Arabian Journal for Science and Engineering
https://doi.org/10.1007/s13369-023-08266-x

RESEARCH ARTICLE-MECHANICAL ENGINEERING

Effects of a CRDI Engine Running on Biodiesel, *n*-Octanol and Nanoparticle Blended Nanofuel on Performance, Emissions and Combustion

Güven Demirtaş[1,2] · Mustafa Kemal Balki[3,4] · Cenk Sayin[5]

Received: 16 November 2022 / Accepted: 22 August 2023

Abstract

In order to popularize the use of pure biodiesel (B100) in diesel engines, its fuel properties should be improved. For this purpose, biodiesel fuel properties are enhanced by *n*-octanol and multi-walled carbon nanotube (MWCNT) nanoparticles. The effects of these fuels on performance, combustion and exhaust emissions in a diesel engine were experimentally investigated. *n*-Octanol is added to biodiesel at a rate of 5%, and it is named B95O5. MWCNT is also added to B95O5 as 100 ppm, and the test fuel is specified as B95O5100MWCNT. The experiments are carried out with a CRDI diesel engine at four different loads (25%, 50%, 75% and 100%) and at a constant engine speed of 1500 rpm. According to the results, all performance, emission and combustion parameters except BSFC are reduced compared to diesel (D100), with the use of B100, B95O5 and B95O5100MWCNT. With the addition of *n*-octanol to pure biodiesel, HC, CO_2 and BTE increase on average by 9.10%, 2.12% and 1.62% for all loads, while NO, BSFC and engine power decrease by around 6.21%, 1.69% and 6.8%, respectively. In addition, with the addition of MWCNT to B95O5, HC, CO_2, NO and BTE increased by 4.5%, 1.58%, 1.46% and 7.10% on average for all loads, respectively. Moreover, BSFC and engine power fell by around 6.27% and 2.04%, respectively. The addition of MWCNT has been found to improve overall performance and emissions, apart from the BSFC. In addition, it is observed that the maximum in-cylinder pressure and HRR improve with the use of *n*-octanol and MWCNT added fuel.

Keywords Nanoparticle · *n*-Octanol · Multi-walled carbon nanotube · CRDI · Engine performance · Combustion · Exhaust emissions

Abbreviations

BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
CA	Crank angle
CNT	Carbon nanotube
CO_2	Carbon dioxide
CO	Carbon monoxide
CP	Cylinder pressure
CRDI	Common rail direct injection
DEE	Diethyl ether
DI	Direct injection
ECU	Electronic control unit
EGT	Exhaust gas temperature
HRR	Heat release rate
UHC	Unburned hydrocarbon
MWCNT	Multi-walled carbon nanotube
NO_x	Nitrogen oxides
SDS	Sodium dodecyl sulfate
SWCNT	Single-walled carbon nanotube

✉ Güven Demirtaş
guven.demirtas@yobu.edu.tr

[1] Institute of Pure and Applied Sciences, Marmara University, 34722 Istanbul, Turkey

[2] Akdağmadeni Vocational School, Yozgat Bozok University, 66300 Yozgat, Turkey

[3] Department of Mechanical Engineering, Sinop University, 57000 Sinop, Turkey

[4] Scientific and Technological Researches Center, Sinop University, 57000 Sinop, Turkey

[5] Department of Mechanical Engineering, Marmara University, 34722 Istanbul, Turkey

Published online: 20 September 2023

1 Introduction

The increase in the number of vehicles in parallel with the world population has caused the oil-based fuel consumption to increase day by day. In addition, petroleum-based fuels are mostly preferred to meet individual and institutional energy demands. However, it is known that the discovered oil reserves are limited [1, 2]. The use of petroleum-derived fuels causes serious environmental problems such as environmental pollution and global warming [3]. In order to reduce these harmful effects, the use of alternative fuels has been an important research topic, as well as the establishment of emission standards for vehicles using petroleum-based fuels by international organizations [4, 5]. There is also world interest in increasing the share of renewable bioenergy in the transportation sector to solve these problems [6].

Diesel engines are preferred more than gasoline engines due to their durability, low operating cost, high reliability, fuel economy and high part load efficiency [7, 8]. Diesel engines are widely used in none-road systems such as generators and conveyors, especially in construction machinery and passenger vehicles. It is important for the environment and economy to search for a fuel that can be an alternative to petroleum-based fuels in diesel engines. Today, biodiesel has an important place among the fuels that can be used as an alternative to diesel. Biodiesel is chemically obtained from vegetable, animal and waste oils with methyl or ethyl alcohol in the presence of a catalyst [9–11]. Biodiesel can be obtained from agricultural products with high oil content. However, in terms of the sustainability of the food supply, the conversion of inedible oils to biodiesel has become more important today. In addition, the use of waste frying oils and waste animal oils, which pollute the environment and cause negative effects on living things, in the production of biodiesel is more economical and environmentally friendly [12, 13]. Biodiesel, which is easily degraded and non-toxic in nature, has sustainable energy potential. In addition, it has more lubricating properties than diesel fuel [14]. Biodiesel, which can be used in diesel engines without the need for any modification, has a high cetane number and oxygen content. Due to these features, it creates an advantage compared to diesel in terms of carbon monoxide (CO), HC and soot emissions. However, it has disadvantages such as high viscosity, low calorific value, cold flow problem and poor fuel atomization [10, 15]. Fuel properties can be improved by using additives to reduce the negative effects of biodiesel.

Another alternative fuel that can be used in diesel engines is alcohols. Alcohols are generally used in diesel engines by mixing with diesel or biodiesel. The combined use of both biodiesel and high alcohol in diesel engines has an improving effect on the overall performance and emissions of the engine, as they compensate for each other's individual characteristics [16]. Addition of high alcohol to biodiesel has a reducing effect on the kinematic viscosity of the fuel. Moreover, while increasing the calorific value of the fuel, it also has a significant reducing effect especially on HC and soot emissions [17]. *n*-Octanol, which is from the high alcohol group, has a higher cetane number and energy content compared to light alcohols [18, 19]. In addition, *n*-octanol has a high mixing ability because it provides better solubility [20, 21]. Thanks to this feature, it can form a good mixture with different fuel types. The use of *n*-octanol creates a reducing effect on soot emissions in diesel engines [22]. Therefore, it can be used as an additive for diesel and biodiesel. Various nano additives are also added to fuels as catalysts in order to obtain better combustion, performance and emission values [23]. Because nano additives provide a high surface/volume ratio, they increase the evaporation rate and oxidation of the fuel. In addition, nano additives have thermal conductivity. Thus, it reduces the ignition delay time [24–26]. Recently, the effects of various nanoparticles on engine performance and exhaust emissions have been investigated. Nanoparticles are called by different names according to the type of raw material from which they are produced and their chemical and physical structure. Carbon nanotube (CNT), which is among the nanoparticles, is preferred as an additive for fuels due to its structure and physical properties [27–29]. Carbon nanotubes (CNTs) are cylindrical molecules composed of rolled sheets of single-layered carbon atoms (graphene). They are formed as graphite sheets. The structure formed by the cylindrical curling of this graphite plate is called as a single-walled carbon nanotube (SWCNT). These intertwined concentric cylindrical structures with different diameters are defined as multi-walled carbon nanotube (MWCNT) [30].

In the literature, there are many studies in which different types of nanoparticles and high alcohol are used together with biodiesel. In one study, the effect of adding 50 mg/L graphene oxide nanoparticles into different types of high alcohol mixture in Jatropha biodiesel on the combustion, exergy and emissions of a diesel engine is investigated. *n*-Butanol, *n*-heptanol and *n*-octanol are used separately as higher alcohols. Mixture fuels are prepared as 50% biodiesel + 40% diesel + 10% high alcohol. According to the results, it is determined that there is a slight increase in the average combustion pressure and net heat release rate of the use of *n*-Butanol blend fuel with the addition of graphene oxide. In addition, it is stated that the use of graphene oxide nanoparticles improved BTE by 15% and significantly reduced HC and smoke emissions. Moreover, it is reported that BTE increases with the use of *n*-octanol added blend fuel [31]. El-Seesy et al. investigated the effect of a quaternary mixture containing biodiesel, methanol, *n*-octanol and diethyl ether on the combustion and emissions of a diesel engine. It is reported that the use of alcohol blended fuels reduces the in-cylinder pressure and the heat release rate compared to the use of pure biodiesel. It is stated that this decrease is caused by the high latent heat of vaporization, low energy content and cetane number of the quaternary blend fuel. Moreover, it is reported that NO_x emission decreased, while CO and smoke opacity increased [32]. The effects of jatropha methyl ester emulsion and CNT mixture on engine performance and emissions in a single-cylinder diesel engine are investigated by Basha and Anand [33]. It is concluded that the addition of CNT into the Jatropha methyl ester emulsion improved the BTE. It has also been reported that it provides serious reductions in soot and NO_x emissions. It is stated that the reduction in NO_x emission is due to the microburst and secondary atomization of CNT added to the fuel. Basha [30] made a study on diethyl ether (DEE) and CNT as additives to biodiesel emulsions in diesel engine. It has been reported that the addition of DEE and CNT to emulsion fuels exhibits better engine performance, combustion and emission values than pure diesel and pure biodiesel. It is also stated that the addition of DEE and CNT shortens the ignition delay time. In addition, it is determined that BTE increases while reducing smoke and NO_x emissions. Balaji and Cheralathan [34] investigated the effects of biodiesel/CNT mixture on performance and emissions in a direct injection diesel engine. It is reported that CO, HC, NO_x and soot emissions are reduced by adding 200 ppm CNT to biodiesel.

