of HVO with LPG or biogas and HVO together with Farnesane, it can be observed that studies have aimed at powering internal combustion engines operating in dual mode with adjustments to the injection timing to achieve good combustion performance. When HVO is present alongside gaseous mixtures, the addition of lubricant is necessary for proper homogenization of the mixture.

CONCLUSIONS

The current context regarding greenhouse gases, along with global warming, leads to the use of biofuels as an alternative solution in a transitional period. HVO used in blends is desired because they provide optimized performance of internal combustion engines without structural modifications of the engine.

HVO blends with fossil diesel shows clear improvements in fuel properties due to their similar paraffinic chemical structures, and in addition to the reduction in pollutant emissions, several enhancements in internal combustion engine performance are observed. Also, introduction of butanol improves smoke reduction while gaseous fuels like LPG and CNG allow blends with HVO in dual-fuel mode engines. Using blends provides increased lubricity compared to pure HVO.

Sustainable mobility cannot be achieved without the help of alternative methods. Each type of transportation will require a tailored approach from the options available today. While battery-powered vehicles may be suitable for urban transportation, heavier-duty and long-distance light-duty vehicle segments will need additional solutions, such as liquid fuels. HVO is compatible with current diesel engine technologies, it is considered a "drop-in" fuel. It can be used either as a 100% renewable fuel or blended with fossil diesel in varying proportions. It is important to recognize that HVO performance can differ depending on the feedstock, production process, and quality standards. However, when identical feedstocks are compared, evidence indicates that HVO performs better than trans-esterified lipids.

In conclusion, the types of blends between fossil diesel and biofuels are very diverse, and the results depend greatly on the testing method used and the experimental setup. The chosen blending ratios and the additives used also play an important role. Moreover, the combustion behavior depends on the injection strategy in the engine, whether it is a dual-fuel mode with double injection or direct injection into the cylinder, as in conventional diesel engines.

Abbreviations

GHG – Greenhouse gases
LPG – Liquefied petroleum gas
CNG – Compressed Natural Gas
HVO – Hydrotreated vegetable oil
CFPP – Cold Filter Plugging Point
CP – Cloud Point
Nox – Nitric oxide
CO – Carbon monoxide
CO_2 - Carbon dioxide
ICE – Internal combustion engine
EU RED III – European Renewable Energy Directive III
SAF – Synthetic aircraft fuel
PM – Particulate Matter
HC - Hydrocarbons

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