

Article

Influence of Biodiesel from Used Cooking Oil and Sunflower Oil on Engine Efficiency and Emission Profiles

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Abstract: This study evaluates the performance and emissions characteristics of a compression ignition engine fueled with biodiesel blends derived from used cooking oil (UO) and sunflower oil (SF) at concentrations of 5%, 10%, 20%, and 50%. Tests were conducted under different load conditions (20%, 50%, and 100%) across engine speeds ranging from 1500 to 3600 rpm, focusing on effective power, torque, brake specific fuel consumption (BSFC), and emissions of NO_x, CO, HC, particulate matter (PM), smoke, and CO₂. Consistent engine operating conditions were maintained for all fuel blends. The results indicated that increasing the biodiesel concentration led to a decrease in brake power and torque—up to 3.18% reduction for SF50 compared to diesel—due to the lower calorific value of biodiesel. For SF biodiesel, the BSFC increased with higher biodiesel content, while for UO biodiesel the results varied across concentrations. Emissions analysis revealed lower CO and HC at 2500 rpm for all biodiesel blends relative to diesel, while NO_x emissions varied depending on fuel type and concentration. In terms of particles, both PM and smoke were measured, and while PM showed different results across blends, smoke was lower for all blends compared to diesel. Our overall analysis shows that biodiesel blends up to 20% can be effectively used in diesel engines without substantial modifications, offering a balance between performance and reduced emissions.



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Keywords: engine performance; CO; NO_x; HC emissions; biodiesel blends; alternative fuels

1. Introduction

The continuous depletion of fossil fuel reserves, combined with rising environmental concerns about greenhouse gas emissions, has led to an increasing interest in sustainable energy alternatives, including biodiesel. Biodiesel is renewable and biodegradable, burns cleaner than petroleum-based fuels, and offers reduced emissions of CO, SO_x, particulate matter (PM), and unburned hydrocarbons (CO₂ and HC). However, the main concern is to ensure that biodiesel production is cost-effective and does not compete with food resources.

The production of biodiesel has undergone significant advancements, focusing on feedstock variety and optimizing transesterification processes. The feedstocks used for biodiesel production are categorized into four generations: edible oils (first generation), non-edible oils, animal fats, and waste materials (second generation), microalgae (third generation), and metabolically engineered biomass (fourth generation) [1].

In order to address the concerns related to food security and production costs, feedstock has shifted toward non-edible oils and waste resources. Second generation feedstocks have become significant due to their cost-effectiveness and minimized competition with food resources.

Recent approach involves insect larvae such as Black Soldier Fly larvae [2], which present rapid growth rates and high lipid content, *Jathropa curcas* [3] a well-studied biodiesel resource, and Neem, Karanja [3], and *Salvia mirzayanii* [4], which offer high yields under optimized conditions, with an increased potential due to their availability and ability to grow on marginal lands. Other sources, such as waste fish oil produced as a byproduct of the fish processing industry [5,6], watermelon seeds [7], *Tamarindus indica* [8], parsley [9], or palm [10,11] are also investigated, with promising results in the production of biodiesel. Nonetheless, waste cooking oils and preheated waste animal oil continues to be a major focus for biodiesel production as a cost-effective feedstock that also addresses the problem of waste disposal [10,12–14].

Several other studies have focused on the potential of waste cooking oil or sunflower oil as a resource for biodiesel production and their performance, both energetical and ecological, as a fuel resource. Simbi et al. [15] focuses on optimizing biodiesel production with sunflowers as a main resource and also analyzes fuel properties (e.g., viscosity, flash point, oxidation stability, acid value, and water content). High interest was shown by Razzaq et al. [16], Zareh et al. [17], and Yildiz et al. [18] on the effects of biodiesel from waste cooking oil on fuel properties, engine performance, and emissions, using mixtures of (B10–B50). More specific blends were analyzed by [19,20]. Dueso et al. [21] focuses on a sunflower biodiesel blend (B10) with antioxidant additives. With no specific biofuel concentration mentioned, Enweremadu et al. [22] and Iglesias et al. [23], investigated the combustion, emissions, and performance parameters of biodiesels.

Engine performance using biodiesel blends varies, depending on the feedstock type and concentration of biodiesel used. Palm biodiesel blends up to 20% (B20) reduced thermal efficiency by 1.5% and increased BSFC by 9% at full load, while reducing CO, HC, and smoke emissions by 2%, 35%, and 18.5%, respectively, compared to diesel [11]. Brake thermal efficiency improved by 36% at high loads, while significantly reducing NO_x and smoke emissions [24]. Preheating proved to increase combustion, increasing in-cylinder pressure by 2.24% and brake thermal efficiency by 9.23% while reducing CO and HC emissions by 13.88% and 26.94%, respectively [12]. Ammonia-biodiesel reactive controlled compression ignition engines achieved a 36.22% improvement in brake thermal efficiency and a reduction in smoke opacity of over 33%, with an increase of NO_x by 36% [25]. Enhanced brake thermal efficiency was obtained by introducing copper oxide nanoparticles (CuO NPs) into mahua biodiesel blends. This also led to reduced CO, HC, and PM emissions, while NO_x emissions remained a challenge [26].

Although most studies report significant reductions in CO, HC, and PM emissions, NO_x emissions present a complex challenge. While biodiesel's higher oxygen content promotes complete combustion, it also increases in-cylinder temperatures, thereby elevating NO_x levels [25,27]. CO emissions were 50.55% reduced compared to diesel, and unburned hydrocarbons were 43.87% reduced using waste fish oil biodiesel blends, while there was a 28.25% increase in NO_x emissions, attributed to higher in-cylinder temperatures during combustion [5].

Despite this challenge, strategies such as incorporating antioxidants, optimizing blending ratios, and employing exhaust gas recirculation have shown promise in reducing NO_x emissions. For instance, Venkatesan et al. [28] demonstrated that using antioxidant-enhanced biodiesel in low-heat rejection engines significantly reduced NO_x emissions while maintaining high thermal efficiency. Use of a 12.5% exhaust gas recirculation rate reduced NO_x emissions by 2.54% while slightly increasing CO and HC emissions due to incomplete combustion, underscoring the delicate balance needed in exhaust gas recirculation applications [29].

The increasing stringency of emission regulations, such as the Euro VI standard, emphasizes the need for alternative fuels like biodiesel, which offer reduced PM and SOx emissions while supporting global efforts to mitigate greenhouse gas impacts and improve air quality [30]. Different studies highlight the ability of biodiesel to lower PM emissions [26,28,31]. Specifically, biodiesel reduced PM emissions by up to 84.2%, with particles being smaller and more aggregated. This reduction was linked to lower iodine numbers in biodiesel, leading to smaller particle sizes and higher fractal dimensions, which affect light extinction and scattering characteristics [5,28]. Blends of high-acid oil produced through supercritical transesterification reduced PM emissions, aligning with regulatory standards [32].

Being sulfur-free, biodiesel reduces SOx emissions significantly [26,27]. Biodiesel derived from waste animal fat-oil exhibited high combustion efficiency with reduced density and viscosity after preheating, resulting in lower SOx emissions [12].

One aspect that is worth mentioning regarding these types of experimental researches is the large amount of data collected which are suitable for statistical analysis and the use of AI to process and optimize engine performance, a general trend in recent years [33].

This paper aims to deepen the current understanding of compression ignition engine performance and emissions by providing a comprehensive analysis of biodiesel for different biodiesel blends made from waste oils and vegetable oils. The study examines how biodiesel concentration, engine operating parameters, and fuel properties affect engine power, torque, hourly fuel consumption, BSFC, cylinder pressure, emissions profiles, and environmental impact, offering valuable insights into the feasibility and sustainability of biodiesel as an alternative fuel for internal combustion engines.

2. Methods

2.1. Methodology

The trials were conducted using an engine fueled with nine fuel blends (standard diesel, UO05, UO10, UO20, UO50) (diesel blended with biodiesel made from used cooking oil in proportions of 5%, 10%, 20%, and 50%, respectively) and SF05, SF10, SF20, SF50 (diesel blended with biodiesel made from sunflower oil in concentrations of 5%, 10%, 20%, and 50%, respectively), at varied loads (20%, 50%, and 100%) and engine speeds (1500, 2000, 2500, 3000, and 3600 rpm).

To ensure repeatability and comparability of the measurements, the data were collected after the coolant and oil temperatures reached constant values. Additionally, to avoid contamination between different the fuels tested, the engine was allowed to run for 30 min with the new fuel to clean the fuel supply system before taking measurements.

The fuels analyzed in this research are biodiesel derived from used cooking oils (especially palm oil) and biodiesel from sunflower oil. The tests conducted in this research are part of a broader program focused on converting used cooking oils into biodiesel, initiated by a local vegetable oil supplier. The supplier provided the biodiesel derived from used cooking oils as well as sunflower oil (pure and blends), using the same diesel fuel for the biodiesel mixtures and 100% diesel reference tests. The oil producer only made available the data that have been included in this research, as presented in Tables 1 and 2.

Table 1. Fatty acid ester composition.

Fatty Acid		SF	UO
Saturated	Palmitic acid—C16:0	6.67%	5.18%
	Stearic acid—C18:0	3.65%	2.10%
Monounsaturated	Oleic acid—C18:1	28.64%	59.7%

Table 1. *Cont.*

	Fatty Acid	SF	UO
Polyunsaturated	Linoleic acid ($\omega 6$)—C18:2	57.63%	19.31%
	Alfa linolenic acid ($\omega 3$)—C18:3	0.48%	6.82%
Other	—	2.93%	6.89%

Table 2. Chemical and physical properties of fuels used in tests.

Property	Diesel	UO05	UO10	UO20	UO50	SF05	SF10	SF20	SF50
Carbon (% <i>v/v</i>)	86.90	86.55	86.10	85.20	82.50	86.59	86.17	85.35	82.87
Hydrogen (% <i>v/v</i>)	13.10	12.93	12.86	12.71	12.28	12.96	12.92	12.84	12.60
Oxygen (% <i>v/v</i>)	0	0.52	1.04	2.09	5.22	0.45	0.91	1.81	4.53
Aromatics (% <i>v/v</i>)	17.6	9.1	10.5	3.8	1	11.9	5	4	0.5
Polyaromatics (% <i>v/v</i>)	1.5	0.8	0.9	0	0	1.2	0	0	0
Density (kg/m ³)	832	835	837	841	853	836	838	842	854
Aniline point (°C)	67	63	59	49	16	64	59	49	24
Diesel index	43.65	54.14	50.90	43.31	20.47	54.51	50.62	43.07	25.18
Kinematic viscosity (mm ² /s, 40 °C)	2.615	2.777	2.925	2.967	3.397	2.873	2.824	2.996	3.197
Inferior calorific power (MJ/kg)	45.9610	44.6532	43.3454	40.7298	32.8830	45.3242	44.6873	43.4136	39.5925
Inflammability temperature (°C)	67	51	53	58	71	60	63	64	69

Multiple resources provide formulas for converting emissions from ppm to g/kWh: Milojević et al. [30], Vergel-Ortega et al. [34], Pilusa et al. [35], and Gurusamy et al. [36]. Several other references express emissions in ppm, including Sabapathy et al. [10], Mandal et al. [20], and Duesso et al. [21]. In this study, emission values were retained in ppm, as provided by the measurement equipment.

Table 1 presents the fatty acid ester profile of the two types of biodiesels analyzed, namely biodiesels obtained through transesterification from SF and UO. The concentrations used for biodiesel from SF and UO are 5%, 10%, 20%, and 50%, and these fuels were the subjects of our experimental engine research. In Table 2 are presented the main characteristics of the used fuels.

