



# Article Comparative Evaluation on Combustion and Emission Characteristics of a Diesel Engine Fueled with Crude Palm Oil Blends

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**Abstract:** Vegetable oil as an alternative fuel for diesel engine has attracted much attention all over the world, and it is also expected to achieve the goal of global carbon neutrality in the future. Although the product after transesterification, biodiesel, can greatly reduce the viscosity compared with vegetable oil, the high production cost is one of the reasons for restricting its extensive development. In addition, based on the current research on biodiesel in diesel engines, it has been almost thoroughly investigated. Therefore, in this study, crude palm oil (CPO) was directly used as an alternative fuel to be blended with commercial diesel. The combustion, engine performance and emissions were investigated on a 4-cylinder, turbocharged, common rail direct injection (CRDI) diesel engine fueled with different diesel-CPO blends according to various engine loads. The results show that adding CPO to diesel reduces the maximum in-cylinder pressure and maximum heat release rate to 30 Nm and 60 Nm. The most noteworthy finding is that the blend fuels reduce the emissions of hydrocarbons (HC), nitrogen oxides (NOx) and smoke, simultaneously. On the whole, diesel fuel blended with 30% CPO by volume is the best mixing ratio based on engine performance and emission characteristics.

Keywords: crude palm oil; diesel engine; combustion; emission; carbon neutral

## 1. Introduction

The diesel engine is widely used in transportation, power generation, agriculture, the military, construction, mining, maritime, propulsion and stationary, because of its high torque, good stability, superior thermal efficiency, fuel economy and other advantages [1,2]. In particular, the diesel engine is a compression-ignition type, which has absolute advantages in high output power. This is also one of the reasons why the current electric engine cannot completely replace the diesel engine. In addition, the carbon monoxide (CO) and hydrocarbons (HC) emitted by a diesel engine are lower than those of a gasoline engine. However, the nitrogen oxides (NOx) and particular matter (PM) emitted from diesel engine are higher than those of a gasoline engine. Therefore, as long as the NOx and PM emission from diesel engines are solved, it is believed that diesel engines will continue to be paid more attention. Compared with the research on changing the engine structure, more researchers focus on alternative and renewable fuels to reduce emissions from an internal combustion engine (ICE) without any modification. The development of alternative fuel for ICE has the advantages of a short cycle, quick effect and low cost [3,4].

Biodiesel, as the most reliable alternative fuel to diesel, has attracted the world's attention because of its renewable, green, non-toxic, decomposable, and other environmental benefits [5]. In addition, the cetane number of biodiesel (about 45–65) is generally higher



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). than that of diesel (about 40–55), which means that diesel engines fueled with biodiesel have better ignition characteristics. Fuel with a high cetane number can shorten the ignition delay, increase the peak combustion pressure and temperature, and promote the formation of NOx. Meanwhile, biodiesel is also a highly oxygenated fuel (about 11–15%). During combustion, it can provide certain oxygen, promote combustion, reduce CO, HC and PM emissions, but slightly increase NOx [6]. In particular, the oxygen content in biodiesel plays an important role in the reduction of CO and PM emissions. Because the diesel engine achieves spontaneous combustion through high pressure and temperature, the mixing degree of fuel and air directly affects the combustion and emission characteristics. Biodiesel has good benefits in improving the local oxygen deficiency area of the mixture. In addition to the above advantages, biodiesel also has some disadvantages compared with diesel fuel, such as high density, high viscosity, high surface tension, and high bulk modulus of elasticity. The higher the kinematic viscosity and surface tension, the larger the diameter of injection droplets, which makes it difficult to vaporize and atomize biodiesel fuel. Therefore, these disadvantages directly affect the fuel injection timing and fuel atomization, resulting in the uneven mixing of fuel and air, thereby increasing the harmful emissions [7,8]. In order to reduce the impact of the disadvantages of biodiesel on combustion and emission, most researchers choose to use a mixture of biodiesel and diesel. An et al. [9] investigated the influence of the use of waste cooking oil biodiesel/blend fuels on performance, combustion and emission characteristics in a Euro IV diesel engine under low engine speed and partial load conditions. They found that engine performance, combustion and emission characteristics were improved with biodiesel addition. Raman et al. [10] studied the performance characteristics of a single cylinder vertical cylinder direct injection diesel engine with rapeseed oil biodiesel blends. It was found that the CO and HC emission of the diesel engine fueled with biodiesel and its blends were lower than diesel fuel. Ağbulut et al. [11] compared the effects of diesel-biodiesel and various metal-oxide based nanoparticles (TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and SiO<sub>2</sub>) blends on combustion, performance, and exhaust emission characteristics of a single-cylinder diesel engine. The results showed that all metal-oxide based nanoparticles increased the cetane number, oxygen content, viscosity, and heating value of biodiesel. Asokan et al. [12] investigated the performance, combustion and emission characteristics of a single cylinder diesel engine fueled with diesel-juliflora biodiesel blends (B20, B30, B40, B100). They reported that the CO, HC and smoke for biodiesel and its blends are smaller or equal compared to diesel; however, the brake thermal efficiency (BTE) for B100 is 31.11% and it is closer to diesel (32.05%) at full load. In summary, the biodiesel is oxygenated fuel, which has an oxygen self-supported effect in the combustion process, therefore, adding biodiesel to diesel can help to improve the mixture, especially to reduce soot and PM emissions from diesel engines.

