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The effect of fusel oil and waste biodiesel fuel blends on a CI engine performance, emissions, and combustion characteristics

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Abstract

In this study, experimental engine tests were conducted to investigate the combustion, performance, and emission characteristics of a diesel engine using a fuel blend composed of diesel, biodiesel, and fusel oil. In the study, which was carried out by using fuels obtained from different wastes together in a diesel engine. Seven different fuels were prepared for experiments by adding waste cooking oil (30% and 50%) and fusel oil (5% and 10%) by volume to commercial diesel fuel. The tests were carried out on the Lombardini LDW 1003 engine, a three-cylinder diesel engine, at four different engine loads (10, 20, 30, and 40 Nm), and a constant speed (2000 rpm). The experimental results revealed that the use of WCO generally led to increased NOx emissions which generally decreased with the fusel oil addition to the fuel mixture. Considering diesel fuel as a reference at maximum load conditions, there was a 12.63% increase in NOx emissions with 50% WCO. A 2.45% decrease in NOx emissions was achieved by adding 10% fusel oil. Furthermore, HC emissions decreased with the addition of both fusel oil and WCO at all load levels. When diesel fuel is taken as a reference at maximum load conditions, a 90% reduction in HC emissions was achieved by adding 50% WCO, and a 50% reduction in HC emissions was achieved by adding 10% fusel oil. Additionally, when diesel fuel is taken as a reference at maximum load condition, it was observed that a 0.05% increase in the maximum cylinder pressure value with the addition of 50% WCO and a 2.09% increase in the maximum cylinder pressure value with the addition of 10% fusel oil.

Keywords Diesel · Waste cooking oil (WCO) · Fusel oil · Combustion · Performance · Emission

Introduction

Despite today's technological developments, internal combustion engines are still widely used in industry, heavy industry, agriculture, and transportation. Insufficient oil reserves and global showdowns create constant fluctuations and uncertainties in both global oil supply and prices [1–3]. Due to dwindling fossil fuel reserves and environmental issues, interest in the use of biofuels in compression ignition engines has increased. The increasing need for petroleum due to industrialization, especially in developing countries, triggers the search for alternative fuels for internal combustion engines. One of the most popular alternative fuels used in internal combustion engines is biodiesel.

Biodiesel, as an alternative fuel, is one of the leading alternative fuels researched in this field because it can be used in diesel engines without the need for any mechanical changes since it has similar chemical properties to diesel fuel. Biodiesel, which can be produced from various vegetable oil, petroleum-derived wastes, and animal fats using different methods, can be used in diesel engines in its pure form or mixed with standard diesel fuel in certain proportions.

The major economic barrier to the commercialisation of the biodiesel is the high cost of vegetable oils, representing 70% to 85% of the total production cost of this energy input [4]. However, due to competition in cooking oil markets and consequent high prices, the availability of

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cooking vegetable oils for biodiesel production is limited. In addition, biodiesel production from edible oils harms the environment due to the large amount of agricultural land required [5]. Therefore, it is necessary to investigate new sources for biodiesel production, such as waste cooking oil (WCO) which can be obtained free of charge. Utilizing WCO as a raw material for biodiesel production will make the process very economical due to its low cost. Compared to edible vegetable oils, the utilization of WCO does not create a food and fuel crisis, is readily available, and does not cause any environmental problems. [6]. WCO is produced as waste in various food industries, especially in urban areas where refined vegetable oil consumption is high. The total annual production of used vegetable oil worldwide exceeds 15 million metric tons [7]. This amount corresponds to approximately 20% of total cooking oil consumption [8]. Considering the potential for waste cooking oil generation in European countries, approximately one million tons of waste are generated each year [9]. More than 60 percent of the huge amount of waste generated is often disposed of inappropriately or illegally, posing a threat to the environment. [10, 11]. The utilization of this waste for biodiesel production is a promising alternative considering the economic benefits it will provide due to its low acquisition cost, the benefits it will provide for the protection of the environment as it prevents pollution of water resources, and at the same time produces a less polluting fuel. Furthermore, some studies have shown that using WCO as a raw material for biodiesel production can reduce the cost by up to 70 percent compared to vegetable oil. [12, 13].

The use of biodiesel in diesel engines improves fuel economy and reduces exhaust emissions. However, there are also disadvantages when using it without any modification to the engine. For example, biodiesel fuel has worse atomization in the cylinder due to its high viscosity value, which worsens combustion and reduces engine efficiency. It also causes damage to engine parts due to carbon buildup in various engine components such as, piston rings, valve housings, cylinder walls, fuel pump, and injectors [14]. In order to overcome the disadvantages arising from the use of biodiesel and to improve the combustion characteristics of the fuel mixture delivered to the cylinder, many different studies have been carried out with additional fuels that can be blended with biodiesel fuel [15–18].

In studies involving additional fuels that can be used with biodiesel, researchers generally prefer alcohol-based fuels because they are in the liquid phase, have a high oxygen content, and are easy to supply. When blended with diesel fuel, alcohol-based supplementary fuels affect properties such as mixture stability, moisture content, viscosity, heating value, and cetane number. These factors can lead to improvements in engine performance, in-cylinder combustion, and emissions [19, 20].

Light alcohols can cause increased ignition delay time during combustion due to their low cetane number and high latent evaporation temperature. In contrast, heavy alcohols with low latent heat of vaporization and high calorific value provide full mixability with diesel fuel and exhibit better combustion characteristics in diesel engines [21, 22]. Interest in alcohol-biodiesel mixtures in diesel engines has also grown due to their high potential for reducing emissions, driven by stringent emission regulations [23–26].

Fusel oil is a type of alcohol with a high oxygen content. It is obtained as a waste product during the fermentation process from high alcohol sources and can be used as an additional fuel in internal combustion engines. Fusel oil can be produced from renewable and biomass sources, making it less harmful to the environment compared to petroleum fuels [27–29]. As a waste product, fusel oil cannot be disposed of directly into the environment as it may cause undesirable environmental impacts. Beyond the economic benefits, the utilization of fusel oil can also contribute to environmental health.

Although many studies have been conducted on the use of fusel oil in gasoline engines, its application in diesel engines is still a relatively new area of research. Fusel oil has a potential to be an alternative fuel for diesel engines, but more research is needed to completely understand its usability and properties. The limited number of studies on the of the fusel oil additives to the diesel fuel in diesel engines in the existing literature has increased the interest in research on this subject.