2.2. Engine Instrumentation—Test Bed Setup

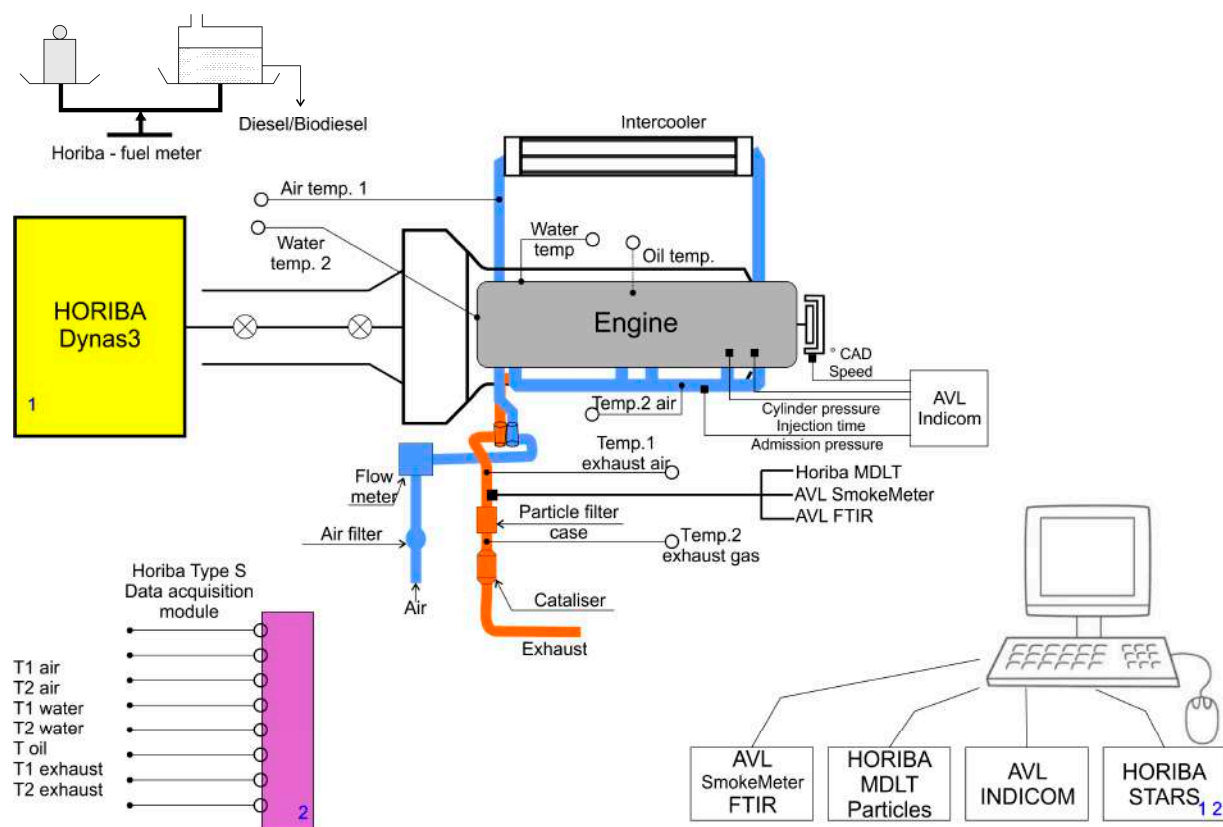
The comprehensive evaluation of engine performance and emissions necessitates a structured test program combined with meticulous engine instrumentation. To effectively assess these aspects, a controlled manipulation of engine speed and load is important, facilitated by the dynamometer. This setup allows for precise adjustments to replicate real-world conditions and gather accurate data. Additionally, the engine instrumentation plays a crucial role in measuring and regulating various parameters, including fuel and air flow rates, temperatures, injection timing, and ignition timing. Furthermore, exhaust gas analysis provides invaluable insights into combustion processes and overall engine efficiency. Together, these components form the backbone of a rigorous testing regime, enabling thorough examination and optimization of engine performance and emissions.

The instrumentation of the engine and the calibration of the sensors and measuring devices included in the test stand equipment were carried out in the pre-test phase of the experimental program. The main specifications of tested diesel engine are shown in Table 3.

Table 3. Tested engine specification.

Property	Detail	Unit
Engine type	Diesel engine	-
Number of cylinders	4 cylinders, in line	-
Fuel injection type	Common Rail	-
Aspiration	Turbocharger and intercooler	-
Bore	76	mm
Stroke	80.5	mm
Displacement	1461	cm ³
Compression ratio	18.8:1	-
Maximum power	78	kW
Maximum engine speed	4000	rpm

Figures 1 and 2 illustrate the connection scheme of the engine to the test stand and the equipment for data acquisition. They describe the locations for placing sensors and transducers for acquiring the temperatures of conditioning fluids, intake air, exhaust gases, intake air pressure, cylinder pressure, the solenoid injector activation detection sensor for injection timing and duration determination, and the crankshaft rotation angle detection sensor. Additionally, it displays the connection method for the exhaust gas sampling probes for emissions measurement, and all equipment to the data acquisition and control center.

**Figure 1.** The connection diagram of the data acquisition and processing equipment for the engine test stand.

The Dynas3 brake, featuring an asynchronous motor, is well-suited for high-speed testing. When combined with the frequency converter, this equipment can function both as a brake and as a generator. The unit is capable of operating in two rotation directions and can be controlled via computer interface. The main characteristics of the brake are: maximum speed of 8000 rpm, response time of 4 ms, maximum torque of 442 Nm, and maximum power of 250 kW.

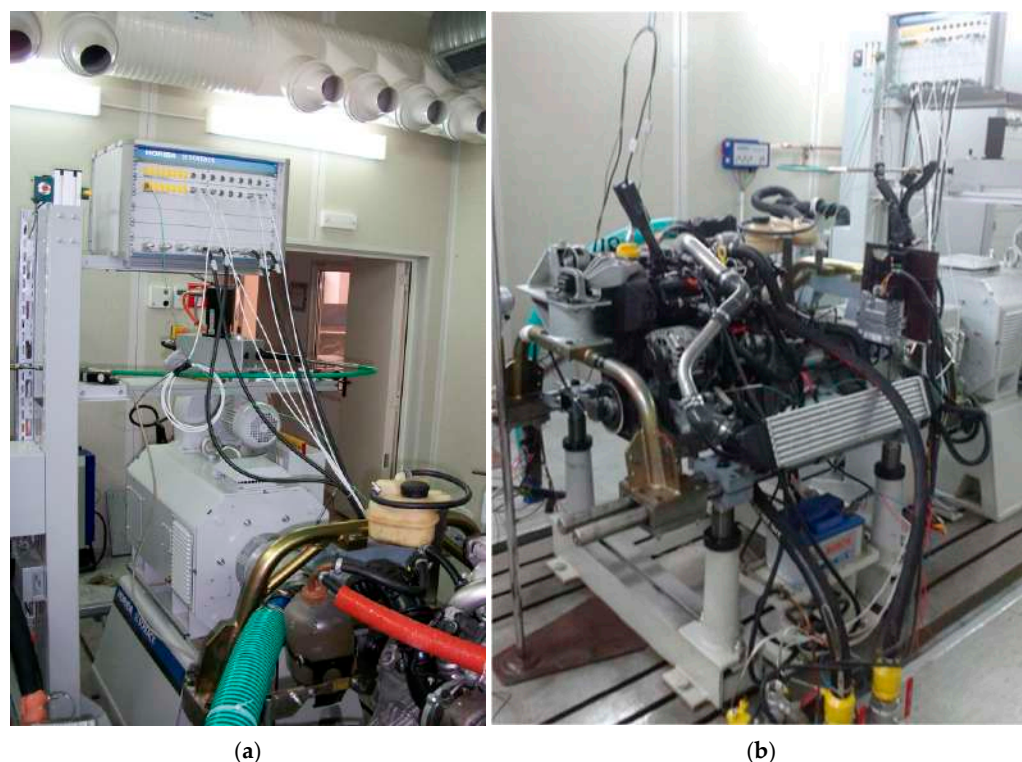


Figure 2. The HORIBA TITAN T250 test stand: (a) Dynas3 LI 250 brake; (b) Diesel engine connected to the stand.

The connection of the water, oil, intake air, and exhaust gas temperature sensors was performed using universal measurement modules. The engine test bench was controlled and operated using a PC through the STARS automatic control system. A test can be planned and prepared independently of the test bench. The stand controller allows the operation of the bench either through the PC or directly from the control panel.

Emission measurements were done in flow for each tested fuel. For measuring concentrations of CO and CO₂, infrared radiation analyzers were used. The operating principle is based on the absorption of infrared radiation by these gases. During the experimental research, the AVL SESAM FTIR analyzer was used. It can detect 21 chemical components and based on these, it can calculate five additional pollutant emissions. Calibration does not require sample gases, but the optical devices need to be cooled to a temperature level that prevents the formation of water vapor, as this can lead to incorrect results. The main characteristics of the AVL SESAM FTIR gas analyzer are: the measurement principle is based on FTIR (Fourier Transform InfraRed) spectroscopy; the circuit cleaning gas is molecular nitrogen; the spectral range is 650–4000 cm^{−1} at a resolution of 0.5 cm^{−1}; the sample flow rate is 10–20 l/min; the measurement cell volume is 200 mL, and the response time is 1 s.

Particulate matter primarily consists of carbonized materials generated from combustion (soot) that have absorbed various organic compounds. We used the AVL Smoke Meter, which is an automated measurement system in which a controlled volume of exhaust gases is passed through a filter paper. Changes in the filter's reflection correspond to the level of smoke. The smoke content of the exhaust gases is reported in Filter Smoke Number (FSN) units, volumetric concentration (mg/m³), or pollution level (%). For the FSN measurements, a value of 10 is assigned to a filter with no reflection, and a value of 0 to a clean filter. Other characteristics include: resolution of 0.001 FSN, exhaust gas pressure range of −100–400 mbar, and a maximum allowable exhaust gas temperature of 800 °C. The MDLT microdilution tunnel is designed to measure particulate matter using

the partial dilution method. It extracts a small quantity from the total exhaust gases, dilutes the sample with air to ensure a constant flow rate, and then passes the diluted gas quantity through filters to measure the number of particles.

During the experimental research, determining the crankshaft angle of the engine was carried out using an AVL sensor mounted at the free end of the crankshaft via an adapter flange (Figure 3a). The operating characteristics of the crankshaft angle encoder are: rotational range 50–20,000 rpm; resolution 0.1 °CAD (Crank Angle Degrees); permissible temperature −40–100 °C.



Figure 3. The sensors used for determining the variation of the cylinder pressure depending on the crank angle: (a) Crankshaft angle encoder; (b) Cylinder pressure sensor.

We used a piezoelectric-type transducer KISTLER 6005 to determine the cylinder pressure. The transducer was mounted using an adapter replacing the spark plug for cylinder 1 (Figure 3b). The measurement range of the sensor is 0–1000 bar, and its sensitivity is -8.37 – -10 pC/bar, depending on the temperature range. To measure pressure in the intake system, we used a piezoresistive-type transducer, specifically the Keller, which records relatively low values. To amplify the signal captured from the cylinder pressure transducer, AVL MicroIFEM equipment was employed. This equipment is a high-precision amplifier with four channels designed for measuring combustion pressure or any piezoelectric signal in engine testing stands or vehicles.

For acquiring signals from the crankshaft angle marking sensor, cylinder pressure sensor, intake manifold pressure sensor, and injection timing detection sensor, we utilized an AVL IndiModul 621 Data Acquisition System. This system is a multi-channel indicating system designed for internal combustion engines.

2.3. Research Program

In designing the test program, careful consideration was given to ensure a comprehensive evaluation of the performance and emissions characteristics of various biofuels in comparison to conventional diesel. The chosen test parameters aim to provide a thorough understanding of the engine's behavior under different operating conditions, spanning a range of rotational speeds and load levels. By systematically varying these parameters, we seek to clarify the impact of biofuel concentration on the engine's efficiency and emissions profiles. This approach is essential for informing future advancements in alternative fuel technologies and optimizing engine performance in alignment with environmental sustainability goals.

The experimental setup of the research program and the specific aspects regarding the conditions and procedures followed for conducting the experiments included:

- Instrumentation of the multi-cylinder engine for testing purposes with transducers, sensors, and equipment for acquiring data with slow and rapid variation parameters;

- Connecting the engine with the HORIBA Dynas3 brake;
- Connecting the engine to the fuel/air supply systems of the HORIBA TITAN stand;
- Connecting sensors, transducers, and acquisition units to the control, command, and processing units for both indicated and effective engine parameters (AVL Indicom, HORIBA Stars);
- Acquisition and processing of parameters such as cylinder pressure, concentration of toxic components in exhaust gases, initiation and completion moments of injection, fuel consumption, engine power and torque, under full load for various characteristic speed regimes (1500, 2000, 2500, 3000, and 3600 rpm).

For the purpose of assessing the influence of fuel characteristics on the energy and ecological parameters of compression ignition engines, a test program was established, the details of which are presented in the logical diagram in Figure 4.