At present, the preparation of biodiesel mainly included direct use and blending of vegetable oils, micro-emulsions, thermal cracking (pyrolysis) and transesterification. Among them, transesterification reaction is the most common method for the preparation of biodiesel [13]. Transesterification takes place between vegetable oils, animal fats, edible waste fats or oils and alcohols (methanol, ethanol, butanol) in the presence of homogeneous base catalysts (e.g., NaOH, KOH) [14]. However, many researchers have shown that when using acid or alkali as catalyst to produce biodiesel, a wastewater containing catalyst is mainly generated by the washing stage, resulting in secondary pollution to the environment. Moreover, the purification process of biodiesel has to go through a cumbersome water washing process and oil-water separation process, resulting in high production cost [15]. With the continuous updating of engine technology, the fuel injection system has been greatly improved in recent decades. The present diesel engines such as fuel direct injection pressures can be increased more than 200 MPa in a fuel pump injection system. Therefore, directly using the mixture of vegetable oil and diesel seems to be another innovation in the diesel engine. It will directly reduce the generation cost of biofuel and reduce the environmental pollution during in the biofuel generation process. Moreover, replacement of petroleum-derived fuels by biogenic fuels from renewable resources is of great significance

to reduce dependence on petroleum oil, reduce greenhouse gas emissions and achieve the goal of global carbon neutrality.

Filling a gap of the relevant literature, the present work presents the application characteristics of direct mixing of crude palm oil (CPO) and diesel in a four-cylinder, four-stroke, common rail direct injection (CRDI) diesel engine. The main input parameters are engine load and fuel blend ratio. The output parameters analyzed are in-cylinder pressure, peak in-cylinder pressure (Pmax), heat release rate (HRR), peak heat release rate (HRRmax), coefficient of variation of the indicated mean effective pressure (COVimep), brake specific fuel consumption (BSFC), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx) and smoke opacity.

#### 2. Materials and Methods

## 2.1. Test Fuels

Five blended fuels were prepared through blending crude palm oil (CPO) at 0%, 10%, 30%, and 50% by volume with diesel fuel, which corresponded to BP0, BP10, BP30, and BP50, respectively. The specific properties of the tested fuels are listed in Table 1. As shown in Table 1, it can be clearly seen that the density and viscosity of CPO are higher than diesel, especially its viscosity is nearly 16 times higher than diesel.

Table 1. Fuel	properties.
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Properties (Units)	Diesel Fuel	Crude Palm Oil
Density (kg/m $^3$ at 15 °C)	836.8	903.8
Viscosity (mm <sup>2</sup> /s at 40 °C)	2.719	42.21
Calorific value (MJ/kg)	43.96	39.34
Cetane index	55.8	49
Flash point (°C)	55	260
Oxygen content (%)	0	11.4

#### 2.2. Test Method

A series of experiments were performed on a four-cylinder, four-stroke, common rail direct injection (CRDI) turbocharged diesel engine with a displacement of 1991cc. The detailed engine specifications are summarized in Table 2. The schematic diagram of the engine test bed is presented in Figure 1. The test engine was coupled with an eddy current (EC) type water-cooled dynamometer (DYTEK230, Hwanwoong Mechatronics Co., Ltd., Gyeongnam, Korea) with a maximum load of 230 kW. The engine speed and engine load were controlled by the dynamometer through a controller. Moreover, a precise electronic balance with 1 g precision (GP-100K, A&D Co. Ltd., Tokyo, Japan) was used to measure fuel consumption; the in-cylinder pressure was measured by a piezoelectric pressure sensor (Type 6056A, Kistler Korea Co., Ltd., Seongnam-si, Korea). The in-cylinder pressure value with a crank angle was recorded from 200 engine cycles to calculate the heat release rate (HRR) for analyzing combustion characteristics. All combustion data were acquired using a National Instruments PCI-6040E (National Instruments, Austin, TX, USA) data acquisition (DAQ) board and stored in a desktop. The CO, HC, and NOx emissions were measured by a MK2 (GreenLine MK2, Eurotron (Korea) Ltd., Seoul, Korea) and HPC-501 (Nantong Huapeng Electronics Co., Nantong City, Ltd., China) multi-gas analyzer. The smoke opacity was measured with an OPA-102 (QROTECH Co., Ltd., Bucheon-si, Korea) smoke meter. Three engine loads of 30, 60, and 90 Nm, were selected as the main engine operating variables to test the blend fuels. The engine speed and the pilot and main injection timings were fixed at 1500 rpm, 22° before top dead center (BTDC), and 7° BTDC, respectively. Detailed operating conditions are listed in Table 3. Before starting to record data, the engine was first warmed up with diesel under idling speed of 750 rpm without an engine load for 30 min until the cooling water temperature reached 85 °C. The engine was started using diesel (BP0); once the engine warmed up, it was switched to BP10, BP30 and BP50. After the testing of one kind of fuel, the fuel return valve was opened, all the fuel inside the fuel

line, injection pump and injector was discharged by using a fuel pump, and finally the fuel supply and return lines were washed with the next test fuel 3 times. After the fuel change was completed, the engine was allowed to run about 10 min to attain a steady state condition for each new test fuel. After all tests were finished, the engine was switched back to diesel fuel again until the blend fuel was removed from the fuel line, injection pump and injector, and then the engine was stopped.

