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On the Increase in the Renewable Fraction in Diesel Blends Using Aviation Fuel in a Common Rail Engine

Ornella Chiavola *, Fulvio Palmieri and Domenico Mario Cavallo

Industrial, Electronic and Mechanical Engineering Department, Roma Tre University, 00154 Roma, Italy; fulvio.palmieri@uniroma3.it (F.P.); domenicomario.cavallo@uniroma3.it (D.M.C.)
* Correspondence: ornella.chiavola@uniroma3.it

Abstract: Biodiesel has gained wide acceptance as an alternative to petroleum-derived fuel due to its environmentally friendly characteristics such as low aromatic and sulfur content, biodegradability and low exhaust gas emission. Although many types of feedstock could be used to produce biodiesel, waste cooking or frying oil (WCO) is a promising multiple-advantage solution. However, the use of WCO biodiesel has some drawbacks: the high viscosity and the low volatility create difficulties in atomization and in fuel–air mixing. Experiments were performed to investigate the potential employment of aviation fuels in blends with biodiesel obtained from WCO, renewable diesel and petrol diesel. The objective of the research was to evaluate Jet A's potential to improve the blend properties, thus helping to overcome the difficulties in biodiesel usage, enabling the percentage of renewable fuel in the blend to be increased and therefore allowing a reduction in the engine's environmental impact. The experimental activity was carried out on a small-displacement, common rail diesel engine; during the tests, the engine control unit settings were unchanged, with the aim of reproducing the engine behavior when it operated with different fuels.

Keywords: waste cooking oil; biodiesel; engine emissions; particulate matter

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1. Introduction

Environmental concerns related to the burning of fossil fuels, especially in urban areas, have led the research to define and investigate new solutions capable of reducing mobile source emissions from on-road and off-road vehicles. Advantages of reducing vehicle exhaust emissions and improving fuel economy have been obtained through different measures such as the implementation of exhaust gas after treatments, the recourse to alternative fuels, the employment of exhaust gas recirculation and injection control strategies.

Numerous types of fuel alternatives to petroleum-derived ones have been proposed; many studies have highlighted the suitability of diesel fuel produced by renewable sources such as vegetable oils, animal fats and waste oils for the partial and total replacement of petrol diesel in order to reduce the dependence on fossil fuel and mitigate air pollution.

Biodiesel obtained via a transesterification process starting from waste products and sources ineligible for human/animal consumption represents a very promising opportunity.

The literature states that carbon monoxide, particulate matter and hydrocarbons generally decrease by increasing the content of biodiesel in the blend. With regard to NOx emission, somewhat contradictory results are presented; this is due to the role of many factors, including the engine technology and the operative conditions in which the blends are tested [1–3]. Research activities have highlighted that biodiesel feedstock and the blend ratio largely impact the results. Biodiesel chemical composition/structure and physical properties deeply affect the fuel injection and ignition process; combustion-phase and exhaust emissions are consequently impacted [4,5].

Peng [6] investigated different types of biodiesel in a turbocharged diesel engine; the results indicated a decrease in smoke opacity, hydrocarbons and carbon monoxide. In

regard to petrol diesel, an increase in fuel consumption was also observed. Serrano et al. [2] analyzed a EURO 5 engine fueled with blends of biodiesel in different percentages (7% and 20% v/v). They observed that biodiesel employment did not cause a significant increase in nitrogen oxide emissions, and fuel consumption did not consistently rise. Ajtai et al. [7] investigated the role of fuel type and engine running condition on the number and size distribution of particulate matter. The authors found that the biodiesel content in a blend modifies the characteristics of the soot particles. Shahir et al. [8] presented a comparative analysis of the emissions of a CRDI engine fueled with biodiesel blends; the results showed a slight increase in nitrogen oxides and a decrease in carbon monoxide, hydrocarbons and particulate emissions. How et al. [9] analyzed the effect of injection timing on emissions and the performance of a diesel engine fueled with biodiesel blends; the obtained data highlight its role in nitrogen oxides and particulate emissions. Oni et al. [10] analyzed the emissions and performance of various blend ratios obtained from non-edible oils.

Among suitable biodiesel feedstocks, the employment of waste cooking oil represents a very promising alternative to vegetable virgin oil. This is due to the low cost of the raw material (WCO's cost is 2–3 times lower than vegetable virgin oils [11]). Furthermore, it has to be considered that the conversion of waste cooking oil into fuel eliminates the impacts on the environment due to its disposal. Previous research activities have highlighted that biodiesel from WCO is suitable to be used as fuel. Attia et al. [3] studied the performance of a single-cylinder diesel engine fueled with WCO in various blend ratios. The authors found that blending WCO with petrol diesel in a percentage of 20% allowed the lowest value of brake-specific fuel consumption to be attained. The environmental impact was reduced with a blending ratio in the range of 20–50% v/v. Gopal et al. [12] studied atmospheric emissions and the performance of a single-cylinder diesel engine for agricultural applications fueled with biodiesel from waste cooking oil and its blends. They found a reduction in smoke CO and HC with respect to petrol diesel. However, drawbacks are related to the increase in NOx emissions and specific fuel consumption in comparison with fossil diesel. Cheung et al. [13] presented the results of an experimentation on a diesel engine fueled with biodiesel from waste cooking oil in different percentages. The results revealed that biodiesel employment causes a reduction in CO, HC, particulate mass and number concentrations. An increase in nitrogen oxides was also observed. Man et al. [14] analyzed the effect of the engine running conditions on the soot size distribution when WCO was used. The results indicated that at low engine speed, more particles with larger sizes are emitted; at low values of engine load, primary particles tend to form. Hwang et al. [15] studied the combustion performance and emission characteristics of an optically accessible diesel engine operating with WCO and fossil fuel. Benefits were found with regard to HC, CO and PM at low loads. The exhaust emissions related to WCO worsened at high engine load conditions in comparison with those obtained with petrol diesel. Sanli [16] experimentally investigated WCO blend employment in CRDI engines. The author observed lower exhaust emissions compared to pure petrol diesel; WCO blend employment resulted in reduced brake-specific fuel consumption and brake thermal efficiency with regard to petrol diesel. Yesilyurt [17] analyzed the effect of injection pressure on the pollutant emissions and performance of a diesel engine operated with biodiesel from WCO. The author found that the increase in injection pressure resulted in unburned hydrocarbons and a smoke opacity decrease. Increases in nitrogen oxide and carbon dioxide emissions was also observed. Borugadda et al. [18] tested a single-cylinder engine at constant speed when fueled with blends of conventional diesel fuel and biodiesel from WCO (B10 and B15). The results indicated that blends facilitated the obtainment of fewer exhaust emissions with little compromise in the engine performance.