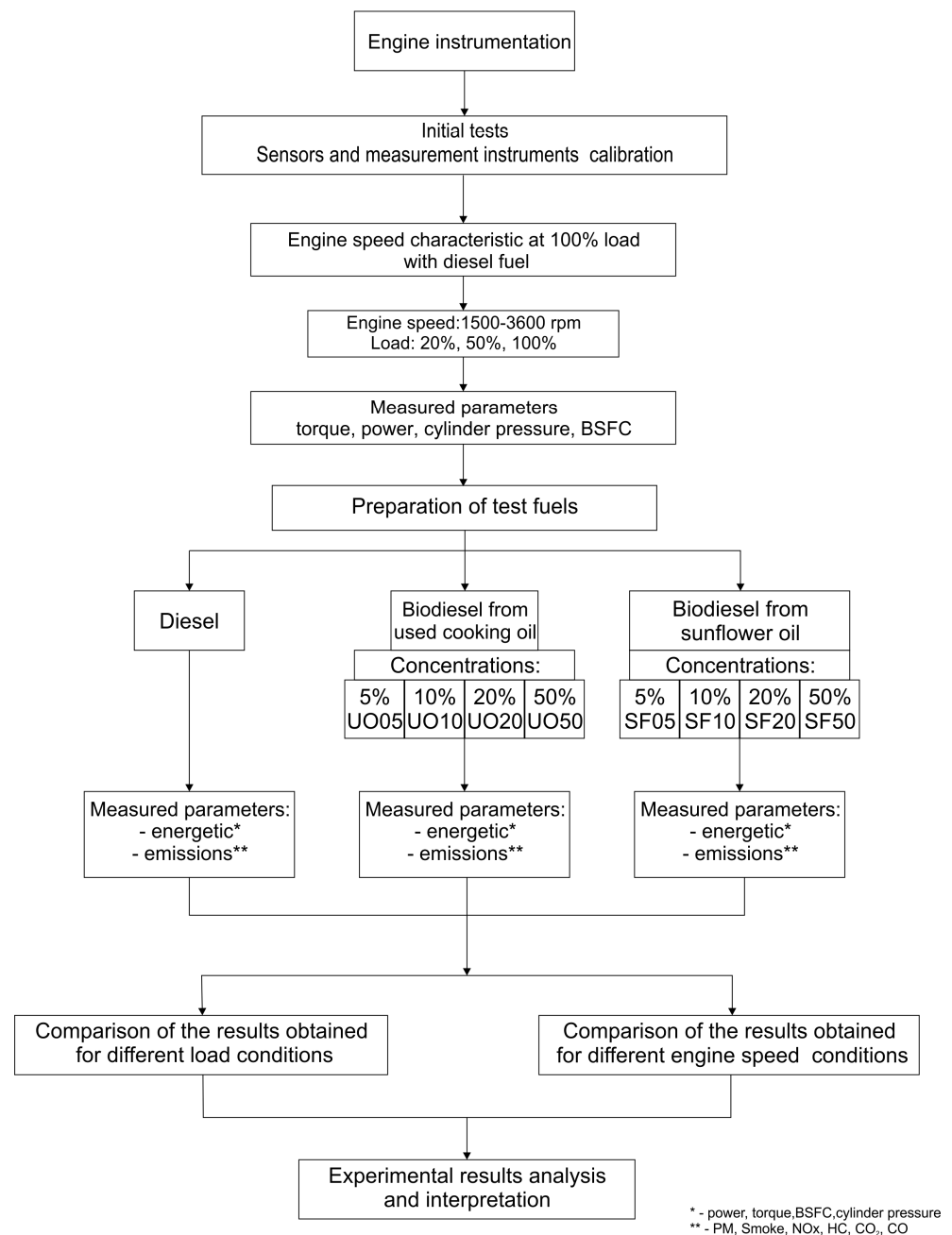


Figure 4. Structure and objectives of the experimental testing program.

3. Results and Discussion

The engine tests aimed to assess the influence of fuel properties on the main energetic parameters of the engine, such as effective power, effective torque, maximum cylinder pressure, hourly fuel consumption, BSFC, injection timing, and duration.

Figure 5, representing the engine characteristics at full load powered with 100% diesel fuel, illustrates the relationship between engine speed and both power and torque curves. It can be observed that the maximum power, at 71.11 kW, is achieved at 3600 rpm, while the maximum torque, at 221 Nm, is obtained at 2500 rpm. This point coincides with the minimum BSFC, which stands at 212 g/kWh. The maximum torque signifies an optimal balance of fuel and air intake, combustion efficiency, and mechanical load, which results in the minimum BSFC. This coincidence is significant because it demonstrates the engine's most efficient operating point, aligning with typical performance trends observed in diesel engines and supporting the findings of other studies.

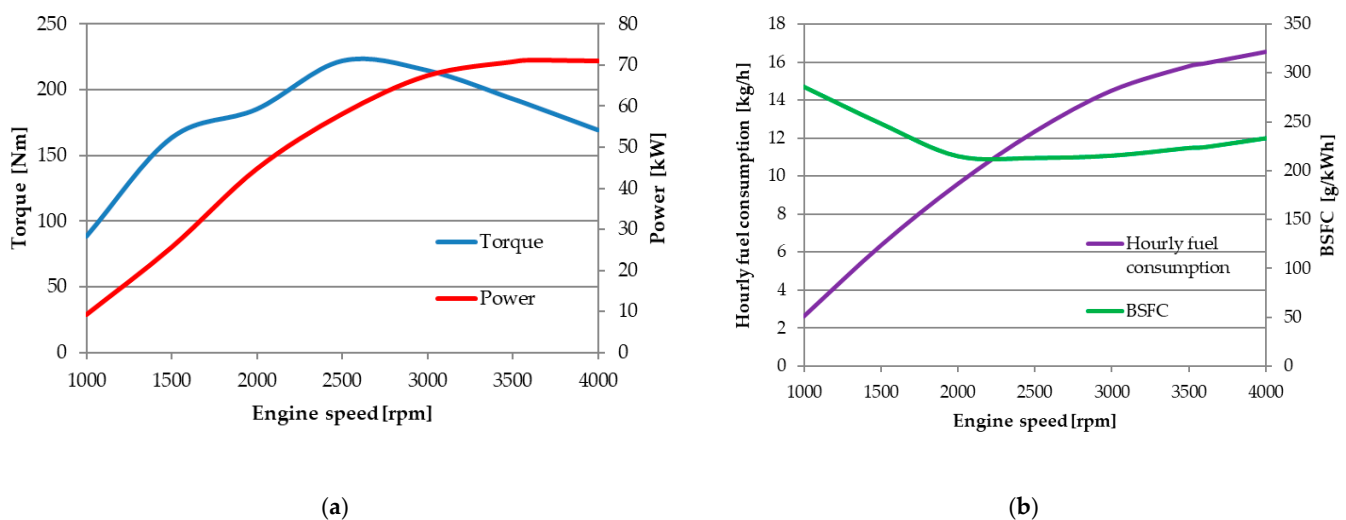


Figure 5. Engine characteristics at full load fueled with 100% diesel: (a) Evolution of the torque and power of the engine; (b) Evolution of hourly fuel consumption and BSFC.

From an ecological perspective, the monitored parameters included particle emissions (weight, smoke number), NO_x, HC, CO, and CO₂. The results described below focus first on the influence of the tested fuels on energetic parameters, followed by descriptions of their effects on engine emissions when operating with alternative fuels.

3.1. Energetic Parameters

The first series of tests aimed to investigate the behavior of the engine fueled with alternative fuels under 100% load. The analysis of the engine's energy parameters, such as effective power, torque, and BSFC, is described below.

It can be observed in Figure 6 that the effective power is influenced by the fuel used as follows. In the case of the SF biodiesel blend, there is a tendency for power to decrease with the increase in the concentration of biodiesel in the blend, up to 3.18%. Regarding the UO biodiesel blend, there is no clear trend up to a concentration of 20%, with differences in effective power ranging between 0.09% and 0.4%. Additionally, it can be noted that for a concentration of 50%, a more pronounced decrease in effective power is observed, with a reduction of 2.61% for UO50 and 3.18% for SF50 compared to diesel.

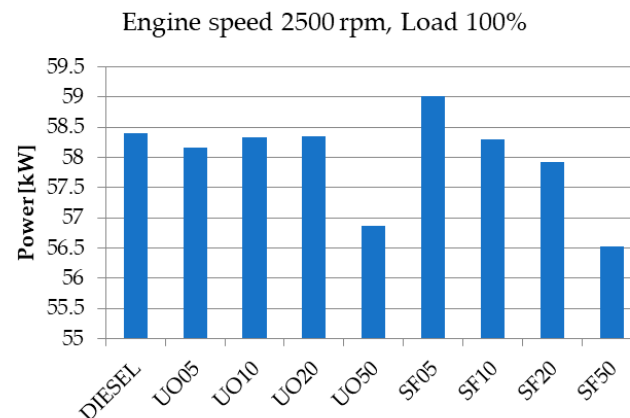


Figure 6. The fluctuation of effective power at 100% load and 2500 rpm speed, depending on the fuel type.

The percentage of biodiesel in a diesel mixture does lead to a slight reduction in engine power compared to 100% diesel, as seen in Figure 6. However, the power reduction is relatively small and may not be noticeable. Furthermore, biodiesel blends offer environmental benefits that might outweigh the minor power loss in many applications.

While higher biodiesel concentrations tend to reduce engine torque due to lower energy content and other combustion factors, the observed impact is generally minor for lower blend percentages and more significant for UO50 and SF50. However, torque loss is often balanced by the environmental benefits of biodiesel.

Fuels with higher carbon contents can enhance the power output of an engine due to their increased energy density. From Table 2 and Figure 6 it can be observed that the difference in the percentage of carbon content between diesel fuel and 50% biodiesel blends of UO and SF is less than 3%, and the power output is almost the same as that exhibited in the 100% diesel fuel tests. Biodiesel contains a lower carbon content than traditional diesel, leading to reduced PM and CO emissions while providing renewable energy benefits.

Lower biodiesel content fuels may have less impact on performance and emissions since the characteristics of the blend are closer to those of conventional diesel regarding density.

Generally, a higher diesel index leads to better engine performance with smoother operation, improved fuel efficiency, and lower PM emissions.

The lower calorific value provided in Table 2, corroborated with the engine power diagram in Figure 6, clearly demonstrates the influence of this parameter, especially at high biodiesel concentrations, such as 50%. As the calorific value decreases, the engine's developed power also decreases. Fuels with higher calorific values release more energy per unit of fuel burned, which can result in higher CO₂ emissions if combustion is complete.

Regarding the hourly fuel consumption, it can be observed in Figure 7a that for the used cooking oil-based fuel, the consumption decreases with the increase in the concentration of biodiesel in the blend. Compared to diesel, this varies between 2.08% for UO05 and 0.43% for UO50. The BSFC is influenced by the type of fuel, with the influence attributed to its density, which varies between 835–854 kg/m³ for the biofuels used in these experiments (Table 2).

From Figure 7b, it can be observed that with the increase in the concentration of biodiesel in the blend, in the case of sunflower biodiesel, the BSFC also increases, correlated with a decrease in effective power.

Biodiesel generally presents a higher fuel consumption compared to 100% diesel due to its lower energy content, different combustion properties, and factors like viscosity and volatility.

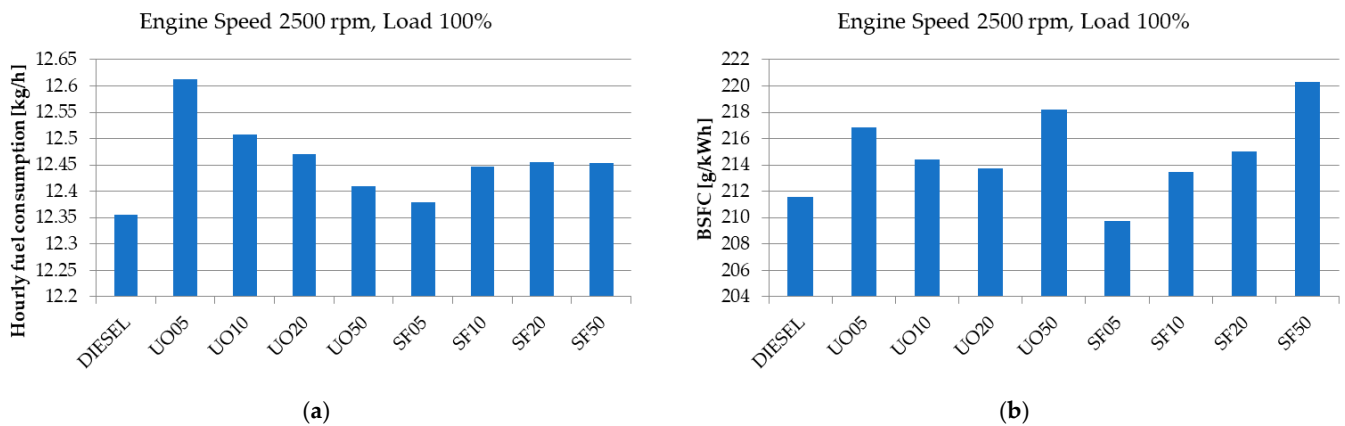


Figure 7. The engine fuel consumption at 100% load and 2500 rpm speed, depending on the fuel: (a) the variation of hourly fuel consumption; (b) the variation of BSFC.

It can be observed from Figure 7a that UO-based biodiesel shows a trend of decreasing hourly fuel consumption as the percentage of UO increases, which can be explained by the high content of monounsaturated fats. Similarly, SF—based biodiesel, which predominantly contains more polyunsaturated fats, exhibits higher fuel consumption as the percentage of SF oil biodiesel in the blend increases.

From the comparative analysis of the two types of fuels, with different concentrations used, it can be observed in Figure 6 that in the case of the blend with 5% biofuel, SF05 recorded an increased power and torque over diesel and UO05 by 1.06% and 1.46%, respectively. At a concentration of 10%, both types of biofuels, UO10 and SF10, had slightly lower values than diesel, by 0.4% and 0.17%, respectively. With the increase in biofuel concentration, it was found that biodiesel made from UO exhibits an improvement in energy parameters compared to that made from sunflower oil and a deterioration compared to diesel, by 0.1% for UO20 and 2.61% for UO50. The lowest energy performance, at 100% load and 2500 rpm speed, is exhibited by SF50, which is 3.18% lower than that of diesel.

Figure 8 illustrates the variation of cylinder pressure curves depending on the concentration of biodiesel in the blend.