Some of the studies on the addition of MWCNT nanoparticle, which is also preferred in this study, to biodiesel in the literature are summarized in Table 1. This table is prepared to include fuel type, alcohol type, nanoparticle dosage, test conditions and engine characteristics. The performance, combustion and exhaust emission characteristics of the engine are expressed with symbols in the form of increase and decrease. Moreover, these characteristics are stated to be the average effect of added MWCNT compared to pure biodiesel or diesel. Accordingly, it is seen that the addition of MWCNT to the fuel generally improves the exhaust emissions. CO_2 and NO_x emissions are determined to be high in some studies depending on the characteristics of biodiesel, dosage amount and experimental conditions. It is observed that there are differences in engine performance and combustion characteristics. El-Seesy et al. reported that the addition of *n*-decanol to biodiesel reduced BTE, but this decrease is limited by the addition of MWCNT [35]. Alenezi et al. carried out experiments by adding MWCNT at three different doses (50, 100 and 150 ppm) to B10, B20, B30 and B40 biodiesel blend fuels. It is observed that the exhaust emissions were improved in all blended fuels. The highest in-cylinder pressure is obtained by adding 150 ppm MWCNT to B10 [1]. Another study is used biodiesel blends of canola and moringa oleifera by adding MWCNT (40 mg/L) to these blends. It is reported that MWCNT contributed to the evaporation of the fuel, and it is emphasized that the ignition delay time is shortened [36]. The effect of adding different types of nanoparticles to diesel, methanol, *n*-octanol and dimethyl ether mixture on diesel engine performance, exhaust emissions and combustion is investigated by El-Seesy et al. In general, it is observed that the addition of nanoparticles to diesel/alcohol blend fuels reduces the in-cylinder pressure and HRR [37]. In another study on MWCNT, honge oil methyl ester (biodiesel) is used in a DI diesel engine by adding MWCNT at different rates (25 ppm, 50 ppm). It is stated that BTE increase with the use of mixed fuel with MWCNT addition compared to the use of pure biodiesel. Moreover, overall improvement in exhaust emissions other than NO_x is reported [38]. Sakthivadivel et al. reported that the addition of MWCNT to 80% neem biodiesel and 20% jatropha biodiesel gives better results in CO, CO_2 and soot emissions compared to diesel fuel. It is stated that the presence of oxygen in neem biodiesel was effective in this improvement. It is emphasized that there is an increase in NO_x emissions due to the changing in-cylinder pressure and heat release with the effect of MWCNT [39].

When the literature studies summarized in Table 1 are examined, it is seen that there are a limited number of experimental studies on biodiesel, *n*-octanol and MWCNT triple blends. Moreover, DI diesel engine is used extensively in these studies. Today's diesel engines are produced with CRDI pilot injection system to reduce fuel consumption values and increase engine performance. Determining the effect of *n*-octanol/MWCNT addition in CRDI diesel engines, which can reach higher injection pressures than DI, stands out as the feature that distinguishes this study from others. Diesel, pure biodiesel, biodiesel-*n*-octanol and biodiesel/*n*-octanol/MWCNT mixtures are used as fuel in the CRDI engine. Engine performance, combustion and exhaust emission characteristics are determined and a comparison between fuels is presented. A detailed investigation of the effect of *n*-octanol and MWCNT nanoparticle addition on engine characteristics in the pure use of biodiesel, which can be an alternative to diesel, in a CRDI engine will be additional information to the limited studies in the literature.

2 Material and Methods

In this study, diesel, pure biodiesel, and blends fuels formed with *n*-octanol and MWCNT nanoparticle are used. Biodiesel supplied from DP Tarım Enerji Sanayi ve Ticaret A.Ş. in Turkey is produced by traditional method from waste frying oil. The *n*-octanol supplied from MERCK has a purity of 99%. Some physical and chemical properties of diesel, biodiesel and *n*-octanol are shown in Table 2.

The MWCNT, which is preferred as nanoparticle, was purchased from Nanography Nano Technology Inc., and its properties are given in Table 3. Because surfactants affect the pH of the nanofuel, they can improve the nanoparticle suspension [35]. Sodium dodecyl Sulfate (SDS) is provided

Table 1 Summary of literature studies on the addition of MWCNT nanoparticles to biodiesel

Reference fuels	Type of engine	Operating condition	Type of nanoparticle	Levels of dose	Findings of performance		Combustion analysis		Emissions		References
Biodiesel	Single cylinder, DI, water cooled	Constant speed, different loads	MWCNT	25, 50, 75, 100 ppm	BTE	▲	No significant change	~	HC	▼	[40]
					BSFC	▼			CO	▼	
									NO_x	▲	
Biodiesel	Single cylinder, DI	Constant speed, different loads	MWCNT, Al_2O_3	50, 100 ppm	BTE	▲	Cylinder pressure	▼	HC	▲	[41]
					BSFC	▲	HRR	▼	CO	▼	
									NO_x	▼	
Biodiesel	Single cylinder, DI, water cooled	Constant speed, different loads	MWCNT	50, 100, 150 ppm	BTE	▲	Cylinder pressure	▲	HC	▼	[42]
					BSFC	▼	HRR	▲	CO	▼	
									NO_x	▲	
Biodiesel	Single cylinder, DI, water cooled	Constant speed, different throttle position	MWCNT	50, 100, 150 ppm	–		No change cylinder presure	~	CO_2	▼	[1]
									NO_x	▼	
Biodiesel	Single cylinder, DI, air cooled	Constant speed, different loads	MWCNT	25 mg/L	–		Cylinder pressure	▲	CO	▼	[39]
							HRR	▲	CO_2	▼	
									NO_x	▼	
Diesel/Methanol/DEE/*n*-octanol	Diesel engine	Constant speed, different loads	MWCNT, Al_2O_3, TiO_2, GO	50 ppm	BTE	▲	Cylinder pressure	▼	HC	▼	[37]
					BSFC	▼	HRR	▼	CO	▼	
									NO_x	▼	
									smoke	▼	

Table 1 (continued)

Reference fuels	Type of engine	Operating condition	Type of nanoparticle	Levels of dose	Findings of performance	Combustion analysis	Emissions	References
Biodiesel/*n*-decanol	Single cylinder, DI, air cooled	Constant speed, different loads	N-MWCNT, NH_2-MWCNT	50, 75 ppm	BTE ▼ BSFC ▲	–	CO ▼ NO_x ▼ smoke ▼	[35]
Biodiesel	Single cylinder, DI, water cooled	Constant speed, different loads	MWCNT	125, 250, 375, 500 ppm	BTE ▲ EGT ▲ BSFC ▼	Cylinder pressure ▼	HC ▼ CO ▼ CO_2 ▲ NO_x ▲	[43]
Biodiesel/Blend	Twin-cylinder, 1670 cc, DI, water cooled,	Different speeds	MWCNT	40 mg/L	BTE ▲ BSFC ▲ Power ▲	–	CO ▼ NO_x ▼ smoke ▼	[36]
Biodiesel	Single cylinder, DI	Constant speed, different engine power	MWCNT	25, 50 ppm	BTE ▲	–	HC ▼ CO ▼ NO_x ▲ smoke ▼	[38]
Biodiesel/Biodiesel-*n*-octanol	Single cylinder, CRDI, pilot injection, water cooled	Constant speed, different loads	MWCNT	100 ppm	BTE ▼ EGT ▼ BSFC ▲	Cylinder pressure ▼ HRR ▼	HC ▼ NO ▼ CO_2 ▼	Current study

Table 2 Physical and chemical properties of diesel, biodiesel and *n*-octanol

Parameters	Diesel	Biodiesel	*n*-Octanol
Density (kg/m^3)	820–845	883.70	830
Cetane number	≥ 51	51.30	–
Lower heating value (MJ/kg)	42.612	39.54	39.55
Viscosity (mm^2/s at 40 °C)	2–4.5	4.367	5.6
Flash point (°C)	≥ 55	171	86
Cold filter plugging point (°C)	–	− 2	–
Sulfur (mg/kg)	–	6.20	–
Iodine value (g Iodine/100 g)	–	109	–
Water content (%)	0.02	0.020	–
Boiling point (°C)	160	–	195

Table 3 Properties of MWCNT

Parameters	
Linear formula	C
Purity (%)	> 92
Inside–outside diameter (nm)	5–10
Length (¯m)	1–3
Specific surface area (m^2/g)	290
Tab density (g/cm^3)	0.25
True density (g/cm^3)	2.4
Appearance	Black, solid

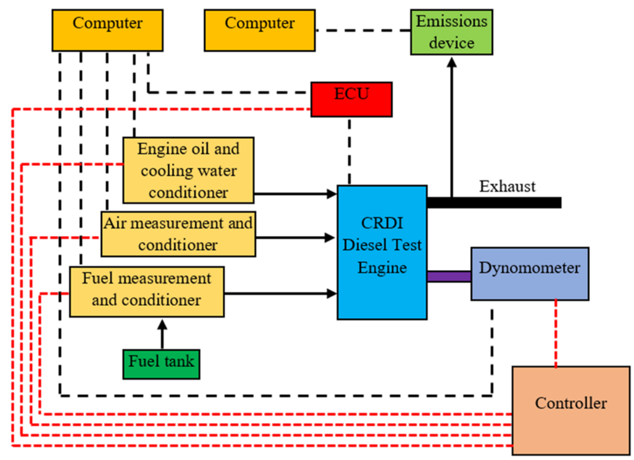

Fig. 1 Schematic view of the experimental setup

Table 4 Test equipment and accuracies

Measurement	Device	Accuracy
Torque	HBM Torque Flange	± 0.1%
Engine speed	AVL Encoder	≤ ± 0.1 CA
Test cell humidity	Vaisala-HMT 330	± 1%RH
Test cell temperature	Vaisala-HMT 330	± 0.2 °C
Injection timing	Angle encoder	± 0.1CA
In-cylinder pressure	AVL Xion	0.05CA
Engine coolant&oil conditioning	AVL-577	± 1 K
Fuel consumption	AVL-735	< 0.15%
Temperature sensors	PT100 (K Type)	< ± 1%

as surfactant for the stability of MWCNT in the fuel mixture. SDS is added to the blend fuels at 2% by volume for the suspension of MWCNT.

When the studies on MWCNT are examined, it is determined that 100 ppm dose generally give better results in engine performance and emissions. For example, Solmaz et al. [40] find the highest improvement in CO, HC and soot emissions with the addition of 100 ppm MWCNT. In another study [44], it is stated that the optimum amount of CNT in terms of engine performance, combustion and exhaust emissions is 100 ppm. For this reason, it is decided to add 100 ppm of MWCNT nanoparticle in the study. The amount of nanoparticle is measured with a four-digit precision scale.