Table 2. Specifications of the test engine.

<b>Engine Parameter</b>	Units	Specifications
Туре	-	turbocharged CRDI diesel engine
Number of cylinders	-	4
Bore $\times$ stroke	mm	83  imes 92
Injector hole diameter	mm	0.17
Compression ratio	-	17.7:1
Max. power	kW/rpm	82/4000



Figure 1. Schematic diagram of the experimental apparatus.

Table 3. Experimental and operating conditions.

Item	Conditions
Test fuels	BP0, B10, B30, B50
Engine load	30, 60, 90 Nm
Engine speed	1500 rpm
Fuel injection pressure	45 MPa
Pilot injection timing	22° BTDC
Main injection timing	7° BTDC
Intake air temperature	$25\pm3~^\circ\mathrm{C}$
Cooling water temperature	$85\pm3~^\circ\mathrm{C}$

## 2.3. Error and Uncertainty Analysis

Generally speaking, uncertainty can be divided into two main factors: fixed error and random error. A variety of factors such as instrument selection and calibration, changes in environmental conditions, testing and observation will lead to variation in error and uncertainty. To reduce the negative impact of these uncertainties and ensure accuracy, an uncertainty analysis is very important. Thus, in order to better evaluate the results of combustion and emissions, all tests were carried out three times and their average values and standard deviation were taken for further analysis. The specifications of the exhaust emission device and measurement systems are given in Table 4.

Table 4. Specifications of exhaust emission device and measurement systems.

Parameter	Accuracy
CO (ppm)	±0.62%
NOx (ppm)	$\pm 0.25\%$
HC (ppm)	$\pm 5\%$
Smoke opacity (%)	$\pm 1\%$
Load monitoring (Nm)	$\pm 0.2\%$
Speed measuring (rpm)	$\pm 5$
Fuel consumption (g)	$\pm 2$
Fuel injection pressure (bar)	$\pm 1$
Intake air temperature (°C)	$\pm 3$
Cooling water temperature (°C)	$\pm 3$

#### 3. Results and Discussions

3.1. Combustion Characteristics

# 3.1.1. In-Cylinder Pressure

To evaluate the effect of various engine loads on the combustion characteristics, in-cylinder pressures for different fuels are compared under different engine loads and at a constant engine speed of 1500 rpm. Figure 2 shows the variations of in-cylinder pressures for four different fuels at engine loads of 30 Nm, 60 Nm and 90 Nm. The physicochemical properties of fuel directly affect the combustion characteristics of diesel engine, and the combustion effect of mixture in cylinder can be analyzed by cylinder pressure [16]. As clearly shown in Figure 2, the peak in-cylinder pressure of the blend fuels (BP10, BP30 and BP50) is lower than that of pure diesel (BP0). The pattern of variation of in-cylinder pressure with a crank angle for BP10, BP30 and BP50 blends is similar under all engine loads. It may be related to the disadvantages of crude palm oil (CPO), such as high viscosity, high density and low cetane index. Especially for high viscosity, as shown in Table 1, the viscosity of CPO is nearly 16 times higher than that of pure diesel, which directly deteriorates the atomization effect and further affects the formation of a homogeneous mixture. Similar results were also found by Nautiyal et al. [16] and Prabu et al. [17]. Nautiyal et al. [16] also pointed out that the low volatility of fuel also leads to poor mixture preparation and atomization, and then reduction of the peak in-cylinder pressure. In addition, as the engine load increases from 30 Nm to 90 Nm, the in-cylinder pressure of the blend fuels gradually approaches that of pure diesel. Moreover, it seems that the initial in-cylinder pressure of blend fuels begins to rise earlier than that of pure diesel. These are the consequence of the oxygen-containing characteristics of CPO, which accelerate the combustion rate.

Figure 3 shows the comparison of peak in-cylinder pressure of all test fuels according to engine load. The in-cylinder pressure peaks of pure diesel are 69.00 bar, 75.40 bar and 83.10 bar at 30 Nm, 60 Nm and 90 Nm, respectively. From Figure 3, it is obvious that the peak in-cylinder pressures of the blend fuels are significantly lower than that of the pure diesel. As mentioned earlier, this is related to the fuel characteristics of CPO, such as low cetane index, high density and high viscosity (see Table 1). With the addition of 10%, 30% and 50% by volume of CPO to pure diesel, the peak in-cylinder pressure at 30 Nm is reduced by 2.90%, 3.62% and 3.33%, respectively; at 60 Nm it is reduced by 2.12%, 1.46% and 3.32%, respectively; at 90 Nm it is reduced by 1.20%, 2.65% and 2.41%, respectively. On the other hand, with the increase of engine load from 30 Nm to 90 Nm, the increase of peak in-cylinder pressure is mainly related to the increase of injected fuel in the cylinder. This result is consistent with [18]. AhmetUyumaz [18] also reported that the peak in-cylinder pressure is obtained later with increase of engine load due to more fuel molecules tending to combust. Compared with 30 Nm, the peak in-cylinder pressures

of blend fuel under medium (60 Nm) and high load (90 Nm) are closer to those of pure diesel. This is because under a low load, the temperature in the cylinder, including wall temperature and residual gas temperature, is relatively lower compared with that under high load, which leads to delayed ignition. Coupled with the high density and high viscosity of CPO, this further increases the physical and chemical delay, thereby increasing the distance from pure diesel at the peak in-cylinder pressure. Similar results have also been reported showing that peak in-cylinder pressure increased with engine load [19].