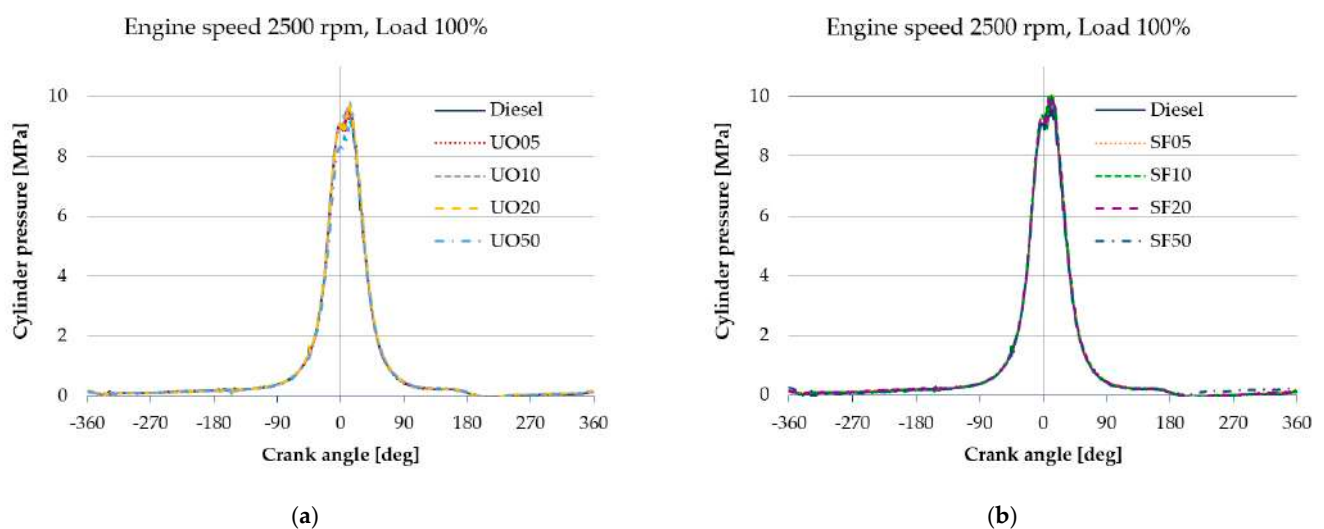


Figure 8. The variation of the cylinder pressure curve at 100% load and 2500 rpm speed, depending on the fuel: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

The cylinder pressure varies depending on the raw material from which the biodiesel was produced. Thus, in the case of sunflower biodiesel, it is observed that the maximum cylinder pressure is approximately 2.5% higher than that recorded when operating with UO biodiesel for all concentrations used.

The UO50 fuel exhibits the lowest maximum cylinder pressure compared to diesel (−3.66%), with a higher BSFC compared to the same benchmark (3.12%), as shown in Figure 9. All mixtures of SF oil show a higher cylinder pressure than diesel.

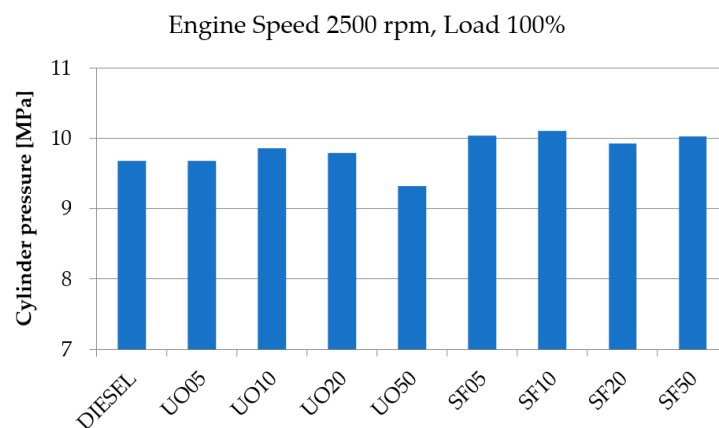


Figure 9. The variation of maximum cylinder pressure at 100% load and 2500 rpm speed, depending on the fuel.

In Figures 10–12, the speed characteristics of effective power, torque, and BSFC for 100% load are presented.

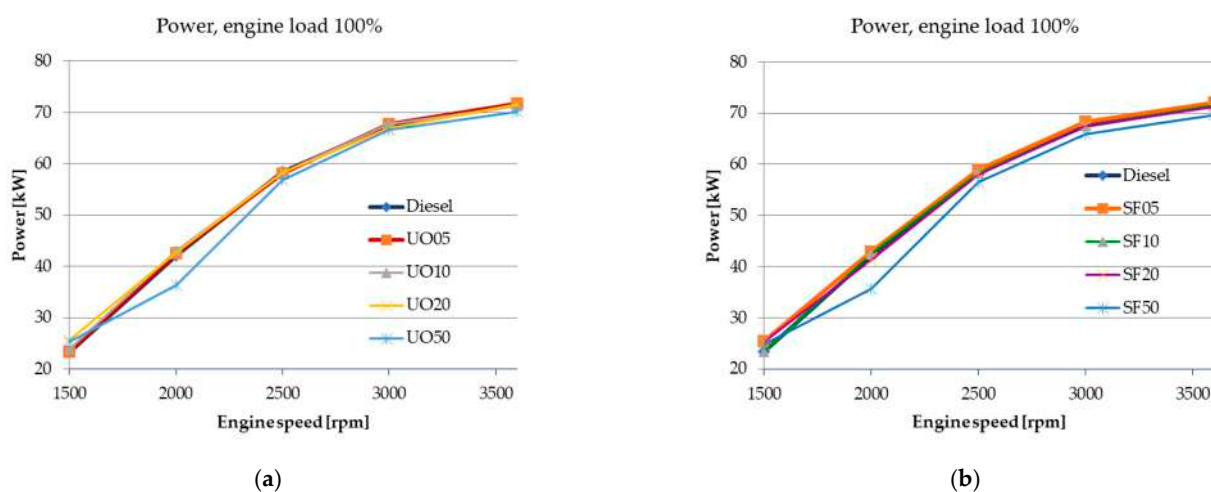


Figure 10. The variation of the speed characteristic for effective power at 100% load, depending on the fuel: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

For concentrations of 50%, namely for the fuels UO50 and SF50, a decrease in energy performance is observed, accompanied by an increase in BSFC at 2000 rpm speed. These fuels exhibit the poorest performance, with values of effective power and effective torque 13.76% lower for UO50 and 15.06% lower for SF50, respectively.

Regarding the injection start and end angles, from the analysis of the experimental data presented in Figure 13 for 100% load and 2500 rpm speed, it can be observed that the test presents two split injections: a pilot injection lasting 3 crank angle degrees and a main injection, which is displayed graphically only for diesel fuel, but is consistent for all

tested fuels, lasting 24 crank angle degrees, between -4 degrees before top dead center and $+19$ degrees after top dead center.

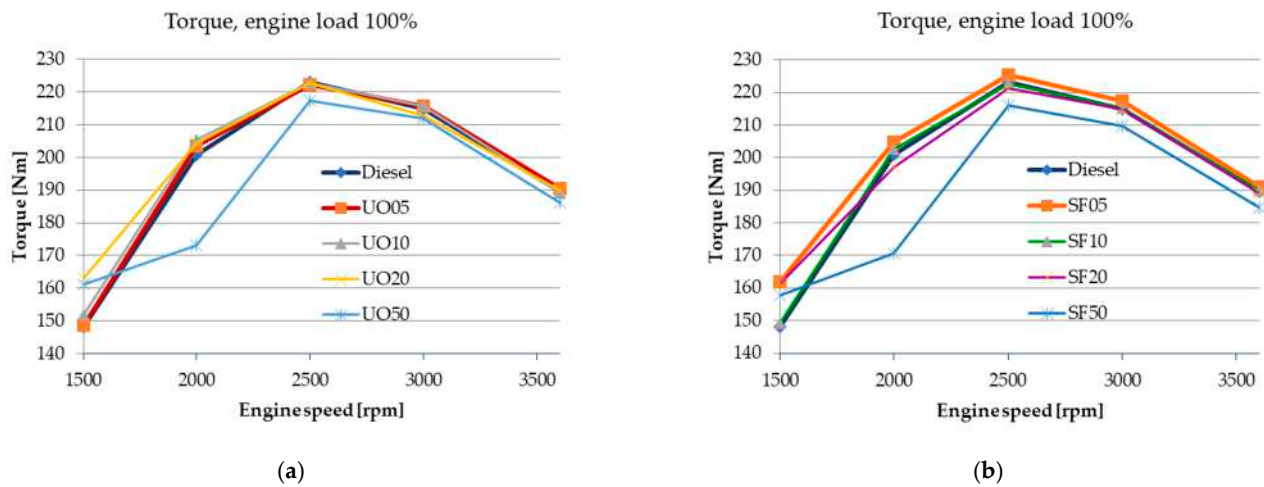


Figure 11. The variation of the speed characteristic for effective torque at 100% load, depending on the fuel: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

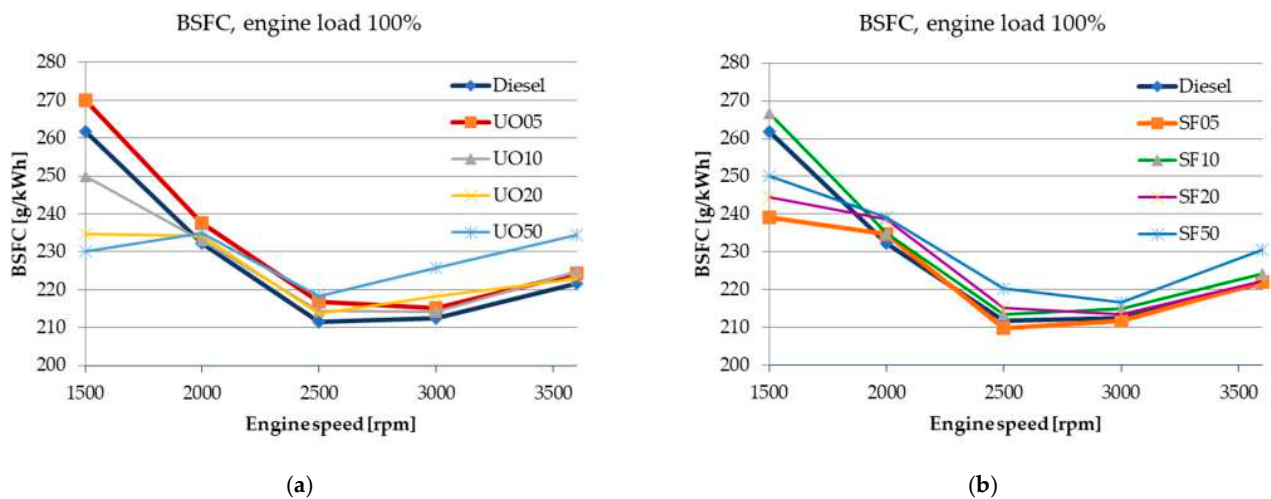


Figure 12. The variation of the speed characteristic for BSFC at 100% load, depending on the fuel: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

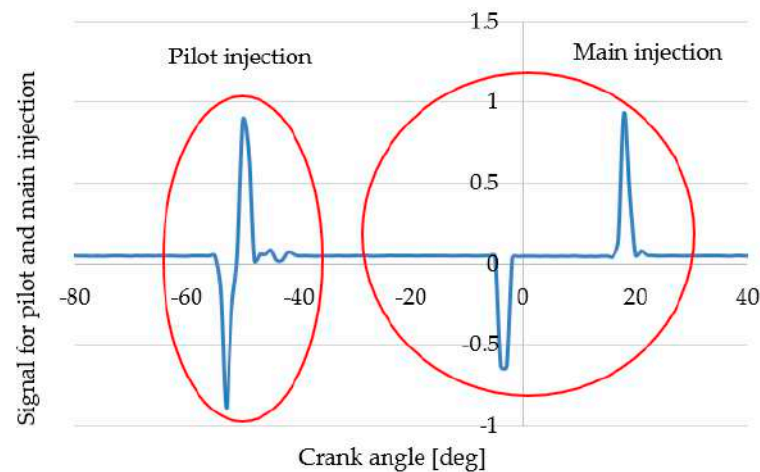


Figure 13. The signal for the two injection events.

3.2. The Ecological Parameters

The analysis of ecological parameters focuses on the concentrations of NO_x, CO, CO₂, HC, and particulate matter in the exhaust gases. The origin of pollutant emissions in compression ignition engines is characterized by the fuel state (vapor or droplets), mixture homogeneity (local dosage coefficient), and cylinder temperature.

Nitrogen oxides form at high pressure and temperature levels in the combustion chamber. The quantity of nitrogen oxides is influenced by the amount of available oxygen. During the formation process of nitrogen oxides from the beginning of combustion, several flame nuclei are created and distributed in depth. The oxygen around these nuclei is consumed more quickly than in the areas further away. These zones, where oxygen maintains its initial concentration, are heated due to the increase in pressure and the heat radiated by the flame. The relatively high concentration and temperature lead to the formation of nitrogen oxides in these zones. An engine running on biodiesel typically produces lower levels of NO_x compared to regular diesel for a few reasons related to the chemical properties of biodiesel and how it burns in the engine.