In experimental studies, four different test fuels containing diesel (D100), pure biodiesel (B100), 95% biodiesel + 5% *n*-octanol (B95O5) by volume and 95% B100 + 5% *n*-octanol + 100 ppm MWCNT (B95O5100MWCNT) are used. To prevent aggregation of the nanoparticle in the fuel and to provide a homogeneous distribution, it is mixed with an ultrasonicator for 30 min.

The schematic view of the experimental setup is shown in Fig. 1. The test setup consists of a single-cylinder diesel engine, eddy current dynamometer, electronic control unit (ECU), air–fuel measurement units, engine oil and cooling water conditioners, emission device and controller.

Experiments are also carried out on a single-cylinder diesel engine with common rail direct injection (CRDI). The engine is water-cooled, and the oil and water temperature are kept constant by conditioning with an auxiliary system. The engine has a displacement of 1120 cc and a compression ratio of 16.4:1. The technical specifications of the test equipment are given in Table 4.

Exhaust emissions are measured with the Bosch BEA 460. Calibrations of the test device are made before the experimental study. The characteristics of the emission device are given in Table 5.

Table 5 Technical specifications of the exhaust emission measuring device

Parameters	Measuring range	Sensibility
HC	0–10000 ppm	1 ppm
O_2	0–22% vol	0.01% vol.
NO	0–5000 ppm	1 ppm
CO_2	0–18% vol	0.01% vol.

Before starting the tests, the engine oil, coolant and fuel temperatures are conditioned by the conditioning unit until they reached 90 °C, 70 °C and 20 °C, respectively. Then, the engine is run until it reached the regime temperature. In preliminary experiments with diesel fuel, it was determined that the engine reached the maximum torque at 1500 rpm. Experiments are carried out at 1500 rpm constant speed and four different loads (25%, 50%, 75% and 100%). Each test is repeated three times for the accuracy of the experimental data. In this study, the load represents the pedal position of the test engine. Full load means the pedal is in the full throttle position. The test system automatically adjusts fuel injection timing and pressure maps according to different load and speed conditions. For example, in this test engine, the fuel system operates according to 11.2° CA main injection and 17.5° CA pilot injection timing at 1500 rpm engine speed and 50% load. At the same time, the injection pressure is around 900 bar. With the load increasing to 75%, the injection pressure reaches 1300 bar. The engine performance, combustion and exhaust emission characteristics obtained from the experiments are determined with the use of test fuels. The error analysis of some test results at 75% load conditions is shown in Table 6.

3 Results and Discussion

In this section, the engine performance, combustion and exhaust emission changes obtained from the experiments performed on a CRDI engine at 1500 rpm at constant speed and four different loads with D100, B100, B95O5 and B95O5100MWCNT test fuels are discussed. Brake engine power, BSFC, BTE and EGT are examined as engine performance, while the changes in the in-cylinder pressure and heat release rate are discussed in the combustion analysis. Also, changes in NO, HC and CO_2 as exhaust emissions are presented.

3.1 Engine Performance

Engine performance characteristics of a CRDI diesel engine such as brake engine power, BSFC, BTE and EGT at different engine loads are evaluated comparatively. The variations in brake engine power obtained from test fuels at different loads are shown in Fig. 2. Here, the load represents the movement percentage of the fuel control lever in the diesel engine. In this context, the open times of the injectors for each load are approximately the same for all test fuels. This results in an almost equal volume of fuel delivered to the cylinder at every percentage of engine load for all test fuels. For this reason, fuel properties have been the main cause of changes in engine performance and exhaust emissions.

As seen in Fig. 2, it is realized that the brake engine power obtained in the B100, B95O5 and B95O5100MWCNT is decreased 14.3%, 20.16% and 16.05% compared to the D100, respectively.

While the maximum brake engine power is 16.3 kW at full load with D100 fuel, the lowest brake engine power value is 3.42 kW at 25% load with B95O5 fuel. It is observed that the brake power values obtained with D100 under all load conditions are higher than other fuels. This increase is caused by the higher energy content of diesel fuel than B100 and other mixed fuels. Surface tensions are also rising

Table 6 Some test result (at load of 75%) and error analysis

	D100	B100	B95O5	B95O5100MWCNT	Error analysis (%)
Thermal efficiency (%)	33.92	31.70	33.31	35.28	0.58
Effective engine power (kW)	11.43	9.84	9.81	9.71	0.97
Specific fuel consumption (g/kWh)	249.03	288.61	274.66	259.3	0.03
NO emission (ppm)	892	868	818	906	1.95
CO_2 emission (%)	5.25	5.17	5.17	5.37	0.19
HC emission (ppm)	18	18	19	18	2.69
Exhaust gas temperature (°C)	321.63	282.66	278.66	286.56	0.41
Max. cylinder gas pressure (bar)	168.6	156.44	159.36	158.09	0.03
Max. net HRR (J/deg)	98.78	88.98	92.38	91.84	1.24

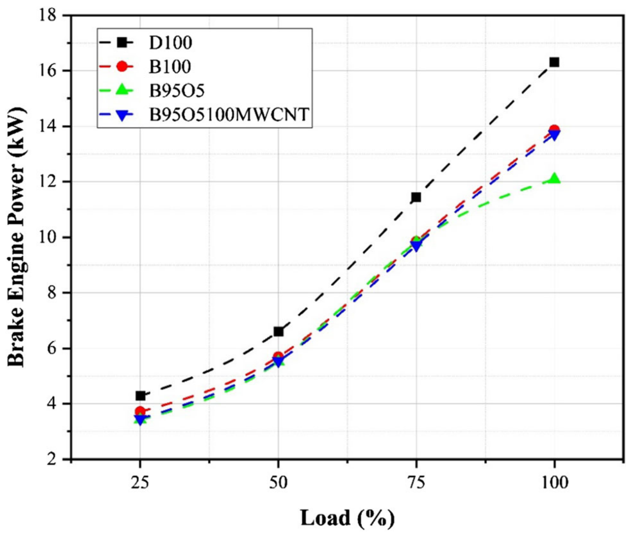

Fig. 2 The variation of brake engine power depending on load

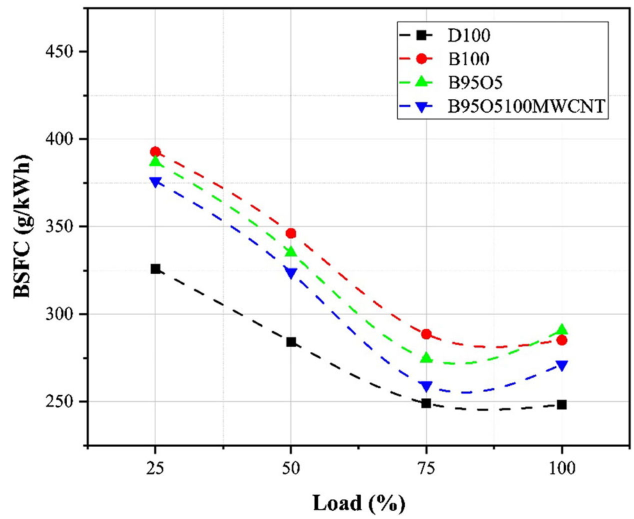

Fig. 3 The variation of brake-specific fuel consumption depending on load

due to the increasing density of fuels [45]. This situation adversely affects the atomization of the injected fuel. The injection pressure and timing of the test engine are optimized by the ECU depending on the different engine speed and load according to the maps adapted to the diesel fuel. The injection pressure optimized for diesel fuel is insufficient for fuels with different viscosities and densities. Therefore, the high densities and viscosities of biodiesel and blended fuels reduce the atomization quality of the fuel injected into the cylinder and thus the brake engine power reduced. These results obtained in brake engine power are similar to some studies in the literature [46, 47]. It is determined that the brake engine power obtained with D100 fuel at low loads is higher than the other fuels. However, as the engine load increases, the brake engine power obtained in the D100 rises more than other fuel types. It is thought that the higher heating value of D100 compared to other fuels causes this increase. It is seen that brake engine power decreases in B95O5 in full load condition. With the increase in load, more fuel is injected into the cylinder. The amount of alcohol injected into the cylinder at full load is higher than at low loads. It is thought that this decrease in brake engine power is due to the lower in-cylinder temperature due to the high latent heat of vaporization of alcohol fuels. Brake engine power obtained from B95O5100MWCNT is slightly higher than B95O5. When MWCNT nanoparticle is added to the fuel, its high thermal conductivity feature creates a positive effect on the evaporation of the fuel drops. This feature of MWCNTs improves the homogeneity of the air–fuel mixture, as well as shortens the ignition delay time. As a result of these effects, a partial improvement in brake engine power is found with the addition of MWCNT.

BSFC refers to the mass amount of fuel consumed per unit brake engine power. The variation of BSFC depending on the load is shown in Fig. 3. When the graph is examined, it is found that BSFC decreases for all test fuels with increasing load.

