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Research Paper

The Effects of Canola Oil/Diesel Fuel/Ethanol/N-Butanol/Butyl Di Glycol Fuel Mixtures on Combustion, Exhaust Gas Emissions and Exergy Analysis

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Abstract

In recent years, there have been many studies on the widespread use of liquid fuels derived from biomass. A common emphasis in such studies is on fewer exhaust gas emissions and the expansion of renewable fuel production. Biodiesel is considered to be an important type of biomass fuel that is already produced commercially. But the production of biodiesel is laborious and comprises combination of several chemical processes. This study examines the effects of using oil used in biodiesel production with oxygen-rich chemicals on combustion (in-cylinder pressure (Cp), heat release rate (HRR), rate of pressure rise (RoPR), and cumulative heat release (CHR)), exhaust emission values, energy and exergy analysis. In this study, the effects of butyl di glycol use were also investigated and compared with commercially used ethanol and n-butanol. A transesterification method produced from canola oil the biodiesel used in the experiments. The experimental fuels were mixed volumetrically. For this purpose, experiments were carried out with canola biodiesel produced at 20% (D80B20) in diesel fuel and the results of the experiments were recorded. Under the same conditions, experiments were carried out by adding ethanol (D60C20E20), n-butanol (D60C20B20), butyl di glycol (D60C20G20) at a rate of 20% by volume to the canola oil added to the diesel fuel. The lowest values in terms of thermal and exergy efficiency were obtained in D60C20G20 fuel at all engine loads. Also, the highest entropy generation was calculated at all engine loads for this fuel blend.

Keywords: Biofuels; Biodiesel; Canola oil; Oxygenated fuels; Butyl di glycol; Energy and exergy

1. Introduction

The conventional fossil fuels, such as diesel and gasoline, have been used in internal combustion (IC) engines for more than a century [1], and their use is expected to continue even in 2040 [2],[3]. However, in addition to having limited lifetimes of fossil fuel sources, it pollutes the atmosphere and leads to serious environmental problems [4]–[6]. This situation has led most researchers to seek renewable and environmentally friendly alternative fuels. Biofuels such as alcohols and biodiesel are recommended as alternative fuel to internal combustion engines. Biodiesel, seen as a renewable fuel with the potential to help reduce exhaust emissions and total carbon dioxide (CO_2) emissions, can reduce net CO_2 emissions by 78% on a life-cycle basis compared to conventional diesel fuel [7]–[9].

Biodiesel is a renewable biofuel that can be produced from vegetable oil, waste vegetable oil, and animal fats [10]. Due to its good solubility with

Nomenclature

BSFC	Brake specific fuel consumption (g/kwh)
BTE	Brake thermal efficiency
$C_{15}H_{25}$	Diesel
CA	Crank angle
CD	Combustion duration (°CA)
CHR	Cumulative heat release (J)
CI	Compression-ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
Cp	In-cylinder pressure (bar)
DI	Direct-injection
D100	100% diesel
D80B20	80% diesel, and 20% biodiesel
D80C20	80% diesel, and 20% canola oil
D80C20E20	60% diesel, 20% canola oil, and 20% ethanol
D80C20B20	60% diesel, 20% canola oil, and 20% n-butanol
D80C20G20	60% diesel, 20% canola oil, and 20% butyl di glycol
EOC	End of combustion (°CA)
HC	Hydrocarbon
HRR	Heat release rate (J/°CA)
H_2O	Water
ICE	Internal combustion engine
ID	Ignition delay
NO_x	Nitrogen oxide
O_2	Oxygen
RoPR	Rate of pressure rise (bar/°CA)
TDC	Top tead center

diesel fuel, biodiesel can be used as an additive to conventional diesel fuel at any mixing ratio [11]. According to Rakopoulos et al. [12], cotton seed biodiesel/diesel blends in a single-cylinder, four-stroke diesel engine performance and exhaust emissions examined the impact on diesel-biodiesel the average effective pressure, brake thermal efficiency were obtained with a mixture of higher and higher. It was stated that hydrocarbon, carbon monoxide, and particulate matter emissions decreased with the use of biodiesel. However, it is indicated that biodiesel production is a time-consuming and expensive process [12], and financial support from the local government is required to promote biodiesel production [13]. Studies have been conducted on the use of oils as fuel in diesel engines without converting them to biodiesel [14], [15]. Some research that vegetable oils used in the engine in the long term can cause serious engine deposits, piston ring jamming and injector clogging problems due to high viscosity and low volatility [16]. In order to prevent negative effects that may occur by improving the viscosity values of oils by heating and/or with fuels with lower viscosity (diesel, alcohols, etc.) it is used by creating mixtures [17].

Deepanraj et al. [18] investigated the effect of pre-heating palm oil (PCPO) and palm oil methyl ester (POME) on the performance and emissions of a single-cylinder, four-stroke diesel engine. The highest brake thermal efficiency (B) is achieved with diesel fuel, while the POME and fuel blends exhibit higher BTE than PCPO fuel for most engine loadings. Also, the highest cylinder pressure (Cp) was achieved with diesel fuel, while POME exhibited a higher Cp than PCPO. Hydrocarbon (HC) and carbon monoxide (CO) emissions of PCPO, POME and their blends are lower than pure diesel due to of excess oxygen. Martin et al., [19] in the study, it was aimed to reduce viscosity by heating cottonseed oil and creating a blend of pure diesel fuel. It was seen that, the engine performance improved with preheated CSO and diesel-CSO blend compared to neat CSO. Rakopoulos et al., [20] investigated the effect of blends of vegetable oils and biodiesel derived from these oils with diesel fuel on engine performance and emissions in a direct injection diesel engine. It made a comparison between vegetable oil-diesel fuel blends and biodiesel-diesel fuel blends. Emissions of smoke and carbon monoxide (CO) decreased with the use of biodiesel mixtures, while they increased with the use of vegetable oil mixtures. Nitrogen oxides (NOx) emissions, according to neat diesel fuel, increased at low blend rates of vegetable oil and biodiesel, while decreased at high blend rates. In terms of engine performance, vegetable oil blends and biodiesel blends have shown a similar trend. Ravi et al., [21] investigated the effect of n-butanol contribution to peanut oil-diesel fuel blends on the combustion, performance and emissions characteristics of a single-cylinder diesel engine. It was stated that the addition of n-butanol to fuel blends caused an insignificant decrease in cylinder pressure (Cp) and heat release (HRR) values. Furthermore, it was indicated that NO_x, CO and HC emissions decreased significantly. El-Seesy et al. [22] examined the combustion and emission parameters of a compression ignition (CI) engine running with diesel-jojoba oil blends and n-butanol additives. It was indicated that the cylinder pressure (Cp) and heat release rate (HRR) values increased with the addition of n-butanol to diesel-jojoba oil blends. Moreover, in this study, CO, HC and NO_x emissions were lowered with introducing n-butanol to diesel-jojoba oil blends. Geo et al. [23] investigated the effects of adding ethanol to rubber seed oil (RSO) and rubber seed oil biodiesel (RSOME) on combustion, performance, and exhaust emissions in a single-cylinder diesel engine. It was observed that the addition of ethanol to RSO and RSOME increased brake thermal efficiency and decreased smoke emissions. Sathiyamoorthi and Sankaranarayanan [24] blended ethanol with lemon grass oil (LGO)-diesel fuel blend and investigated the effects of ethanol concentration on combustion, performance, and emissions in a direct injection diesel engine. It was stated that ethanol-blended fuels exhibited a higher combustion pressure, heat release rate (HRR), brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) than diesel and LGO25 (75% pure diesel + 25% pure lemon oil). Furthermore, it was reported that while smoke and HC emissions decreased with the addition of ethanol, NO_x and CO emissions increased.

Compression ignition engines, not all of the mechanical energy obtained by the combustion of fuel can be converted into useful work due to various losses. With the energy analysis, the change in the useful work obtained from the engine is determined according to the energy of the fuel [25]. Energy analysis is used to determine the efficiency of fuels in internal combustion engines [26]. In internal combustion engines, energy is conserved. But the exergy is not preserved [27]. The maximum work that can be obtained from a particular system is defined as exergy [28]. With the exergy analysis, the work capacity and quality of the energy of the fuel used in engines can be determined [29], [30]. The unusable part of the energy in the engine and in which parts and in what amount there are losses caused by irreversibilities can be determined [31]. In the literature, energy and exergy analysis studies have been carried out in diesel, biodiesel, and alcohol-based fuels [32]–[39]. In these studies, exergy efficiencies of fuels were calculated by considering exergy losses and entropy generation.

In the literature review, it was observed that pure vegetable oils were used as alternative fuels in diesel engines by improving some fuel properties with different techniques without converting them to biodiesel. However, no detailed study was found in the literature in which the effects of canola oil and ethanol, n-butanol, butyl di glycol blends and canola oil biodiesel on combustion, engine performance and harmful exhaust emissions were presented comparatively, and exergy analyses were examined. The aim of this study is to blend canola oil and ethanol, n-butanol and butyl di glycol and to investigate the potential for direct and more efficient use in a single-cylinder, four-stroke diesel engine without converting canola oil to biodiesel. Moreover, the thermodynamic evaluation of fuel blends was performed by using energy and exergy analyses in the study. The results obtained are presented comparatively with diesel-biodiesel and diesel-canola oil blend. The experimental study was carried out at a constant motor speed of 3000 rpm and at different motor loads of 500 W, 1000 W, 1500 W, 2000 W, 2500 W and 3000 W.

2. Materials and Methods

2.1. Test Fuels

In this study, diesel fuel-canola oil biodiesel, diesel fuel-canola oil and diesel fuel-canola oil-oxygenated fuels (ethanol, butanol and butyl di glycol) were used by creating a blend. Diesel fuel was purchased from local OPET gas station. Canola oil was purchased from a local market. The transesterification method, which is widely used in the production of biodiesel from canola oil, was applied. To carry out the reaction, a 4000 ml three-necked batch reactor in **Figure 1** was used.

In the transesterification reaction, methanol up to 20% (%V/V) of the oil by volume and NaOH up to 0.5% (%W/W) of the oil by weight were used [40]. The reaction temperature is 60 °C, the duration is 1.5 hours and the mixing speed is 800 rpm. At the end of the reaction, the mixture is taken into the separation funnel and left to rest for 12 hours, and then the biodiesel at the top is separated from the glycerin phase at the bottom. The obtained biodiesel was washed 3 times (until the pH value was neutral) with distilled water at 55 °C. In each washing process, it was taken to a separatory funnel again to separate the water and biodiesel. The drying process was applied at 110 °C for 1 hour against the possibility of water remaining in the biodiesel. Finally, it was filtered under vacuum, taken into amber bottles and stored in a refrigerator at 4 °C until engine tests and fuel analysis. After all these processes, it was seen that 963 ml of biodiesel could be produced from 1000 ml of oil. In this biological condition, diesel survival was calculated as 96.3%. Some physical and chemical properties of fuels and chemicals used in experimental studies are given in **Table 1**.