Figure 2. In-cylinder pressure for all test fuels at (a) 30 Nm, (b) 60 Nm and (c) 90 Nm.



Figure 3. Maximum in-cylinder pressure for all test fuels according to various engine loads.

#### 3.1.2. Heat Release Rate

Figure 4 illustrates the variation of heat release rate (HRR) with the crank angle of four different blend fuels under different engine loads. In Figure 4, three peaks of different sizes can be obviously observed. The leftmost one is a small trough (negative HRR), which is a slight decrease caused by the absorption of ambient temperature after pilot fuel injected in the cylinder. The middle peak and the rightmost peak are the HRR rise caused by pilot and main injection fuel combustion, respectively. Similar results have been reported by Yilmaz et al. [20] and Nautiyal et al. [16]. It is widely known that the combustion process of diesel engines can be divided into two major phases: premixed combustion phase (PCH) and diffusion combustion phase (DCH). The PCH begins after the start of injection (SOI) and reacts rapidly due to the presence of fuel-rich combustible areas formed by mixing fuel and air during the ignition delay period. The PCH leads to a rapid increase in the pressure and heat release in the cylinder. After the air around the fuel is consumed, PCH immediately enters the DCH. Generally, PCH is much shorter than DCH due to the burning being controlled with the air-fuel mixture [1,16]. From the combustion process analysis in Figure 4, the combustion processes of all test fuels are similar. However, on the whole, the HRR curves of the blend fuels are slightly shifted to the right which can be attributed to the ignition delay (ID). ID is defined as the time between the SOI and the start of combustion (SOC). ID can be divided into physical delay and chemical delay, which are mainly determined by the properties of the fuel itself, such as viscosity, surface tension, volatility and cetane number [21]. Therefore, the high viscosity and density of CPO are the direct factors affecting fuel atomization, resulting in longer ID. On the other hand, with the increase of engine load, the maximum values of HRR of blend fuels are closer to those of diesel. Especially under high load (90 Nm), the maximum HRR of BP10 (46.67 J/CA) and BP30 (47.06 J/CA) is slightly higher than that of diesel (46.46 J/CA). These phenomena are mainly because the increase in load increases the temperature and pressure in the cylinder, and reduces the negative effects of the high viscosity and high density of palm oil. Moreover, the oxygen-containing characteristics of palm oil itself positively improve combustion characteristics. Similar results were also reported by Patel et al. [22].



Figure 4. Heat release rates for all test fuels at (a) 30 Nm, (b) 60 Nm and (c) 90 Nm.

Figure 5 plots the maximum values of HRR (HRRmax) profiles for four fuel blends under different engine loads. As clearly shown in Figure 5, the HRRmax of blend fuels are lower than that of pure diesel under medium and low load. At 30 Nm, the HRRmax of BP10, BP30 and BP50 is 30.63 J/CA, 30.38 J/CA and 29.01 J/CA, which decreases by 6.49%, 7.26% and 11.43% compared with that of BP0, respectively. At 60 Nm, the HRRmax of BP10, BP30 and BP50 is 37.11 J/CA, 37.78 J/CA and 38.19 J/CA, which decreases by 4.78%, 3.08% and 2.03% compared with that of BP0, respectively. However, at 90 Nm, the HRRmax of BP10 and BP30 increases by 0.45% and 1.29% compared with that of BP0, respectively. Moreover, only a large amount of palm oil (50% by volume) added to diesel leads to the slightly decline of HRRmax compared with pure diesel. The above results show that HRR is mainly affected by engine operating conditions and fuel properties. With the increase of engine load, a large amount of fuel and air enter the cylinder for combustion, which greatly increases the temperature and pressure in the cylinder, especially the temperature of the cylinder wall, and reduces the negative effects caused by the disadvantages of high viscosity, high density and low cetane number of palm oil. In addition, the oxygen carried by palm oil improves the oil-rich area and provides favorable conditions for improving combustion quality. However, when the volume mixing ratio of palm oil is excessive, i.e., up to 50%, the disadvantage characteristics of palm oil break the balance. Even if the engine load is very high, the HRRmax of BP50 is still reduced by 3.33% compared with that of pure diesel. Therefore, choosing an appropriate engine load and palm oil mixing ratio can give full play to the best performance of the fuel. Similar observations were also reported by An et al. [2] and Patel et al. [22]. Bari et al. [23] reported that the decrease in HRRmax was related to the composition (roughly 50% saturated and 50% unsaturated fatty acids) of palm oil. They also indicated that some chemical reactions, such as the cracking of double bond of carbon chain, shorten the ignition delay, resulting in less fuel injection, which is also one of the reasons for reducing HRRmax.



Figure 5. Maximum heat release rate for all test fuels according to various engine loads.