Agbulut et al. investigated the effects of diesel fuel–fusel oil blends on engine performance, exhaust emissions, and combustion characteristics. Tests were carried out with different volumetric percentages (10–20%) of fusel oil blended with pure diesel fuel under steady state operating conditions. The addition of fusel oil has resulted in a higher peak cylinder pressure (CPmax) and maximum heat release rates (HRRmax) due to the longer ignition delay and oxygen content of fusel oil. Fusel oil–diesel blends exhibited lower nitrogen oxide (NOx) and carbon monoxide (CO) emissions compared to pure diesel fuel (F0), with reductions of 52% and 20%, respectively. However, the blends showed an increase of up to 40 percent in unburned hydrocarbon (UHC) emissions. The highest brake thermal efficiency (BTE) and lowest brake-specific fuel consumption (BSFC) were observed for F0 due to its higher heating value [16].

Awad et al. investigated the effects of a fusel oil–diesel blend on the combustion characteristics, performance, and emissions of a single-cylinder diesel engine. Engine power and torque decreased slightly with F20 compared to pure diesel, while the specific fuel consumption increased, particularly at high engine speeds and loads. The ignition delay with F20 was longer than with pure diesel due to the low cetane number and high water content of the fusel oil. NOx emissions were reduced with F20 at all engine loads and speeds, with the highest reduction recorded at 1500 rpm. Carbon dioxide (CO_2) and CO emissions increased with the fuelling of F20 [29].

Ardebili et al. carried out an investigation on the performance and emissions of a diesel engine fuelled with different fusel oil blends and sugarcane nanocoal (SNB). The study showed that engine speed and torque were positively correlated, while there was no correlation between fusel oil concentration and nanocoal dosage. The researchers concluded that a 10% fusel oil blend with a 100 ppm SNB concentration and an engine speed of 2300 rpm was the optimal value with a maximum desirability value of 66%. The use of the fusel oil/SNB fuel mixture resulted in a decrease of UHC and NOx emissions by up to approximately 20.51% and 14.6%, respectively, while CO emissions increased by up to around 33% [30].

Hassan Pour et al. studied engine performance and emissions while using different levels of fusel oil (0–20%) and biodiesel (0–20%) at various engine speeds (1400, 1700, 2000, 2300, and 2600 rpm) and engine loads (0–100%). They employed the response surface method (RSM) to identify better engine running parameters that optimize engine performance and reduce exhaust emissions. They found that a combination of D90F5B5 (90% diesel, 5% fusel oil, and 5% biodiesel), 46% engine load, and an engine speed of 2026 resulted in the best operating parameters. The results showed that the use of fusel oil in fuel blends (up to 10%) increased engine power by up to 5.6%. It was also found that NOx emission was reduced by up to about 20% with the use of fusel oil, but CO and UHC CO emissions increased by up to 22% and 32%, respectively [31].

Yılmaz investigated the effects of blending diesel fuel with fusel oil in a single-cylinder compression ignition engine at different engine loads and a constant engine speed of 2200 rpm. The experimental study conducted on blending fusel oil with diesel fuel (F0, F5, and F10) showed effects on combustion, engine performance, and exhaust emissions. The study showed that the blended fuels with higher fusel oil content had lower engine torque due to water content and lower cetane number, which affect the combustion process. As the amount of fusel oil in fuel mixtures increased, the BSFC also increased. This is because the calorific value decreases with the increased percentage of fusel oil, making it necessary to use more fuel to produce the same amount of power for the same operating conditions. Higher proportions of fusel oil in the blend resulted in decreased smoke and NOx emissions compared to pure diesel, while CO emission increased [28].

Agbulut et al. studied the use of fusel oil, which is a waste product from the production of ethyl alcohol, as an alternative fuel in a single-cylinder diesel engine. They tested fuel blends containing 5–20% fusel oil and compared them to diesel fuel. The experimental results showed that the blends with fusel oil resulted in lower BTE and higher BSFC compared to pure diesel. However, the addition of fusel oil to diesel fuel led to a significant reduction in CO, HC, NOx, and smoke emissions. The combustion of these blends also improved as evidenced by the increase in CO_2 and oxygen emissions, indicating improved combustion. In-cylinder pressure and net heat release rates also generally increased with the addition of fusel oil [32].

Liu et al. investigated the impact of three fuel types on combustion and emission characteristics in a diesel engine. The tested fuels were pure diesel, 20% fusel oil with 0% and 6% water content. They analyzed the fusel oil/diesel blends in terms of water holding capacity, emission, and combustion characteristics. The composition of fusel oil affects its water stability, with amyl alcohol being dominant. Adding 20% fusel oil with water content to diesel fuel increases brake thermal efficiency by 0.7%. Soot emissions can be reduced by up to 38.5% with the addition of 20% fusel oil at a BMEP of 0.5 MPa. They also stated adding 20% fusel oil reduces fuel costs by approximately 15% while maintaining the same driving distance [33].

When looking at the literature, it is very important to dispose of wastes under certain conditions and to transform them into valuable products that do not harm the environment. Although there are some initiatives in this framework, the proper utilization of fuels produced from wastes can be a guideline for the fuel sector. Our aim is to fill the identified knowledge gaps and to safely implement the utilization of waste for fuel production, considering industrial conditions. In this context, it can be stated that this study has many objectives. One of the best ways in the search for alternative fuels is to produce fuel from waste. This is because when the wastes are disposed of, valuable fuel is produced that can be used in internal combustion engines. Thus, both the environmental impact of waste and the dependence on fossil-based fuel are reduced. One of the aims of this study is to show that a better product can be obtained by using alternative fuels obtained from different wastes together. For this purpose, the optimum ratio was tried to be determined by adding different ratios of WCO and fusel oil to standard diesel. Another aim of the study is to ensure the usability of fuel blends produced from wastes after many processes in a diesel engine. Various tests were carried out for the fuel blends and their properties were determined. There are a limited number of studies on the use of fusel oil in diesel engines. In this study, the use of fusel oil with WCO in a diesel engine was demonstrated. The obtained end products were mixed with standard diesel fuel at different ratios by volume and tested in a water-cooled diesel engine under different engine loads (10, 20, 30, and 40 Nm) and at constant speed (2000 rpm). The data obtained from the experiments were analyzed, and the results were compared with reference diesel fuel. As a result of this study, the applicability of fuel blends obtained from the by-product of the distillation process of alcoholic liquids and WCO will be determined to minimize the negative impact on the sustainable environment. Thus, WCO and process waste with high energy content will no longer be classified as 'waste' but as 'raw material.' According to Article 5, subparagraph 1 published in the Official Gazette dated 16.06.2017, 'It is obligatory for distributor license holders to blend at least 0.5% (V/V) of biodiesel produced from domestic agricultural products and/or vegetable waste oils into the total diesel fuel imported and supplied from refineries excluding land tanker filling units within a calendar year.' [34]. This makes it compulsory to add alternative fuel to diesel fuel. With a small revision to this article, fuels obtained from waste can be used in diesel engines. Thus, fuels obtained from waste can be used as additives in diesel engines. In this way, dependence on fossil fuels and foreign dependence on fuel will be relatively reduced.