Research has demonstrated that the employment of biodiesel (net or blended at high percentages) in unmodified diesel engines may cause difficulties since the high density and viscosity of vegetable oils and their poor volatility and flow properties can create operation problems. Usually, engine manufacturers approve biodiesel employment only up to a fixed percentage in the blend; the utilization of additives could solve the issues caused by

operation with high biodiesel ratios in unmodified engines. Among possible additives, the employment of jet fuels represents a very attractive solution due to their lower viscosity and density and better flow properties. Blending aviation fuel with biodiesel could improve the injection process; furthermore, the mixing inside the chamber could be enhanced. The lower cetane number of jet fuels may be responsible for a longer ignition delay; this issue could be balanced by the lower distillation temperature which reduces the ignition delay.

The single-fuel concept proposed by the United States Armed Forces specifies a single fuel, F34 (JP-8), to be used to supply all based military aircrafts, vehicles and equipment, with the objective of guaranteeing a simplification of the logistic chain of petroleum by-products [19]. JP-8 and Jet A have the same specifications except for the addition of additives (lubricity improver, antioxidant, corrosion inhibitor and static dissipator) [20].

Only a few studies have been devoted to the analysis of the employment of biodiesel–kerosene blends in diesel engines. Roy et al. [21] investigated the employment of blends of biodiesel and kerosene in a compression ignition engine. The obtained results indicated that the percentages of 80% biodiesel and 20% kerosene facilitated the lowering of exhaust emissions in comparison to petrol fuel. Chen et al. [22] studied the emissions of a single-cylinder diesel engine fueled by kerosene. The results indicated thermal efficiency improvement and lower particulate emissions. No deep effect was observed on NOx. Gowdagiri et al. [23] investigated the influence of jet fuels (JP-5 and Jet A), biodiesel (hydroprocessed algae diesel and hydroprocessed camelina) and petroleum diesel on exhaust emissions and fuel consumption. They found a relationship between fuel properties and engine performance.

Rothamer et al. [24] examined the effect of jet fuels and petrol diesel on the ignition delay of a heavy-duty diesel engine. Bayindir et al. [25] investigated an unmodified engine fed with a high percentage of biodiesel. Two blends containing 80% biodiesel were tested: 20% kerosene was added to one of them, whereas kerosene (10%) and petrol diesel (10%) were used in the other one. They found a decrease in density and viscosity in the blend in which aviation fuel was employed as an additive to biodiesel.

Within this context, research was performed to explore the potential use of aviation fuel (Jet A) as an additive in blends of biodiesel from WCO, petroleum diesel and renewable diesel. The objective was to enhance combustion development and exhaust emissions using a higher renewable fraction in the blend.

Renewable diesel, also frequently referred to as green diesel or second-generation diesel, is a petroleum-like fuel (branched paraffin-based deoxygenated) fully compatible with petroleum diesel [26–28]. It is produced through a hydrogenation reaction where hydrogen reacts with biological sources. Blends of renewable diesel and petrol diesel have been demonstrated to reduce carbon monoxide and unburned hydrocarbons [29]. However, the high concentration of n-paraffin constitutes a drawback since it is responsible for the deterioration of the fuel's cold properties [30].

A comprehensive experiment was carried out on a small-displacement, common rail diesel engine whose principal application is in urban and leisure vehicles. During the tests, the engine control unit settings were unchanged in order to reproduce the engine behavior during the operation with different exchangeable fuels. As a reference fuel, it was decided to employ diesel+, which is an ultralow sulfur diesel fuel containing 15% v/v renewable diesel [31].

The manuscript is organized as follows: Section 2 describes the experimental apparatus, the fuels and the blends used during the experimentation; in Section 3, the obtained emission data are presented and discussed by firstly analyzing blends of biodiesel from WCO, renewable diesel and petrol diesel; then, the impact of a small percentage of Jet A in diesel fuel is examined. The last part focuses on the analysis of the exhaust emissions as affected by Jet A, which was used as an additive in blends with a high percentage of diesel from a renewable source.

2. Experimental Setup and Engine Tests

2.1. Test Apparatus

Experimental tests were carried out in the ICE Laboratory of the Department of Industrial, Electronic and Mechanical Engineering, at 'ROMA TRE' University. A naturally aspirated two-cylinder diesel engine, not equipped with emission control systems, was used during the experimentation (the engine main data are listed in Table 1). Regarding the injection system, the pump delivered the fuel with a maximum pressure of 80 MPa.

Table 1. Main technical data of the engine.

Engine Type	LDW442CRS Naturally Aspirated
Cylinders	2
Bore	68 mm
Stroke	60.0 mm
Displacement	440 cm^3
Compression ratio	20:1
Maximum torque	21 Nm @ 2000 rpm
Maximum power	8.5 kW @ 4400 rpm

The engine was connected to an asynchronous motor (Siemens 1PH7, nominal torque 360 Nm, power 70kW; control system, SIEMENS SINAMICS S120), as shown in Figure 1.

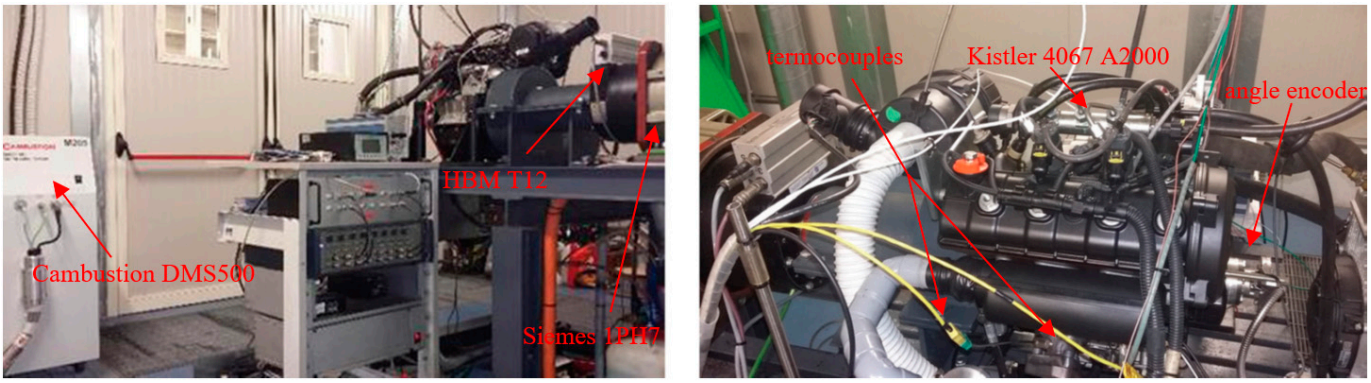


Figure 1. Engine setup.

Torque measurements were performed by using HBM T12. An optical encoder, AVL 364C, was used to determine the engine speed and the crank angle position. An AVL gravimetric balance allowed the fuel consumption measurement, with an accuracy of 0.12%.

In order to analyze the in-cylinder pressure, a piezoelectric pressure transducer (AVL GU13P) was placed in the preheating plug. Instantaneous pressure was measured in the intake and the exhaust systems. A high-pressure piezoelectric transducer (Kistler 4067A2000, Kistler, Winterthur, Switzerland) was used for in-line injection pressure measurement. Thermocouples K were employed for temperature monitoring in the intake and exhaust systems.