The amount and data of the fuels produced are suitable for use in **Table 2**.

Fuel blends were created according to the ratios specified in **Table 2** and placed in special bottles, and kept under suitable conditions for one week against the possibility of phase separation. It was observed that no phase separation occurred at the end of one week. The images of the fuels used in experimental studies in special bottles are shown in **Figure 2**. Afterward, the fuel blends in the amount required for the engine tests were prepared before starting the experiments, and the prepared fuels were finished during the experiment. Some physical and chemical properties of all fuels and fuel blends are presented in **Table 3**.

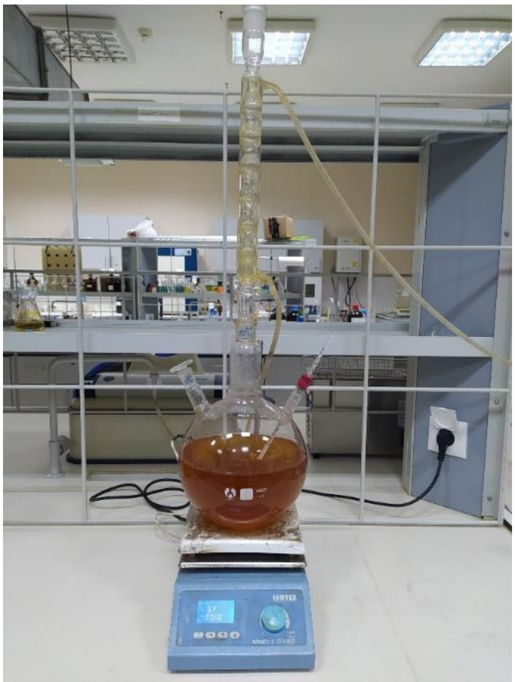


Figure 1. Reactor for transesterification reaction.

Table 1. Properties of diesel, canola oil, canola oil methyl ester and chemicals

Fuel Properties	Diesel	Biodiesel	Canola oil	Ethanol*	Butanol**	Butyl di glycol
Kinematics viscosity (mm^2/s), at 40 °C	3.43	4.68	31.23	1.2	2.63	3.15
Density (g/cm^3) at 15 °C	0.834	0.83	0.90	0.786	0.81	1.18
Lower heating value (MJ/kg)	43.08	38.93	40.12	28.4	33.2	59.59
Flash point (°C)	66.0	162	234	15	35	99
Cetane number	59.5	56.8	-	6	17-25	61

*Ref [2], **Ref [41]

Table 2. The blending concentrations of the test fuels

No	Abbreviation	Diesel	Biodiesel	Canola oil	Ethanol	n-butanol	Butyl di glycol
1	D100	100%	-	-	-	-	-
2	D80B20	80%	20%	-	-	-	-
3	D80C20	80%	-	20%	-	-	-
4	D60C20E20	60%	-	20%	20%	-	-
5	D60C20B20	60%	-	20%	-	20%	-
6	D60C20G20	60%	-	20%	-	-	20%

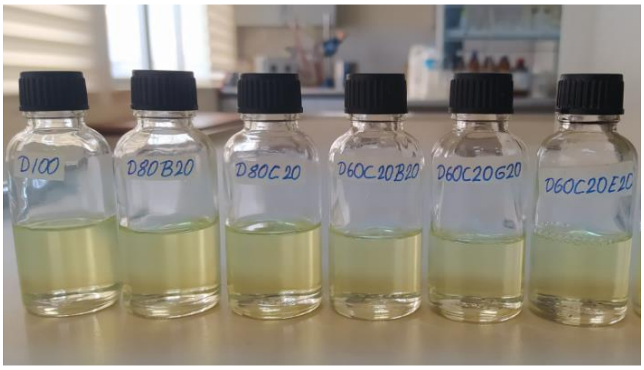


Figure 2. Test fuels used in experimental studies

Table 3. The physical and chemical properties of test fuels and blends

Properties	D100	D80B20	D80C20	D60C20E20	D60C20B20	D60C20G20
Kinematics viscosity (mm^2/s), at 40 °C	3.43	3.68	8.99	8.54	8.83	8.93
Density (g/cm^3) at 15 °C	0.834	0.83	0.85	0.84	0.84	0.92
Lower heating value (kJ/kg)	43.08	42.25	42.49	39.55	40.51	45.79
Flash point (°C)	66.0	85.20	99.60	89.40	93.40	106.20
Cetan number	59.5	58.96	-	-	-	-

2.2. *Experimental Setup and Methodology*

Within the scope of this study, a naturally aspirated, four-stroke, air-cooled, direct injection, single-cylinder diesel engine powered electrical generator was used in experimental studies. The properties of the diesel engine used in the study are given in **Table 4**. All tests within the scope of the study were conducted at a constant engine speed of 3000 rpm and different engine loads (500 W-3500 W, with the 500 W increments). Projectors with different powers (250 W and 1000 W) were used to apply load to the generator. Fuel consumption was determined in mass by the time it took to consume 10 g of the fuel on an electronic balance with 0.01 g accuracy. Piezo resistor Kistler 4065B0200DS1 model air-cooled pressure sensor was used to measure in-cylinder pressure values. Charge amplifier (Kistler 4624AK21) was used to amplify the signals from the in-cylinder pressure sensor. Oprant AutoPSI-A model air-cooled pressure sensor was used to measure the fuel line pressure. The crankshaft position was determined by an FNC 50B incremental optical encoder. 4-channel PicoScope 2406B oscilloscope was used to instantly monitor and record the data from the sensors. Each in-cylinder pressure and fuel line pressure values were obtained by averaging 100 cycles with 0.1 °CA precision. Again, the heat release rate analysis (HRR) was carried out using the average value of 100 consecutive in-cylinder pressures. All losses and leaks were ignored while calculating the heat release. The heat release rate for each crank angle was calculated using Eq.1.

The exhaust gas temperature was measured using a K-type thermocouple. The exhaust gas concentrations of unburned hydrocarbons (HC), nitrogen oxide (NO_x), carbon monoxide (CO), carbon dioxide (CO_2) and smoke emission concentrations were determined by a Mobydic 5000 COMBI exhaust gas analyzer. The technical specifications of the exhaust emission device are presented in **Table 5**. The schematic view of the experimental setup is given in **Figure 3**.

Table 4. The technical specifications of the diesel engine used in the experimental studies

Diesel engine	
Parameters	**Specifications**
Model	186 FAG
Number of cycle	4
Number of cylinder	1
Maximum engine power	7 kW (3600 rpm)
Type of fuel	Diesel fuel
Type of ignition	Compression-ignition
Type of fuel injection	Direct-injection
Intake system	Naturally-aspirated
Engine speed	3000 rpm
Swept volume	418 cm^3
Stroke	70 mm
Bore	86 mm
Cooling system	Air-cooled
Injector nozzle number	4
Pressure of injection	19.6 ±0.49 Mpa
Fuel delivery advance angle	22 ±1 (°CA) BTDC
Compression ratio	18:1

$$\frac{dQ}{d\theta} = \frac{k}{k-1}\left(P\frac{dV}{d\theta}\right) + \frac{1}{k-1}\left(V\frac{dP}{d\theta}\right) \quad (1)$$

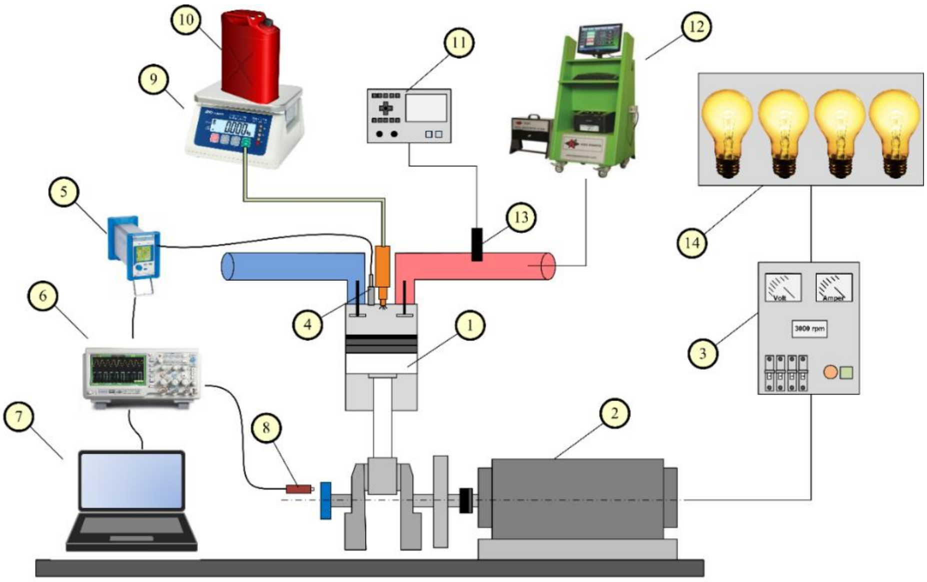
where $dQ/d\emptyset$ is the heat release rate (J/kma), k is the ratio of specific heats (Cp/Cv), P is the cylinder pressure (Pa), and V is the variable cylinder volume (m^3).

Table 5. Technical properties of the devices used to measure exhaust emissions

Measurement	Measuring Range	Resolution	Precision
CO (% vol)	0-10	0.01	± 1%
CO_2 (% vol)	0-20	0.01	± 0.5%
HC (ppm)	0-20000	1	± 12
NO_x (ppm)	0-5000	1	± 10
O_2 (% vol)	0-21	0.01	± 0.5%
Smoke opacity (%)	0-20	0.01	± 2

2.3. *Energy and Exergy Analysis*

Energy and exergy analyses were conducted using the data obtained from engine performance and exhaust emission tests. In the analyses, it was assumed that the engine ran in a steady state, the



1) Diesel engine, 2) Generator, 3) Generator control panel, 4) Cylinder pressure sensor, 5) Charge amplifier, 6) Oscilloscope, 7) Computer, 8) Crank encoder, 9) Precision scale, 10) Fuel tank, 11) Data logger, 12) Exhaust gas analyzer, 13) K-type thermocouple, 14) Lamp load unit

Figure 3. The schematic view of the experimental setup

combustion air and exhaust gases were ideal gases, the combustion took place at a constant pressure, and the potential and kinetic energies of the combustion air, fuel and exhaust gases were zero. In the study, the energy entering the control volume, thermal losses and thermal efficiency were calculated with the energy analysis. The conservation of mass can be calculated using Eq. 2 and the conservation by mass of energy using Eq. 3. Here, $\dot{E}_{fuel}$ refers to the chemical energy of the fuel, $\dot{W}$ refers to the useful work, and $\dot{Q}_{loss}$ refers to the heat losses. Thermal efficiency is the ratio of the useful work to the fuel energy entering the control volume.