## 3.1.3. Engine Performance

Figure 6 compares the coefficient of variation of the indicated mean effective pressure (COVimep) for all test fuels according to various engine loads. Cyclic variations occur during combustion due to mixture composition, thermodynamic conditions, initial temperature and pressure alteration for each cycle [18]. The higher the COVimep, the more unstable the combustion, which even leads to vehicle drivability problems. As shown in Figure 6, the variation of COVimep of this CRDI diesel engine fueled with all test fuels under low (30 Nm) load and high load (90 Nm) is slightly larger than that under medium load (60 Nm) and does not show a stable change with the increase of the palm oil blend

ratio. However, at 60 Nm, the COVimep decrease gradually with the addition of palm oil to diesel. That is, the COVimep of BP10, BP30 and BP 50 decrease by 9.32%, 17.31% and 21.43% compared with that of BP0, respectively. In addition, the average value of COVimep for all test fuels at 60 Nm and 90 Nm are lower than that at 30 Nm due to the increase of the fuel extent in the mixture [24]. Generally, COVimep less than 2.5% is the upper limit of stable combustion [24], while more than 10% being the upper limit of vehicle drivability problems [25]. On the whole, all test fuels obtained relatively stable combustion without large cycle-to-cycle variations under all engine operating conditions. This may be attributed to the improved combustion quality of palm oil as an oxygenated fuel.



Figure 6. COVimep for all test fuels according to various engine loads.

Figure 7 shows the brake specific fuel consumption (BSFC) for all test fuels according to various engine loads. BSFC is an important indicator to evaluate the fuel economy of an engine. The smaller the BSFC is, the more economical the fuel is. As shown in Figure 7, the BSFCs of most blend fuels are higher than that of pure diesel. At 30 Nm, the BSFC of BP 10, BP30 and BP 50 increase by 9.16%, 8.38% and 14.23% compared with that of BP 0, respectively. At 60 Nm, the BSFC of BP 10, BP30 and BP 50 increase by 1.99%, 5.31% and 9.02% compared with that of BP 0, respectively. However, at 90 Nm, the BSFC of BP 10, BP30 and BP 50 decrease by 5.71%, 0% and 1.34% compared with that of BP 0, respectively. This means that palm oil blended fuels consume more fuel per energy extracted under medium and low load. This is because the calorific value of palm oil is lower than that of diesel (see Table 1), thereby more fuel needs to be consumed to achieve the same output. Moreover, the disadvantages of high density and high viscosity of palm oil cannot be improved under medium and low load, which further leads to incomplete combustion and consumes a lot of fuel. A similar result was reported in Ref. [26]. Generally, the lower the calorific value of the fuel, the more fuel needs to be consumed. However, in this study, the addition of palm oil reduced BSFC at 90 Nm. This shows that the variation of BSFC is not only related to physical properties of palm oil such as calorific value, density and viscosity, but also related to whether it contains oxygen. Under high load, the blend fuels get rid of the negative effects of high density and high viscosity of palm oil, and the oxygen-containing characteristics play a major role in promoting the full combustion of the fuel. In addition, it is clearly seen that the BSFCs for all test fuels are reduced with an increase of the engine load. This may be mainly attributed to the increase of temperature and pressure in the cylinder due to the increase of the engine load, which improves the combustion quality and reduces the combustion loss. This is consistent with the results of other researchers [17,27].



Figure 7. BSFC for all test fuels according to various engine loads.

## 3.2. Emission Characteristics

# 3.2.1. CO Emission

Figure 8 illustrates the variation of CO emission for four different fuels according to various engine loads from 30 Nm to 90 Nm. As shown in Figure 8, the CO emission is significantly increased as the percentage of palm oil is increased at all engine loads. At 30 Nm, the CO emission of BP10, BP30 and BP50 increases by 7.04%, 31.69% and 36.62% compared with that of BP 0, respectively. At 60 Nm, the CO emission of BP10, BP30 and BP50 increases by 1.48%, 18.52% and 27.41% compared with that of BP 0, respectively. At 90 Nm, the CO emission of BP10, BP30 and BP50 increases by 21.13%, 24.65% and 45.77% compared with that of BP0, respectively. It is widely known that CO emission is produced by incomplete combustion of fuel due to insufficient oxygen. Many researchers have reported that oxygenated fuels such as biodiesel reduce diesel engine CO emission due to the oxygen contained in biodiesel. The oxygen carried by biodiesel improves the fuel/air equivalence ratio, especially for improving the problem of insufficient oxygen in local fuel-rich areas, thereby promoting more carbon molecules to oxidize [24,28]. However, in this study, the increase in CO caused by adding palm oil to diesel may be mainly related to the high density, high viscosity and low cetane index of palm oil. Bari et al. [23] and Altın et al. [29] also reported similar results. Bari et al. [23] reported that the increase of CO emission is related to the difficult atomization caused by the heavy compounds produced by the chemical reactions of palm oil. Altin et al. [29] also reported that the CO emission of a single cylinder diesel engine fueled with various raw vegetable oil fuels is more than that of diesel engine. They pointed out that the poor spraying qualities and uneven mixture were the main reasons for increasing CO emission. On the other hand, the CO emissions for all test fuels are decreased with the increase of engine loads from 30 Nm to 90 Nm. Compared with at 30 Nm, the CO emissions of all fuels are reduced by 55.26% and 48.30% on average at 60 N and 90 Nm, respectively. This is mainly attributed to the rise of temperature in the cylinder, which is conducive to the oxidation of CO emission with the increase of engine load [28].



Figure 8. CO emissions for all test fuels according to various engine loads.

#### 3.2.2. HC Emission

Figure 9 describes the effect of four different fuels on HC emission at different loads.