Exhaust gases were sampled at the engine outlet, and a Bosch BEA352 analyzer was used to evaluate the concentration of CO, CO_2, HC, O_2 and NOx (expressed as NO equivalent). In the instrument, HC measurement is based on a heated flame ionization detector, the CO analyzer is based on non-dispersive infrared detectors and NOx measurement is based on a heated chemiluminescence detector. The accuracies of HC, CO and NO are 1 ppm vol, 0.001% vol and 1 ppm vol, respectively.

Cambustion DMS500 was used to measure soot particles; particulate size distribution was computed in the range of 5 nm^{-1} µm. The instrument has a size resolution of 16 channels per decade. The instrument uncertainty is 5% in particle size measurement for particles smaller than 300 nm, it is 10% over the full spectrum for particle number density

measurement [32]. At first, the exhaust gas sample flows in a cyclone to remove all particles above 1 µm; two dilution stages are provided (primary dilution was set to 5:1; secondary dilution was set to 400:1). The sample goes through a corona charger in order to let the particles be collected depending on their aerodynamic drag and charge; a user interface allows the user to obtain the particle number and size distribution. Further details may be found in [33].

Test conditions were managed in the LabVIEW10 environment; a program was designed and realized for the data monitoring and acquisition [34].

2.2. Fuels and Tests

During the experimentation, blends of diesel+ (a petrol diesel with 15% renewable diesel), biodiesel from waste cooking oil and Jet A were tested. Renewable diesel was obtained via the EcofiningTM Process [35]. This is a process able to produce renewable diesel starting from different types of feedstock. Decarboxylation, hydrodeoxygenation, and hydroisomerization reactions are employed to obtain a high-quality diesel fuel from bio-oils plus hydrogen in mild conditions. The final product is a hydrocarbon fuel in which, unlike traditional biodiesel, oxygen is not contained.

The biodiesel used during the test came from a mixture of waste cooking oils; due to the poor quality of the initial material, some treatments were required. A first-stage self-cleaning disk separator was employed to remove the water-soluble matter and solids. The removal of the water left over was provided using a second-stage disk separator machine. Physical deacidification was also necessary to eliminate organic free acidity caused by product deterioration due to its use in food cooking. A transesterification process was used to convert the material; the resulting raw product was distilled in order to comply with the specifications of biodiesel (EN 14214). Further details may be found in [36]. Table 2 presents the mass fractions of the obtained biodiesel.

Table 2. Composition of WCO biodiesel.

Mass Fraction	
Carbon	0.812
Oxygen	0.117
Hydrogen	0.065
Sulfur	0.006

Jet A is a kerosene-type fuel that complies the international requirement (ASTM D1655 standard, British DEF STAN 91-91 standard, NATO F-35 specification). Table 3 shows the properties of pure WCO biodiesel, together with those related to diesel+ and Jet A.

Table 3. Properties of diesel+ [37], WCO biodiesel [36] and Jet A [38].

Property	**Diesel+**	**Biodiesel from WCO**	**Jet A**
density (kg/m at 15 °C)	840	877	801
lower heating value (MJ/kg)	43.2	37.1	43.4
cetane number	55	56	47

The table highlights the lower viscosity, cetane number and distillation temperature range of aviation fuel; the lower values of viscosity, density and surface tension are responsible for its better atomization with regard to diesel [22].

Aimed at individuating the maximum amount of biodiesel percentage in the fuel that could be tested without needing to modify the engine hardware, some tests were firstly carried out. The results showed that 40% is the maximum percentage of WCO biodiesel that could be used; higher values were responsible for the degradation of some materials of the engine fuel system.

Based on this highest percentage of biodiesel that allows the blends to be ready for usage in actual engine arrangements with no additional analysis of the reliability of the materials, the following blends were prepared and tested:

- D60B40: 60% diesel+, 40% WCO biodiesel;
- D70B30: 70% diesel+, 30% WCO biodiesel;
- D80K20: 80% diesel+, 20% Jet A;
- D90K10: 50% diesel+, 10% Jet A;
- D50B40K10: 50% diesel+, 40% WCO biodiesel, 10% Jet A;
- D50B30K20: 50% diesel+, 30% WCO biodiesel, 20 % Jet A.

Experimentation was performed under stationary running once a steady-state thermal regime was reached by oil and coolant temperatures. Engine speed values were fixed in the range of 2400–3600 rpm; the load condition was always established at 80% as regards the value of available torque at 100% of load obtained with petrol diesel. Such a value of load allowed a high value of torque to be imposed on the engine, which was the same for all tested fuels. Data acquired for 25 engine cycles were averaged to thus guarantee the accuracy of the results. During the testing, a two-shot injection was imposed; the timing and phasing of each injection were varied by the ECU according to the specific engine running condition, but they were not modified according to the fuel. During the pre-injection, 1 mm^3/stroke of fuel was supplied for all the operative conditions of the engine. Columns 2 to 6 of Table 4 report the crank angle values of the start of injection (pre and main injection) and the rail pressure imposed by the ECU for the specific value of engine speed and torque (first and second line of the table, respectively).

Table 4. Injection settings.

Engine speed (rpm)	2400	2700	3000	3300	3600
Torque (Nm)	18.2	19.0	17.5	17.0	15.2
SOI pre (cad BTDC)	18.5	18.4	15.5	6.0	18.1
SOI main (cad BTDC)	5.9	5.9	6.0	16.8	6.7
Prail (bar)	620	610	610	630	650

During the tests, when fuel was changed, data acquisition started once the engine had consumed all remaining fuel in the supply system.

3. Results

In the first part of this section, the results of the experimentation of diesel+ blended with various percentages of biodiesel from waste cooking oil are presented. The aim is to highlight the advantages and drawbacks of biodiesel employment. The second part focuses on the measures related to the testing of diesel+ mixed with different amounts of Jet A. The third part is devoted to presenting the effect of biodiesel and Jet A blended with diesel+ on emissions.

3.1. Diesel+ Blended with Biodiesel from WCO

Figure 2a shows the carbon monoxide trends versus the engine speed (80% as engine load). Carbon monoxide is an intermediate product that is formed during combustion; its high concentration in the exhaust is caused by the low reaction temperature, low oxygen concentration and reduced available reaction time. The oxygen content of WCO biodiesel blends causes an improvement in the fuel–air mixing process and therefore a lower CO concentration in the exhaust with regard to diesel+. When 30% biodiesel was used in the fuel, a relevant reduction in CO was observed (it was even more remarkable with 20% WCO, as reported in [39]). The further addition of WCO in the blend did not improve CO emissions with regard to diesel+.