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{2}$$

$$\dot{E}_{fuel} = \dot{W} + \dot{Q}_{loss} \tag{3}$$

$$\eta = \frac{\dot{W}}{\dot{E}_{fuel}} \tag{4}$$

The exergy provided to the engine by the fuel, effective power exergy (useful work), exhaust exergy, exergy occurring with heat transfer, exergy destroyed as a result of combustion, and exergy efficiency were found with the exergy analysis. In the exergy analysis, the formulas in the study conducted by Doğan et al. [33] were used.

3. Result and Discussions

The change in the cylinder pressure (Cp) values of the fuels used in the experimental studies according to the crank angle is shown in Figure 4. It is seen that the combustion profile of the additive fuel encounters looks similar from the D100. In-cylinder combustion pressure may increase as a result of the accumulation of fuel in the cylinder and its sudden combustion, depending on parameters such as viscosity, cetane number, density in addition to the heating values of the fuels. Moreover, the in-cylinder pressure value may decrease depending on the extension of the combustion to the exhaust time with the increasing ignition delay. The lowest in-cylinder pressure value at all engine loads was obtained as 36.4 bar with D80C20 fuel blend at an engine load of 500 W. Under the same conditions, an in-cylinder pressure value of 39.3 bar was obtained with D100 fuel, while the highest in-cylinder pressure value was obtained as 39.6 bar with D60C20B20 fuel blend. Considering all engine loads, the highest in-cylinder pressure value was obtained as 44.9 bar with D60C20B20 fuel blend at an engine load of 3000 W. In this case, there was an increase of 2.27% compared to D100 fuel. Studies indicate that oxygen-rich fuels shorten the combustion duration (CD) or accumulate in the cylinder, causing sudden combustion and increasing the in-cylinder pressure values [42]–[45].

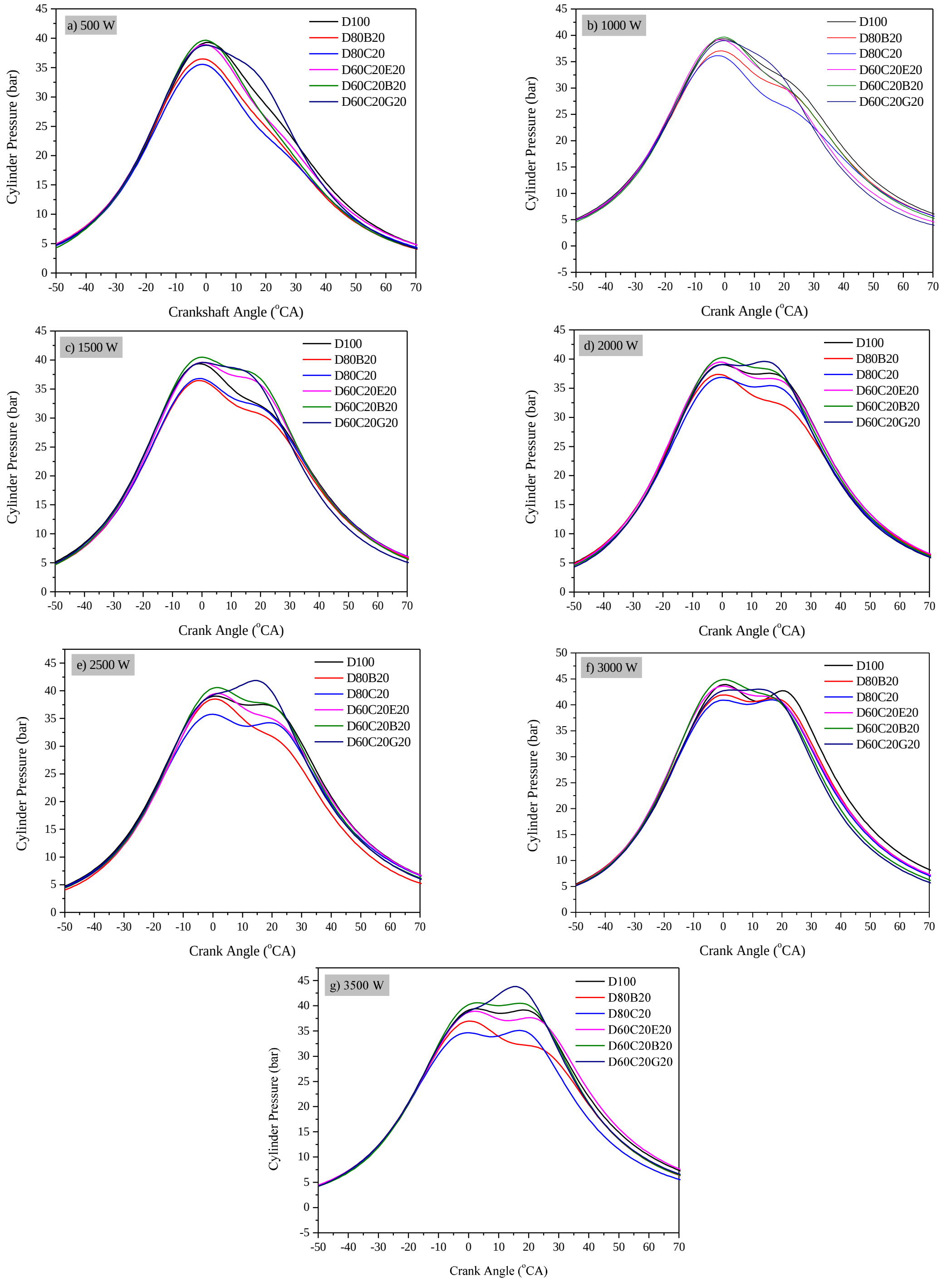


Figure 4. The variation of cylinder pressures depending on the crank angle with test fuels at different engine loads

The change in the rate of pressure rise (RoPR) value depending on the crank angle for each fuel blend is given in **Figure 5**. According to many researchers, the RoPR value is the point where the maximum pressure is formed and also the place where combustion starts. In internal combustion engines, it is reported that the RoPR value should be lower than 9 bar/°C for the engine to run without knocking [46]. If this value is higher, it means that the engine is knocking. In this study, at all engine loads and with different fuel blends, the rate of pressure rise varied between 1.05 bar/°C and 1.38 bar/°C. The highest RoPR value was obtained as 1.38 bar/°CA with D60C20B20 fuel at an engine load of 3000 W. Studies have reported that fuels with high latent heat of vaporization influence the ignition delay time and increase the rate of pressure rise due to sudden accumulations in the cylinder [47]–[49].

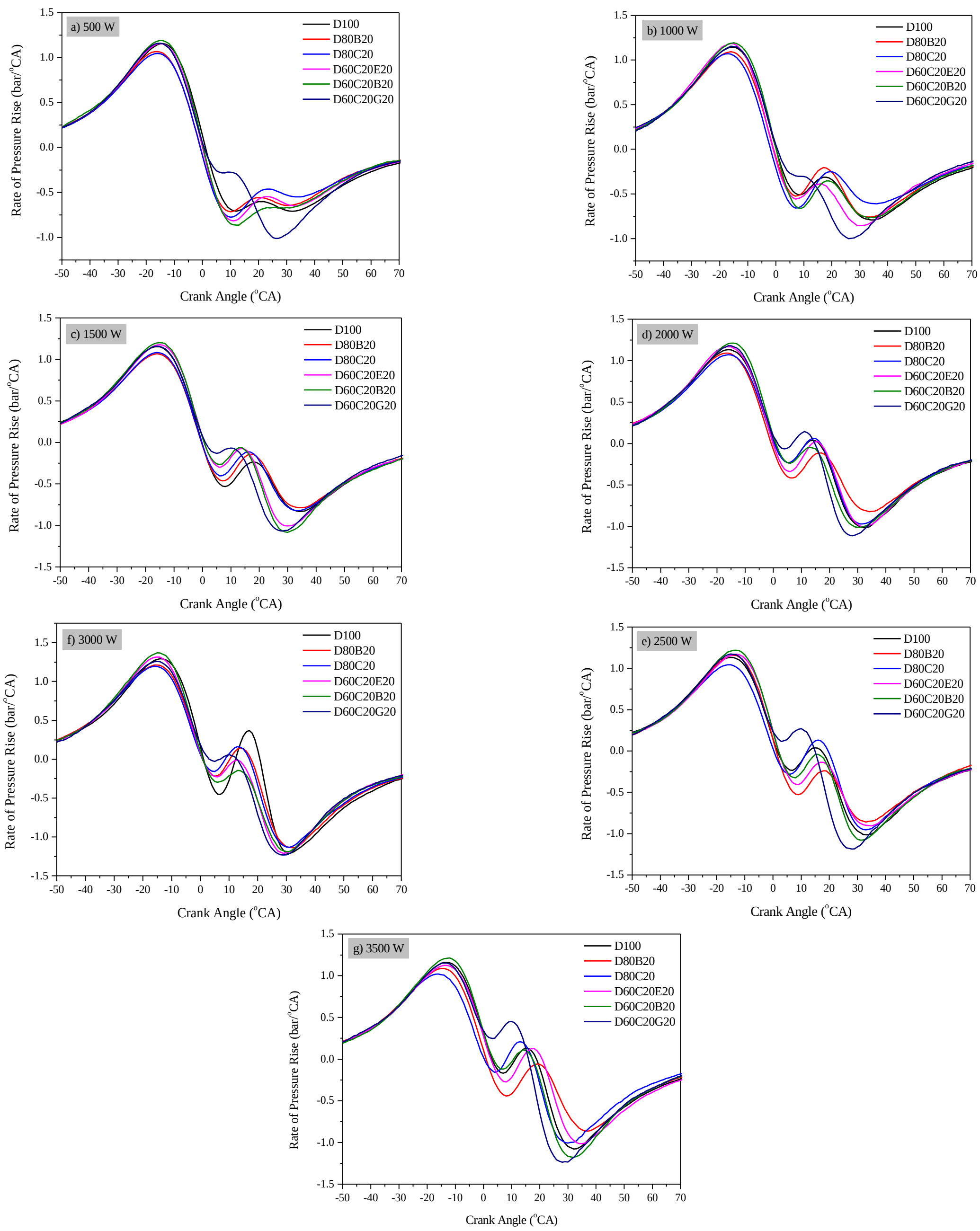


Figure 5. The variation of rate of pressure rise (RoPR) depending on the crank angle with test fuels at different engine loads

The heat release rate (HRR) values of the fuels used in the experimental studies are presented in Figure 6. Studies in the literature express HRR as the change in the heat generated in the combustion chamber according to the crankshaft angle [50]. Upon examining the graphs, it was observed that the amount of HRR decreased with the addition of pure canola oil. Increasing flash point, viscosity, and density values worsen combustion, making it difficult to obtain energy from the entire fuel [51]. Therefore, it is observed that the HRR amount of D80C20 fuel blend is lower than D100 fuel and alcohol-added fuels. While the highest HRR value in the study was obtained as 19.2 J/°CA with D100 fuel at an engine load of 3000 W, the lowest HRR value was calculated as 13 J/°CA with D60C20G20 fuel blend. It is observed that HRR amounts of alcohol-added (D60C20B20) fuels are higher at some engine loads (1500 W). This situation can be expressed by the presence of oxygen in the content of fuels. Studies indicate that additives added to diesel fuel reduce the cetane number and increase the amount of oxygen in the fuel blends, increasing the HRR amount [51], [52].