Figure 9. HC emissions for all test fuels according to various engine loads.

As shown in Figure 9, the HC emission is significantly decreased as the percentage of the palm oil is increased at all engine loads. At 30 Nm, the HC emission of BP10, BP30 and BP50 decreases by 15.15%, 36.36% and 42.42% compared with that of BP 0, respectively. At 60 Nm, the HC emission of BP10, BP30 and BP50 decreases by 18.75%, 40.63% and 53.13% compared with that of BP0, respectively. At 90 Nm, the HC emission of BP10, BP30 and BP50 decreases by 5.41%, 43.24% and 43.24% compared with that of BP0, respectively. In general, the generation of HC is mainly related to the following four reasons: (i) misfires and partial burns; (ii) flame quenching in crevice volumes; (iii) wall quenching and deposits; (iv) oil absorption [30]. In addition, fuel properties such as density, viscosity, surface tension, cetane number and oxygen content are also the main factors affecting HC emission.

On the whole, the impact factors affecting HC emission are divided into positive impact factors (i.e., oxygen) and negative impact factors (i.e., high viscosity, high surface tension). The positive impact factor is beneficial to reduce HC emission, while the negative impact factor is to increase HC emission. As shown in Figure 9, adding palm oil to diesel

reduces HC emission because the influence of positive factors is stronger than negative factors. Palm oil is an oxygenated fuel. The oxygen carried by palm oil changes the fuel/air equivalence ratio and reduces the possibility of flame quenching in crevice volumes. Moreover, in this study, the addition of palm oil reduced HC emission, but increased CO emission due to the difference of formation mechanism. Similar findings have been reported by An et al. [2] Moreover, the average HC emissions of all test fuels first decrease and then increase with the engine load increasing from 30 Nm to 90 Nm. As explained earlier, the increase of engine load leads to the increase of temperature and pressure in the cylinder and the increase of turbulence rate, so as to promote the formation of a more uniform mixture of fuel and air, improve combustion efficiency and finally reduce HC emission [31].

#### 3.2.3. NOx Emissions

Figure 10 depicts the NOx emissions for all test fuels according to various engine loads. It can be seen that the NOx emissions are significantly reduced with the addition of palm oil at each engine load. At 30 Nm, the NOx emissions of BP10, BP30 and BP50 decrease by 2.44%, 10.13% and 13.88% compared with that of BP 0, respectively. At 60 Nm, the NOx emissions of BP10, BP30 and BP50 decrease by 5.44%, 14.85% and 19.61% compared with that of BP0, respectively. At 90 Nm, the NOx emissions of BP10, BP30 and BP50 decrease by 4.99%, 6.13% and 14.76% compared with that of BP0, respectively. In addition, the NOx of all fuels at 60 Nm and 90 Nm increase by 86.29% and 178.85% respectively compared with that at 30 Nm. According to the NOx generation mechanism, NOx emissions are divided into thermal NOx, prompt NOx and fuel NOx. Generally, a large amount of NOx emissions is generated when the temperature in the cylinder is higher than 1500  $^{\circ}$ C [32]. In addition, oxygen concentration and residence time are factors affecting NOx emissions. Many researchers have reported that most biodiesel has a high cetane number and oxygen content, which makes the premixed phase closer to the stoichiometric conditions, resulting in the increase of the cylinder temperature, thereby increasing NOx emissions [16]. Nevertheless, the NOx emissions decrease significantly with the increase of palm oil percentage in blend. This is because palm oil has a lower cetane number and calorific value than diesel, and its viscosity is nearly 16 times higher than diesel (see in Table 1). These characteristics hinder the excessive rise of temperature in the cylinder, thus curbing the generation rate of NOx emissions. Moreover, the significant increase of NOx emissions caused by the increase of engine load is mainly due to the rise of temperature in the cylinder and the larger flame area generated when more fuel is supplied. This is consistent with the study results from Leevijit et al. [33].



Figure 10. NOx emissions for all test fuels according to various engine loads.

#### 3.2.4. Smoke Emission

Figure 11 presents smoke opacity for four different test fuels according to various engine loads. At 30 Nm, the smoke opacity of BP10, BP30 and BP50 decreases by 9.38%, 6.25% and -18.75% (increase) compared with that of BP 0, respectively. At 60 Nm, the smoke opacity of BP10, BP30 and BP50 decreases by 5.88%, 11.77% and 8.82% compared with that of BP0, respectively. At 90 Nm, the smoke opacity of BP10, BP30 and BP50 decreases by 9.88%, 11.11% and 6.17% compared with that of BP0, respectively. Except for B50, the smoke opacity under 30 Nm is increased, and the smoke opacity of most blend fuels is lower than that of diesel. This may be because the density and viscosity of palm oil with a higher mixing ratio are higher, which worsens the atomization effect and leads to incomplete combustion. The reason for the reduction of smoke opacity caused by the addition of palm oil may be mainly attributed to the oxygen content of palm oil. In addition, the formation of diesel smoke is not only related to incomplete combustion, but also related to the combustion of aromatic hydrocarbons [16]. Palm oil is a kind of vegetable oil, which does not contain sulfur and aromatic hydrocarbons. Therefore, adding palm oil to diesel reduces smoke emission. Silitonga et al. [34] pointed out that oxygenated fuel can inhibit the formation of aromatic hydrocarbons and carbon black due to the strong bond combination of carbon atoms and oxygen atoms in oxygenated fuel. Moreover, the low cetane number of the fuel leads to longer ignition delay, which provides longer mixing time between fuel and air, thereby reducing smoke emission. On the other hand, with the increase of engine load, the average smoke opacity of all fuels first decreases slightly and then increases significantly. This is mainly because there are more fuel rich areas under lower and higher loads. The reason for the obvious increase of smoke opacity under 90 Nm may be mainly due to the increase of fuel injected into the cylinder, which increases the fuel droplet size and is not conducive to the formation of homogeneous mixture [31].