Combustion occurs at higher temperatures as the engine load increases. This allows for a more efficient combustion reaction. This situation, which causes less fuel consumption per unit brake engine power, contributes to the decrease in BSFC [48]. BSFC values obtained from B100, B95O5 and B95O5100MWCNT are found to increase by 18.54%, 16.54% and 11.10%, respectively, compared to D100. The main reason for this increase is that the heating value of B100, B95O5 and B95O5100MWCNT is lower than D100 due to their oxygen content. This factor led to the increase in BSFC. Also, the viscosity of biodiesel and *n*-octanol is higher compared to D100. Moreover, due to the high surface tension of these fuels, the droplet size of the fuel increases in atomization. These factors are effective in increasing BSFC [49]. This result is similar to many studies in the literature [50–52]. It is determined that the heating values of B100 and *n*-octanol are very close to each other. As seen in Fig. 3, B95O5 has a lower BSFC than B100. Since the addition of *n*-octanol to B100 fuel improves the physical and chemical properties of biodiesel, it accelerates the oxidation of the fuel. This situation is thought to be a factor that plays a role in the decrease in BSFC [53, 54]. BSFC decrease with the addition of 100 ppm MWCNT to B95O5 fuel. The greatest decrease in BSFC values is realized with the addition of MWCNT. Properties such as high contact surface area and good thermal conductivity of MWCNT nanoparticles accelerate the evaporation of the fuel. At the same time, its special tubular structure improves the ignition feature and combustion phenomenon of the blend

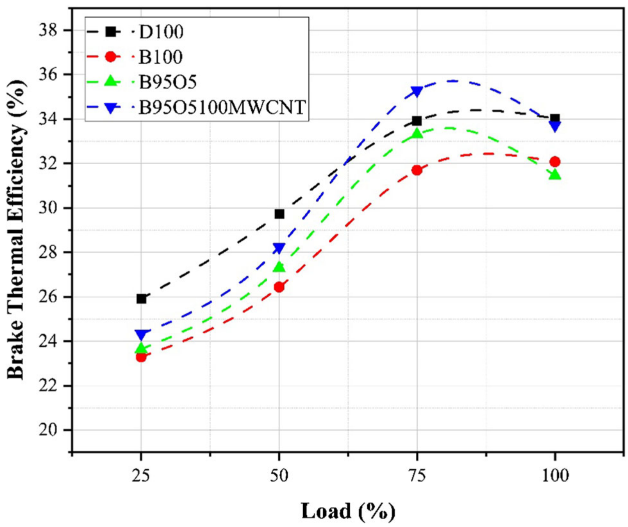

Fig. 4 The variation of brake thermal efficiency depending on load

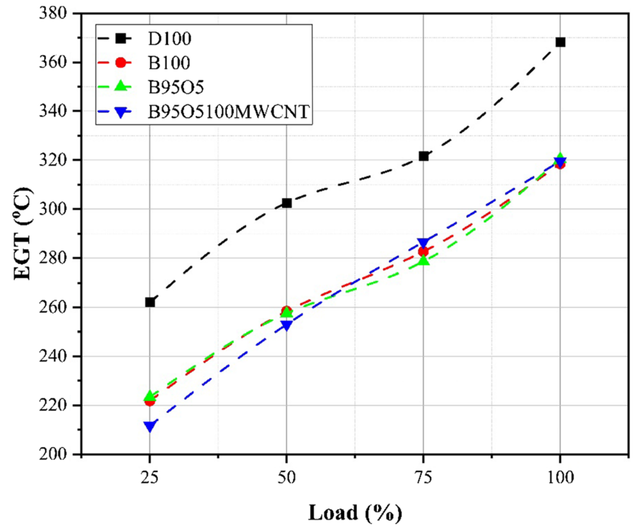

Fig. 5 The variation of exhaust gas temperature depending on load

fuel. When these factors are evaluated together with the oxygen content in the biodiesel/alcohol mixture, the combustion improves, and therefore the BSFC is reduced. These results obtained in terms of BSFC are compatible with other studies [19, 49, 55] using MWCNT nanoparticles in the literature.

The changes in BTE obtained by using different test fuels under different load conditions are presented in Fig. 4. BTE is expressed as an indicator of how much of the chemical energy of the fuel applied to the engine is converted into useful work [56, 57]. It is calculated by the ratio of the brake engine power of the engine to the fuel supplied to the engine. Therefore, the BTE is related to the brake engine power, the heating value of the fuel and the mass flow rate of the fuel. It is an important parameter in the comparison of engine performance in different types of test fuel [48, 58].

It is found that BTE from all test fuels increases with increasing engine load. BTE increases with decrease in BSFC. Also, the calorific value of the fuel/air mixture in the cylinder increases with the amount of fuel increasing depending on the load. In this case, it causes BTE to increase with increasing load [49, 59]. There is a decrease in BTE under full load conditions. The possible reason for this reduction may be the decrease in combustion efficiency and the increased BSFC. When Fig. 4 is examined, the BTE obtained from B100 and blend fuels is lower than that of D100. It is determined that the BTE obtained with the use of B95O5100MWCNT at high loads reaches 35.28%. In the tests, it is observed that the BTE is the lowest at 23.3%, and it is achieved with B100 fuel at 25% load. It is determined that the BTE values obtained with B100, B95O5 and B95O5100MWCNT decreases by 8.15%, 6.66% and 1.63%, respectively, compared to D100 fuel. The low energy content of the B100 fuel and it's high BSFC value may be the main reasons for the decrease in BTE [60]. Addition of *n*-octanol to biodiesel increases the evaporation ability of the blended fuel and shortens the ignition delay time. As a result, a high rate of combustion may occur in the combustion chamber. These properties of the alcohol mixture are thought to have a positive effect on BTE [53].

It is observed that the BSFC obtained by adding MWCNT to the blend fuel is reduced compared to B100 and B95O5 as seen in Fig. 3. The high thermal conductivity of MWCNT contributes to the evaporation of the fuel. With the combined effect of MWCNT and *n*-octanol, high combustion efficiency is achieved by rapid evaporation of the fuel. These factors cause an increase in BTE. Moreover, due to the structural feature of MWCNT, the flame front in the combustion chamber can spread into narrow spaces. This contributes to the acceleration of the flame spread and the improvement of the burning time. These effects of nanoparticles are similar to the literature [19, 55].

EGT is an important parameter as it is an indicator of the in-cylinder temperature that occurs at the end of combustion [61]. Figure 5 shows the EGT depending on the engine load. EGT increase in all test fuel studies with increasing load. The EGT rises because more fuel is injected into the cylinder with the increase in engine load. Another reason for this increase in EGT may be due to the decrease in the cooling effect of the air with the decrease in the air/fuel ratio [62].

The highest EGT is obtained with D100 fuel as 368.11 °C at full load. The lowest EGT is obtained in B95O5100MWCNT fuel at 25% load and reached 211.69 °C. Compared to D100, the mean reduction in EGT measured in B100, B95O5 and B95O5100MWCNT is around 13.78%, 13.89% and 14.63%, respectively. The oxygen content of biodiesel and *n*-octanol rise the air/fuel ratio. In addition, it is known that the lower calorific value of these fuels. Moreover, the high cetane number of biodiesels shortens the ignition

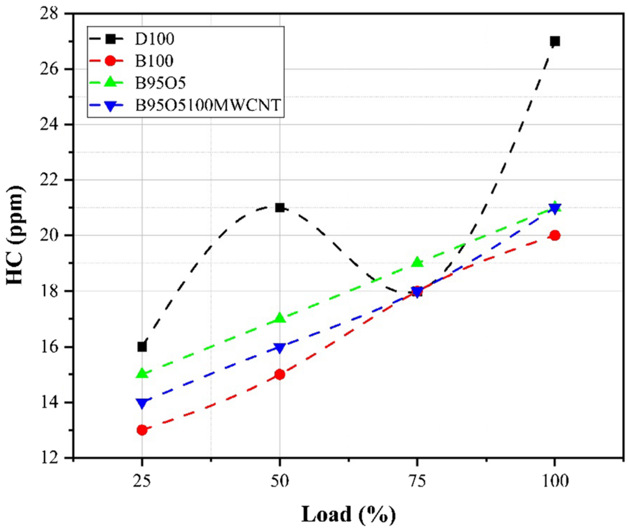

Fig. 6 The variation of HC emission depending on load

delay time. At the same time, the pre-combustion process is carried out with pilot injection, so the shorter duration of the combustion process in the expansion time. This may be another reason for the decrease in EGT. The obtained findings are similar to other studies [44, 63, 64]. The addition of *n*-octanol to the biodiesel fuel does not significantly change the heating value of the blended fuel. However, since the high latent heat of evaporation of *n*-octanol creates a cooling effect in the cylinder. Therefore, the EGT is slightly reduced compared to B100. EGT reduce with addition of nanoparticles to the blend fuel at low loads. Since MWCNT improves the homogeneity of its mixture, it contributes to the participation of all the fuel injected into the combustion process. In addition, another factor reducing EGT might be the reduction of rich mixture regions in the diffusion combustion phase [18].

3.2 Exhaust Emissions

The factor causing the formation of HC emissions is the phenomenon of incomplete combustion of the fuel [65]. Injection strategies of fuels into the cylinder, fuel/air ratio, cylinder wall temperature, the abundance of in-cylinder spaces, physical and chemical properties of the fuel are the parameters that affect HC emissions [54]. In Fig. 6, the variation of HC emission depending on the load at constant engine speed is given.

In the graph, it is seen that HC emissions rises in D100, B100, B95O5 and B95O5100MWCNT with the increase in engine load, in general. The increase in the amount of fuel injected into the cylinder with load increases the fuel/air ratio. In addition, the accumulation of liquid fuel in the cylinder walls and slit areas may be another reason that contributes to some HC increase compared to D100 [51, 53]. While the highest HC at full load is 16 ppm with D100 fuel, it is seen that the lowest HC emission is 13 ppm at 25% load, and this is achieved with B100 fuel. The average reductions in HC emission from B100, B95O5 and B95O5100MWCNT are calculated to be 19.51%, 12.2% and 15.55%, respectively, compared to D100. This reduction in HC emissions may be due to a better combustion formation with the effect of oxygen content of biodiesel and *n*-octanol fuels [66]. In addition, in the test engine, which has pilot injection in the fuel system, the fuel injected with the main injection evaporates faster thanks to the heat created by the pre-burning. Therefore, excessive delivery of fuel to the cylinders is limited during the main injection process. This situation reduces the formation of unburned HC emissions that may be caused by excess fuel. Since the high cetane number of biodiesel fuels shortens the ignition delay time, the time allocated to the combustion process increases. This may be another reason for the decrease in HC emissions [67]. An increase in HC emissions is observed with the addition of *n*-octanol to the biodiesel fuel. This increase in HC emissions may be due to the cooling effect in the cylinder due to the high latent heat of vaporization of the *n*-octanol fuel. The HC emission obtained with 100 ppm MWCNT additive test fuel decrease slightly compared to the pure mixed fuel. The combustion efficiency of the fuels is high due to the high injection pressure of CRDI engines which is the pilot and main injection strategy and the ignition timing depending on the load by the ECU. Therefore, with the addition of MWCNT, a small reduction in HC emission is achieved. The high surface area-to-volume ratio of MWCNTs promotes the air–fuel mixture and improves the ignition characteristics of the fuel [18, 49]. At the same time, the catalytic effects of MWCNT are high [51, 55]. The combined effect of these properties of nanoparticles may be the reason for the reduction in HC emissions.