Sunflower oil biodiesel and UO biodiesel may behave differently in terms of NO_x emissions primarily due to differences in their chemical composition, fatty acid profiles, and how these factors influence combustion characteristics.

Different oils have varying levels of saturated, monounsaturated, and polyunsaturated fatty acids, and these affect combustion in several ways. SF typically has a higher percentage of polyunsaturated fatty acids. These are more reactive, which can result in higher combustion temperatures when burned in the engine. Since NO_x is formed at higher combustion temperatures, this can lead to increased NO_x emissions. UOs have in their compositions a mixture of saturated, monounsaturated, and polyunsaturated fats, but they are often higher in monounsaturated fats than oils like SF. The presence of more monounsaturated fats can lead to more stable combustion and lower peak combustion temperatures, due to better oxidative stability, resulting in lower NO_x emissions compared to diesel. From Table 2, it can be observed that both SF and UO contain a small percentage of saturated fats, with monounsaturated and polyunsaturated fats being predominant. SF oil predominantly contains polyunsaturated fats, more than 50%, and approximately 30% monounsaturated fats. In comparison, UO contains approximately 60% monounsaturated fats and 20% polyunsaturated fats.

Saturated fatty acids have a high melting point, are more viscous, and tend to burn at higher temperatures. Fuels rich in saturated fatty acids tend to increase combustion temperatures, which can lead to higher thermal NO_x emissions. NO_x is produced at high temperatures in the presence of oxygen, and the higher the temperature, the greater the NO_x formation.

Monounsaturated fats have one double bond in their fatty acid chains and polyunsaturated fats have multiple double bonds in their fatty acid chains. These structural differences influence how the biodiesel burns in the engine and can affect its combustion characteristics, including temperature, combustion efficiency, and emissions such as NO_x. Biodiesel made from oils with monounsaturated fats in the composition tends to produce slightly lower NO_x emissions compared to biodiesel made from polyunsaturated fats, due to the smoother combustion process and lower peak temperatures. If a biodiesel blend contains a higher percentage of monounsaturated fats, the smoother and more controlled combustion process can lead to lower NO_x emissions. A biodiesel blend with more monounsaturated fats is likely to produce lower NO_x emissions compared to one with a higher percentage of polyunsaturated fats.

Nitrogen oxide emissions are also influenced by the amount of available oxygen (from the aspirated air, correlated with the amount of oxygen in the molecule of the tested

biofuels) by the temperature of the exhaust gases, which should be as low as possible, and the contact time between oxygen and the gases in the combustion chamber. Biodiesel contains more oxygen than conventional diesel fuel. The presence of oxygen helps promote more complete combustion, which can reduce the formation of NO_x. During combustion, the biodiesel generally burns at a lower peak combustion temperature than petroleum diesel. Since NO_x is formed at higher combustion temperatures, the cooler combustion conditions of biodiesel result in lower NO_x production. The lower carbon content of biodiesel compared to diesel 100% may also help reduce the overall heat generated during combustion, indirectly contributing to lower NO_x levels.

However, the impact on NO_x emissions also depends on several other factors, including the specific engine design, operating conditions, and the biodiesel blend's overall formulation. The relationship is not always linear.

A lower aniline point generally improves fuel performance by promoting better atomization, quicker ignition, and more complete combustion, leading to higher engine efficiency and lower PM and smoke emissions, but it may result in slightly higher NO_x emissions due to the higher combustion temperatures associated with better combustion.

The viscosity of biodiesel has an important role in how it is injected into the combustion chamber and how efficiently it burns. The higher the viscosity, the harder it is for the fuel to atomize properly, which can affect combustion efficiency. Biodiesel derived from SF tends to have a lower viscosity compared to UO biodiesel (Table 2) which can result in better atomization and more complete combustion. However, higher polyunsaturation levels and possible higher combustion temperatures might still lead to an increase in NO_x emissions. However, other factors such as viscosity, and engine calibration can also influence the final emissions profile.

From the analysis of the graph in Figure 14, it can be observed that NO_x emissions at all concentrations of biofuels are lower than those of diesel, with percentage values ranging from 6.21% (SF05) to 15.62% (SF20).

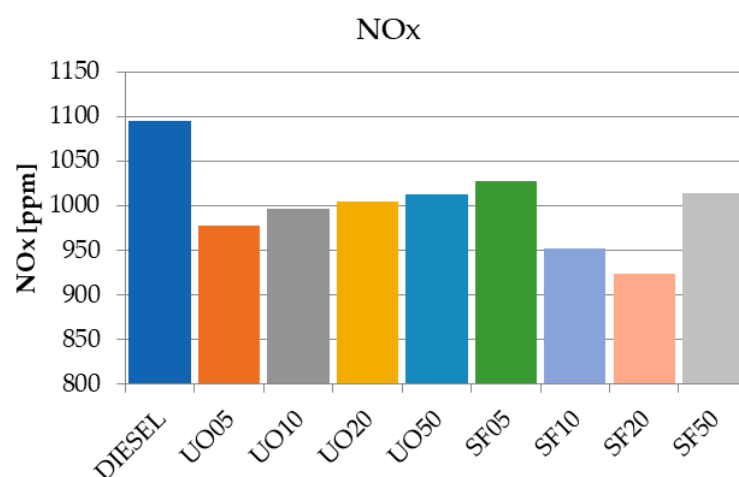


Figure 14. The variation of NO_x emissions, at 100% load and 2500 rpm speed, depending on the fuel type.

From Figure 14, it can be seen that NO_x emissions increase with the increase in the concentration of biodiesel from UO in the blend and decrease with the concentration of biodiesel from sunflower oil. Mixtures with 50% biofuel recorded similar values, both being lower than diesel. The lower values of nitrogen oxides observed in the case of biofuels compared to diesel indicate that the maximum cycle temperatures were lower in the case of biofuel blends.

Figure 15 presents NO_x emissions for a speed of 2500 rpm, varying the load. It can be observed that for all tested biofuels, these emissions are lower than those for diesel.

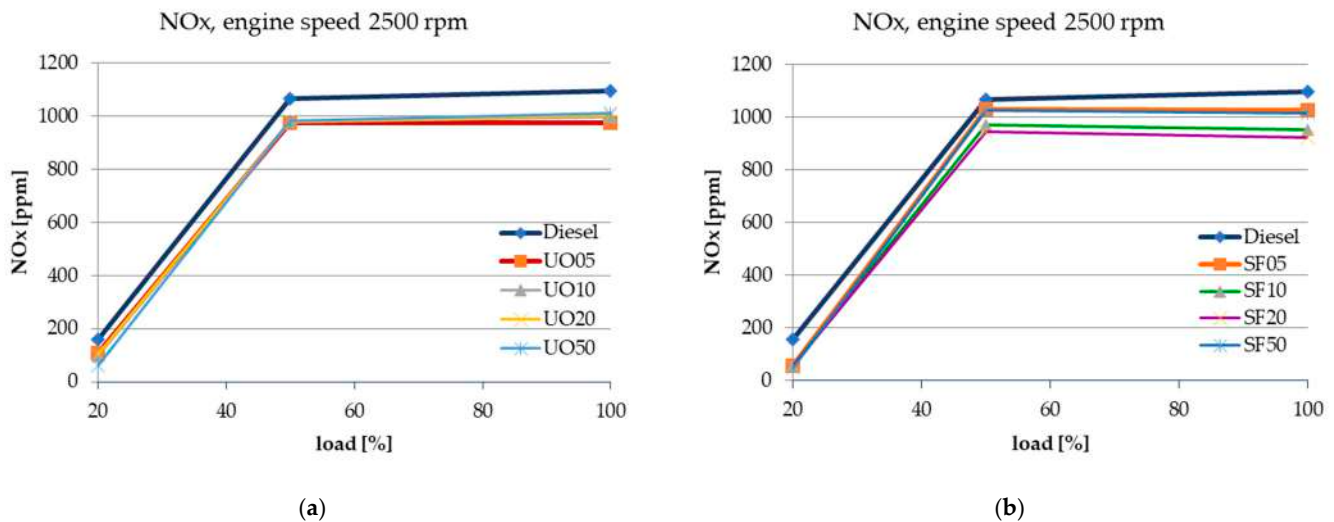


Figure 15. The variation of NO_x at 2500 rpm speed, depending on the engine load and fuel types: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

As the load increases, so does the pressure and maximum temperature in the combustion chamber, favoring the formation of NO_x. This trend is also observed in the graphs presented in Figure 15.

The analysis of NO_x emissions at constant load confirms the previously formulated conclusions. Additionally, from Figure 16, it can be observed that for speeds of 2000, 2500, and 3000 rpm, emissions recorded with alternative fuels are lower than those of diesel. At 3600 rpm, there is an increase in NO_x emissions by 12% for SF05 and by 16.63% for SF50. For fuel UO, all concentrations were above the diesel value, ranging from 2 to 7%.

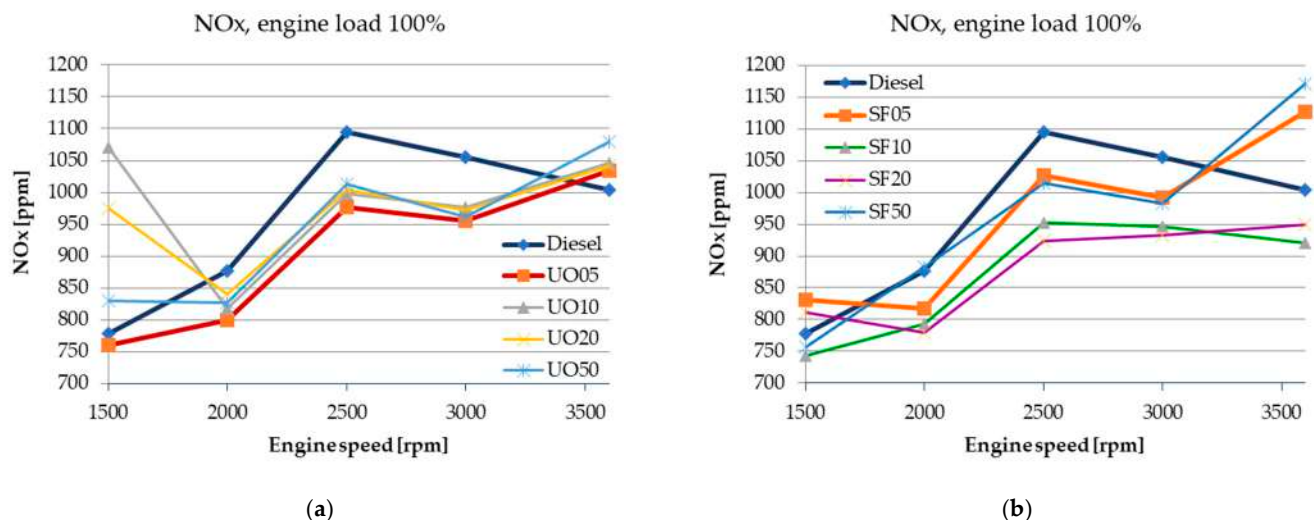


Figure 16. The variation of NO_x at a constant load of 100%, varying the speed, depending on the fuel: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

The graphs in Figure 17 show the variation of CO and HC emissions. Apart from fuel SF20, which records a 50% increase in CO emissions compared to diesel, the other fuels register lower values than diesel, up to 20%, demonstrating good mixture formation. Also, in the case of HC, the same fuel, SF20, records an increase of 23.29% compared to diesel. Overall, from the data analysis presented in Figures 14 and 17, it can be observed that

the emissions of NO_x, CO, and HC of the tested biofuels are generally lower than those recorded in the case of diesel.