Figure 11. Smoke opacity for all test fuels according to various engine loads.

# 4. Conclusions

In this work, different diesel–crude palm oil (CPO) blend fuels were investigated in terms of combustion, engine performance and emission characteristics in a four-cylinder, turbocharged common rail direct injection (CRDI) diesel engine according to various engine loads. The major findings can be summarized as follow:

- I. With the increase of palm oil concentration, the in-cylinder pressure and heat release rate (HRR) of most blend fuels are reduced, and the ignition start is delayed.
- II. Based on the coefficient of variation of the indicated mean effective pressure (COVimep), most of the tested fuels are lower than 2.5%, which indicates that this diesel engine can run all the blend ratios of palm oil without any operating

problems. However, based on the high density, high viscosity and low calorific value of palm oil, burning diesel-CPO blends lead to the increase of brake specific fuel consumption (BSFC).

- III. HC, NOx and smoke opacity are reduced simultaneously when the diesel engine burning diesel-CPO blends, compared with diesel, however, CO emission is increased.
- IV. Overall, by comparing the effects of diesel-CPO blends on engine performance, combustion and emission characteristics, it is found that the direct mixing of up to 30% CPO is the most appropriate for this CRDI diesel engine.

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# References

- 1. Özener, O.; Yüksek, L.; Ergenç, A.T.; Özkan, M. Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel* **2014**, *115*, 875–883. [CrossRef]
- An, H.; Yang, W.; Chou, S.; Chua, K.J. Combustion and emissions characteristics of diesel engine fueled by biodiesel at partial load conditions. *Appl. Energy* 2012, 99, 363–371. [CrossRef]
- Liu, J.; Yang, J.; Sun, P.; Gao, W.; Yang, C.; Fang, J. Compound combustion and pollutant emissions characteristics of a common-rail engine with ethanol homogeneous charge and polyoxymethylene dimethyl ethers injection. *Appl. Energy* 2019, 239, 1154–1162. [CrossRef]
- 4. Jaichandar, S.; Kumar, P.S.; Annamalai, K. Combined effect of injection timing and combustion chamber geometry on the performance of a biodiesel fueled diesel engine. *Energy* **2012**, *47*, 388–394. [CrossRef]
- 5. Kegl, B. Influence of biodiesel on engine combustion and emission characteristics. Appl. Energy 2011, 88, 1803–1812. [CrossRef]
- 6. Suh, H.K.; Lee, C.S. A review on atomization and exhaust emissions of a biodiesel-fueled compression ignition engine. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1601–1620. [CrossRef]
- 7. Kegl, B. Numerical analysis of injection characteristics using biodiesel fuel. Fuel 2006, 85, 2377–2387. [CrossRef]
- 8. Lee, C.S.; Park, S.W.; Kwon, S.I. An experimental study on the atomization and combustion characteristics of biodiesel-blended fuels. *Energy Fuels* **2005**, *19*, 2201–2208. [CrossRef]
- An, H.; Yang, W.M.; Maghbouli, A.; Li, J.; Chou, S.K.; Chua, K.J. Performance, combustion and emission characteristics of biodiesel derived from waste cooking oils. *Appl. Energy* 2013, 112, 493–499. [CrossRef]
- 10. Raman, L.A.; Deepanraj, B.; Rajakumar, S.; Sivasubramanian, V. Experimental investigation on performance, combustion and emission analysis of a direct injection diesel engine fuelled with rapeseed oil biodiesel. *Fuel* **2019**, *246*, 69–74. [CrossRef]
- 11. Ağbulut, Ü.; Karagöz, M.; Sarıdemir, S.; Öztürk, A. Impact of various metal-oxide based nanoparticles and biodiesel blends on the combustion, performance, emission, vibration and noise characteristics of a CI engine. *Fuel* **2020**, 270, 117521. [CrossRef]
- 12. Asokan, M.A.; Prabu, S.S.; Bade, P.K.K.; Nekkanti, V.M.; Gutta, S.S.G. Performance, combustion and emission characteristics of juliflora biodiesel fuelled DI diesel engine. *Energy* **2019**, *173*, 883–892. [CrossRef]
- 13. Abbaszaadeh, A.; Ghobadian, B.; Omidkhah, M.R.; Najafi, G. Current biodiesel production technologies: A comparative re-view. *Energy Convers. Manag.* 2012, 63, 138–148. [CrossRef]
- 14. Yoosuk, B.; Udomsap, P.; Puttasawat, B.; Krasae, P. Modification of calcite by hydration–dehydration method for hetero-geneous biodiesel production process: The effects of water on properties and activity. *Chem. Eng. J.* **2010**, *162*, 135–141. [CrossRef]
- 15. Kawashima, A.; Matsubara, K.; Honda, K. Development of heterogeneous base catalysts for biodiesel production. *Bioresour. Technol.* **2008**, *99*, 3439–3443. [CrossRef]
- 16. Nautiyal, P.; Subramanian, K.A.; Dastidar, M.G.; Kumar, A. Experimental assessment of performance, combustion and emis-sions of a compression ignition engine fuelled with Spirulina platensis biodiesel. *Energy* **2020**, *193*, 116861. [CrossRef]
- 17. Prabu, S.S.; Asokan, M.; Prathiba, S.; Ahmed, S.; Puthean, G. Effect of additives on performance, combustion and emission behavior of preheated palm oil/diesel blends in DI diesel engine. *Renew. Energy* **2018**, 122, 196–205. [CrossRef]

