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Araştırma Makalesi
Research Article

Effects of corn oil biodiesel–diesel blends on performance, combustion, and emissions under different engine loads

Farklı motor yükleri altında mısır yağı biyodizeli-dizel karışımlarının performans, yanma ve emisyonlar üzerindeki etkileri

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Abstract: Corn oil biodiesel (CB) is an alternative fuel component that reduces carbon monoxide (CO) and hydrocarbon (HC) emissions by increasing combustion efficiency through its high oxygen content, while also forming stable and homogeneous fuel blends with diesel fuel. In this study, biodiesel was produced from corn oil via transesterification and blended with neat diesel at 10% and 20% volumetric ratios to prepare B10 and B20 fuels, respectively. The performance, combustion, and emission characteristics of the fuels were investigated in a single-cylinder diesel research engine. The experiments were conducted at the engine's maximum torque speed of 1800 rpm and at three different engine loads: 10.98, 16.47, and 21.96 Nm. Within the scope of this study, in-cylinder pressure, heat release rate (HRR), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), indicated mean effective pressure (IMEP), IMEP coefficient of variation (COV_{IMEP}), combustion phase (CA50), maximum pressure rise rate (MPRR), and CO, HC, and nitrogen oxide (NOx) emissions were evaluated. B10 fuel yielded the highest BTE value, particularly at medium load, while BSFC values were very close to those of diesel fuel across all load conditions. Fuels containing biodiesel shifted the CA50 point to earlier crankshaft angles and produced lower MPRR values, demonstrating a more controlled combustion characteristic. The CB additive reduced CO and HC emissions thanks to the oxygen content in the fuel; however, it caused an increase in NOx emissions due to more efficient combustion. Compared to diesel fuel, the use of B20 reduced CO and HC emissions by an average of 17.6% and 8.9%, respectively, while NOx emissions increased by an average of 10.9%. In the overall evaluation, B10 fuel was determined to be the test fuel that provides the optimal balance among engine performance, fuel economy, combustion stability, and emission characteristics.

Keywords: Biodiesel, Combustion, Corn Oil, Diesel Engine, Performance.

Özet: Mısır yağı biyodizeli (CB), bünyesindeki yüksek oksijen içeriğiyle yanma verimliliğini artırarak karbonmonoksit (CO) ve hidrokarbon (HC) emisyonlarını azaltan, aynı zamanda dizel yakıt ile kararlı ve homojen karışımlar oluşturabilen bir alternatif yakıt bileşenidir. Bu çalışmada, mısır yağından transesterifikasyon yöntemi ile biyodizel üretilmiş ve saf dizel yakıt ile hacimsel olarak %10 ve %20 oranlarında karıştırılarak sırasıyla B10 ve B20 yakıtları hazırlanmıştır. Yakıtların performans, yanma ve emisyon karakteristikleri, tek silindirli bir dizel araştırma motorunda incelenmiştir. Deneyler, motorun maksimum tork devri olan 1800 rpm'de ve 10,98, 16,47 ve 21,96 Nm olmak üzere üç farklı motor yükünde gerçekleştirilmiştir. Çalışma kapsamında silindir içi basınç, ısı yayılım oranı (HRR), fren termal verim (BTE), fren özgül yakıt tüketimi (BSFC), indike ortalama efektif basınç (IMEP), IMEP değişim katsayısı (COV_{IMEP}), yanma fazı (CA50), maksimum basınç artış oranı (MPRR) ile CO, HC ve azot oksit (NOx) emisyonları değerlendirilmiştir. B10 yakıtı özellikle orta yük koşulunda en yüksek BTE değerini üretirken tüm yüklerde dizel yakıta oldukça yakın BSFC değerleri sergilemiştir. Biyodizel içeren yakıtlar, CA50 noktasını daha erken krank açılarına kaydırmış ve daha düşük MPRR değerleri üreterek kontrollü bir yanma karakteristiği sergilemiştir. CB katkısı, yakıtın içerdiği oksijen sayesinde CO ve HC emisyonlarını azaltmış, buna karşılık daha etkin yanma nedeniyle NOx emisyonlarında artış meydana getirmiştir. Dizel yakıta kıyasla B20 kullanımı ile CO ve HC emisyonları sırasıyla ortalama %17,6 ve %8,9 oranında azalırken NOx emisyonları ortalama %10,9 oranında artmıştır. Genel değerlendirmede B10 yakıtının motor performansı, yakıt ekonomisi, yanma kararlılığı ve emisyon özellikleri arasında en uygun dengeyi sağlayan test yakıtı olduğu belirlenmiştir.

Anahtar Kelimeler: Biyodizel, Dizel Motor, Mısır Yağı, Performans, Yanma.