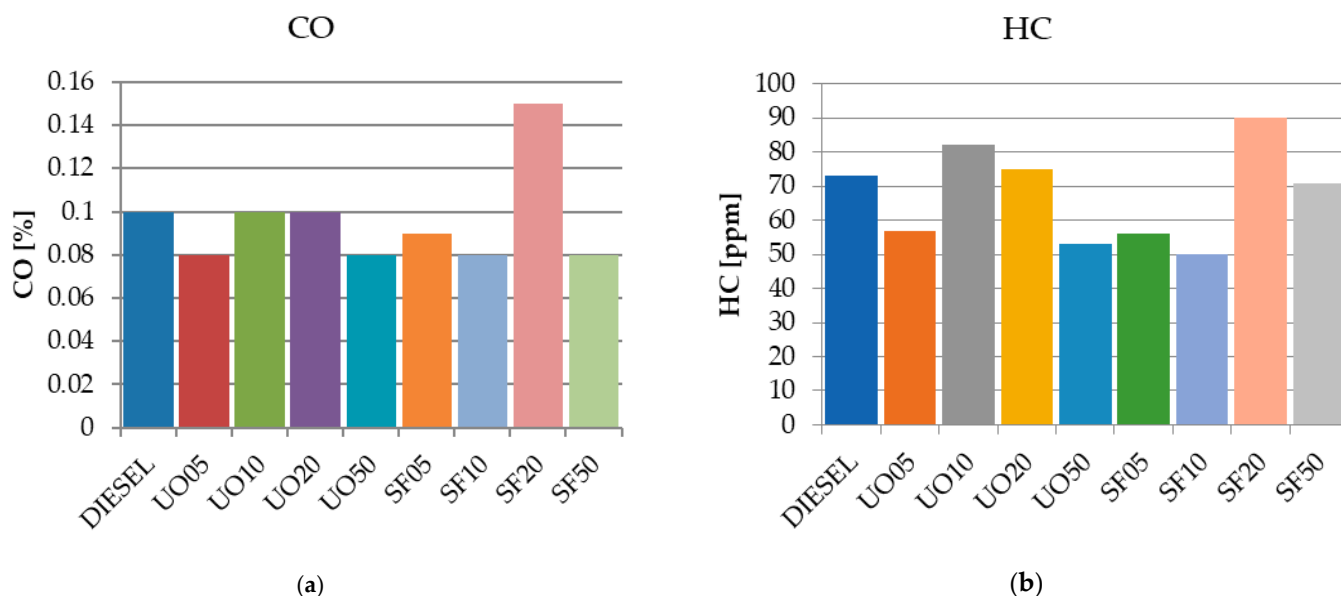


Figure 17. The variation of CO (a) and HC emissions (b), at 100% load, 2500 rpm speed, depending on the fuel type.

Oxygen in biodiesel mixtures shows a decrease of NO_x and CO values, compared with diesel, as shown in Figures 14 and 17. Fuels with higher oxygen contents, like biodiesel, enhance combustion efficiency by promoting more complete oxidation of carbon.

Carbon monoxide, shown in Figure 18, is generated due to localized oxygen deficiency, low temperatures in the combustion chamber, and insufficient time for complete combustion reactions, making it a product of incomplete combustion. In general, a higher cetane number, better mixture formation due to lower viscosity, and density characteristics favoring fuel vaporization lead to a lower delay in autoignition and consequently lower CO emissions.

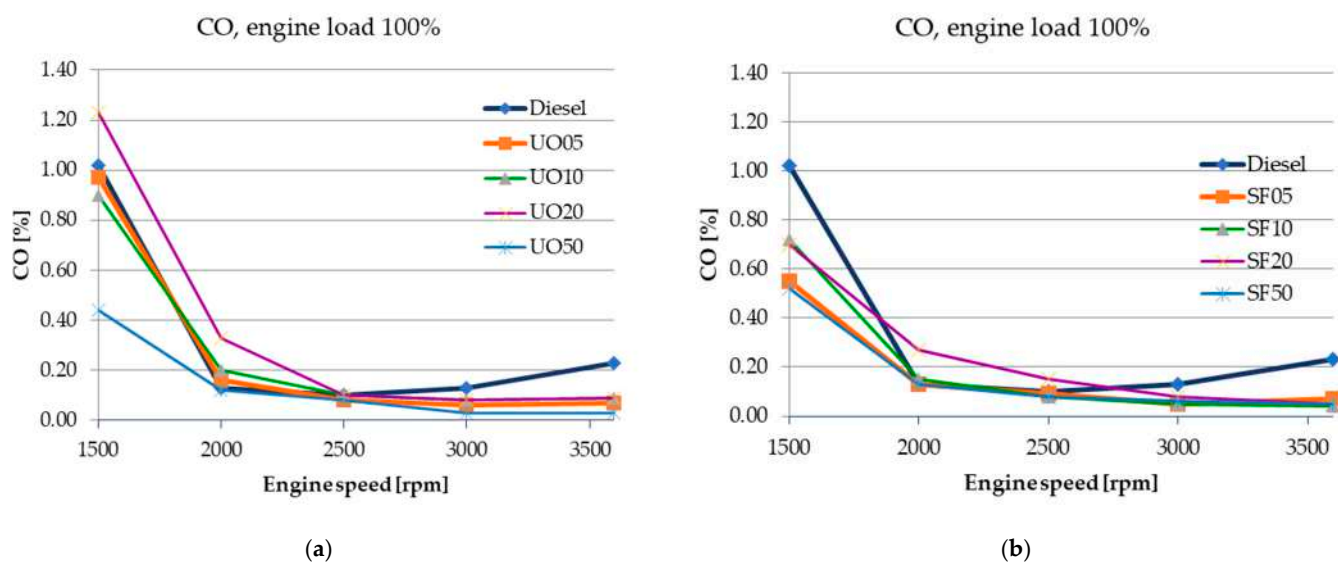


Figure 18. The variation of CO emissions, at a constant load of 100%, with varying engine speed, depending on the fuel type: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

The analysis conducted at a constant speed proved that the emissions of CO and HC for the 2500 rpm engine speed point are lower for all tested fuels compared to diesel, as displayed in Figures 19 and 20. Furthermore, from these figures, it can be stated that CO and HC emissions decrease with increasing engine speed, in both cases being lower than the values recorded for diesel.

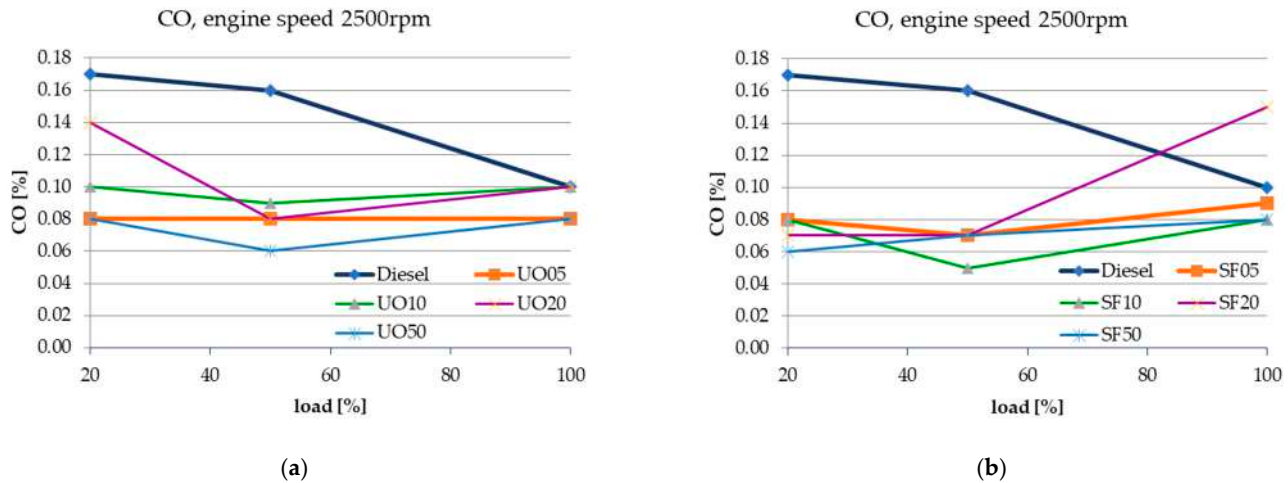


Figure 19. The variation of CO emissions, at 2500 rpm speed, varying the engine load, depending on the fuel: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

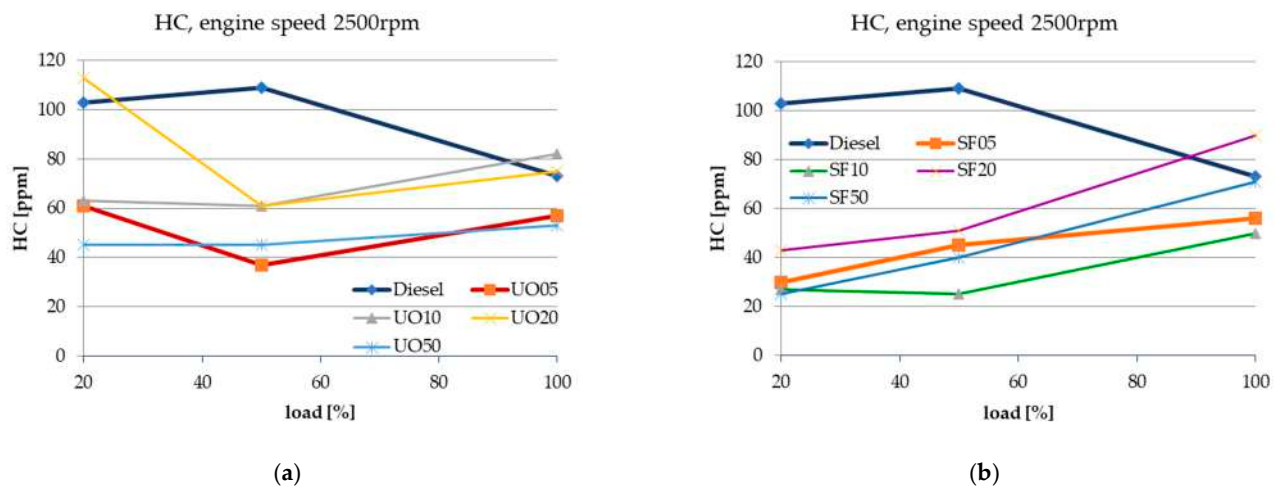


Figure 20. The variation of HC emissions at 2500 rpm speed, varying the load, depending on the fuel: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

As observed in Figure 20, at high loads, areas with a rich fuel mixture are formed in the fuel jet, where fresh air penetrates more slowly, generating higher HC emissions compared to low loads.

The hydrocarbon emissions from exhaust gases (displayed in Figure 21) are determined by the poor propagation of the fuel-air mixture flame front. When fuel droplets reach the walls of the combustion chamber due to incomplete combustion, they undergo slow chemical transformations that lead to the formation of hydrocarbons.

Regarding particle emissions, Figure 22 presents measurements conducted with two different devices: an AVL SmokeMeter for determining the soot content (FSN) and a Horiba MDLT microdilution tunnel for determining particle mass.

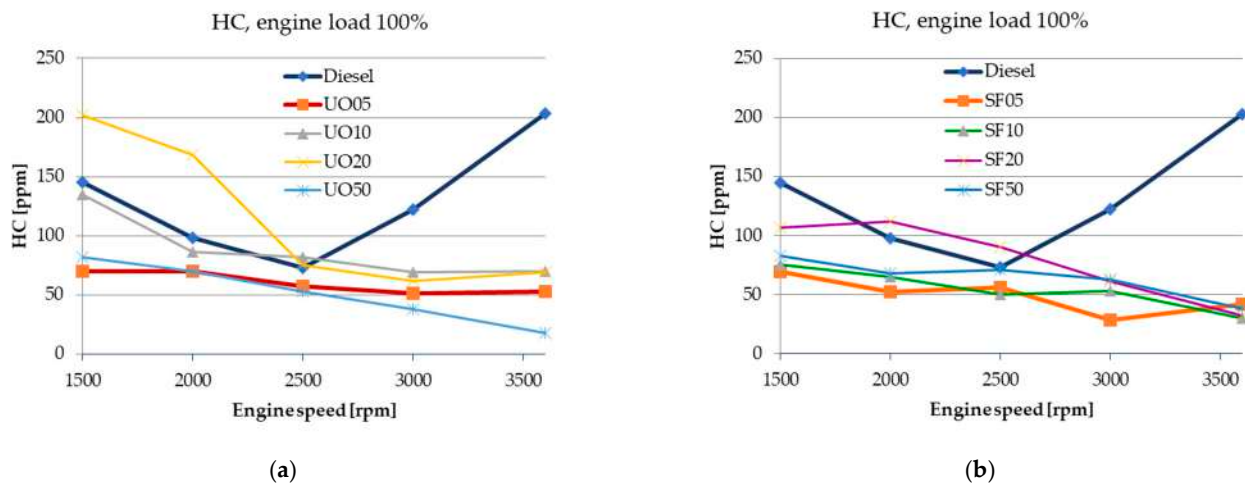


Figure 21. The variation of HC emissions, at a constant load of 100%, with varying engine speed, depending on the fuel type: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

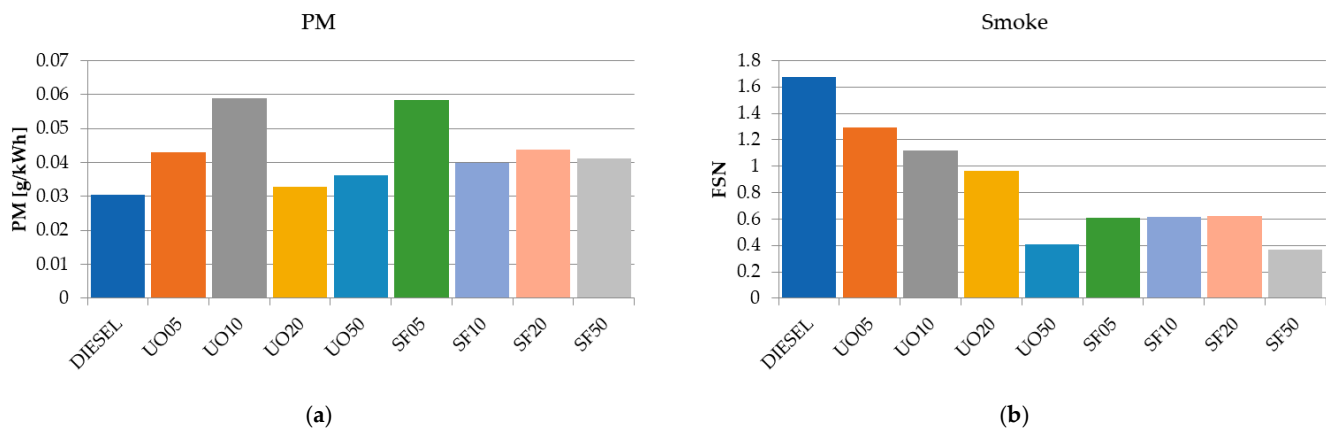


Figure 22. The variation of PM (a) and smoke emissions (b), at 100% load, 2500 rpm speed, depending on the fuel type.