The study is considered to have positive outputs in terms of both the utilization of wastes and the elimination of the harmful effects of these wastes on the environment by evaluating the fusel oil that emerges as a by-product in the biodiesel and alcohol production process obtained from waste oils. For the reasons explained above, This study aimed to investigate engine performance, emissions, and combustion characteristics of fusel oil/WCO blends in a single-cylinder diesel engine.

Materials and methods

In the study, biodiesel and fusel oil were added to the diesel fuel supplied by a commercial enterprise. The resulting fuels were created by blending them with diesel fuel based on volume. The resulting fuels were named WCO30, WCO50, WCO30F5, WCO50F5, WCO30F10, and WCO50F10. The WCO50F10 fuel consists of 50% WCO biodiesel by volume, 10% fuel oil, and the remaining percentage is diesel fuel (DF). The general characteristics of these fuels are provided in Table 1. After preparing the test fuel, it was mixed in a magnetic stirrer for 30 min before the tests to ensure the homogeneity of the test fuels.

Table 1 Test fuels general properties

	Density/g L^{-1} @15 °C	Cetane number	Viscosity/cSt @40 °C	LHV/MJ kg^{-1}
DF	835.50	54.90	2.96	45.80
WCO30	843.93	52.58	3.72	43.60
WCO50	849.55	51.04	4.22	42.13
WCO30F5	842.17	51.95	3.78	43.07
WCO50F5	847.79	50.40	4.28	41.61
WCO30F10	840.41	51.31	3.84	42.55
WCO50F10	846.03	49.77	4.34	41.08

Turkiye's market prices were used for the cost/benefit analyses. The cost/benefit analysis was provided in Table 2. The specific costs of WCO biodiesel, fusel oil, and diesel fuel were 0.88 USD L^{-1}, 0.95 USD L^{-1}, and 1.32 USD L^{-1}, respectively. These prices were based on market prices in Turkey. The specific costs of the prepared test fuel blends were computed by using these market prices. When the WCO–fusel oil ratio increased in fuel mixtures, fuel costs decreased.

Experiments were conducted using the Lombardini LDW 1003 model engine, a 3-cylinder 4-stroke engine, at a constant speed of 2000 rpm and four different engine loads (10 Nm, 20 Nm, 30 Nm, and 40 Nm). The technical specifications of the test engine are presented in Table 3.

The test engine is connected to a Kemsan dynamometer, which allows the motor to be loaded. The dynamometer can load engines up to 25 kW power. A coupling connects the motor and dynamometer. To measure the motor torque, a Kistler Rotor-Type 4550 A torque meter is connected to the shaft between the motor and the dynamo. The torque meter

Table 2 The specific costs of the prepared test fuel blends

Fuel blend	Specific cost /USD L^{-1}
DF	1.32
WCO30	1.19
WCO50	1.10
WCO30F5	1.17
WCO50F5	1.08
WCO30F10	1.15
WCO50F10	1.06

Table 3 Test engine properties

Brand	Lombardini
Model	LDW 1003
Cylinder arrangement and number	Inline, 3
Cooling type	Water Cooled
Bore	75 mm
Stroke	77.6 mm
Compression ratio	22.8:1
Total cylinder volume	1028 cc
Max. Engine Speed	3600 rpm
Max. Engine Power	19.5 kW

is capable of precise measurement over a wide torque range (0–5000 Nm). The experimental setup is depicted in Fig. 1.

The experiments commenced when the engine oil temperature reached 50 ºC, and it was expected that the engine temperature would return to 50 ºC after each test. Each experiment was repeated three times, and the average of the experimental results was calculated. K-type thermocouples were used for temperature measurements. The thermocouple used can make precise measurements up to 1200 °C. Intake air temperature (the thermocouple is located at the intake manifold inlet), engine oil temperature (the thermocouple is located at the carter), and exhaust outlet temperatures (the thermocouple is located at the exhaust manifold outlet) were recorded on the computer using a data logger.

A Kübler encoder and an Optrand in-cylinder pressure sensor were employed to monitor changes in in-cylinder pressure relative to the piston's position. The in-cylinder pressure sensor is located in the glow plug housing of the engine. An apparatus connects the encoder directly to the crankshaft. The data were transferred to the febris program, which is a combustion analysis program, through a data logger. For each experiment, an average of 500 cycles was taken, and in-cylinder pressure graphs were generated.

Data for fuel consumption and effective efficiency calculations were collected and recorded using a stopwatch and a metered fuel consumption beaker. Exhaust emissions were measured using the K test exhaust emission device, and data collection began once stability was reached. The sensitivities of the test equipment are outlined in Table 4.

The acquisition of data and the devices used for calculating brake-specific fuel consumption, power, and thermal efficiency have been discussed above. The formula used to determine BSFC is given in Eq. 1, the formula used to determine power is given in Eq. 2, and the formula used to determine thermal efficiency is given in Eq. 3 [16].

$$\mathrm{BSFC} = \frac{B_{\mathrm{e}}.10^{3}}{P_{\mathrm{e}}} \tag{1}$$

where BSFC g kWh^{-1}, Be fuel consumption kg h^{-1}, and Pe effective engine power (kW) [16].