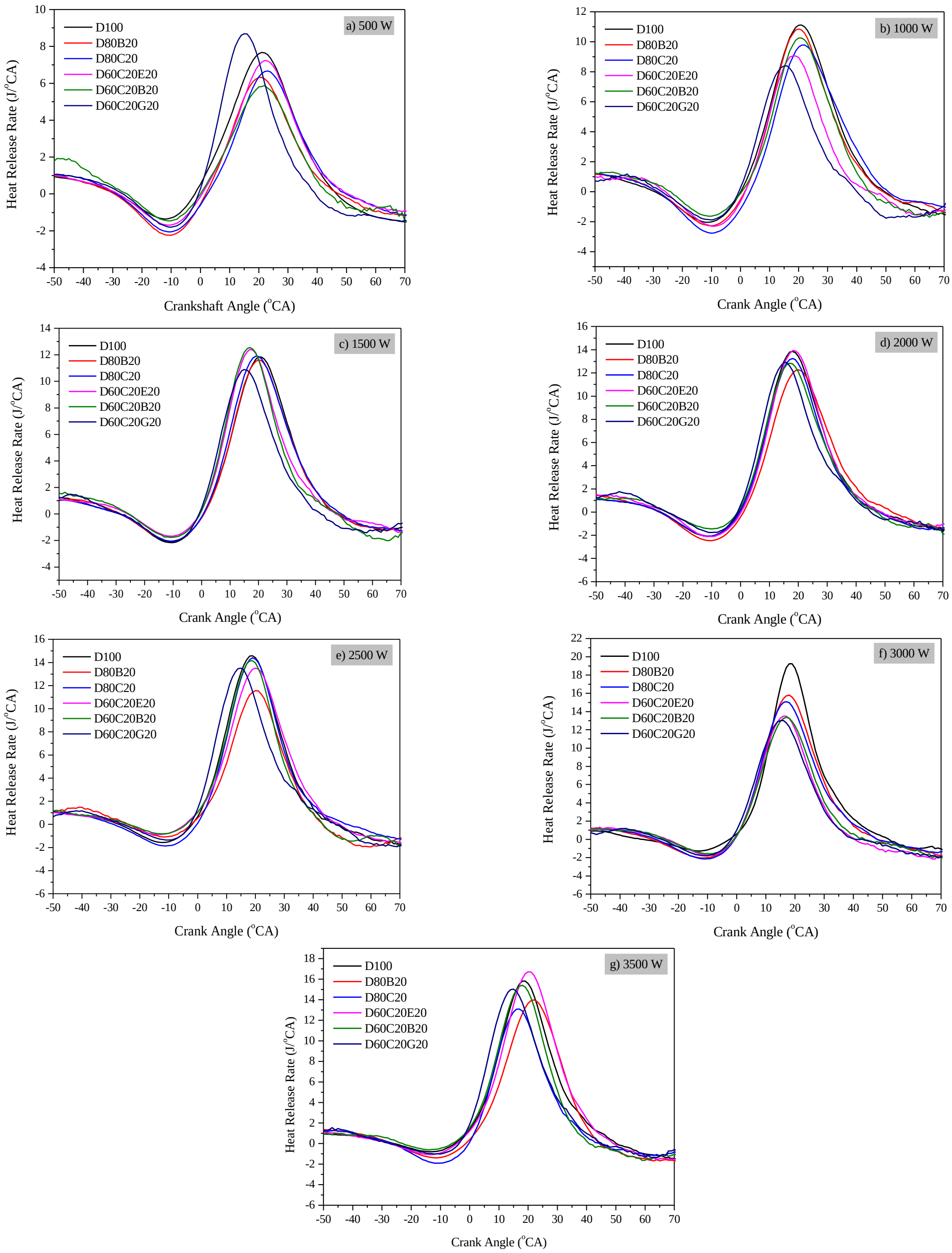


Figure 6. The variation of heat release rate (HRR) depending on the crank angle with test fuels at different engine loads

Figure 7 presents the cumulative heat release (CHR) values obtained for each fuel used within the scope of the experimental study. Cumulative heat release (CHR) expresses the change in the heat released per crankshaft as a result of the combustion of the air/fuel ratio taken into the combustion chamber [53], [54]. The highest CHR value obtained in experimental studies was 374 J with D100 fuel at an engine load of 300 W. CHR value decreased with the increasing engine load. In this case, it is possible to interpret that the higher fuel/air blend taken into the cylinder cannot burn completely and the unburned fuels are thrown out of the cylinder. The lowest CHR value was obtained as 133 J at an engine load of 500 W with D60C20B20 fuel blend. In general, the highest CHR value was obtained with diesel fuel. As is known, the fuel injected into the cylinder in diesel engines absorbs some heat from the cylinder to evaporate. The amount of heat absorbed varies depending on the latent heat of vaporization of the fuel. The latent heat of vaporization and low heating values of alcohols are considerably higher compared to diesel fuel. Studies in the literature report that additives with low heating values and high latent heat of vaporization reduce the CHR value [55]. It is seen that the in-cylinder pressure decreases in similar studies in the literature [42], [56].

Change in the brake specific fuel consumption (BSFC) values of fuels used in experimental studies depending on engine load is given in **Figure 8**. While brake specific fuel consumption (BSFC) significantly depends on the heating value, it also varies depending on parameters such as viscosity, density, and cetane number that affect the combustion of fuels in the cylinder [57]. It is expected that the amount of BSFC will change

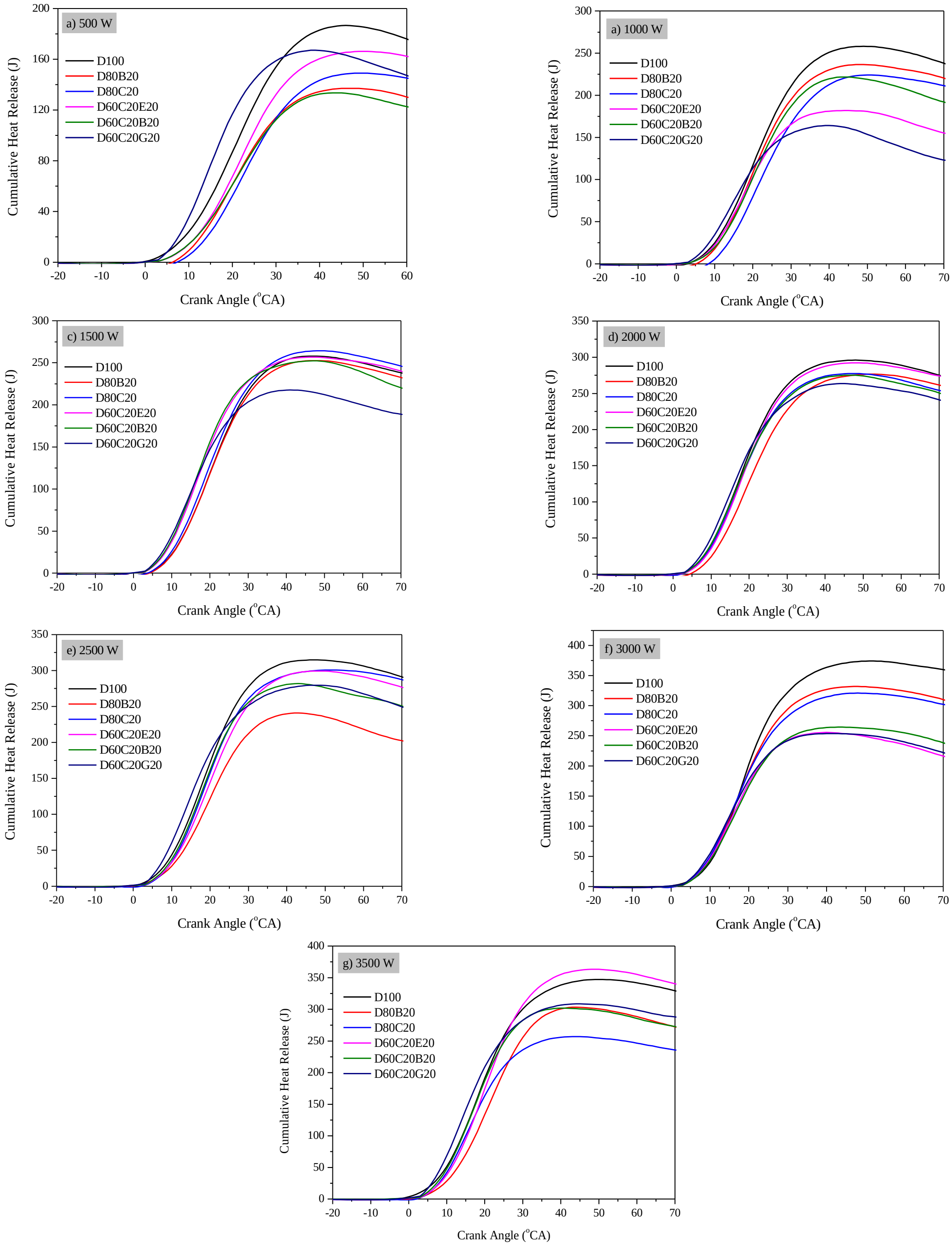


Figure 7. The variation of cumulative heat release (CHR) depending on crank angle with test fuels for different engine loads

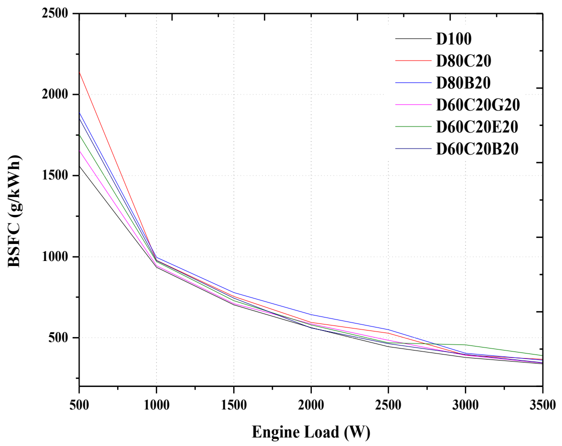


Figure 8. The variation of BSFC depending on engine load

since the oils and alcohols added to diesel fuel change the fuel properties (viscosity, density, cetane number, and heating value). While the lowest fuel consumption amount was obtained with D100 fuel at all engine loads, the highest consumption value was obtained with D80C20 fuel blend. While the highest amount of increase was 27% at an engine power of 500 W, the lowest increase rate was 1% at an engine load of 2000 W with D60C20B20 fuel blend. Studies also indicate that the amount of oxygen in alcohols partially improves combustion. It is stated in many studies that fuel consumption values increase by mixing fuels with high viscosity and low calorific value into diesel fuel. In this respect, the results obtained are similar to the studies conducted with such fuels in terms of the increase in fuel consumption values [58], [59].