Most of the NO_x emissions in diesel engines are NO [49]. The main factors determining NO formation are in-cylinder temperatures, oxygen concentration in the combustion chamber and the duration of the combustion process [18, 68, 69]. Among these factors, the Zeldovich Mechanism, in which chemical reactions based on high temperature occur, has a dominant role [49]. In Fig. 7, the changes in NO emission obtained by using different test fuels at different load conditions are presented.

When the graph is examined, it is seen that NO emission increased in all test fuels with increasing engine load. The main reason for this is the high temperatures that occur when more fuel is injected into the cylinder with the increased load [70]. While the lowest NO emission is obtained with B95O5 as 379.05 ppm at 25% load, the highest NO emission is found as 1444.45 ppm with D100 fuel at full load. The average reduction in NO emissions with the use of B100, B95O5 and B95O5100MWCNT' is 12.6%, 18.03% and 11.32%, respectively, when compared to D100 fuel. The low calorific value of B100 reduces in-cylinder temperatures, and therefore NO

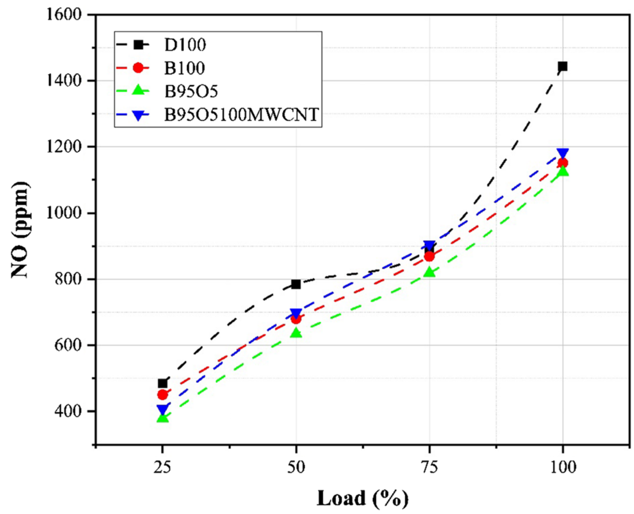

Fig. 7 The variation of NO_x emission depending on load

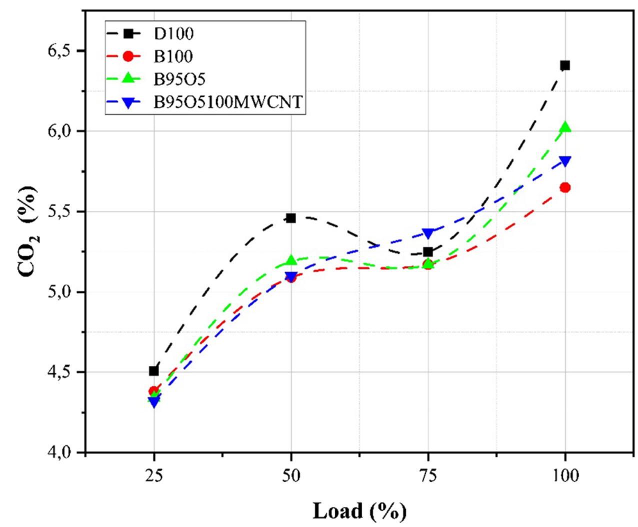

Fig. 8 The variation of CO_2 emission depending on load

emission is lower than D100. It is determined that the lowest NO emissions are obtained with B95O5, since the high latent heat of vaporization of *n*-octanol fuel creates a cooling effect in the cylinder. Studies have shown that alcohol fuels cause a decrease in NO_x emissions due to the high latent heat of vaporization [32, 71, 72]. The addition of 100 ppm MWCNT to the B95O5 fuel mixture caused a slight increase in NO emissions. MWCNTs increase HC oxidation because they play a supporting role in the air–fuel mixture and improve the combustion process. The increase in HC oxidation means that more fuel is involved in the combustion process. Combustion of more fuel increases the in-cylinder temperatures, and therefore the exhaust gas temperatures rise. As a result, it is thought that B95O5100MWCNT contributes to higher NO emission production compared to B100 and B95O5.

CO_2 and water (H_2O) are compounds formed in an ideal complete combustion reaction. Therefore, an increase in CO_2 emission is an indication that the fuel is close to complete combustion. Changes in CO_2 emissions obtained from test fuels used at different loads are shown in Fig. 8.

It is seen that CO_2 emissions increase with increasing load in all test fuels. While the highest CO_2 emission is 6.41% at full load with D100, the lowest CO_2 value is determined as 4.32% at 25% load with B95O5100MWCNT. Biodiesel and *n*-octanol have lower heating value than D100. Therefore, it produce less brake engine power than D100 at the same load values. As a result, B100, B95O5 and B95O5100MWCNT have lower CO_2 emissions than D100.

As seen in Fig. 8, the amount of CO_2 occurring in B100, B95O5 and B95O5100MWCNT is lower than D100. Compared to the D100, the reductions obtained with the B100, B95O5 and B95O5100MWCNT are around 6.2%, 4.21% and 4.72%, respectively. This reduction in CO_2 emissions can be attributed to the lower C/H ratios of biodiesel and *n*-octanol [65, 67]. It is determined that the average CO_2 occurring in the B95O5 is higher than the B100. This may be due to the higher oxygen content of alcohol fuels [53]. The CO_2 concentration of the MWCNT blended fuel increased compared to the B95O5. It is thought that the catalytic effect of MWCNTs cause more HC oxidation, resulting in an increase in CO_2 emissions [64].

3.3 Combustion Analysis

Figure 9 shows in-cylinder pressure and the heat release rate (HRR). In-cylinder pressure generally increased due to more fuel being sent to the cylinder per unit time at full load. When the graph is examined, it is seen that the pressure value obtained from D100 is higher than other test fuels. When the maximum in-cylinder pressure values at full load are examined, it is determined that they are 220.04 bar, 212.35 bar, 215.39 bar and 214.59 bar for D100, B100, B95O5 and B95O5100MWCNT, respectively. The positions of the maximum in-cylinder pressures are 8° crank angles (CA) for the D100, B100 and B95O5 and 7° CA for the B95O5100MWCNT. The engine provides the lowest specific fuel consumption in the position where the maximum in-cylinder pressure is 6–10° CA [73]. In this experimental study, all fuels exhibited a maximum in-cylinder pressure between 6° and 10° CA.

The injection strategy of the CRDI engine according to the D100 has been adapted to provide the highest maximum in-cylinder pressure. The B100 has the lowest maximum in-cylinder pressure compared to other test fuels. The factors that reduce the in-cylinder pressure are B100's low calorific value and high density. B95O5 exhibited slightly higher cylinder gas pressure than B95O5100MWCNT. However, the maximum in-cylinder pressure of MWCNT added fuel was higher than that of pure biodiesel, and the peak point approached the top dead point by 1 degree. Maximum