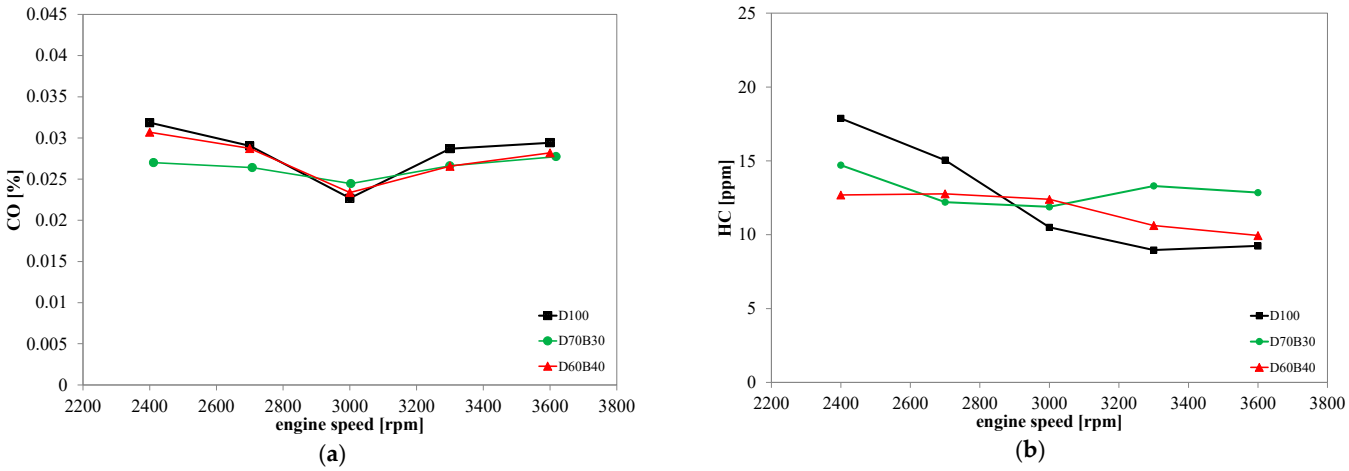


Figure 2. (**a**) Carbon monoxide and (**b**) HC concentrations at 80% load.

The effect of engine speed on hydrocarbons' concentration is highlighted in Figure 2b. Most of the emissions are due to the flame extinction in the cold part of the cylinder; moreover, it is produced in the chamber's locally lean regions. Fuel properties, such as cetane number, viscosity and volatility, play a significant role in the HC concentration in the exhaust [40,41]. The experimental data show that the effect of adding WCO to diesel+ depends on the blend ratio and the engine speed. When low values of engine speed are imposed on the engine, HC emissions related to diesel+ are higher in comparison to those obtained with WCO blends. When higher engine speed values are considered, diesel+ exhibits the lowest emission, although D60B40 is characterized by values that do not differ markedly from diesel+ ones. The exhaust gas temperature (which increases with the increase in engine speed) is a key parameter to characterize the combustion process, and it has an important role in emissions analysis. During previous experimentations [36], a reduction in temperature was observed when the biodiesel content in the blend increased.

Figure 3 presents the relation between engine speed and NO_x emission. The formation of thermal NO_x depends on the oxygen concentration, residence time and maximum temperature. In agreement with data from the literature [42], NO_x concentration in the exhaust decreases with the increase in engine speed. Such behavior is to attributed to the enhancement of gas motion in the cylinder which leads to faster air and fuel mixing; ignition delay is shortened, and thus, the maximum temperature decreases. Moreover, the increase in engine speed leads to a reduction in residence time at high temperatures in the cylinder; NO_x emissions are therefore decreased. The WCO blend ratio affects the NO_x concentration; D60B40 has the minimum emission level in the complete speed range; B30 behaves better at lower values of engine speed and worse at higher velocity.

Figure 4a,b report the nonvolatile particle concentration (PNC) and the particle mean diameter (CMD) variation with the engine velocity. An increase in the PNC characterizes all tested fuels as the rpm rises; this is caused by the balance between the increase in turbulence, which is responsible for the promotion of the combustion completeness, and the reduction in the reaction's disposal time, which affects incomplete combustion products and particle formation. The reduction in number concentration with the increase in the WCO fraction increase is due to the oxygen contained in the biodiesel and its role in limiting the primary smoke fraction, according to [43]; on the other hand, it has to be considered that the higher values of WCO density and viscosity deteriorate fuel atomization, as reported in the literature [44]. The obtained data are in agreement with the literature [40], which states that biodiesel employment is responsible for an increase in nanoparticles and a reduction in ultrafine ones, characterized by a diameter less than 100 nm.

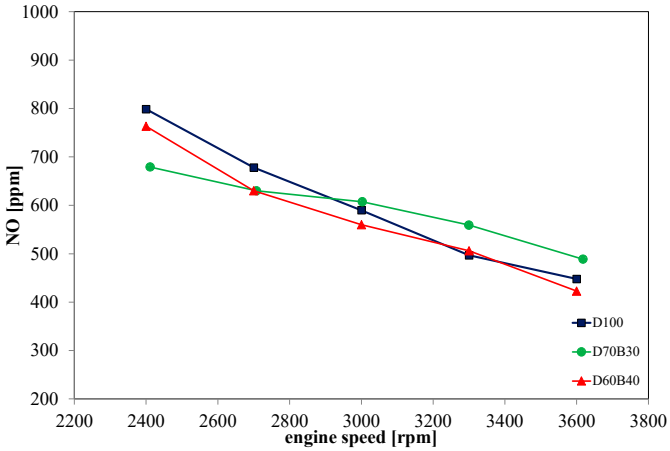


Figure 3. Nitrogen oxide emissions at 80% load.

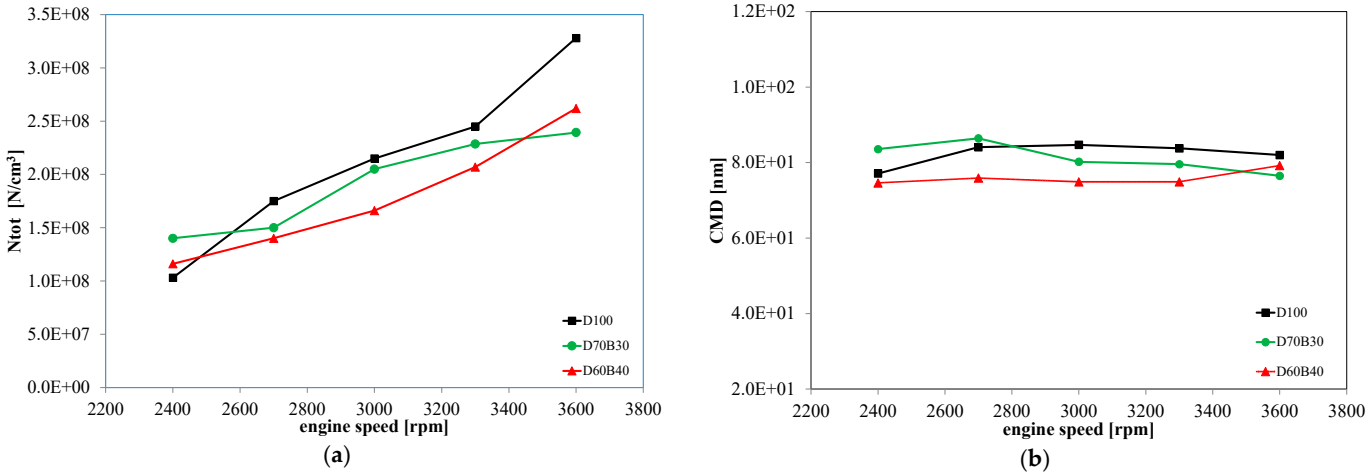


Figure 4. (**a**) Particle concentration and (**b**) mean diameter of particles at 80% load.