The change in the exhaust gas temperature values of each test fuel used in this study depending on the engine load is given in **Figure 9**. Exhaust gas temperature may vary with parameters such as heating values of fuels, viscosity, cetane number, heating value, and oxygen content [60]. Studies have reported that fuel blends accumulate in the cylinder, prolonging the ignition delay (ID), with the change in the properties of fuels, such as cetane number, viscosity, density, etc. [61]. The excessive prolongation of the ignition delay time causes the fuel to be ejected from the exhaust before it is burned completely in the exhaust valve timing. In this case, it was reported that combustion continued in the exhaust, increasing the exhaust gas temperature [62]. The lowest exhaust gas temperature value was obtained as 201 °C with D80C20 fuel blend at all engine loads. In comparison with D100 fuel, the highest amount was determined to be 10% at an engine load of 500 W. It is known that the heating value decreases and the viscosity and density values increase with the direct addition of oil in the fuel blends. All these conditions worsened the combustion, lowered the end-of-combustion (EOC) temperature and thus caused a decrease in the exhaust gas temperature. In the case of biodiesel-added fuel blend and alcohol addition, increases were determined compared to diesel fuel, except for engine loads of 3000 W and 3500 W. The highest exhaust gas temperature was obtained as 435 °C in D60C20E20 fuel blend. Compared to diesel fuel, the highest rate of increase occurred as a result of using D60C20E20 fuel blend with a rate of 28% at an engine load of 1000 W. It is possible to explain the increased exhaust gas temperature values despite the decrease in heating values, by changing the diffusion combustion process of the fuel blends because studies have reported that the extension of the diffusion combustion phase increases the exhaust gas temperature. Exhaust gas temperature continues to increase, resulting in a higher combustion rate during the diffusion combustion phase with the combined effects of higher flame velocity and oxygen content, along with the oxygen content of fuels. In previous studies, it is frequently stated that high density and viscosity values are effective in the combustion of fuels. The findings obtained in this article are similar to the results of previous high viscosity and density fuel mixtures [63], [64].

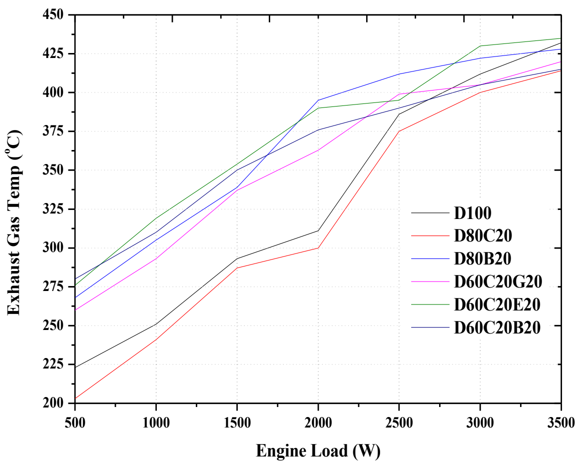


Figure 9. The variation of exhaust gas temperature depending on engine load

The change in carbon monoxide (CO) emission values of fuels used in experimental studies depending on engine load is shown in **Figure 10**. The lack of oxygen in internal combustion engines affects the formation of CO emissions [60]. Although diesel engines run with a high percentage of air, CO emissions can occur. CO emissions reached the highest values in all situations when the engine was not loaded. It is understood from this situation that the fuel taken into the cylinder cannot burn completely. At low engine loads, a small amount of fuel is taken into the cylinder, and the lowest combustion temperature is obtained. In this case, the in-cylinder temperature that will completely burn the fuel blend cannot be obtained. With the increasing engine load, the in-cylinder temperature increases, and the blend burns completely, causing a decrease in CO emissions. With the addition of alcohol to diesel and canola oil, CO emissions decreased at all engine loads compared to D100 fuel. It is possible to explain this situation by the decrease in the amount of oxygen and the total number of carbon (C) atoms in alcohol fuels. Studies have reported that oxygen-rich fuels are effective in reducing CO emissions [65]. The highest CO emission was obtained with D80C20 fuel at all engine loads. Despite the oxygen content of canola oil, the increase in CO emissions can be expressed by the increased viscosity of the fuel blend and the decrease in the heating value. Increasing viscosity is thought to worsen combustion. The lowest CO emission was obtained with D60C20G20 fuel. Butyl di glycol is an important oxygen-containing chemical that is also used commercially as a solvent. It is thought that the oxygen content of butyl di glycol partially improves combustion and reduces CO emissions. In comparison with diesel fuel, CO emissions increased by 26% at the highest rate under the unloaded condition with the use of D80C20 fuel blend, while the lowest increase rate was observed as 10% at an engine load of 2000 W. Among the fuel blends, the lowest CO emission was obtained with D60C20G20 fuel blend at a rate of 86%. It is thought that the high oxygen level in the fuel mixture is effective in this situation. With the use of oxygen high fuels in internal combustion engines, carbon atoms are fully burned, triggering the increase in carbon dioxide emissions. In this case, CO emissions are reduced [66], [67].

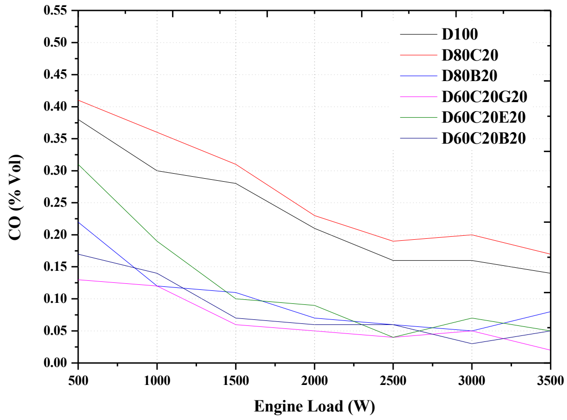


Figure 10. The variation of CO emissions depending on engine load

The change in carbon dioxide (CO_2) emission values of fuels used in experimental studies depending on engine load is shown in **Figure 11**. It is indicated that CO_2 emission is a function of complete combustion in the cylinder. In internal combustion engines, CO_2 gases are formed with the complete combustion of fuels in the cylinder [68]. Therefore, it is frequently mentioned in studies that oxygen-rich fuels increase CO_2 emissions [69]. On the other hand, fuels with high viscosity and density partially worsen combustion. In this case, a decrease can occur in CO_2 emissions. Compared to pure diesel fuel, the highest CO_2 emission was obtained with the addition of butyl di glycol. This situation can be explained by the oxygen content of butyl di glycol and its viscosity and density values being close to diesel fuel. The highest CO_2 emission value was acquired as 2.21% with D60C20G20 fuel blend at an engine load of 1000 W. The lowest CO_2 emission value was measured as 1.54% with D60C20B20 fuel blend at an engine load of 1500 W. In the fuel blends used, while the highest increase rate was 36% with D60C20B20 fuel blend at an engine load of 3500 W, the lowest increase was obtained as 1% with D60C20G20 fuel blend under the same conditions. In this case, it can be stated that better combustion occurs with the addition of n-butanol depending on the increased amount of fuel, while the addition of butyl di glycol partially worsens combustion and, accordingly, causes a decrease in CO_2 emissions.

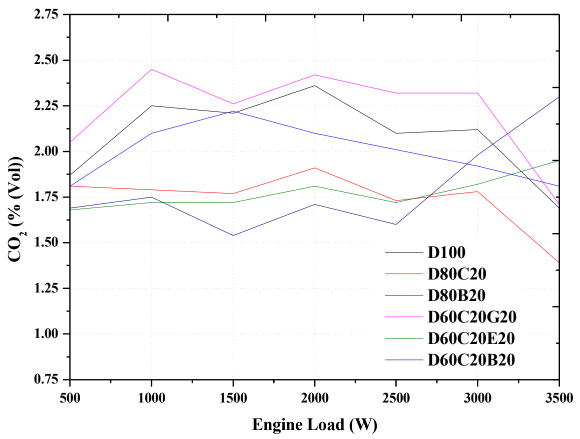


Figure 11. The variation of CO_2 emissions depending on engine load

The change in unburned hydrocarbon (HC) emission values of the fuels used in experimental studies depending on engine load is shown in **Figure 12**. While the lowest HC emission was obtained with D60C20G20 fuel blend between engine loads of 0-2000 W, it was observed that D60C20B20 fuel was more effective with the engine load increasing to 2500, 3000, and 3500 W. The highest HC emission compared to diesel fuel was obtained with D60C20E20 fuel blend. It is possible to explain this situation with the heating values and evaporation heats of the fuel blends. It is reported that the use of chemicals with a high heat of evaporation as fuel additives draws more heat from the cylinder and creates partially dim regions, resulting in an increase in HC emissions [70], [71]. Since the oxygen content of fuel mixtures improves combustion, it causes a decrease in HC emissions. The maximum decrease in HC emissions compared to diesel fuel was obtained as 89% with D60C20G20 fuel blend at an engine load of 1500 W. The change in nitrogen oxide (NOx) emission values of the fuels used in experimental studies depending on engine load is shown in **Figure 13**.

The change in the smoke emission values of the fuels used in the experimental study depending on the engine load is shown in **Figure 14**. While there was a decrease in smoke emissions in general with the increasing engine load, an increase was observed with D80C20 fuel. Furthermore, in all fuel blends in which alcohol is used as an additive, a decreasing trend is observed in parallel with the engine load. It is possible to explain this situation with the increasing amount of fuel and the increase in the in-cylinder temperatures and, accordingly, the partial improvement of combustion. Additionally, it can be said that the oxygen content of alcohols improves combustion and reduces smoke emissions. The obtained data demonstrate that blending pure vegetable oil into diesel fuel increases smoke emissions at all engine loads. However, the smoke emission decreased with the addition of alcohols to diesel/oil blends. It is possible to explain this situation by the fact that the amount of oxygen in alcohol fuels partially improves combustion. In general, the lowest smoke emission values were obtained with D60C20G20 fuel blend.