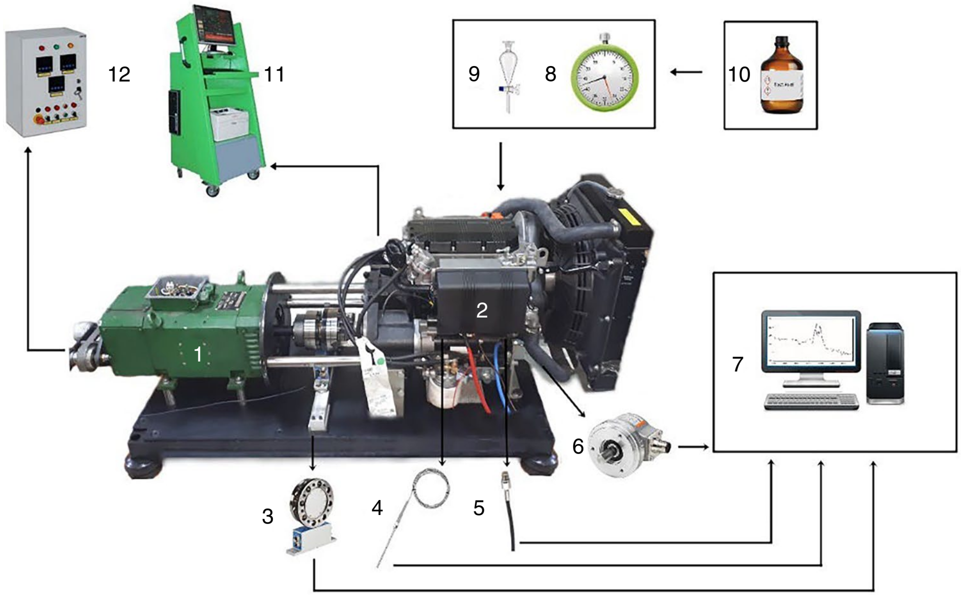
$$\mathrm{Pe} = \frac{2\pi.M_{\mathrm{e}}.n}{60000} \tag{2}$$

Equation 2 denotes Pe power (kW), Me denotes engine torque (Nm), and n denotes engine speed (rpm)[16].

Table 4 Sensitivities of test devices

Measuring instrument	Range	Accuracy
Pressure (PSI TC Optrand Auto)	0 ~ 3000 psi	± 1%
Encoder (Kübler Brand Sendix)	0 ~ 360°	0.1° CA
HC (ppm)	0 ~ 20,000	1 ppm
NO_x (ppm)	0 ~ 5000	0.1%
Thermocouple (Type K)	0 ~ 1200 °C	± 0.1 °C
Torque Measuring Unit (Rotortype 4550 A Kistler)	0 ± 100 ~ 0 ± 5000	0.01%

Fig. 1 Scheme of the experimental setup



1-Dynamometer, 2-Test engine, 3-Torquemeter, 4-Thermocouple, 5-In-cylinder pressure sensor, 6-Encoder, 7-Main board and computer, 8-Stopwatch, 9-Fuel consumption level, 10-Test fuel, 11-Exhaust gas emissions analyzer, 12-Dynamometer control panel

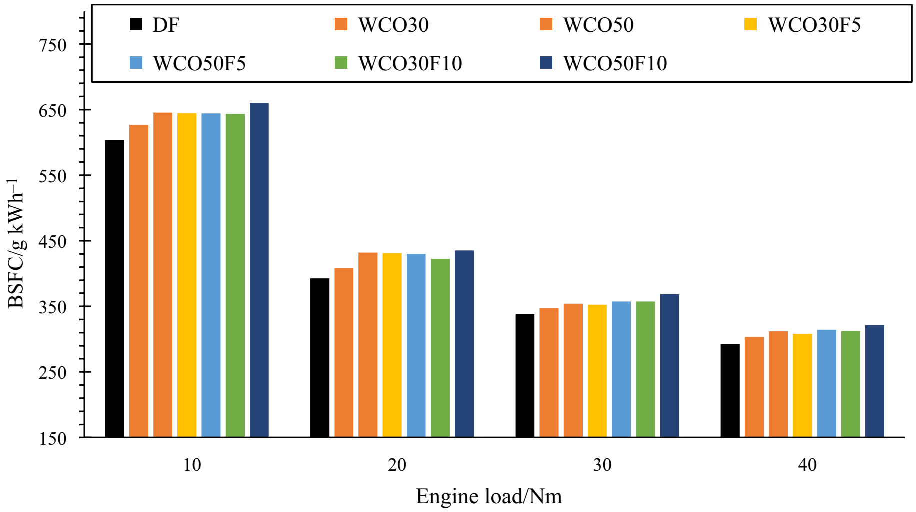


Fig. 2 BSFC changes of diesel–biodiesel–fusel oil fuels depending on engine load

$$\mathrm{BTE} = \frac{P_e.3600}{B_e.\mathrm{LHV}} \tag{3}$$

In Eq. 3, BTE represents brake thermal efficiency, Pe represents effective power (kW), Be represents fuel consumption kg h^{-1}, and LHV represents the lower heating value kJ kg^{-1} of the fuel used.

In the study, the general uncertainty calculation was performed using the data in Table 3 and Eq. 4 [16].

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \ldots\ldots. + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \tag{4}$$

Results and discussion

In this study, experimental engine tests were conducted to examine the combustion, performance, and emission characteristics of a diesel engine using a fuel mixture composed of diesel, biodiesel, and fusel oil. In the study, WCO and fusel oil were added to commercial diesel fuel based on volume. The resulting fuels were named WCO30, WCO50, WCO30F5, WCO50F5, WCO30F10, and WCO50F10. WCO50F10 fuel consists of 50% WCO biodiesel by volume, 10% fusel oil, and the remaining percentage is diesel fuel. The engine tests were carried out on a Lombardini LDW 1003 model, a 3-cylinder diesel engine which was operated at a constant speed with four different engine loads. The engine speed was set at 2000 rpm, and the engine loads were 10 Nm, 20 Nm, 30 Nm, and 40 Nm, respectively. The device sensitivities provided in Table 3 and the general uncertainty, calculated using Eq. 4, were determined as 2.77%. Additionally, after the experiments, the following results were obtained.

Performance

In this section, the performance characteristics of a diesel engine powered by a fuel mixture composed of diesel, biodiesel, and fusel oil will be examined. When evaluating engine performance, we consider BTE, which is the ratio of effective power to the unit fuel energy required to produce that power, and BSFC, which is the ratio of fuel consumption to effective power. Figure 2 illustrates the changes in BSFC for diesel–biodiesel–fusel oil fuels based on engine load.