Aimed at obtaining an indicator of the engine's conversion efficiency when the blends are used with regard to diesel+ in its pure form, the specific fuel consumption was measured and the brake thermal efficiency (BTE) was calculated as a ratio of the power delivered at the crankshaft to the fuel energy supplied to the engine. Figure 5 shows the obtained trend.

The trends exhibit moderate variations in values; it is possible to observe some improvements in the efficiency of the blend with a higher percentage of biodiesel from WCO: the decrease in caloric values of biodiesel in relation to diesel+ is larger than the increase in brake specific fuel consumption, and then, the oxygenated nature of biodiesel should be responsible for some improvements in the combustion development, resulting in lower values of fuel consumption.

3.2. Diesel+ Blended with Jet A

Figure 6a,b present the carbon monoxide and hydrocarbon concentrations measured in the exhaust when the engine was fed with diesel+ net and blended with Jet A (10% and 20% by volume).

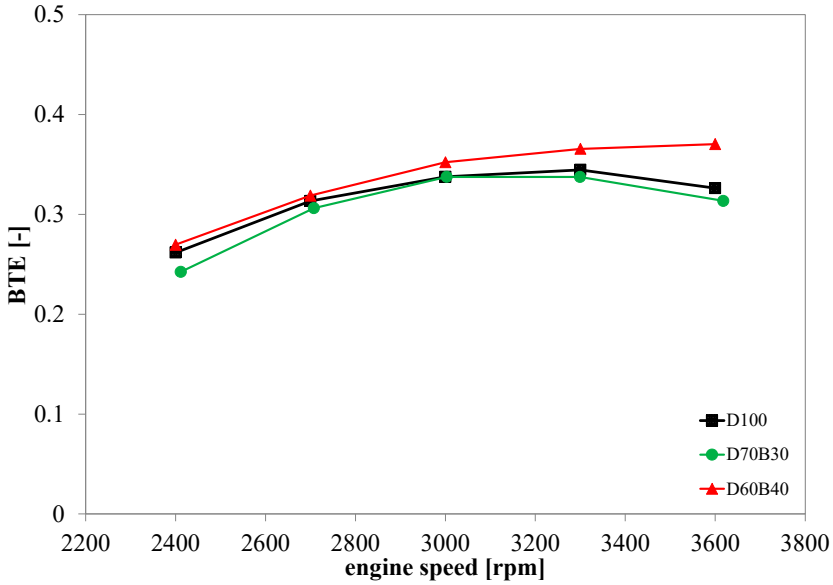


Figure 5. Brake thermal efficiency at 80% load.

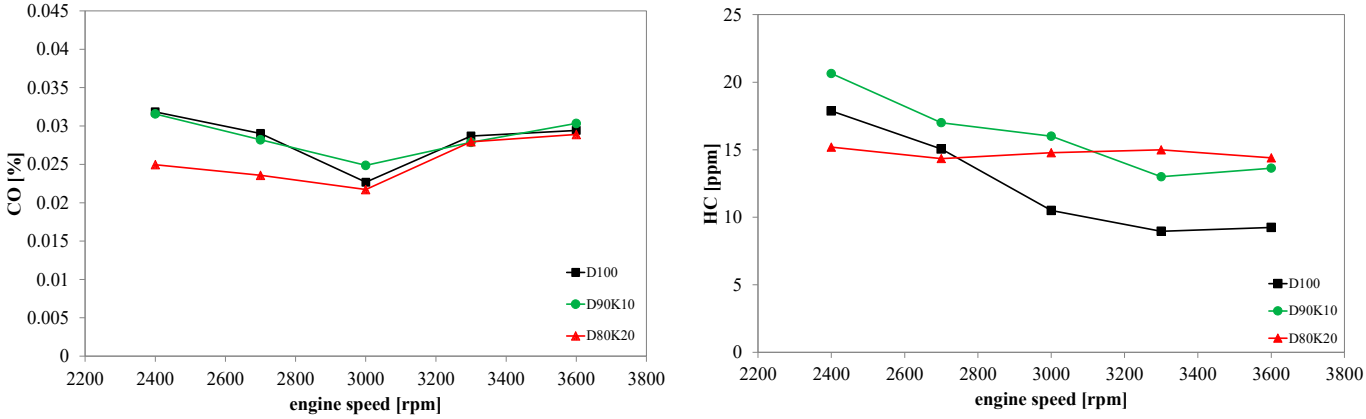


Figure 6. (**a**) CO and (**b**) HC concentrations at 80% load.

Carbon monoxide trends are characterized by a decrease in the values as the Jet A content in the blend increases, especially in the range of lower values of engine velocity. The high volatility of Jet A can promote combustion in the field of lower engine speed; the cetane number and the longer ignition delay of Jet A are responsible for the increase in CO emissions in the high-speed range. Jet A in the blend penalizes HC emission, according to [44], with exception of D80K20 at the lowest values of engine velocity.

Aviation fuel employment allows the depletion of NO_x concentration in the exhaust gas to be obtained (Figure 7), especially in the range of lower values of engine speed.

Diesel+ and its blends with Jet A present a comparable air–fuel ratio; probably, the increased premixed combustion of diesel+ causes the higher temperature in the chamber, thus promoting NO_x formation [39].

The particulate emissions shown in Figure 8a highlight an increment in values as the engine velocity rises, according to the trends presented in Figure 4.

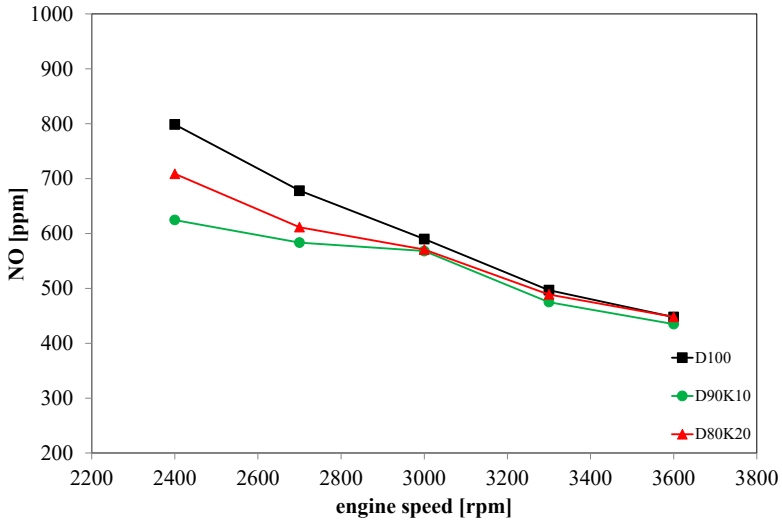


Figure 7. NO emissions at 80% load.