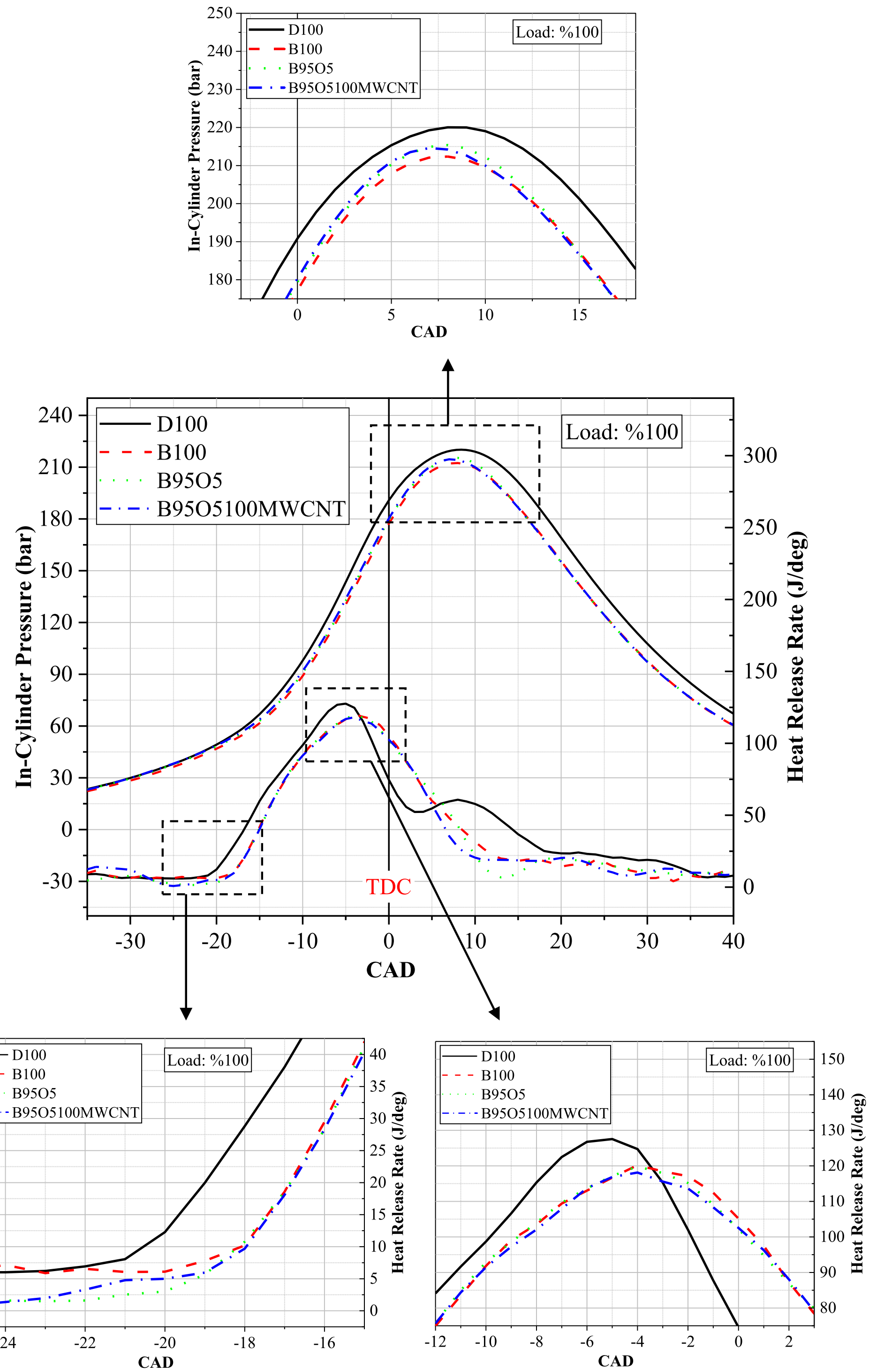

Fig. 9 The variation of in-cylinder pressure and heat release rate at 100% load

in-cylinder pressure close to TDC indicates improved atomization and air–fuel mixing. The properties of MWCNT such as improving its physical properties, catalytic effects and heat transfer properties may cause this improvement in in-cylinder pressure. This feature supports the participation of all the fuel in the cylinder in the combustion process. The calorific value of B95O5 is slightly higher than B100. Therefore, higher in-cylinder pressure is achieved at full load compared to pure biodiesel.

When the HRR curves are examined in Fig. 9, it is seen that the maximum value is reached with D100 fuel as 127.54 J/deg. The low viscosity and density of D100 helps the fuel to atomize and vaporize well, so the ignition delay

Table 7 Data of maximum in-cylinder pressure and HRR obtained from test fuels at different loads

Test fuels	Load (%)	Max. CP (bar)	Max.CP_{CAD} (CAD)	Max. HRR (J/deg)	Max.HRR_{CAD} (CAD)
D100	25	88.07	8	57.41	− 5
	50	110.31	7	78.8	− 5
	75	168.61	7	98.78	− 2
	100	220.04	8	127.54	− 5
B100	25	87.09	7	64.69	− 4
	50	105.83	7	75.93	− 5
	75	156.44	8	88.98	− 2
	100	212.36	8	120.19	− 4
B95O5	25	86.61	7	66.01	− 4
	50	106.22	6	88.64	− 4
	75	159.36	7	92.38	− 2
	100	215.39	8	119.82	− 4
B95O5100MWCNT	25	86.65	7	72.22	− 4
	50	104.99	7	75.72	− 5
	75	158.09	7	91.85	− 2
	100	214.59	7	118.11	− 4

time is shorter compared to other test fuels. The closeness of the fuel properties (viscosity, density, etc.) of B100, B95O5 and B95O5100MWCNT caused the ignition delay time to be very close to each other [18]. It is thought that optimizing the injection strategies of the CRDI engine according to the D100 fuel properties provides a more efficient combustion than other test fuels. When the maximum HRR is examined, it is calculated as 127.54 J/deg for D100, 120.19 J/deg for B100, 119.82 j/deg for B95O5 and 118.11 J/deg for B95O5100MWCNT. The locations with maximum heat dissipation are − 5° CA for D100 and − 4° CA for B100, B95O5 and B95O5100MWCNT. The highest heat release rate is obtained with D100, while the lowest is determined with B95O5100MWCNT. D100's properties such as high calorific value, low viscosity and density are thought to provide the highest HRR. The relatively high viscosity value of other test fuels may impair fuel atomization compared to D100. The high viscosity and density of B100, B95O5 and B95O5100MWCNT can result in an extended ignition delay time [74]. This may cause the maximum HRR from other test fuels to be lower than the D100. It is determined that MWCNT does not provide an improvement in the rate of heat release under these operating conditions. The values of the maximum in-cylinder pressure and HRR obtained from the test fuels at different loads, and the values of the crank angle corresponding to these values are given in Table 7.

When Table 7 is examined, it is seen that the in-cylinder pressure and HRR obtained from D100 are higher than other fuel types at all loads. It is thought that this situation is caused by the fact that the tests are carried out with a system adapted for diesel. The system automatically adjusts the ideal injection pressure and timing to provide the best performance. Because the system automatically adjusts the ideal spray pressure and advance to provide the best performance. However, since the strategy of the ECU is not changed in other fuel types, it is considered that the differences in fuel properties have a limited effect. When the test fuels containing biodiesel are examined, it is seen that the in-cylinder pressure obtained from the test fuel containing *n*-octanol (B95O5) is generally higher than the other fuels. The addition of MWCNT nanoparticles (B95O5100MWCNT) improved in-cylinder pressure compared to B100 at 75% and 100% loads. At the same time, it is observed that the HRR obtained with B95O5100MWCNT at 25% load reaches the highest value compared to other fuels. When evaluated in general, it is determined that the addition of *n*-octanol and MWCNT to biodiesel causes a partial improvement on the combustion characteristics.

4 Conclusions

In this study, D100, B100, B95O5 and B95O5100MWCNT are used as test fuels. Engine performance, combustion and exhaust emissions characteristics are investigated in a CRDI engine at a constant speed of 1500 rpm under different load conditions. The results of the study are summarized below.

- Due to the low heating values of B100, B95O5 and B95O5100MWCNT fuels, the brake engine power is lower than D100. However, there is an improvement in brake engine power from the test fuel with the addition of MWCNT nanoparticle compared to B95O5.

- BSFC improves overall at all loads with the addition of *n*-octanol and MWCNT to biodiesel.
- Test fuel with MWCNT nanoparticles reached the highest BTE value at 75% load. Also, BTE increase with the addition of *n*-octanol and MWCNT nanoparticles to pure biodiesel (B100).
- The EGT values obtained in B100, B95O5 and B95O5100MWCNT fuels at all loads are lower than D100. Addition of *n*-octanol and MWCNT does not significantly differ in terms of EGT.
- Exhaust emissions from biodiesel and blended fuels are generally lower than diesel at all loads. The addition of *n*-octanol to biodiesel increases HC and CO_2 emissions with its cooling effect, while NO emission decreases. However, with the addition of MWCNT nanoparticles, NO and CO_2 increase in general, while it creates a reducing effect on HC.
- The peak values of in-cylinder pressure and HRR obtained from B100, B95O5 and B95O5100MWCNT are lower than D100. However, the crank angle values of these peaks approach the top dead center. Maximum in-cylinder pressure and HRR values improve with the addition of *n*-octanol and MWCNT to B100.

According to the results, in general, the engine performance, combustion and exhaust emission characteristics of CRDI diesel engines can be improved by adding both *n*-octanol and *n*-octanol/MWVCNT to pure biodiesel, which can be used as an alternative fuel. These mixture fuels can be used in engines without any modification. More research is needed on the atomization and combustion behavior of fuels with MWCNT additives by applying different injection strategies (such as injection pressure and advance) in experimental engines with pilot injection systems. Similar studies should be carried out with today's engines that have systems such as EGR, supercharger and catalytic converter. At the same time, the long-term effects of the addition of nanoparticles in the fuel on engine parts should be investigated.