As can be seen in the figure, the BSFC value decreased for all test fuels as the engine load increased. At higher engine powers, the amount of consumed fuel per unit of effective power decreased, resulted in lower specific fuel consumption. The highest BSFC value was observed in WCO50F10 fuel with 10 Nm of torque, while the lowest BSFC value was observed in DF fuel with 40 Nm of torque. Although fuel consumption increases due to the addition of biodiesel and fusel oil, this increase is not significantly substantial. When considering all load values, this increase is observed to be at a maximum of around 8% compared to diesel fuel consumption. The increase in BSFC value due to the addition of biodiesel and fusel oil is due to the lower heating value of the added fuels than diesel fuel. The same trends were observed in studies using fuels with similar characteristics. Studies using biodiesel [35, 36]. Studies using fusel oil [16, 29].

Figure 3 displays the variations in BTE for diesel–biodiesel–fusel oil fuels depending on engine load. In the BTE chart, it can be observed that the pattern contrasts with the BSFC chart but exhibits similar changes. BTE increases in parallel with the increase in load, while BTE generally decreases with the addition of biodiesel and fusel oil to diesel fuel. The lower thermal values of biodiesel and fusel oil compared to DF fuel and their higher fuel densities have

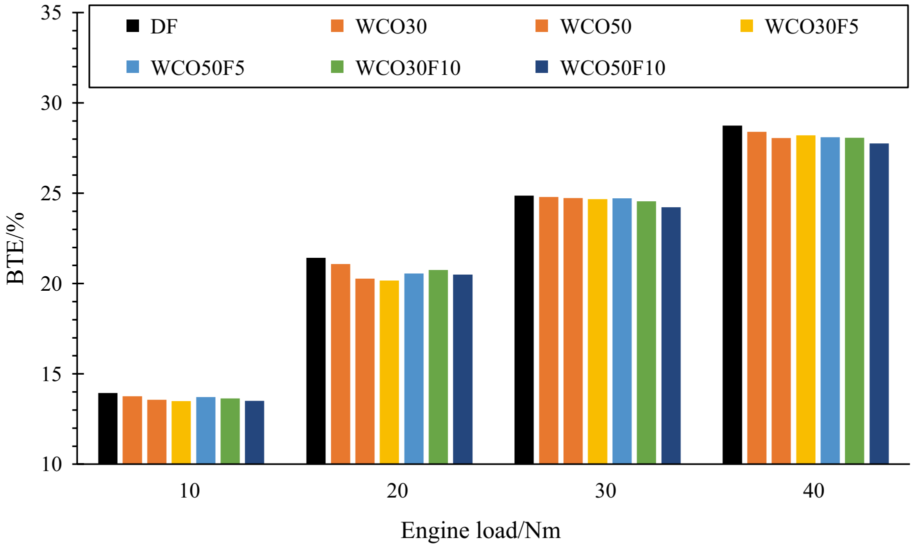


Fig. 3 BTE changes of diesel–biodiesel–fusel oil fuels depending on engine load

slightly reduced combustion efficiency. Additionally, as the ratio of biodiesel and fusel oil increases, it increases the viscosity and density of the fuel mixture, negatively affecting atomization, evaporation, and combustion [37].

Exhaust gas temperature

To better understand exhaust emissions, knowing engine temperatures is of great importance. Figure 4 illustrates the changes in exhaust gas temperatures for diesel–biodiesel–fusel oil fuels based on engine load. As depicted in the figure, exhaust temperatures increase in relation to the engine load. The reason for this increase in exhaust temperatures with engine load is the higher volume of fuel being injected into the cylinder at higher load values. The high viscosity of the mixture formed by adding it to DF fuel results in poor atomization of the fuel, leading to the presence of a small amount of unburned fuel during the premixed combustion phase. This unburned fuel further combusts, contributing to the rise in exhaust temperature [12, 16, 38].

The addition of fusel oil to the mixture reduces the viscosity and sub-thermal value of the mixture, which has proven effective in lowering exhaust temperatures.

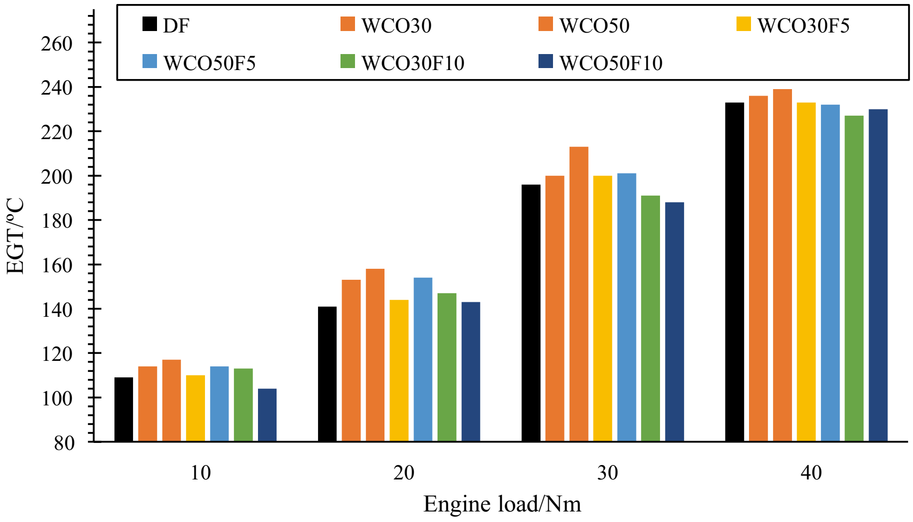


Fig. 4 EGT changes of diesel–biodiesel–fusel oil fuels depending on engine load

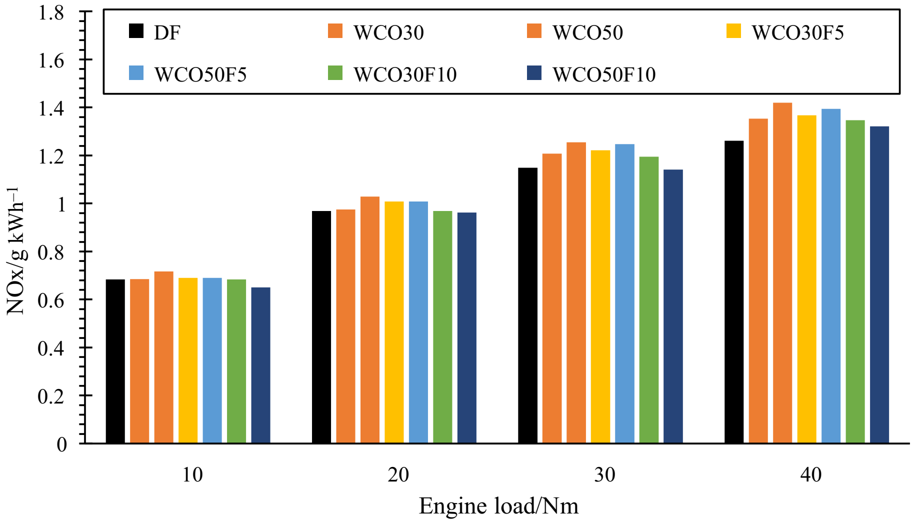


Fig. 5 NOx emission changes of diesel–biodiesel–fusel oil fuels depending on engine load

Emissions

One of the most significant factors in the reduction and limitation of vehicles equipped with internal combustion engines is the exhaust emission they emit into the environment. In this section, emission changes of diesel–biodiesel–fusel oil fuels due to engine load will be examined. Specifically, NOx and HC emissions will be discussed in this section.