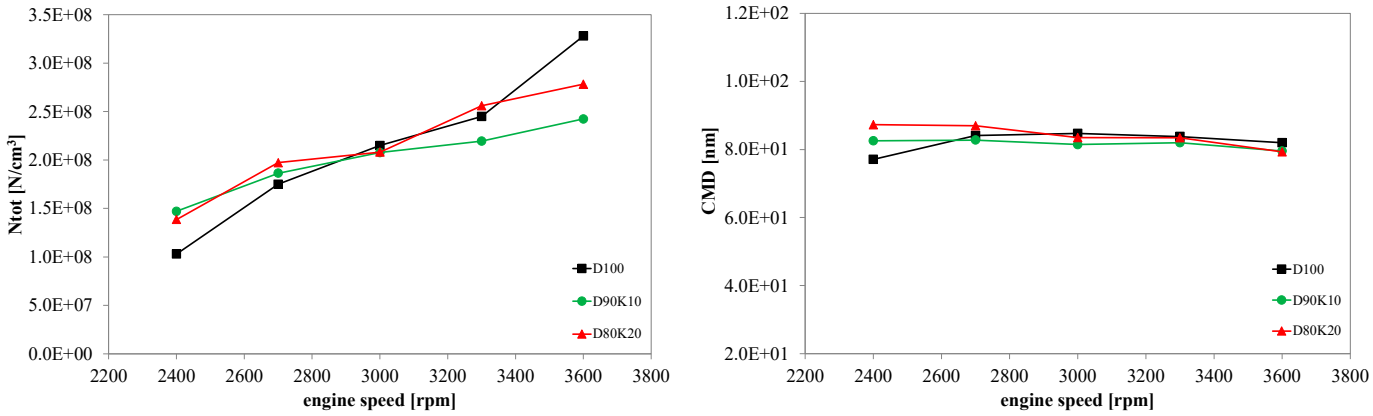


Figure 8. (**a**) Particle number concentration and (**b**) mean diameter of particles at 80% load.

In the lower engine speed range, mixing Jet A with diesel+ is responsible for an increase in particle number; the trend is the opposite for higher values of rpm. This behavior is due to the combination of engine operative conditions and fuel properties. At a fixed value of the load, the increase in engine speed determines two opposite effects: the enhancement in turbulence, the improvement in combustion performance and the reduction in the disposal time, which affects the combustion completeness and particle formation.

The court mean diameter trend is depicted in the diagram of Figure 8. The data highlight that all fuels have an average diameter of approximately 80 nm.

The effect of mixing diesel+ with Jet A on brake thermal efficiency at different engine speeds is shown in Figure 9. The trends highlight that raising the kerosene percentage in the blend is responsible for a moderate reduction in the BTE values.

The observed behavior is caused by fuel properties such as the lower viscosity and density and higher calorific value of blends K10 and K20.

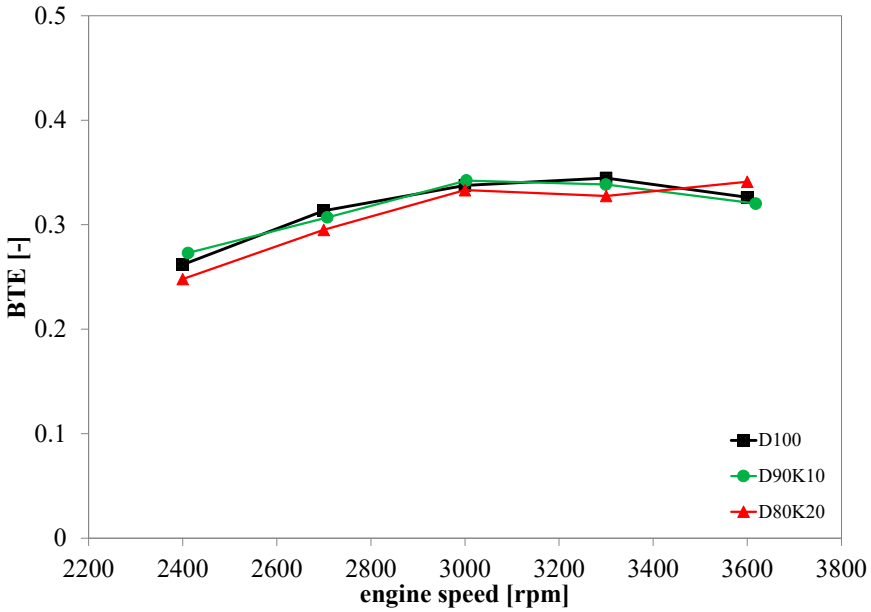


Figure 9. Brake thermal efficiency at 80% load.

3.3. Diesel+ Blended with Biodiesel from WCO and Jet A

Carbon monoxide and hydrocarbon concentrations in the exhaust are shown in Figure 10. Under the same amount of WCO (30% and 40% by volume), when Jet A is used in place of diesel+, the CO emissions exhibit an increase.

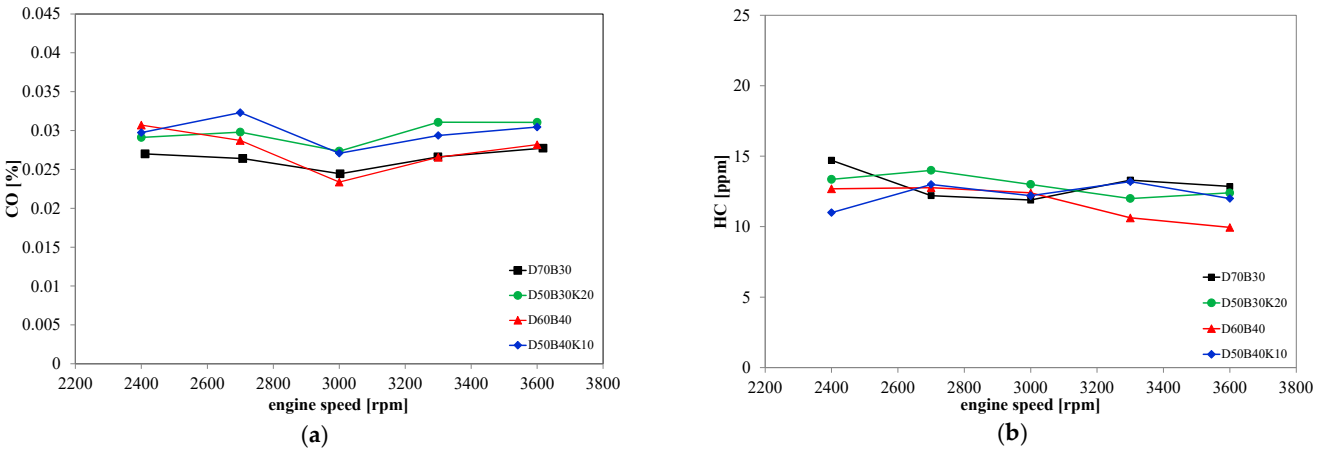


Figure 10. (**a**) CO and (**b**) HC concentrations at 80% load.