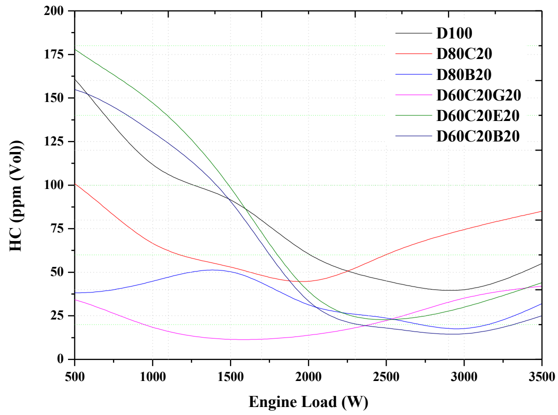


Figure 12. The variation of HC emissions depending on engine load

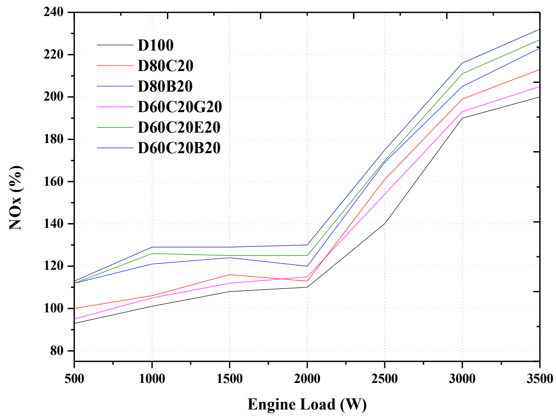


Figure 13. The variation of NOx emissions depending on engine load

The thermal efficiency of the fuels entering the control volume in the energy analysis is given in **Figure 15**. Thermal efficiency increases with the increasing engine load. The thermal efficiency of D60C20B20 fuel with the lowest thermal losses was calculated as the highest value at all engine loads. While the thermal efficiency of D100 fuel was higher at low engine loads, the efficiency of D60C20B20 fuel was higher than that of D100 fuel with the increasing engine load. The thermal efficiency of the canola oil-pure diesel fuel blend is higher than the biodiesel-pure diesel blends obtained from canola oil. The exergy efficiencies given in **Figure 16** exhibit similar behavior to the energy efficiencies. The total exergy losses emerging from the exhaust and heat transfer in the fuel blends were calculated with the exergy analysis and given in **Figure 17**. The total exergy losses increased with the increasing engine load. The highest total exergy loss was found as 4.28 kW in D60C20E20 fuel at an engine load of 3000 W. Entropy generation originates from exergy destruction of fuel blends. As seen in **Figure 18**, the highest entropy generation occurs in D60C20G20 fuel at all engine loads.

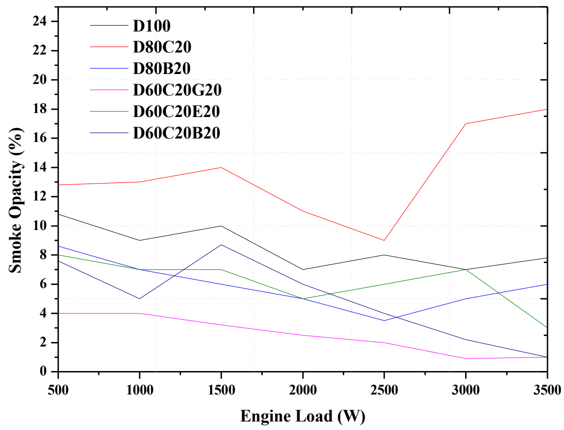


Figure 14. The variation of smoke opacity emissions depending on engine load

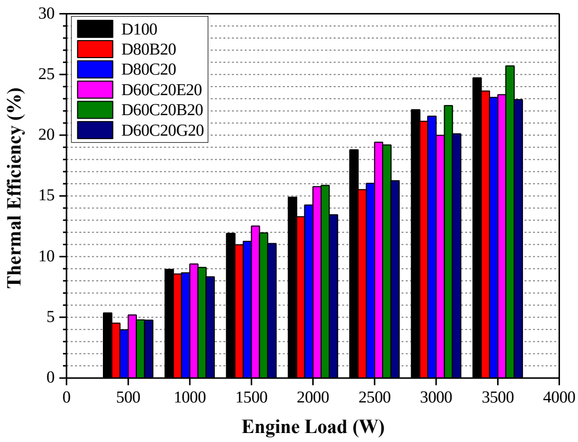


Figure 15. The variation of thermal efficiency of fuel blends at different engine loads

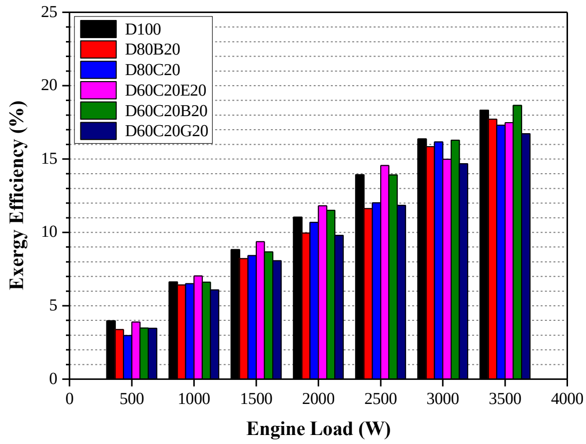


Figure 16. The variation of exergy efficiency of fuel blends at different engine loads

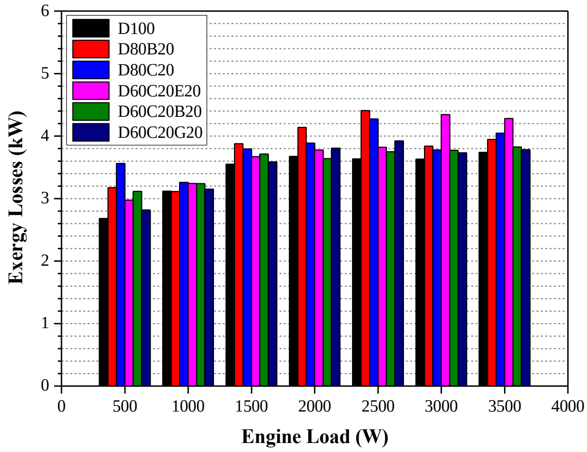


Figure 17. The variation of exergy losses of fuel blends at different engine loads

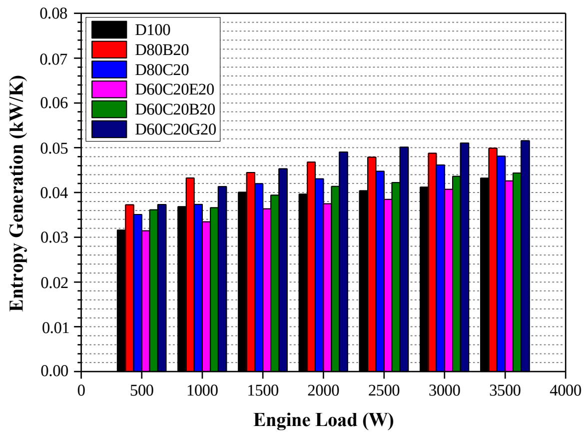


Figure 18. The variation of entropy productions of fuel blends at different engine loads

4. Conclusions

This study, experimentally investigated the effects of binary or ternary fuel blends obtained using diesel fuel-canola oil biodiesel blend, diesel fuel-pure canola oil blend, and ethanol, n-butanol, and butyl di glycol additives on engine performance and exhaust emissions in a four-stroke, compression ignition engine. Furthermore, energy and exergy analyses were also examined using the experimental results obtained in the study. According to the results obtained:

- For each engine load, D80C20 and D80B20 fuel blends exhibited lower combustion performance (Cp, RoPR, and HRR) than pure diesel fuel.
- D80C20 fuel blend exhibited lower Cp and RoPR values in general than D80B20 fuel. Combustion performance improved with the addition of oxygen-containing fuel. Considering all fuels, the highest Cp value was obtained with D60C20G20 fuel at an engine load of 3500 W, and the highest RoPR value was obtained with D60C20B20 fuel at an engine load of 2500 W.
- D80C20 and D80B20 fuel blends, in general, showed lower HRR and CHR than D100 fuel for each engine load. The HRR value increased with the addition of oxygen-containing fuel to D80C20 fuel. While CHR decreased at low engine loads with the addition of oxygen-containing fuel, it increased at high engine loads. It was observed that the highest HRR and CHR values according to all fuels were obtained with D60C20E20 fuel at an engine load of 3500 W.
- While the lowest brake specific fuel consumption was obtained with D100 fuel at all engine loads, the highest was obtained with D80C20 fuel. With the addition of oxygen-containing fuel to D80C20 fuel, the specific fuel consumption decreased, and the lowest specific fuel consumption was obtained with D60C20G20 at an engine load of 3500 W.
- The lowest exhaust gas temperature value was obtained as 201 ℃ with D80C20 fuel blend at all engine loads. Exhaust gas temperatures increased with the addition of oxygen-containing fuel, and the highest exhaust gas temperature was obtained as 435 ℃ with D60C20E20 fuel.
- The highest CO emission for each engine load was obtained with D80C20 fuel. However, CO emissions decreased with the addition of oxygenated fuels to D80C20 fuel. The lowest CO emission values among all fuels were obtained with D60C20G20 fuel.
- While D80C20 fuel exhibited lower CO_2 emissions than D100 and D80B20 fuels, CO_2 emissions increased with the addition of oxygen-containing fuel to D80C20 fuel. Considering each test fuel, the highest CO_2 emission was obtained with D60C20G20 fuel.
- Except for butyl di glycol, with the addition of other oxygen-containing alcohol-based fuels to D80C20 fuel, HC emissions increased at low engine loads and decreased at high engine loads. Among all test fuels, HC emissions were the lowest at low engine loads with D60C20G20 fuel. At high engine loads, the lowest HC emissions were obtained with D60C20B20.
- The highest smoke emissions for each engine load were obtained with D80C20 fuel. Smoke emissions decreased with the addition of oxygen-containing fuel to D80C20 fuel. Considering all test fuels, it was observed that the lowest smoke emissions were obtained with D60C20G20 fuel.
- The highest thermal and exergy efficiency in fuel blends were calculated for D60C20B20 fuel, respectively.
- The highest total exergy loss was found as 4.28 kW in D60C20E20 fuel at an engine load of 3500 W. The lowest total exergy loss occurred in D100 fuel at all engine loads.

Entropy generation increases with the increasing engine load. The highest entropy generation was calculated as 0.052 kW/K in D60C20G20 fuel at an engine load of 3500 W.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Competing interests

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References

[1] C. Patel *et al.*, "Comparative compression ignition engine performance, combustion, and emission characteristics, and trace metals in particulates from Waste cooking oil, Jatropha and Karanja oil derived biodiesels," *Fuel*, vol. 236, pp. 1366–1376, 2019, doi: 10.1016/j.fuel.2018.08.137.

[2] M. A. Ghadikolaei, L. Wei, C. S. Cheung, and K. F. Yung, "Effects of engine load and biodiesel content on performance and regulated and unregulated emissions of a diesel engine using contour-plot map," *Science of the Total Environment*, vol. 658, pp. 1117–1130, 2019, doi: 10.1016/j.scitotenv.2018.12.270.