References

1. Alenezi, R.A.; Norkhizan, A.M.; Mamat, R.; Erdiwansyah; Najafi, G.; Mazlan, M.: Investigating the contribution of carbon nanotubes and diesel–biodiesel blends to emission and combustion characteristics of diesel engine. Fuel (2021). https://doi.org/10.1016/j.fuel.2020.119046
2. Nanthagopal, K.; Ashok, B.; Tamilarasu, A.; Johny, A.; Mohan, A.: Influence on the effect of zinc oxide and titanium dioxide nanoparticles as an additive with Calophyllum inophyllum methyl ester in a CI engine. Energy Convers. Manag. (2017). https://doi.org/10.1016/j.enconman.2017.05.021
3. Mirbagheri, S.A.; Safieddin Ardebili, S.M.; Kiani Deh Kiani, M.: Modeling of the engine performance and exhaust emissions characteristics of a single-cylinder diesel using nano-biochar added into ethanol–biodiesel–diesel blends. Fuel (2020). https://doi.org/10.1016/j.fuel.2020.118238
4. Mujtaba, M.A.; Kalam, M.A.; Masjuki, H.H.; Gul, M.; Soudagar, M.E.M.; Ong, H.C., et al.: Comparative study of nanoparticles and alcoholic fuel additives–biodiesel–diesel blend for performance and emission improvements. Fuel **279**, 118434 (2020). https://doi.org/10.1016/j.fuel.2020.118434
5. Ettefaghi, E.; Ghobadian, B.; Rashidi, A.; Najafi, G.; Khoshtaghaza, M.H.; Rashtchi, M., et al.: A novel bio-nano emulsion fuel based on biodegradable nanoparticles to improve diesel engines performance and reduce exhaust emissions. Renew. Energy **125**, 64–72 (2018). https://doi.org/10.1016/j.renene.2018.01.086
6. Attia, A.M.A.; Kulchitskiy, A.R.; Nour, M.; El-Seesy, A.I.; Nada, S.A.: The influence of castor biodiesel blending ratio on engine performance including the determined diesel particulate matters composition. Energy **239**, 121951 (2022). https://doi.org/10.1016/j.energy.2021.121951
7. Vellaiyan, S.; Amirthagadeswaran, K.S.: Zinc oxide incorporated water-in-diesel emulsion fuel: formulation, particle size measurement, and emission characteristics assessment. Pet. Sci. Technol. **34**, 114–122 (2016). https://doi.org/10.1080/10916466.2015.1122621
8. Singh, N.; Kaushal, R.: Outcomes of advanced biodiesel with nanoparticle additives on performance of CI engines. Mater. Today Proc. (2020). https://doi.org/10.1016/j.matpr.2020.10.913
9. Deepak Kumar, T.; Hussain, S.S.; Ramesha, D.K.: Effect of a zinc oxide nanoparticle fuel additive on the performance and emission characteristics of a CI engine fuelled with cotton seed biodiesel blends. Mater. Today Proc. (2019). https://doi.org/10.1016/j.matpr.2020.02.509
10. Nagaraja, S.; Rufuss, D.D.W.; Hossain, A.K.: Microscopic characteristics of biodiesel—graphene oxide nanoparticle blends and their Utilisation in a compression ignition engine. Renew. Energy **160**, 830–841 (2020). https://doi.org/10.1016/j.renene.2020.07.032
11. Alptekin, E.; Sanli, H.; Canakci, M.: Combustion and performance evaluation of a common rail DI diesel engine fueled with ethyl and methyl esters. Appl. Therm. Eng. (2019). https://doi.org/10.1016/j.applthermaleng.2018.12.042
12. Yaşar, F.: Comparison of fuel properties of biodiesel fuels produced from different oils to determine the most suitable feedstock type. Fuel **264**, 116817 (2020). https://doi.org/10.1016/j.fuel.2019.116817
13. Jahirul, M.I.; Rasul, M.G.; Brown, R.J.; Senadeera, W.; Hosen, M.A.; Haque, R., et al.: Investigation of correlation between chemical composition and properties of biodiesel using principal component analysis (PCA) and artificial neural network (ANN). Renew. Energy (2021). https://doi.org/10.1016/j.renene.2020.12.078
14. Su, B.; Wang, L.; Xue, Y.; Yan, J.; Dong, Z.; Lin, H., et al.: Effect of pour point depressants combined with dispersants on the cold flow properties of biodiesel–diesel blends. J. Am. Oil Chem. Soc. (2021). https://doi.org/10.1002/aocs.12456
15. Gad, M.S.; El-Seesy, A.I.; Radwan, A.; He, Z.: Enhancing the combustion and emission parameters of a diesel engine fueled by waste cooking oil biodiesel and gasoline additives. Fuel **269**, 117466 (2020). https://doi.org/10.1016/j.fuel.2020.117466
16. El-Seesy, A.I.; He, Z.; Kosaka, H.: Combustion and emission characteristics of a common rail diesel engine run with *n*-heptanol-methyl oleate mixtures. Energy (2021). https://doi.org/10.1016/j.energy.2020.118972
17. El-Seesy, A.I.; Xuan, T.; He, Z.; Hassan, H.: Enhancement the combustion aspects of a CI engine working with Jatropha biodiesel/decanol/propanol ternary combinations. Energy Convers. Manag. (2020). https://doi.org/10.1016/j.enconman.2020.113524
18. El-Seesy, A.I.; Hassan, H.: Investigation of the effect of adding graphene oxide, graphene nanoplatelet, and multiwalled carbon

nanotube additives with n-butanol-Jatropha methyl ester on a diesel engine performance. Renew. Energy (2019). https://doi.org/10.1016/j.renene.2018.08.026
19. Mei, D.; Zuo, L.; Adu-Mensah, D.; Li, X.; Yuan, Y.: Combustion characteristics and emissions of a common rail diesel engine using nanoparticle-diesel blends with carbon nanotube and molybdenum trioxide. Appl. Therm. Eng. (2019). https://doi.org/10.1016/j.applthermaleng.2019.114238
20. Ashok, B.; Nanthagopal, K.; Anand, V.; Aravind, K.M.; Jeevanantham, A.K.; Balusamy, S.: Effects of n-octanol as a fuel blend with biodiesel on diesel engine characteristics. Fuel (2019). https://doi.org/10.1016/j.fuel.2018.07.126
21. Xuan, T.; Sun, Z.; El-Seesy, A.I.; Mi, Y.; Zhong, W.; He, Z., et al.: An optical study on spray and combustion characteristics of ternary hydrogenated catalytic biodiesel/methanol/n-octanol blends; part II: liquid length and in-flame soot. Energy (2021). https://doi.org/10.1016/j.energy.2021.120543
22. Li, J.; Liang, Y.; Wang, S.; Wu, S.; Yang, W.; Liu, R.: Blending n-octanol with biodiesel for more efficient and cleaner combustion in diesel engines: a modeling study. J. Clean. Prod. (2023). https://doi.org/10.1016/j.jclepro.2023.136877
23. Manigandan, S.; Sarweswaran, R.; Booma Devi, P.; Sohret, Y.; Kondratiev, A.; Venkatesh, S., et al.: Comparative study of nanoadditives TiO_2, CNT, Al_2O_3, CuO and CeO_2 on reduction of diesel engine emission operating on hydrogen fuel blends. Fuel (2020). https://doi.org/10.1016/j.fuel.2019.116336
24. Hasannuddin, A.K.; Yahya, W.J.; Sarah, S.; Ithnin, A.M.; Syahrullail, S.; Sidik, N.A.C., et al.: Nano-additives incorporated water in diesel emulsion fuel: fuel properties, performance and emission characteristics assessment. Energy Convers. Manag. (2018). https://doi.org/10.1016/j.enconman.2018.05.070
25. Alenezi, R.A.; Norkhizan, A.M.; Rani, H.A.; Maulana, M.I.; Yasar, M.: An Experimental investigation of a diesel engine using carbon nanotubes blended with biodiesel. IOP Conf. Ser. Mater. Sci. Eng. (2019). https://doi.org/10.1088/1757-899X/506/1/012048
26. Shaafi, T.; Sairam, K.; Gopinath, A.; Kumaresan, G.; Velraj, R.: Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blends—a review. Renew. Sustain. Energy Rev. (2015). https://doi.org/10.1016/j.rser.2015.04.086
27. Thostenson, E.T.; Ren, Z.; Chou, T.W.: Advances in the science and technology of carbon nanotubes and their composites: a review. Compos. Sci. Technol. (2001). https://doi.org/10.1016/S0266-3538(01)00094-X
28. El-Seesy, A.I.; Abdel-Rahman, A.K.; Bady, M.; Ookawara, S.: The influence of multi-walled carbon nanotubes additives into non-edible biodiesel–diesel fuel blend on diesel engine performance and emissions. Energy Procedia (2016). https://doi.org/10.1016/j.egypro.2016.10.160
29. El-Seesy, A.I.; Abdel-Rahman, A.K.; Bady, M.; Ookawara, S.: Performance, combustion, and emission characteristics of a diesel engine fueled by biodiesel–diesel mixtures with multi-walled carbon nanotubes additives. Energy Convers. Manag. (2017). https://doi.org/10.1016/j.enconman.2016.12.090
30. Basha, J.S.: Impact of carbon nanotubes and di-ethyl ether as additives with biodiesel emulsion fuels in a diesel engine—an experimental investigation. J. Energy Inst. **91**, 289 (2016). https://doi.org/10.1016/j.joei.2016.11.006
31. El-Seesy, A.I.; Nour, M.; Hassan, H.; Elfasakhany, A.; He, Z.; Mujtaba, M.A.: Diesel-oxygenated fuels ternary blends with nano additives in compression ignition engine: a step towards cleaner combustion and green environment. Case Stud. Therm. Eng. (2021). https://doi.org/10.1016/j.csite.2021.100911
32. El-Seesy, A.I.; Waly, M.S.; He, Z.; El-Batsh, H.M.; Nasser, A.; El-Zoheiry, R.M.: Influence of quaternary combinations of biodiesel/methanol/n-octanol/diethyl ether from waste cooking oil on combustion, emission, and stability aspects of a diesel engine. Energy Convers. Manag. (2021). https://doi.org/10.1016/j.enconman.2021.114268
33. Basha, J.S.; Anand, R.B.: The influence of nano additive blended biodiesel fuels on the working characteristics of a diesel engine. J. Braz. Soc. Mech. Sci. Eng. (2013). https://doi.org/10.1007/s40430-013-0023-0
34. Balaji, G.; Cheralathan, M.: Effect of CNT as additive with biodiesel on the performance and emission characteristics of a DI diesel engine. Int. J. Chemtech. Res. **7**, 1230 (2014)
35. El-Seesy, A.I.; Waly, M.S.; El-Batsh, H.M.; El-Zoheiry, R.M.: Enhancement of the waste cooking oil biodiesel usability in the diesel engine by using n-decanol, nitrogen-doped, and amino-functionalized multi-walled carbon nanotube. Energy Convers. Manag. (2023). https://doi.org/10.1016/j.enconman.2022.116646
36. Manigandan, S.; Gunasekar, P.; Praveenkumar, T.R.; Sabir, J.S.M.; Mathimani, T.; Pugazhendhi, A., et al.: Performance, noise and emission characteristics of DI engine using canola and Moringa oleifera biodiesel blends using soluble multiwalled carbon nanotubes. Fuel (2021). https://doi.org/10.1016/j.fuel.2020.119829
37. El-Seesy, A.I.; Waly, M.S.; He, Z.; El-Batsh, H.M.; Nasser, A.; El-Zoheiry, R.M.: Enhancement of the combustion and stability aspects of diesel-methanol-hydrous methanol blends utilizing n-octanol, diethyl ether, and nanoparticle additives. J. Clean. Prod. (2022). https://doi.org/10.1016/j.jclepro.2022.133673
38. Tewari, P.; Doijode, E.; Banapurmath, N.R.; Yaliwal, V.S.: Experimental investigations on a diesel engine fuelled with multiwalled carbon nanotubes blended biodiesel fuels. Int. J. Emerg. Technol. Adv. Eng. **3**, 72 (2013)
39. Sakthivadivel, D.; Ganesh Kumar, P.; Stephen, S.; Vigneswaran, V.S.; Iniyan, S.: Experimental investigation of doped MWCNTs on biodiesel for enhancement of the performance and exhaust emissions in a diesel engine. Fullerenes Nanotubes Carbon Nanostruct. (2019). https://doi.org/10.1080/1536383X.2019.1574761
40. Solmaz, H.; Calam, A.; Yılmaz, E.; Şahin, F.; Ardebili, S.M.S.; Aksoy, F.: Evaluation of MWCNT as fuel additive to diesel–biodiesel blend in a direct injection diesel engine. Biofuels (2023). https://doi.org/10.1080/17597269.2022.2122154
41. Sathish, T.; Muthukumar, K.; Abdulwahab, A.K.; Rajasimman, M.; Saravanan, R.; Balasankar, K.: Enhanced waste cooking oil biodiesel with Al_2O_3 and MWCNT for CI engines. Fuel (2023). https://doi.org/10.1016/j.fuel.2022.126429
42. Venkatesan, H.; Kumar, V.U.; Sivamani, S.; Premkumar, T.M.: Evaluation of combustion, performance and emission characteristics of a diesel engine fuelled with diesel – Jojoba biodiesel – n butanol with multi-walled carbon nanotubes as fuel additive. Int. J. Ambient Energy (2023). https://doi.org/10.1080/01430750.2023.2188256
43. Sunil, S.; Chandra Prasad, B.S.; Kotresh, M.; Kakkeri, S.: Studies on suitability of multiwalled CNT as catalyst in combustion on a CI engine fueled with dairy waste biodiesel blends. Mater. Today Proc. (2019). https://doi.org/10.1016/j.matpr.2019.12.179
44. Gad, M.S.; Jayaraj, S.: A comparative study on the effect of nano-additives on the performance and emissions of a diesel engine run on Jatropha biodiesel. Fuel (2020). https://doi.org/10.1016/j.fuel.2020.117168
45. Esteban, B.; Riba, J.R.; Baquero, G.; Puig, R.; Rius, A.: Characterization of the surface tension of vegetable oils to be used as fuel in diesel engines. Fuel (2012). https://doi.org/10.1016/j.fuel.2012.07.042
46. Örs, I.; Sarıkoç, S.; Atabani, A.E.; Ünalan, S.; Akansu, S.O.: The effects on performance, combustion and emission characteristics of DICI engine fuelled with TiO_2 nanoparticles addition in diesel/biodiesel/n-butanol blends. Fuel (2018). https://doi.org/10.1016/j.fuel.2018.07.024