It can be observed that, according to Figures 2 and 6, the blend with 30% by volume of biodiesel allows an enhancement in the CO emissions to be obtained in terms of B40 at lower values of engine speed, where the blend with 20% Jet A also behaves better than that with 10%. In the field of higher velocity, the differences are very limited.

Data related to hydrocarbon emissions present a remarkable variation in values. D60B40 exhibits better behavior at higher values of engine speed with regard to D50B40K10, due to the unfavorable effect of Jet A in the blend, according to Figure 6.

NO_x emissions are presented in Figure 11. The trends of D70B30 and D50B30K20 almost overlap. At lower engine speed values, D50B40K10 exhibits better performance in comparison to D60B40, and the opposite occurs in the range of higher speeds.

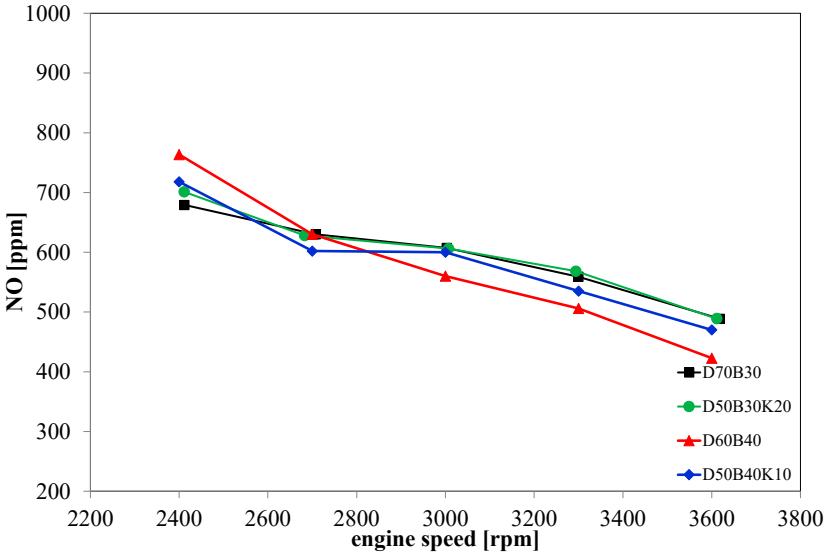


Figure 11. NO emissions at 80% load.

D50B40K10 behaves better than D50B30K20 almost in the complete range of operative conditions; this is probably due to the higher amount of biodiesel in the blend that affects nitrogen oxide formation according to the traces in Figure 3.

Concerning particulate matter emission (Figure 12), the employment of D70B30 causes a higher concentration in the exhaust in comparison to D50B30K20. The lower density and viscosity of Jet A improve the atomization of the fuel; the longer ignition delay leads to an enhancement of the fuel–air mixing that is responsible for a reduction in soot formation in the fuel-rich zone of the chamber. When 40% biodiesel is blended, particulate emissions reduce further.

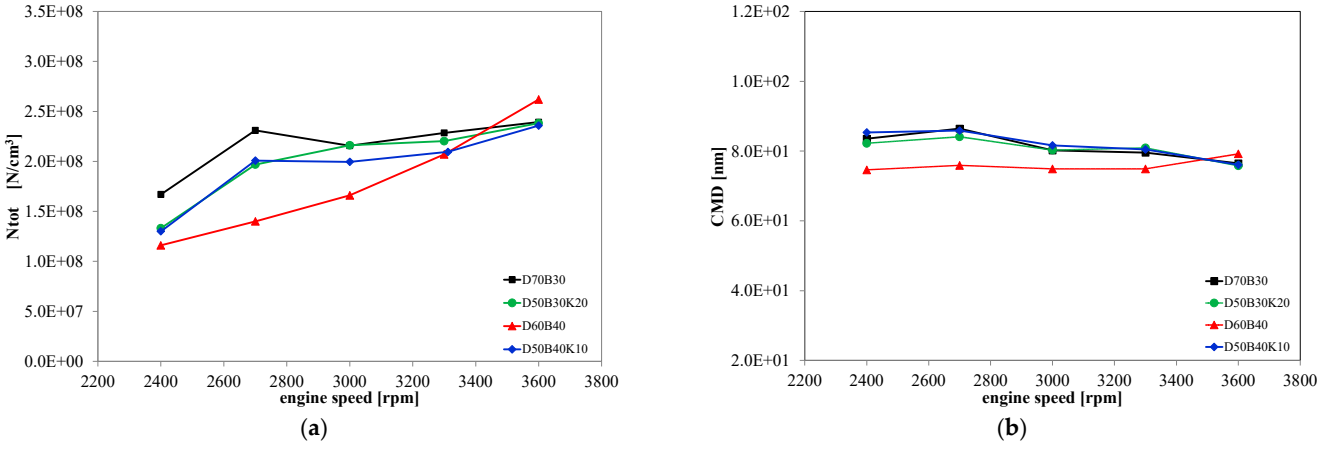


Figure 12. (**a**) Particle number concentration and (**b**) mean diameter of particles at 80% load.

Adding Jet A to the blend does not improve the emission, except for the highest values of velocity.

The mean diameter of emitted particles always has values around 80 nm. Lower diameters characterize D60B40, especially in the range of low values of speed.

Figure 13 shows how Jet A, used in different percentages in mixtures of diesel+ and biodiesel from WCO, affects BTE.