[3] T. Kivevele, T. Raja, V. Pirouzfar, B. Waluyo, and M. Setiyo, "LPG-Fueled Vehicles: An Overview of Technology and Market Trend," *Automotive Experiences*, vol. 3, no. 1, pp. 6–19, 2020, doi: 10.31603/ae.v3i1.3334.

[4] M. Setiyo, "Alternative fuels for transportation sector in Indonesia," *Mechanical Engineering for Society and Industry*, vol. 2, no. 1, pp. 1–6, 2022.

[5] F. B. Elehinafe, O. B. Okedere, Q. E. Ebong-Bassey, and J. A. Sonibare, "Data on Emission Factors of Gaseous Emissions from Combustion of Woody Biomasses as Potential Fuels for Firing Thermal Power Plants in Nigeria," *Mechanical Engineering for Society and Industry*, vol. 1, no. 2, pp. 75–82, 2021, doi: 10.31603/mesi.5548.

[6] S. Sunaryo, P. A. Sesotyo, E. Saputra, and A. P. Sasmito, "Performance and Fuel Consumption of Diesel Engine Fueled by Diesel Fuel and Waste Plastic Oil Blends: An Experimental Investigation," *Automotive Experiences*, vol. 4, no. 1, pp. 20–26, 2021, doi: 10.31603/ae.3692.

[7] M. A. Hazrat, M. G. Rasul, M. M. K. Khan, N. Ashwath, and T. E. Rufford, "Emission characteristics of waste tallow and waste cooking oil based ternary biodiesel fuels," *Energy Procedia*, vol. 160, pp. 842–847, 2019, doi: 10.1016/j.egypro.2019.02.149.

[8] M. M. Roy, W. Wang, and J. Bujold, "Biodiesel production and comparison of emissions of a DI diesel engine fueled by biodiesel–diesel and canola oil–diesel blends at high idling operations," *Applied Energy*, vol. 106, pp. 198–208, 2013, doi: 10.1016/j.apenergy.2013.01.057.

[9] I. C. Setiawan and M. Setiyo, "Renewable and Sustainable Green Diesel (D100) for Achieving Net Zero Emission in Indonesia Transportation Sector," *Automotive Experiences*, vol. 5, no. 1, pp. 1–2, 2022.

[10] E. Alptekin, H. Sanli, and M. Canakci, "Combustion and performance evaluation of a common rail DI diesel engine fueled with ethyl and methyl esters," *Applied Thermal Engineering*, vol. 149, pp. 180–191, 2019, doi: 10.1016/j.applthermaleng.2018.12.042.

[11] C. Zhan, Z. Feng, M. Zhang, C. Tang, and Z. Huang, "Experimental investigation on effect of ethanol and di-ethyl ether addition on the spray characteristics of diesel/biodiesel blends under high injection pressure," *Fuel*, vol. 218, pp. 1–11, 2018, doi: 10.1016/j.fuel.2017.12.038.

[12] C. D. Rakopoulos, D. C. Rakopoulos, D. T. Hountalas, E. G. Giakoumis, and E. C. Andritsakis, "Performance and emissions of bus engine using blends of diesel fuel with bio-diesel of sunflower or cottonseed oils derived from Greek feedstock," *Fuel*, vol. 87, no. 2, pp. 147–157, 2008, doi: 10.1016/j.fuel.2007.04.011.

[13] M. A. Kalam, H. H. Masjuki, M. H. Jayed, and A. M. Liaquat, "Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil," *Energy*, vol. 36, no. 1, pp. 397–402, 2011, doi: 10.1016/j.energy.2010.10.026.

[14] K. Phoungthong, S. Tekasakul, P. Tekasakul, and M. Furuuchi, "Comparison of particulate matter and polycyclic aromatic hydrocarbons in emissions from IDI-turbo diesel engine fueled by palm oil–diesel blends during long-term usage," *Atmospheric Pollution Research*, vol. 8, no. 2, pp. 344–350, 2017, doi: 10.1016/j.apr.2016.10.006.

[15] D. Capuano, M. Costa, S. Di Fraia, N. Massarotti, and L. Vanoli, "Direct use of waste vegetable oil in internal combustion engines," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 759–770, 2017, doi: 10.1016/j.rser.2016.11.016.

[16] J. Kataria, S. K. Mohapatra, and K. Kundu,

"Biodiesel production from waste cooking oil using heterogeneous catalysts and its operational characteristics on variable compression ratio CI engine," *Journal of the Energy Institute*, vol. 92, no. 2, pp. 275–287, 2019, doi: 10.1016/j.joei.2018.01.008.

[17] A. Kolakoti, B. Prasadarao, K. Satyanarayana, M. Setiyo, H. Köten, and M. Raghu, "Elemental, Thermal and Physicochemical Investigation of Novel Biodiesel from Wodyetia Bifurcata and Its Properties Optimization using Artificial Neural Network (ANN)," *Automotive Experiences*, vol. 5, no. 1, pp. 3–15, 2022.

[18] B. Deepanraj, P. Lawrence, R. Sivashankar, and V. Sivasubramanian, "Analysis of pre-heated crude palm oil, palm oil methyl ester and its blends as fuel in a diesel engine," *International Journal of Ambient Energy*, vol. 37, no. 5, pp. 495–500, 2016, doi: 10.1080/01430750.2015.1004106.

[19] M. L. J. Martin, V. E. Geo, and B. Nagalingam, "Effect of fuel inlet temperature on cottonseed oil–diesel mixture composition and performance in a DI diesel engine," *Journal of the Energy Institute*, vol. 90, no. 4, pp. 563–573, 2017, doi: 10.1016/j.joei.2016.05.005.

[20] C. D. Rakopoulos, K. A. Antonopoulos, D. C. Rakopoulos, D. T. Hountalas, and E. G. Giakoumis, "Comparative performance and emissions study of a direct injection diesel engine using blends of diesel fuel with vegetable oils or bio-diesels of various origins," *Energy conversion and management*, vol. 47, no. 18–19, pp. 3272–3287, 2006, doi: 10.1016/j.enconman.2006.01.006.

[21] S. Ravi, P. G. Sajin, K. M. Kasir, N. Kumar, and E. Balaji, "Enhancing the combustion and emission parameters of a CI engine operated with diesel-butanol-pea nut oil ternary blends," *Materials Today: Proceedings*, vol. 37, pp. 1394–1398, 2021, doi: 10.1016/j.matpr.2020.07.061.

[22] A. I. EL-Seesy, Z. He, H. Hassan, and D. Balasubramanian, "Improvement of combustion and emission characteristics of a diesel engine working with diesel/jojoba oil blends and butanol additive," *Fuel*, vol. 279, p. 118433, 2020, doi: 10.1016/j.fuel.2020.118433.

[23] V. E. Geo, A. Sonthalia, G. Nagarajan, and B. Nagalingam, "Studies on performance, combustion and emission of a single cylinder diesel engine fuelled with rubber seed oil and its biodiesel along with ethanol as injected fuel," *Fuel*, vol. 209, pp. 733–741, 2017, doi: 10.1016/j.fuel.2017.08.036.

[24] R. Sathiyamoorthi and G. Sankaranarayanan, "The effects of using ethanol as additive on the combustion and emissions of a direct injection diesel engine fuelled with neat lemongrass oil-diesel fuel blend," *Renewable Energy*, vol. 101, pp. 747–756, 2017, doi: 10.1016/j.renene.2016.09.044.

[25] J. Jannatkhah, B. Najafi, and H. Ghaebi, "Energy-exergy analysis of compression ignition engine running with biodiesel fuel extracted from four different oil-basis materials," *International Journal of Green Energy*, vol. 16, no. 10, pp. 749–762, 2019, doi: 10.1080/15435075.2019.1619568.

[26] M. K. Yesilyurt and M. Arslan, "Analysis of the fuel injection pressure effects on energy and exergy efficiencies of a diesel engine operating with biodiesel," *Biofuels*, vol. 10, no. 5, pp. 643–655, 2018, doi: 10.1080/17597269.2018.1489674.

[27] S. Manigandan, A. E. Atabani, V. K. Ponnusamy, and P. Gunasekar, "Impact of additives in Jet-A fuel blends on combustion, emission and exergetic analysis using a micro-gas turbine engine," *Fuel*, vol. 276, p. 118104, 2020, doi: 10.1016/j.fuel.2020.118104.

[28] A. Gholami, A. Hajinezhad, F. Pourfayaz, and M. H. Ahmadi, "The effect of hydrodynamic and ultrasonic cavitation on biodiesel production: An exergy analysis approach," *Energy*, vol. 160, pp. 478–489, 2018, doi: 10.1016/j.energy.2018.07.008.

[29] J. Jannatkhah, B. Najafi, and H. Ghaebi, "Energy and exergy analysis of combined ORC–ERC system for biodiesel-fed diesel engine waste heat recovery," *Energy Conversion and Management*, vol. 209, p. 112658, 2020, doi: 10.1016/j.enconman.2020.112658.

[30] M. Aghbashlo, M. Tabatabaei, M. A. Rajaeifar, and M. A. Rosen, "Exergy-based sustainability analysis of biodiesel production and combustion processes," in

Biodiesel, Springer, 2019, pp. 193–217.

[31] B. Doğan, "Energy and Exergy Analysis of Piston Type CNG Compressors With Different Number of Stages," *Fresenius Environmental Bulletin*, vol. 27, 2018.

[32] B. G. Şanli and E. Uludamar, "Energy and exergy analysis of a diesel engine fuelled with diesel and biodiesel fuels at various engine speeds," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 42, no. 11, pp. 1299–1313, 2020, doi: 10.1080/15567036.2019.1635229.

[33] B. Dogan, A. Cakmak, M. K. Yesilyurt, and D. Erol, "Investigation on 1-heptanol as an oxygenated additive with diesel fuel for compression-ignition engine applications: An approach in terms of energy, exergy, exergoeconomic, enviroeconomic, and sustainability analyses," *Fuel*, vol. 275, p. 117973, 2020, doi: 10.1016/j.fuel.2020.117973.

[34] M. Canakci and M. Hosoz, "Energy and Exergy Analyses of a Diesel Engine Fuelled with Various Biodiesels," *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 1, no. 4, pp. 379–394, Dec. 2006, doi: 10.1080/15567240500400796.

[35] G. Khoobbakht, A. Akram, M. Karimi, and G. Najafi, "Exergy and Energy Analysis of Combustion of Blended Levels of Biodiesel, Ethanol and Diesel Fuel in a DI Diesel Engine," *Applied Thermal Engineering*, vol. 99, pp. 720–729, 2016, doi: https://doi.org/10.1016/j.applthermaleng.2016.01.022.

[36] A. K. Das, D. Hansdah, A. K. Mohapatra, and A. K. Panda, "Energy, exergy and emission analysis on a DI single cylinder diesel engine using pyrolytic waste plastic oil diesel blend," *Journal of the Energy Institute*, vol. 93, no. 4, pp. 1624–1633, 2020, doi: 10.1016/j.joei.2020.01.024.