Particle formation in compression ignition engines is linked to incomplete combustion in certain areas of the combustion chamber due to insufficient time for the formation of a homogeneous fuel-air mixture. Particles are formed from aggregates of spherical carbon particles and volatile substances, including hydrocarbons and sulfates.

Fuels with higher aromatic contents tend to increase soot and PM emissions and to potentially increase NO_x emissions due to higher combustion temperatures. They may also contribute to higher HC and CO emissions because of incomplete combustion. The presence of higher polyaromatic contents in diesel fuel generally results in higher PM emissions and lower combustion efficiency.

Fuels that present a high viscosity can affect the atomization (spray pattern) of the fuel during injection. Poor atomization can lead to inefficient combustion, potentially increasing emissions of PM compared to diesel.

From analyzing these data, it can be observed that regarding the soot content, the emissions from biofuels are lower compared to diesel. Moreover, there is a significant difference between the two types of alternative fuels at concentrations of 5%, 10%, and 20%. Thus, differences ranging from 22.93% (UO05) to 78.21% (SF50) compared to diesel are observed, with the highest value recorded for UO05, and the lowest values compared to diesel observed for the fuels UO50 and SF50 (75.46% and 78.21%, respectively). On the other hand, the particle mass shows an uneven trend depending on the fuel, suggesting that the differences stem from the chemical composition of the fuels.

As observed in Figure 23, as the load increases, the measured PM values for biofuels are close to diesel.

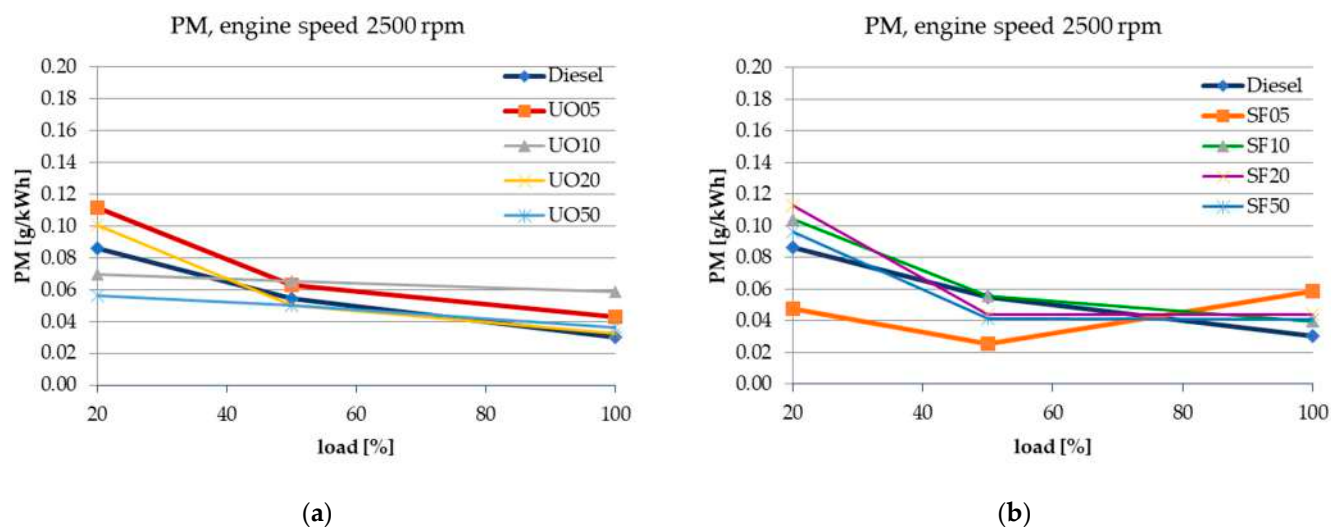


Figure 23. The variation of PM, at 2500 rpm speed, varying the engine load, depending on the fuel type: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

In general, there are three reasons leading to lower particle emissions when using biodiesel. Firstly, the delayed autoignition associated with biodiesel results in a longer period for soot oxidation. Secondly, the higher oxygen content in biodiesel allows for more complete combustion and assists in the oxidation of already formed soot. Thirdly, the absence of polycyclic aromatics in biodiesel composition reduces soot formation.

From the analysis of the data presented in Figure 24, the uneven nature of particle mass depending on engine speed is confirmed, but with a very clear trend in the case of the FSN. For both types of fuels, lower values are recorded compared to diesel fuel. The lowest values (approximately 70% lower across the entire rpm range) are recorded for 50% biofuel concentrations in the blend, correlated with the lower energy efficiency of these fuels as well.

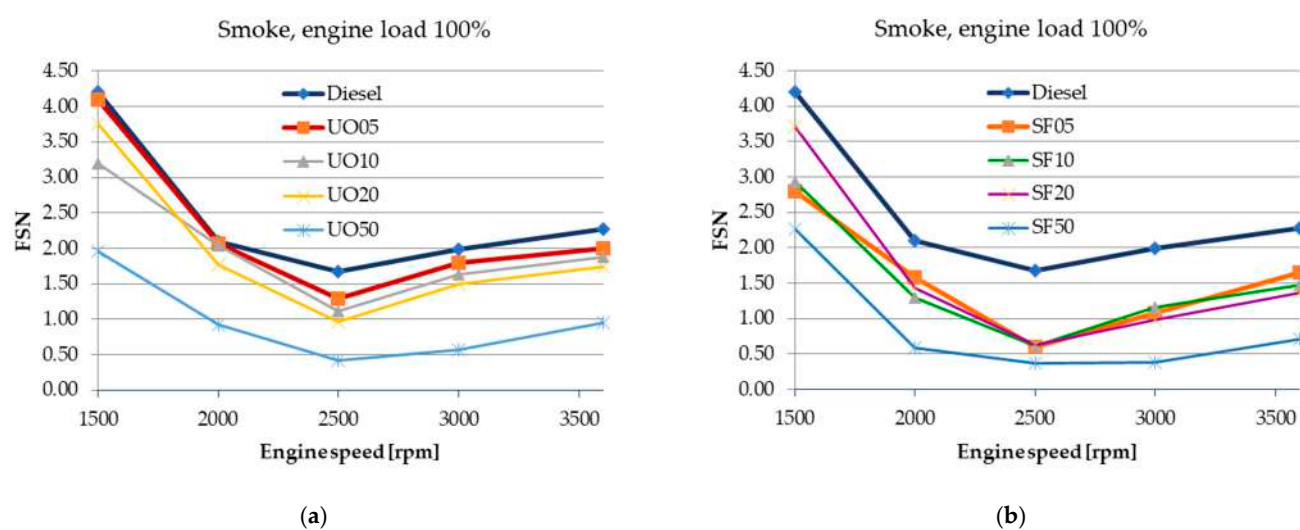


Figure 24. The variation of smoke emissions, at a constant load of 100%, with varying the engine speed, depending on the fuel: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

CO₂ emissions do not directly affect health but are one of the components of greenhouse gases. In compression ignition engines, CO₂ emissions are directly proportional to the amount of fuel injected into the cylinder, and therefore to the load.

As can be seen from Figure 25, CO₂ emissions are also lower in the tested biofuels compared to diesel. The emissions show similar trends for both types of fuels. The lowest values are presented by fuels with a concentration of 5%. Specifically, for UO05, the value is lower by 9.38% than the value for diesel, while for SF05, the CO₂ emissions are 8.59% lower than in the case of diesel.

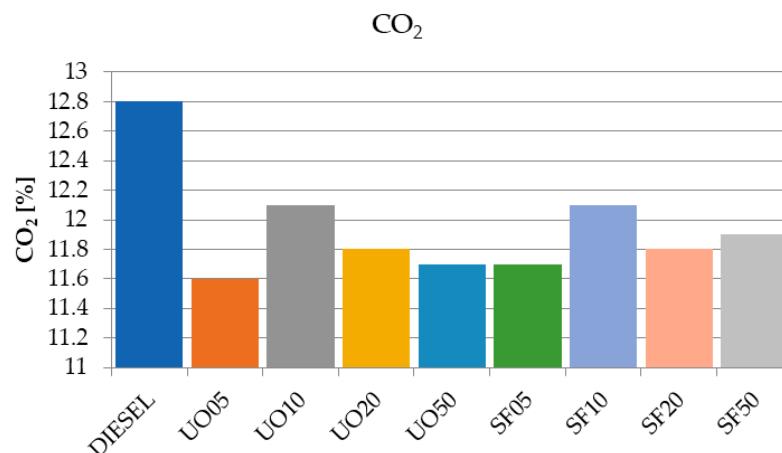


Figure 25. The variation of CO₂ at 100% load, 2500 rpm speed, depending on the fuel.

The analysis of the graphs in Figure 26 shows that CO₂ emissions decrease with increasing engine speed at 100% load. Additionally, for both types of fuel, it can be observed that CO₂ emissions are lower than those measured for diesel across the entire range of speeds.

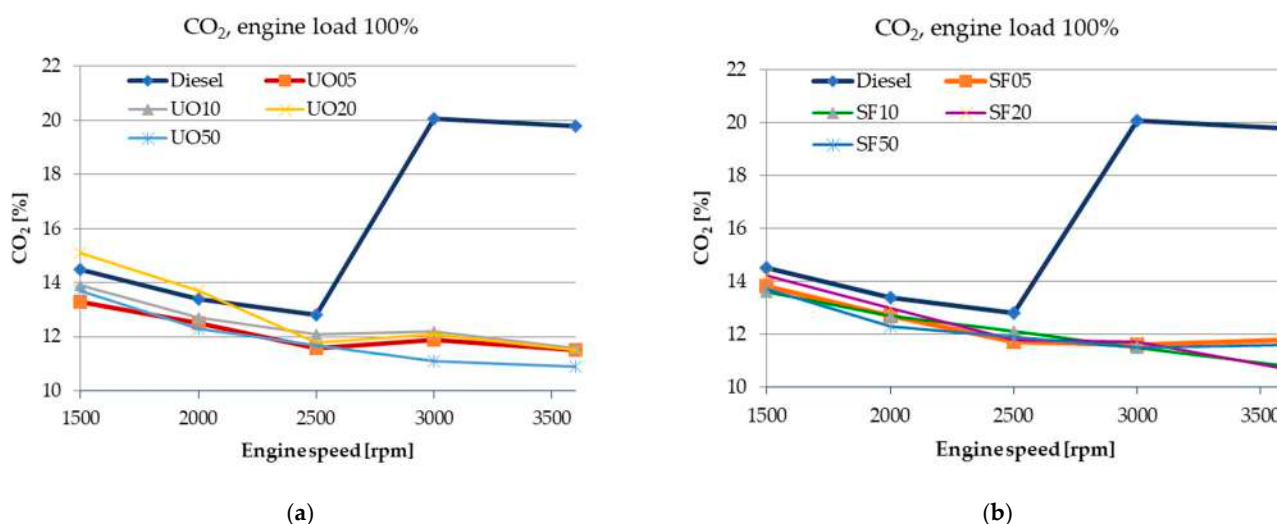


Figure 26. The variation of CO₂ emissions at a constant load of 100%, with varying engine speed, depending on the fuel type: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

The CO₂ emission values for biofuels are noticeably lower than those for diesel, showing a tendency to increase with the load, as depicted in Figure 27.

Higher hydrogen content in the mixture promotes better combustion, which can slightly increase NO_x emissions while reducing overall CO₂ emissions due to the production of water vapor instead of CO₂ during combustion, as can be noted from the data in

Table 2 and Figures 14 and 25–27. Additionally, biodiesel typically burns at a lower peak combustion temperature than petroleum diesel, contributing to reduced CO₂ emissions.