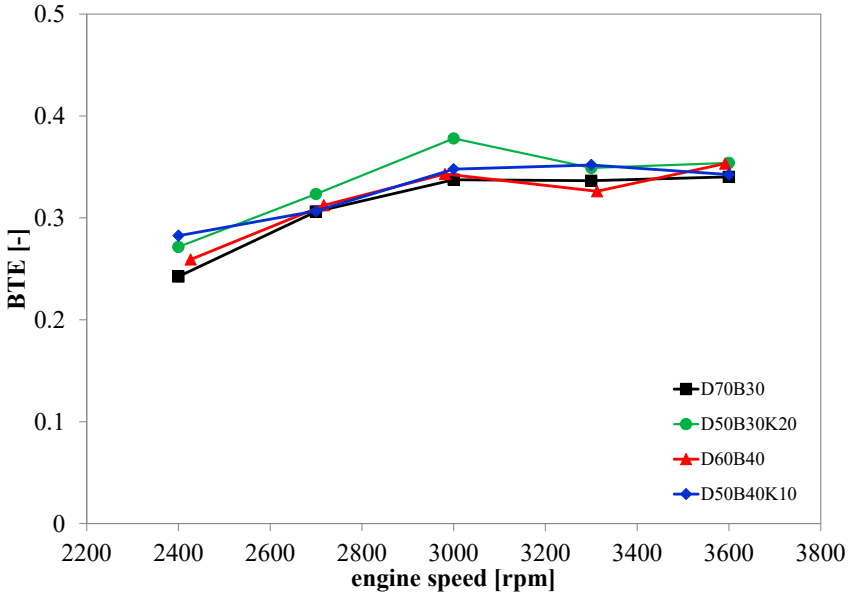


Figure 13. Brake thermal efficiency at 80% load.

The data highlight how improvements in the combustion process are obtained when, once the percentage of biodiesel in the blend is fixed, diesel+ is substituted by Jet A. D50B30K20 exhibits the highest efficiency in almost the complete range of engine speed. Unremarkable differences characterize the data related to D50B40K10 in comparison with D60B40.

Figure 14 shows the rate of heat release (RoHR) traces computed starting from the in-cylinder pressure measurements. It is possible to observe the different stages of the combustion; the first one lasts for only few crank angle degrees; the burning rate is very high and it is responsible for the spike in the curve. The main heat release occurs in the second stage; the curve is characterized by a more rounded shape with a longer duration. The third stage of combustion is the tail, in which the chemical energy of the fuel is released when burned gases mix with excess air that did not take part in the main combustion.

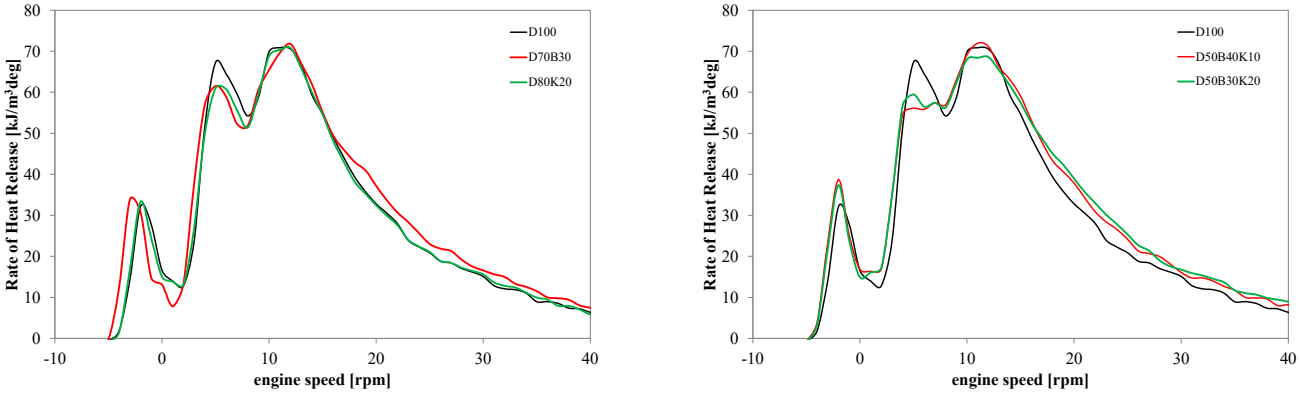


Figure 14. (**a**) Particle number concentration and (**b**) mean diameter of particles at 80.

Ignition delay and start of combustion are affected by the fuel properties, such as density, viscosity, cetane number, atomization, vaporization and mixing with air.

Both plots present the curve related to pure diesel+, in order to highlight how biodiesel and aviation fuel affect the heat release evolution.

The left-hand-side plot compares pure diesel+ data with the curves obtained when biodiesel or Jet A is used in the blend. The different ignition characteristics of the curves

are due to the effect of the cetane number on the combustion evolution; the higher cetane number of biodiesel is responsible for a shorter ignition delay. The longer combustion duration of the blend containing biodiesel might be due to the increased value of viscosity and to the reduced volatility of biodiesel. Jet A's low cetane number causes a delayed start of combustion, but rapid burning may be a result of the higher volatility of its lighter fractions.

The right-hand-side plot compares the pure diesel+ curve with those obtained with blends containing the same amount of diesel+ but a different percentage of biodiesel and Jet A. The profiles highlight the shortened ignition delay of biodiesel blends; the ignition appears in a very brief interval of time after injection begins. The increase in combustion duration is also shown. The presence of Jet A in the blends enhances the volatility of the lighter fractions in the fuel.

4. Conclusions

An extensive experiment was carried out with the objective of analyzing the emission performance of petrol fuel when it is blended with renewable diesel, biodiesel from waste material and aviation fuel.

Due to the problem of material degradation reported during previous experimentations, in order to keep the system hardware unchanged, the highest content of biodiesel in the fuel was fixed at 40% by volume. Blends with 30% and 40% by volume of biodiesel content were tested. The employment of diesel+, in which the renewable percentage of the fuel is equal to 15%, allowed blends in which approximately 50% volume has a renewable origin to be obtained.

The experimentation highlighted that:

- WCO biodiesel has a good opportunity to be used in common rail diesel engines since it is able to enhance hydrocarbon, carbon monoxide and soot emission in comparison with petrol diesel.
- A drawback is represented by the increase in nitrogen oxide emissions.
- Jet A used as an additive in the fuel (10% and 20% by volume) allows benefits in terms of carbon monoxide in the range of low engine speed; HC is penalized. A significant reduction in NO_x is also achieved. Concerning particulate matter, an increase in emission characterizes the lower engine velocity, and this is the opposite at higher speeds.
- Mixing Jet A (10% and 20% by volume) in blends of diesel fuel (50%) and biodiesel (40% and 30%, respectively) is responsible for an attenuation of the drawbacks related to biodiesel employment and allows for an enhancement of the pollutant emissions.

The results indicate that the relation between engine speed and emissions is not affected by Jet A mixing: carbon monoxide and hydrocarbons have a weak dependence on the engine rpm. A rise in PNC was observed with the increase in speed. Nitrogen oxides decrease with the increase in engine speed.

The experimental data show that the addition of 10% of Jet A allows a decrease in NO_x concentration at a lower engine velocity; the opposite is obtained at higher speeds. Particulate emissions behave oppositely. Adding 20% aviation fuel does not substantially modify NO_x emissions, and particulate matter is improved.

The observed trends suggest the suitability of Jet A use in blends aimed at increasing the rate of renewable fuel in ICE without disadvantages regarding exhaust emissions.

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Nomenclature

BTDC	before top dead center
CMD	court mean diameter
CRDI	common rail direct injection
PNC	particle number concentration
RoHR	rate of heat release
WCO	waste cooking oil

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