NOx emission

NOx emissions, which include NO, NO2, and their derivatives, are primarily formed through the reaction of nitrogen in the air with fuel. These emissions are considered undesirable, and their allowable limits in standards are progressively decreasing. NOx emissions are a major contributor to the formation of photochemical smog [39]. Figure 5 illustrates the changes in NOx emissions for diesel–biodiesel–fusel oil fuels based on engine load.

As can be seen in Fig. 5, NOx emissions have increased due to increased engine load. This is an expected result because the pressure inside the cylinder increases with engine load, and the temperature inside the cylinder increases in parallel. It is a known fact that the mechanism of NOx formation increases at high temperatures [39].

Compared to DF, the NOx emissions of DF70WCO30 fuel increased by 0.19%, 0.68%, 5.20%, and 7.37% for 10, 20, 30, and 40 Nm load values, respectively. Similarly, in comparison to DF fuel, the emission values of DF50WCO50 fuel increased by 4.85%, 6.16%, 9.25%, and 12.63%, respectively.

The adiabatic flame temperature affects the maximum temperatures inside the cylinder, and therefore, it plays a significant role in the formation of NOx emissions. The higher oxygen content of biodiesel and the adiabatic flame temperature have been instrumental in increasing NOx emissions. Similar results can be seen in the relevant sources [35, 40, 41].

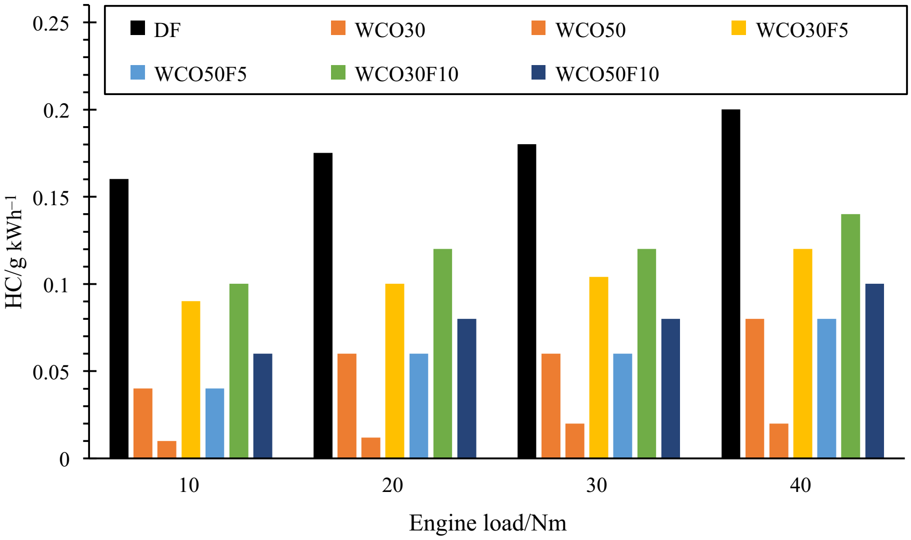
There was a decrease in the increasing NOx values due to the addition of biodiesel when fusel oil was added to the DF-WCO fuel mixture. Thus, compared to DF fuel, the emission values of DF50WCO50 fuel increased by 4.85%, 6.16%, 9.25%, and 12.63%, respectively, and the NOx increase of WCO50F5 fuel with fusel oil addition compared to DF fuel was 0.97%, 4.11%, 8.67%, and 10.53%. Increasing the amount of fusel oil by 10% resulted in fewer NOx emissions compared to diesel fuel at low loads. The higher humidity when fusel oil is included, along with its lower thermal value compared to diesel fuel, has helped reduce NOx emissions. In open literature, it can be seen that fusel oil tends to reduce NOx [16, 28].

HC emission

In addition to HC emissions having irritating and odor-forming effects when mixed with the atmosphere, HC components can react with gases in the atmosphere to form photochemical smog [36, 42, 43]. HC emissions depend on many factors, such as fuel composition, combustion chamber shape, and engine operating parameters. Furthermore, if the fuel sprayed into the combustion chamber does not encounter sufficient oxygen, high levels of HC emissions in the exhaust are inevitable. Figure 6 illustrates the changes in HC emissions for diesel–biodiesel–fusel oil fuels depending on engine load.

HC emissions increased in parallel with the increase in engine load. The reason for the increase in HC emissions due to engine load is that with engine load, there is less oxygen content despite the increased fuel consumption.

Fig. 6 HC emission changes of diesel–biodiesel–fusel oil fuels depending on engine load



The results are consistent with references [44–46]. Additionally, a decrease in HC emissions was observed due to the increased presence of biodiesel in the fuel mixture. This may be attributed to the fact that biodiesel contains oxygen [35]. The increased oxygen content in the mixture provides additional oxygen within the combustion chamber, enhancing the complete combustion capability of the fuel mixture and subsequently reducing the level of hydrocarbons in the exhaust [47]. However, the addition of fusel oil to the diesel–biodiesel fuel mixture resulted in an increase in HC emissions. Despite fusel oil containing oxygen in its composition, the moisture content of fusel oil played a role in a slight increase in HC emissions [16]. Furthermore, the lower cetane content of fusel oil in comparison to DF and WCO fuel led to ignition delay, contributing to increased HC emissions [16, 48].