47. Yogaraj, D.; Ragothaman, G.; Devaraj, A.; Udhayakumar, K.: Performance and emission characteristics evaluation of CRDI engine using alternate fuel. Mater. Today Proc. (2020). https://doi.org/10.1016/j.matpr.2020.07.468
48. Yasar, F.; Altun, S.: The effect of microalgae biodiesel on combustion, performance, and emission characteristics of a Diesel Power Generator. Therm. Sci. (2018). https://doi.org/10.2298/tsci180403156y
49. Tomar, M.; Kumar, N.: Effect of multi-walled carbon nanotubes and alumina nano-additives in a light duty diesel engine fuelled with schleichera oleosa biodiesel blends. Sustain. Energy Technol. Assess. (2020). https://doi.org/10.1016/j.seta.2020.100833
50. Seraç, M.R.; Aydın, S.; Sayın, C.: Comprehensive evaluation of performance, combustion, and emissions of soybean biodiesel blends and diesel fuel in a power generator diesel engine. Energy Sources Part A Recovery Util. Environ. Effects (2020). https://doi.org/10.1080/15567036.2020.1748144
51. Nutakki, P.K.; Gugulothu, S.K.: Influence of the effect of nanoparticle additives blended with mahua methyl ester on performance, combustion, and emission characteristics of CRDI diesel engine. Environ. Sci. Pollut. Res. (2022). https://doi.org/10.1007/s11356-021-12533-5
52. Nutakki, P.K.; Gugulothu, S.K.; Ramachander, J.; Sivasurya, M.: Effect Of n-amyl alcohol/biodiesel blended nano additives on the performance, combustion and emission characteristics of CRDi diesel engine. Environ. Sci. Pollut. Res. (2022). https://doi.org/10.1007/s11356-021-13165-5
53. Devarajan, Y.; Choubey, G.; Mehar, K.: Ignition analysis on neat alcohols and biodiesel blends propelled research compression ignition engine. Energy Sources Part A Recovery Util. Environ. Effects **42**, 2911–2922 (2020). https://doi.org/10.1080/15567036.2019.1618998
54. Chandra Sekar, M.S.; Ananthan, V.R.; Baskaran, N.; Suresh Kumar, H.K.; Arumugam, R.: Combustion, performance, and emission study on the octanol- neem biodiesel blends fueled diesel engine. Energy Sources Part A Recovery Util. Environ. Effects (2020). https://doi.org/10.1080/15567036.2020.1741736
55. Praveen, A.; Jamuna Rani, G.; Balakrishna, B.: Effect of MWCNTs as nano additives in *C. inophyllum* biodiesel blend (CIB20) on the performance and emission parameters of a diesel engine. Mater. Today Proc. (2021). https://doi.org/10.1016/j.matpr.2021.11.158
56. Sidharth; Kumar, N.: Performance and emission studies of ternary fuel blends of diesel, biodiesel and octanol. Energy Sources Part A Recovery Util. Environ. Effects (2020). https://doi.org/10.1080/15567036.2019.1607940
57. Sayin, C.: Engine performance and exhaust gas emissions of methanol and ethanol-diesel blends. Fuel (2010). https://doi.org/10.1016/j.fuel.2010.02.017
58. Atabani, A.E.; Kulthoom, S.A.L.: Spectral, thermoanalytical characterizations, properties, engine and emission performance of complementary biodiesel–diesel–pentanol/octanol blends. Fuel (2020). https://doi.org/10.1016/j.fuel.2020.118849
59. Rangabashiam, D.; Jayaprakash, V.; Ganesan, S.; Christopher, D.: Investigation on the performance, emission and combustion pattern of research diesel engine fueled with higher alcohol and pongamia biodiesel blends. Energy Sources Part A Recovery Util. Environ. Effects (2019). https://doi.org/10.1080/15567036.2019.1670760
60. 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 **246**, 69–74 (2019). https://doi.org/10.1016/j.fuel.2019.02.106
61. Rajesh Kumar, B.; Saravanan, S.; Rana, D.; Anish, V.; Nagendran, A.: Effect of a sustainable biofuel—*n*-octanol—on the combustion, performance and emissions of a DI diesel engine under naturally aspirated and exhaust gas recirculation (EGR) modes. Energy Convers. Manag. (2016). https://doi.org/10.1016/j.enconman.2016.04.001
62. Özsezen, A.N.: Investigation of the effect of biodiesel produced from waste palm oil on engine performance and emission characteristics. Ph.d. Thesis. Kocaeli University Institute of Science and Technology (2007)
63. Elkelawy, M.; Alm-Eldin Bastawissi, H.; Esmaeil, K.K.; Radwan, A.M.; Panchal, H.; Sadasivuni, K.K., et al.: Experimental studies on the biodiesel production parameters optimization of sunflower and soybean oil mixture and DI engine combustion, performance, and emission analysis fueled with diesel/biodiesel blends. Fuel (2019). https://doi.org/10.1016/j.fuel.2019.115791
64. Heydari-Maleney, K.; Taghizadeh-Alisaraei, A.; Ghobadian, B.; Abbaszadeh-Mayvan, A.: Analyzing and evaluation of carbon nanotubes additives to diesohol-B2 fuels on performance and emission of diesel engines. Fuel (2017). https://doi.org/10.1016/j.fuel.2017.01.091
65. EdwinGeo, V.; Fol, G.; Aloui, F.; Thiyagarajan, S.; Jerome Stanley, M.; Sonthalia, A., et al.: Experimental analysis to reduce CO_2 and other emissions of CRDI CI engine using low viscous biofuels. Fuel (2021). https://doi.org/10.1016/j.fuel.2020.118829
66. Mikulski, M.; Duda, K.; Wierzbicki, S.: Performance and emissions of a CRDI diesel engine fuelled with swine lard methyl esters-diesel mixture. Fuel (2016). https://doi.org/10.1016/j.fuel.2015.09.083
67. Duda, K.; Wierzbicki, S.; Śmieja, M.; Mikulski, M.: Comparison of performance and emissions of a CRDI diesel engine fuelled with biodiesel of different origin. Fuel (2018). https://doi.org/10.1016/j.fuel.2017.09.112
68. Canakci, M.: Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel. Bioresour. Technol. (2007). https://doi.org/10.1016/j.biortech.2006.05.024
69. Bala Prasad, K.; Meduri, O.; Dhana Raju, V.; Azmeera, A.K.; Venu, H.; Subramani, L., et al.: Effect of split fuel injection strategies on the diverse characteristics of CRDI diesel engine operated with tamarind biodiesel. Energy Sources, Part A Recovery Util. Environ. Effects (2020). https://doi.org/10.1080/15567036.2020.1856973
70. Erdogan, S.; Balki, M.K.; Aydın, S.; Sayin, C.: Performance, emission and combustion characteristic assessment of biodiesels derived from beef bone marrow in a diesel generator. Energy **207**, 118300 (2020). https://doi.org/10.1016/j.energy.2020.118300
71. Devarajan, Y.; Munuswamy, D.B.; Nagappan, B.; Pandian, A.K.: Performance, combustion and emission analysis of mustard oil biodiesel and octanol blends in diesel engine. Heat Mass Transf. (2018). https://doi.org/10.1007/s00231-018-2274-x
72. Lapuerta, M.; Herreros, J.M.; Lyons, L.L.; García-Contreras, R.; Briceño, Y.: Effect of the alcohol type used in the production of waste cooking oil biodiesel on diesel performance and emissions. Fuel (2008). https://doi.org/10.1016/j.fuel.2008.05.013
73. Erdoğan, S.; Balki, M.K.; Sayin, C.: The effect on the knock intensity of high viscosity biodiesel use in a DI diesel engine. Fuel (2019). https://doi.org/10.1016/j.fuel.2019.05.114
74. Söyler, H.; Balki, M.K.; Sayin, C.: Determination of optimum parameters for esterification in high free fatty acid olive oil and ultrasound-assisted biodiesel production. Biomass Convers. Biorefin. (2021). https://doi.org/10.1007/s13399-021-01976-y