- 18. Uyumaz, A. Combustion, performance and emission characteristics of a DI diesel engine fueled with mustard oil biodiesel fuel blends at different engine loads. *Fuel* **2018**, *212*, 256–267. [CrossRef]
- 19. Qi, D.H.; Chen, H.; Geng, L.M.; Bian, Y.Z.; Ren, X.C. Performance and combustion characteristics of biodiesel–diesel–methanol blend fuelled engine. *Appl. Energy* **2010**, *87*, 1679–1686. [CrossRef]
- 20. Yılmaz, I.T.; Gumus, M. Investigation of the effect of biogas on combustion and emissions of TBC diesel engine. *Fuel* **2017**, *188*, 69–78. [CrossRef]
- 21. Shahabuddin, M.; Liaquat, A.M.; Masjuki, H.H.; Kalam, M.A.; Mofijur, M. Ignition delay, combustion and emission character-istics of diesel engine fueled with biodiesel. *Renew. Sustain. Energy Rev.* **2013**, *21*, 623–632. [CrossRef]
- 22. Patel, C.; Lee, S.; Tiwari, N.; Agarwal, A.K.; Lee, C.S.; Park, S. Spray characterization, combustion, noise and vibrations inves-tigations of Jatropha biodiesel fuelled genset engine. *Fuel* **2016**, *185*, 410–420. [CrossRef]
- Bari, S.; Lim, T.; Yu, C. Effects of preheating of crude palm oil (CPO) on injection system, performance and emission of a diesel engine. *Renew. Energy* 2002, 27, 339–351. [CrossRef]
- 24. Gharehghani, A.; Mirsalim, M.; Hosseini, R. Effects of waste fish oil biodiesel on diesel engine combustion characteristics and emission. *Renew. Energy* 2017, *101*, 930–936. [CrossRef]
- 25. Ge, J.C.; Kim, H.Y.; Yoon, S.K.; Choi, N.J. Optimization of palm oil biodiesel blends and engine operating parameters to improve performance and PM morphology in a common rail direct injection diesel engine. *Fuel* **2020**, *260*, 116326. [CrossRef]
- 26. Sheng, Y.; Brindhadevi, K.; Eed, E.M.; Xia, C.; Chi, N.T.L. Enzymatic lipase-based methyl esterified *Citrullus colocynthis* L. biodiesel for improved combustion, performance and emission characteristics. *Fuel* **2022**, 307, 121899. [CrossRef]
- 27. Keskin, A.; Şen, M.; Emiroğlu, A.O. Experimental studies on biodiesel production from leather industry waste fat and its effect on diesel engine characteristics. *Fuel* **2020**, *276*, 118000. [CrossRef]
- 28. Li, L.; Wang, J.; Wang, Z.; Xiao, J. Combustion and emission characteristics of diesel engine fueled with diesel/biodiesel/pentanol fuel blends. *Fuel* **2015**, *156*, 211–218. [CrossRef]
- Altın, R.; Çetinkaya, S.; Yücesu, H.S. The potential of using vegetable oil fuels as fuel for diesel engines. *Energy Convers. Manag.* 2001, 42, 529–538. [CrossRef]
- 30. Yilmaz, N.; Atmanli, A.; Vigil, F.M. Quaternary blends of diesel, biodiesel, higher alcohols and vegetable oil in a compression ignition engine. *Fuel* **2018**, *212*, 462–469. [CrossRef]
- Appavu, P.; Ramanan, M.V.; Venu, H. Quaternary blends of diesel/biodiesel/vegetable oil/pentanol as a potential alternative feedstock for existing unmodified diesel engine: Performance, combustion and emission characteristics. *Energy* 2019, 186, 115856. [CrossRef]
- 32. Varatharajan, K.; Cheralathan, M. Influence of fuel properties and composition on NOx emissions from biodiesel powered diesel engines: A review. *Renew. Sustain. Energy Rev.* 2012, *16*, 3702–3710. [CrossRef]
- Leevijit, T.; Prateepchaikul, G. Comparative performance and emissions of IDI-turbo automobile diesel engine operated using degummed, deacidified mixed crude palm oil-diesel blends. *Fuel* 2011, 90, 1487–1491. [CrossRef]
- Silitonga, A.; Masjuki, H.; Ong, H.C.; Sebayang, A.; Dharma, S.; Kusumo, F.; Siswantoro, J.; Milano, J.; Daud, K.; Mahlia, T.M.I.; et al. Evaluation of the engine performance and exhaust emissions of biodiesel-bioethanol-diesel blends using kernel-based extreme learning machine. *Energy* 2018, 159, 1075–1087. [CrossRef]