Combustion characteristics

In Fig. 7, the in-cylinder maximum pressure values for diesel–biodiesel–fusel oil fuels are presented based on engine load, and in Fig. 8, the changes in in-cylinder pressure and heat release for diesel–biodiesel–fusel oil fuels are displayed depending on the engine load. Cylinder pressure increased in line with the rise in engine load. At lower engine loads, the amount of fuel injected into the cylinder is relatively lower, whereas the engine load increase results in more fuel being sprayed into the cylinder. The elevated engine load leads to increased combustion of the fuel mixture inside the cylinder, resulting in higher temperature and pressure at the end of combustion. Pmax increased alongside the temperature due to greater fuel consumption. Although Pmax increases in parallel with the increase in engine load, this increase is

Fig. 7 In-cylinder max. pressure values of diesel–biodiesel–fusel oil fuels depending on engine load

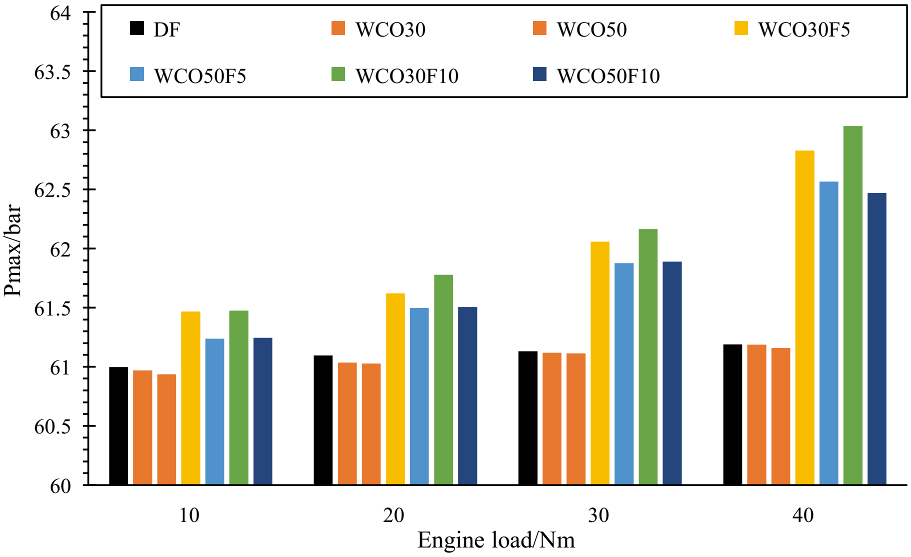


Fig. 8 Changes in in-cylinder pressure and heat dissipation of diesel–biodiesel–fusel oil fuels depending on engine load, **a** 10 Nm, **b** 20 Nm, **c** 30 Nm, and **d** 40 Nm

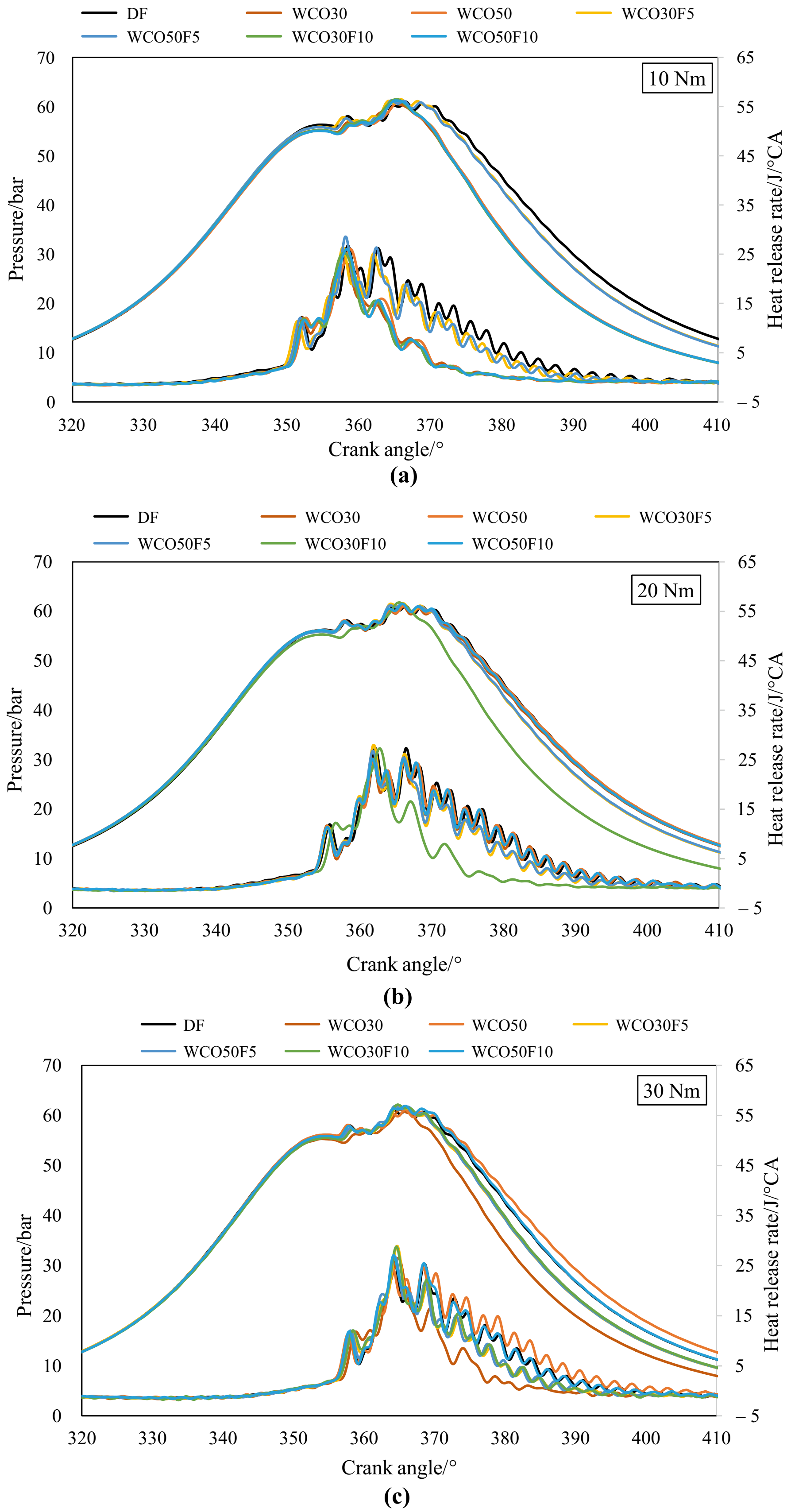
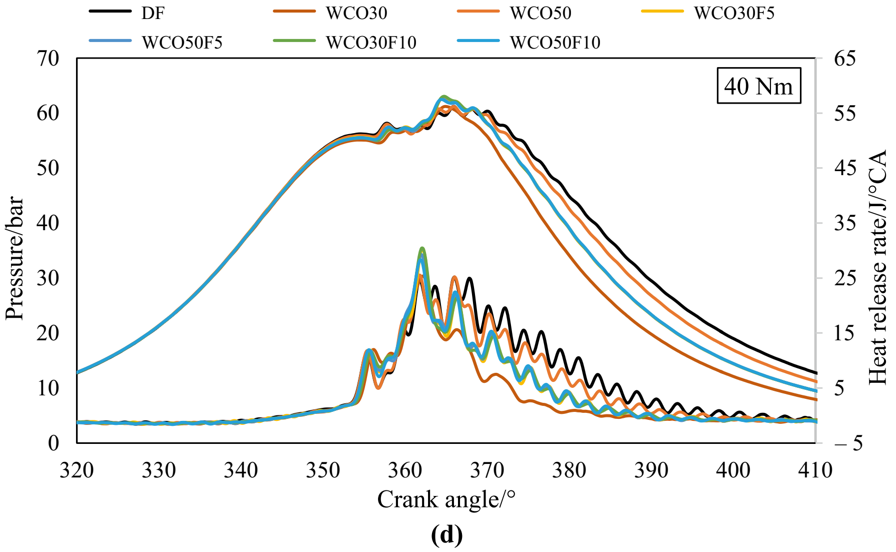