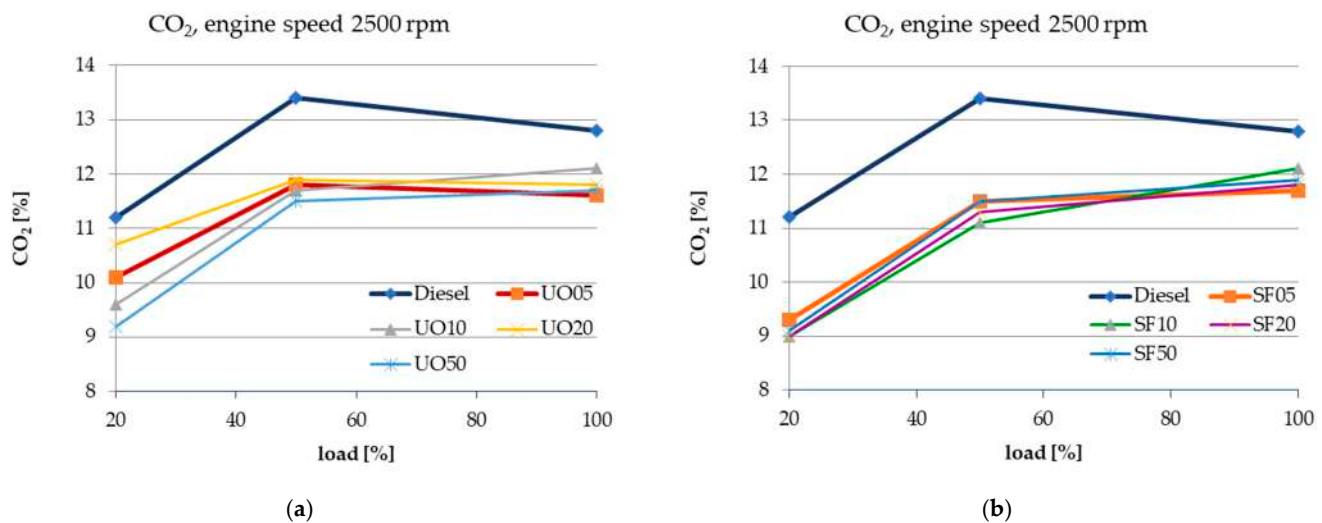


Figure 27. The variation of CO₂, at 2500 rpm speed, varying the engine load, depending on the fuel type: (a) used cooking oil biodiesel; (b) sunflower oil biodiesel.

From the analysis of full load characteristics, it was observed that the maximum power was achieved at 3600 rpm, with a value of 71.11 kW in the reference tests with diesel fuel. Additionally, at 2500 rpm, the maximum engine torque of 221 Nm was obtained, along with the minimum BSFC, with a value of 212 g/kWh. From the analysis of the engine's energetic parameters when operating with the nine tested fuels according to the research program, several key observations can be noted.

Overall, fuels based on UO displayed similar energy efficiency to diesel, with minor differences. Notable differences were observed at lower loads. At a concentration of 50%, UO50 exhibited a significant decrease compared to diesel across all speed ranges and tested loads.

Effective power decreased with increasing concentrations of SF biodiesel, with SF50 showing a 3.18% reduction at 2500 rpm. UO biodiesel shows minimal fluctuations up to UO20 but exhibits a 2.61% reduction at UO50 under the same conditions. For SF oil, Simbi et al. [15] reported that B50 blends showed significant decreases in both torque and power. Similarly, UO biodiesel blends exhibit torque reductions ranging from 2–5% relative to diesel, as noted by Razzaq et al. [16]. More pronounced reductions for B20 and B30 waste cooking oil blends were observed Zareh et al. [17], while Yildiz et al. [18] linked these decreases to the higher density and lower energy content of waste cooking oil biodiesels.

Both sets of blends showed similar energetic parameter values for the same concentrations. Used cooking oil-based fuels displayed a non-uniform trend in energy parameters with varying speed but had similar values among them. In contrast, sunflower oil-based fuels exhibited a decreasing trend in energy efficiency with increasing biofuel concentration, as confirmed by the BSFC graph, which increased with concentration.

Density is one of the properties influencing BSFC. For UO biodiesel, it ranged from 835 kg/m³ (UO05) to 853 kg/m³ (UO50), while for sunflower oil biodiesel, it ranged from 836 kg/m³ (SF05) to 854 kg/m³ (SF50), compared to diesel's density of 832 kg/m³. The impact of density on engine performance is complex and depends on blend percentage, engine design, and operating conditions.

With regard to fuel efficiency, the hourly fuel consumption for UO decreases as the biodiesel concentration increases, with a 2.08% reduction at UO05 and a 0.43% reduction

at UO50 compared to diesel. No significant changes in hourly fuel consumption were observed for SF biodiesel blends.

BSFC increases with higher concentrations of both sunflower oil biodiesel and UO biodiesel. Other studies support the increase in BSFC with biodiesel blends. For example, Mahmood et al. [16] reported that BSFC increases with higher concentrations of waste cooking oil biodiesel blends due to a lower heating value and higher viscosity, while Mandal et al. [17] observed similar trends for waste cooking oil biodiesel blends, with B40 and B80 blends showing increased BSFC as engine speed increased. The increase in BSFC for sunflower oil biodiesel was also confirmed by Dueso et al. [21], who found that sunflower biodiesel blends exhibited higher BSFC than diesel.

For SF, the SF50 blend shows a 3.18% increase compared to diesel at 2500 rpm, aligned with reductions in power and torque. UO exhibits a similar trend, with the higher density of UO50 (835–854 kg/m³) contributing to increased BSFC due to its impact on combustion efficiency.

Cylinder pressure varied depending on the biodiesel's properties. The maximum pressure for SF was approximately 2.5% higher than that recorded for UO across all concentrations. At 2500 rpm and full load, UO50 exhibited the lowest cylinder pressure, 3.66% lower than diesel.

An analysis of energy parameters by speed showed nearly equal values for all concentrations, with fuels at the 50% concentration exhibiting the largest differences compared to diesel.

Regarding the ecological parameters and their variations with speed and load during the tests, based on the concentration of biofuel in the blend, the analysis generates several conclusions.

It can be observed that NO_x emissions increase with the increasing concentration of UO biodiesel in the blend and decrease with SF biodiesel concentration. The evolution of NO_x emissions displayed a pronounced increase up to 50% load, after which the changes are minimal, which can be explained by the proportional modification of exhaust gases. The same trend is observed at the speed corresponding to maximum torque, 2500 rpm. Mixtures with 50% biofuel recorded similar values, both lower than diesel. The same findings were also observed by Enweremadu et al. [22], who attributed the increase to the oxygenated nature of biodiesel, leading to higher in-cylinder temperatures, while multiple studies found that NO_x increased for all waste cooking oil biodiesel blends (B40, B80) [17,18,20,22]. For SF biodiesel blends, the NO_x emissions decreased with the concentration of SF biodiesel, with 50% biofuel blends showing lower NO_x than diesel, as confirmed by Dueso et al. [21] and Vergel-Ortega et al. [34], whose NO_x emissions results were slightly lower than diesel for low-concentration SF biodiesel blends, but increased at higher concentrations due to the higher oxygen content in the fuel.

Emissions of HC and CO for the 2500 rpm point are lower for all tested fuels than those of diesel. Additionally, CO and HC emissions decrease with increasing speed, both being lower than the values recorded for diesel. These observations are supported by Mandal et al. [20], who reported a 52% reduction in CO and a 60% reduction in HC for waste cooking oil biodiesel blends compared to diesel. Yildiz et al. [18] confirmed that HC and CO emissions were lower for waste cooking oil biodiesel, especially for B20 and B30 blends. Similar findings were reported by Iglesias et al. [23], Venkatesan et al. [28], and I-Dawody et al. [37] who observed a reduction in CO and HC for SF and UO biodiesel blends. Density values (according to Table 2) confirm this trend of reduced HC and CO emissions due to better combustion.

Lower levels of HC emissions compared to diesel demonstrate good atomization due to the lower viscosity and density of alternative fuels compared to diesel. The points where

increases in these emissions are recorded above the diesel level suggest the need to improve the jet formation mechanism.

A comparison of the combustion process of SF biodiesel versus UO biodiesel indicates that the SF biodiesel typically generates a better combustion process in terms of efficiency, power output, and overall performance. SF biodiesel is made from refined sunflower oil and it mainly contains polyunsaturated fatty acids, which typically burn efficiently, contributing to better combustion. This allows for smoother combustion with more complete fuel oxidation, which improves engine performance and reduces emissions of HC and PM.

Both SF biodiesel and UO biodiesel contain oxygen within their molecular structure, which helps improve combustion by enabling more complete oxidation of the fuel. UO biodiesel may generate higher PM and HC due to its less efficient combustion, but it may produce lower NO_x emissions because of the lower combustion temperatures.

SF biodiesel tends to have lower viscosity than used oil biodiesel, which promotes better atomization of the fuel in the engine's injector system. Good atomization leads to better mixing with air, which results in more complete and efficient combustion. This efficiency generally translates to better engine performance, more power output, and less unburned fuel and lower emissions. SF biodiesel generates a better combustion process because it is cleaner, has a lower viscosity, and burns more efficiently, leading to higher combustion temperatures, better engine performance, and lower emissions of PM and HC. In summary, SF biodiesel provides a more efficient, cleaner, and more consistent combustion process, which leads to better overall engine performance compared to used oil biodiesel.

The value of particulate matter emissions displays a clear trend of decreasing with engine speed, with both types of fuels recording lower values than diesel. The lowest values (approximately 70% across the entire engine speed range) were recorded for 50% biofuel concentrations in the blend, correlated with the lower energy efficiency of these fuels. Studies indicate that PM emissions can be reduced by up to 30% when using biodiesel blends like B20, B30 [5,38], and B50 blends [18], particularly with 50% biofuel concentrations at higher speeds [32]. Vergel-Ortega et al. [34] observed similar trends with waste cooking oil biodiesel, in which PM emissions decreased as biodiesel concentration increased. Simbi et al. [15] and Zareh et al. [17] confirmed that SF biodiesel exhibited a notable reduction in PM emissions.

Analysis of particle mass data reveals non-uniformity between measured values, which may be due to the different chemical compositions of the tested fuels and the particle formation mechanism influenced by several factors of the combustion process (temperature, oxygen quantity, mixture homogeneity), which vary for each point and tested fuel. Zareh et al. [17] found that PM and opacity decreased with waste cooking oil biodiesel blends, particularly B20 and B30, with B50 exhibiting the largest reduction. Mandal et al. [20] found lower opacity for waste cooking oil biodiesel blends (B40, B80) compared to diesel.

CO₂ emissions show lower values for the tested alternative fuels compared to diesel, both in terms of load and speed characteristics. The reduction in CO₂ emissions also depends on the life cycle assessment of the biodiesel, as CO₂ absorbed during feedstock growth offsets the emissions produced during combustion, as confirmed by multiple studies [15,17,18,20,23].

Emission formation in a compression ignition engine is influenced by the starting point of the injection. Tests results showed that the pilot injection time for all tested fuels is equal at a speed of 2500 rpm. Although the lower advance of the pilot injection should negatively influence the ecological parameters [39], it can be observed that the properties of the fuels play a more important role in this regard. The analysis of all load and speed

points shows that the injection system self-regulates depending on the engine speed, load, and the specific properties of the tested fuel.

These findings highlight the environmental benefits and potential areas for further optimization and research in alternative fuel utilization.

4. Conclusions

Following the experimental program described in the previous sections, using bio-fuels derived from waste cooking oil and sunflower oil mixed with diesel, the following conclusions can be drawn from an energy and environmental perspective:

The analysis demonstrates that biodiesel from used oil components shows a non-uniform trend, but a similar energy efficiency to diesel, though 50% concentrations show a significant drop.

Biodiesel properties influence cylinder pressure, with sunflower oil-based fuels having approximately 2.5% higher maximum pressure than used cooking oil-based fuels across all concentrations.

CO₂ emissions are lower for all alternative fuels compared to diesel, both at varying loads and speed. NO_x emissions can increase depending on the biofuel type, and particulate matter emissions are reduced at higher speeds, particularly with 50% biofuel concentrations. Fuels with a 50% biofuel blend exhibit the lowest PM emissions (around 70% lower than diesel) across all speed ranges, though this is linked to lower energy efficiency in these fuels. While reductions in CO, HC, and PM emissions align well with the standards, the observed increase in NO_x for certain blends highlights the need for further optimization to fully comply with stringent NO_x limits.

From the comprehensive analysis of the data obtained from the experimental research on the engine, it can be said that from an energetic point of view, although the effective and indicated parameters were close in value for alternative fuels and diesel, a decrease in performance was observed when using biofuels. Fuels with 50% concentrations showed the lowest energy efficiency. From an ecological point of view, operation with alternative fuels resulted in an improvement in the emissions level from the exhaust gases for most concentrations of biofuels used, with the lower energy efficiency of UO50 and SF50 fuels being reflected here as well, with the lowest emissions values for these fuels.

These findings underscore the complex interplay between fuel composition, engine performance, and environmental considerations, providing valuable insights for further optimization and research in alternative fuel applications.

5. Further Research

Further investigations may focus on including parameters such as in-cylinder temperature and the excess air coefficient to study their influence on NO_x and PM emissions. Additionally, incorporating advanced fuel additives or exploring engine modifications such as exhaust gas recirculation or low-heat rejection engines could provide deeper insights into optimizing biodiesel blends for diesel engines. Finally, the application of AI technologies in data analysis is expected to become a significant asset in quantitative research and could be implemented in future studies.

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