[37] B. Ma *et al.*, "Exergy loss analysis on diesel methanol dual fuel engine under different operating parameters," *Applied Energy*, vol. 261, p. 114483, 2020, doi: 10.1016/j.apenergy.2019.114483.

[38] S. Sarıkoç, İ. Örs, and S. Ünalan, "An experimental study on energy-exergy analysis and sustainability index in a diesel engine with direct injection diesel-biodiesel-butanol fuel blends," *Fuel*, vol. 268, p. 117321, 2020, doi: 10.1016/j.fuel.2020.117321.

[39] A. Çakmak and A. Bilgin, "Exergy and energy analysis with economic aspects of a diesel engine running on biodiesel-diesel fuel blends," *International Journal of Exergy*, vol. 24, no. 2–4, pp. 151–172, 2017, doi: 10.1504/IJEX.2017.087700.

[40] Y. Gürkan, "Experimental investigation of the usability of ethanol doped canola biodiesel in a diesel engine," Firat University, 2019.

[41] S. Ravi, A. Karthikeyan, R. N. Kumar, and E. Balaji, "Augmentation of performance and Emission distinctiveness of heavy duty constant pressure combustion engine supplemented through n-butanol-mustard oil-diesel composition," *Materials today: PROCEEDINGS*, 2020, doi: 10.1016/j.matpr.2020.10.188.

[42] Q. Ma, Q. Zhang, and Z. Zheng, "An experimental assessment on low temperature combustion using diesel/biodiesel/C2, C5 alcohol blends in a diesel engine," *Fuel*, vol. 288, p. 119832, 2021, doi: 10.1016/j.fuel.2020.119832.

[43] A. Shirneshan, S. A. Bagherzadeh, G. Najafi, R. Mamat, and M. Mazlan, "Optimization and investigation the effects of using biodiesel-ethanol blends on the performance and emission characteristics of a diesel engine by genetic algorithm," *Fuel*, vol. 289, p. 119753, 2021, doi: 10.1016/j.fuel.2020.119753.

[44] S. K. Nayak, A. T. Hoang, B. Nayak, and P. C. Mishra, "Influence of fish oil and waste cooking oil as post mixed binary biodiesel blends on performance improvement and emission reduction in diesel engine," *Fuel*, vol. 289, p. 119948, 2021, doi: 10.1016/j.fuel.2020.119948.

[45] D. Qi, W. Xing, P. Luo, J. Liu, and R. Chen, "Effect of alcohols on combustion characteristics and particle size distribution of a diesel engine fueled with diesel-castor oil blended fuel," *Asia-Pacific Journal of Chemical Engineering*, vol. 15, no. 4, p. e2477, 2020, doi: 10.1002/apj.2477.

[46] S. P. Jagtap, A. N. Pawar, and S. Lahane, "Improving the usability of biodiesel blend in

low heat rejection diesel engine through combustion, performance and emission analysis," *Renewable Energy*, vol. 155, pp. 628–644, 2020, doi: 10.1016/j.renene.2020.03.115.

[47] A. I. EL-Seesy, T. Xuan, Z. He, and H. Hassan, "Enhancement the combustion aspects of a CI engine working with Jatropha biodiesel/decanol/propanol ternary combinations," *Energy Conversion and Management*, vol. 226, p. 113524, 2020, doi: 10.1016/j.enconman.2020.113524.

[48] I. M. Yusri, R. Mamat, M. K. Akasyah, M. F. Jamlos, and A. F. Yusop, "Evaluation of engine combustion and exhaust emissions characteristics using diesel/butanol blended fuel," *Applied Thermal Engineering*, vol. 156, pp. 209–219, 2019, doi: 10.1016/j.applthermaleng.2019.02.028.

[49] D. P. Satsangi and N. Tiwari, "Experimental investigation on combustion , noise , vibrations , performance and emissions characteristics of diesel / n-butanol blends driven genset engine," *Fuel*, vol. 221, no. September 2017, pp. 44–60, 2018, doi: 10.1016/j.fuel.2018.02.060.

[50] S. Siluvaimuthu, S. Thiyagarajan, L. J. Martin, and B. Nagalingam, "Comparative analysis of premixed combustion and blending of alcohols with neem and wintergreen oil biofuel blends in CI engine," *Journal of Thermal Analysis and Calorimetry*, vol. 140, no. 4, pp. 1945–1956, 2020, doi: 10.1007/s10973-019-08956-5.

[51] M. K. Yesilyurt, M. Aydin, Z. Yilbasi, and M. Arslan, "Investigation on the structural effects of the addition of alcohols having various chain lengths into the vegetable oil-biodiesel-diesel fuel blends: An attempt for improving the performance, combustion, and exhaust emission characteristics of a compressi," *Fuel*, vol. 269, p. 117455, 2020, doi: 10.1016/j.fuel.2020.117455.

[52] U. Rajak, P. Nashine, and T. N. Verma, "Characteristics of microalgae spirulina biodiesel with the impact of n-butanol addition on a CI engine," *Energy*, vol. 189, p. 116311, 2019, doi: 10.1016/j.energy.2019.116311.

[53] M. Loganathan, A. Velmurugan, T. Page, E. J. Gunasekaran, and P. Tamilarasan, "Combustion analysis of a hydrogen-diesel fuel operated DI diesel engine with exhaust gas recirculation," *Frontiers in Energy*, vol. 11, no. 4, pp. 568–574, 2017, doi: 10.1007/s11708-017-0461-y.

[54] V. Hariram and R. V. Shangar, "Influence of compression ratio on combustion and performance characteristics of direct injection compression ignition engine," *Alexandria Engineering Journal*, vol. 54, no. 4, pp. 807–814, 2015, doi: 10.1016/j.aej.2015.06.007.

[55] M. Z. Isik, "Comparative experimental investigation on the effects of heavy alcohols-safflower biodiesel blends on combustion, performance and emissions in a power generator diesel engine," *Applied Thermal Engineering*, vol. 184, no. July 2020, 2021, doi: 10.1016/j.applthermaleng.2020.116142.

[56] R. Gautam and S. Kumar, "Performance and combustion analysis of diesel and tallow biodiesel in CI engine," *Energy reports*, vol. 6, pp. 2785–2793, 2020, doi: 10.1016/j.egyr.2020.09.039.

[57] V. Kumar and S. K. Mahla, "Influence of EGR on a CI engine running on 20% blend of jatropha biodiesel," *Materials Today: Proceedings*, vol. 43, pp. 273–280, 2021, doi: 10.1016/j.matpr.2020.11.659.

[58] Ü. Ağbulut, M. K. Yeşilyurt, and S. Sarıdemir, "Wastes to energy: Improving the poor properties of waste tire pyrolysis oil with waste cooking oil methyl ester and waste fusel alcohol–A detailed assessment on the combustion, emission, and performance characteristics of a CI engine," *Energy*, vol. 222, p. 119942, 2021, doi: 10.1016/j.energy.2021.119942.

[59] A. O. Emiroğlu and M. Şen, "Combustion, performance and exhaust emission characterizations of a diesel engine operating with a ternary blend (alcohol-biodiesel-diesel fuel)," *Applied Thermal Engineering*, vol. 133, pp. 371–380, 2018, doi: 10.1016/j.applthermaleng.2018.01.069.

[60] A. Atmanli and N. Yilmaz, "An experimental assessment on semi-low temperature combustion using waste oil biodiesel/C3-C5 alcohol blends in a diesel engine," *Fuel*, vol. 260, p. 116357, 2020, doi:

10.1016/j.fuel.2019.116357.

[61] A. Nayyar, D. Sharma, S. L. Soni, and A. Mathur, "Characterization of n-butanol diesel blends on a small size variable compression ratio diesel engine: Modeling and experimental investigation," *Energy conversion and management*, vol. 150, pp. 242–258, 2017, doi: 10.1016/j.enconman.2017.08.031.

[62] A. Uyumaz *et al.*, "Experimental investigation on the combustion, performance and exhaust emission characteristics of poppy oil biodiesel-diesel dual fuel combustion in a CI engine," *Fuel*, vol. 280, p. 118588, 2020, doi: 10.1016/j.fuel.2020.118588.

[63] A. Atmanli, "Comparative analyses of diesel–waste oil biodiesel and propanol, n-butanol or 1-pentanol blends in a diesel engine," *Fuel*, vol. 176, pp. 209–215, 2016, doi: 10.1016/j.fuel.2016.02.076.

[64] M. S. M. Zaharin, N. R. Abdullah, G. Najafi, H. Sharudin, and T. Yusaf, "Effects of physicochemical properties of biodiesel fuel blends with alcohol on diesel engine performance and exhaust emissions: A review," *Renewable and Sustainable energy reviews*, vol. 79, pp. 475–493, 2017, doi: 10.1016/j.rser.2017.05.035.

[65] S. Ganesan and Y. Devarajan, "Emission investigation of higher alcohol and biodiesel blends in constant speed diesel engine," *International Journal of Ambient Energy*, vol. 42, no. 1, pp. 11–14, 2021, doi: 10.1080/01430750.2018.1517695.

[66] N. Joy, Y. Devarajan, B. Nagappan, and A. Anderson, "Exhaust emission study on neat biodiesel and alcohol blends fueled diesel engine," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 40, no. 1, pp. 115–119, 2018, doi: 10.1080/15567036.2017.1405119.

[67] Ü. Ağbulut, S. Sarıdemir, and M. Karagöz, "Experimental investigation of fusel oil (isoamyl alcohol) and diesel blends in a CI engine," *Fuel*, vol. 267, p. 117042, 2020, doi: 10.1016/j.fuel.2020.117042.

[68] M. K. Yesilyurt, Z. Yilbasi, and M. Aydin, "The performance, emissions, and combustion characteristics of an unmodified diesel engine running on the ternary blends of pentanol/safflower oil biodiesel/diesel fuel," *Journal of Thermal Analysis and Calorimetry*, vol. 140, no. 6, pp. 2903–2942, 2020, doi: 10.1007/s10973-020-09376-6.

[69] H. K. Imdadul *et al.*, "Higher alcohol–biodiesel–diesel blends: an approach for improving the performance, emission, and combustion of a light-duty diesel engine," *Energy Conversion and Management*, vol. 111, pp. 174–185, 2016, doi: 10.1016/j.enconman.2015.12.066.

[70] R. Sathyamurthy *et al.*, "Performance, combustion and emission characteristics of a DI-CI diesel engine fueled with corn oil methyl ester biodiesel blends," *Sustainable Energy Technologies and Assessments*, vol. 43, p. 100981, 2021, doi: 10.1016/j.seta.2020.100981.

[71] M. Subramaniam, J. M. Solomon, V. Nadanakumar, S. Anaimuthu, and R. Sathyamurthy, "Experimental investigation on performance, combustion and emission characteristics of DI diesel engine using algae as a biodiesel," *Energy Reports*, vol. 6, pp. 1382–1392, 2020, doi: 10.1016/j.egyr.2020.05.022.