Fig. 8 (continued)



insignificant. In the study, the Pmax increase was between 0.02% and 3.01%. This may be due to the fact that the engine is a commercial engine with a pre-combustion chamber. Similar trends were also exhibited in studies using the same engine [49–51]

As observed in the in-cylinder pressure graphs, the lowest in-cylinder pressure value was recorded for WCO50 fuel at a 10 Nm load, and the highest in-cylinder pressure value was recorded for WCO30F10 fuel at a 40 Nm load. The in-cylinder pressure values for DF fuel are 60.996, 61.095, 61.130, and 61.188 bars for small to large engine loads, respectively. With the addition of biodiesel to DF fuel, the in-cylinder pressure value decreased in proportion to the increase in biodiesel content. This reduction is approximately 1%. The reduction in in-cylinder pressure with the addition of biodiesel is attributed to the decrease in the lower heating value of the mixture resulting from the added biodiesel [33, 43, 52].

The reduction in in-cylinder pressure further increased with the addition of fusel oil to the mixture. Compared to DF fuel, WCO30F5 fuel, which is formed by adding 5% fusel oil to the fuel mixture, increased the pressure inside the cylinder by 0.77%, 0.86%, 1.51%, and 2.68% for small to large loads, respectively. When the amount of fusel oil was increased (for WCO30F10 fuel), the in-cylinder pressure increased by 0.78%, 1.11%, 1.68%, and 3.01% compared to DF fuel. The low cetane number of fusel oil caused a longer ignition delay during the combustion of the mixture fuel. The longer ignition delay increased the amount of fuel accumulated in the combustion chamber, leading to a rise in maximum pressures inside the cylinder [16].

Additionally, as seen in Fig. 8, heat release increased with the increase in engine load. The peak values of heat release, which slightly decreased with the addition of biodiesel to DF fuel, increased with the addition of fusel oil to DF fuel. This increase can be attributed to the elevated peak pressure values resulting from the addition of fusel oil [16].

Conclusions and recommendations

In this study, experimental engine tests were conducted to examine the combustion, performance, and emission characteristics of a diesel engine using a fuel mixture composed of diesel–biodiesel–fusel oil. In the study, WCO and fusel oil were added to commercial diesel fuel by volume, resulting in fuels named WCO30, WCO50, WCO30F5, WCO50F5, WCO30F10, and WCO50F10. WCO50F10 fuel consists of 50% WCO biodiesel by volume, 10% fusel oil, and the remaining percentage is diesel fuel. These engine tests were conducted on a 3-cylinder Lombardini LDW 1003 model diesel engine at constant speed and four different engine loads: 10, 20, 30, and 40 Nm, respectively. After the experiments, the following results and recommendations were reached:

Fuel mixtures containing WCO and fusel oil in different volumetric ratios can be used without the need for any engine modifications.

The use of biodiesel can mitigate adverse conditions in combustion and emissions when a third fuel is added.

The fuel production from alternative sources and waste materials reduces the reliance on fossil fuels.

Fuel production from waste can protect the environment and relatively reduce dependence on fossil fuels.

NOx emissions, which increase by adding WCO to diesel fuel, can be reduced by adding fusel oil. Considering diesel fuel as a reference at maximum load conditions, there was a 12.63%

increase in NOx emissions with 50% WCO. A 2.45% decrease in NOx emissions was achieved by adding 10% fusel oil.

Compared to the HC emissions that occur when diesel fuel is used, HC emissions decreased with the addition of WCO and fusel oil for all load conditions. When diesel fuel is taken as a reference at maximum load conditions, a 90% reduction in HC emissions was achieved by adding 50% WCO, and a 50% reduction in HC emissions was achieved by adding 10% fusel oil.

The peak pressure value in the cylinder, which decreased with the addition of WCO to diesel fuel, increased again with the addition of fusel oil.

The experimental data collection began when the engine oil temperature was stable and ended when emissions reached a steady state. Experiments can be conducted over extended periods to assess their impact on the engine and its components.

After long operating tests, the effects of the fuel on the wear of engine equipment can be examined by measuring material wear.

The effects of the fuels used on engine vibration and noise emissions can be assessed through measurements.

In this study, food process wastes were investigated as fuel. The conversion of different wastes into fuel and their combined use in internal combustion engines can be investigated (such as tires, cables, waste oil, and organic wastes).

There are some challenges in producing fuel from waste. These can be summarized as follows.

Although there are incentives and presence of laws in place for the collection and utilization of waste, a considerable amount of this waste is still disposed of illegally. In addition, public incentives for the conversion of waste into internal combustion engine fuel can ensure that the waste collection and disposal process is carried out efficiently.

Wastes may be found in different places and must be collected for high-capacity production.

Physical and chemical processes may be needed to convert waste into fuel.

Different processes may be required for different wastes.

Processes and additives may be needed to improve fuel properties.

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