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1. Introduction

Compression-ignition (CI) diesel engines play a critical role in transportation, agriculture, energy production, and various industrial applications due to their high thermal efficiencies, long service lives, and reliable performance under demanding operating conditions (Demir et al., 2026; Poorghasemi et al., 2026). The fact that diesel engines offer lower specific fuel consumption (SFC) and higher torque than spark-ignition (SI) engines makes them a widely preferred choice, particularly in heavy-duty applications (Cunanan et al., 2021). However, the growing dependence on fossil fuels brings significant challenges in terms of energy supply security, economic sustainability, and environmental impacts (Duca et al., 2024). Emissions of nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM), and smoke from diesel engines, in turn, have serious adverse effects on air quality and human health (Landwehr et al., 2021; Arslan and Kocakulak, 2023). For this reason, recent studies have simultaneously addressed the goals of improving performance and efficiency in diesel engines while reducing exhaust emissions. In this context, advanced combustion strategies (Gopinathan and Ibrahim, 2025), optimization of injection parameters (Zareei et al., 2024), exhaust gas aftertreatment systems (Li et al., 2025), and alternative fuels (Gürsoy et al., 2024) are among the forefront research topics.

Biodiesel is defined as a renewable fuel consisting of monoalkyl esters of long-chain fatty acids derived from vegetable, animal, and waste oils, as well as algae-based raw materials (Horoz and Baydır, 2026). Among alternative fuels, biodiesel is considered an attractive and sustainable option because it can be produced from renewable sources, is biodegradable, and can be used in existing engines without requiring significant modifications (Solmaz et al., 2023; Şanlı, 2026). The most common method used in biodiesel production is transesterification; in this process, triglycerides react with short-chain alcohols—typically methanol or ethanol—in the presence of a catalyst to form fatty acid methyl esters and glycerol as a byproduct (Özgören et al., 2025). Biodiesels offer significant advantages over conventional diesel fuels due to their high lubricity, low sulfur content, ability to be produced from renewable sources, and potential to reduce CO, HC, and PM emissions (Yeşilyurt and İnce, 2026). Furthermore, their oxygen-containing molecular structures facilitate more efficient oxidation during combustion, thereby improving combustion efficiency (Chuah et al., 2022). However, biodiesels also have certain technical limitations. The high oxygen content of biodiesel can increase local combustion temperatures under certain operating conditions, leading to an increase in NOx emissions (Solmaz et al., 2025). Relatively high viscosity and density values can negatively affect spray and atomization characteristics, making it more difficult to form a mixture (Feng et al., 2025). Similarly, the lower heating value of biodiesel is lower than that of neat diesel, increasing the amount of fuel required to produce a unit of power (Haşimoğlu et al. 2008). To minimize the technical limitations of biodiesel, selecting suitable feedstocks and determining optimal blending ratios for blended fuels are critical for the performance-emission balance. Güler et al. tested the B15 fuel—produced by blending safflower oil biodiesel with neat diesel—under full-load conditions at different engine speeds. It was determined that B15 fuel reduced engine torque by 2.66% compared to diesel and increased the SFC by an average of 9.28%, while the indicated thermal efficiency (ITE) was 26.86% for diesel and 26.27% for B15. Additionally, it was reported that the use of B15 reduced CO and HC emissions by 12.53% and 14.8%, respectively (Güler et al., 2026). İnce et al. experimentally investigated the performance, emissions, noise, and vibration characteristics of waste-oil-based B10 and B20 biodiesel blends. The study found that B10 fuel increased torque and power output, particularly at low and medium loads, and reduced SFC by 17.54% compared to diesel at 40% engine load. It was reported that the biodiesel blend generally increased vibration levels; however, B20 fuel reduced noise levels by 1.42% under full-load conditions. On the other hand, it was observed that biodiesel blends cause an increase in NOx and carbon dioxide (CO_2) emissions (İnce et al., 2024).

Among the numerous biodiesel feedstocks examined in the literature, corn oil is an important raw material source due to the widespread agricultural production and availability of corn (Veljković et al., 2018). Corn oil biodiesel (CB) exhibits more efficient combustion characteristics by supporting oxidation reactions during the combustion process, thanks to the presence of oxygen in its chemical structure (Saravankumar et al., 2019). Furthermore, its high miscibility with neat diesel facilitates the preparation of homogeneous and stable fuel blends, such as those used in binary or ternary systems (Balamurugan et al., 2018). Previous studies have shown that blends containing CB tend to reduce CO, HC, and PM emissions, while engine performance parameters remain within acceptable limits (Imran and Kurji, 2018, Lee and Cho, 2024). Furthermore, it has been reported that CB's high lubricity helps protect engine components by reducing wear in fuel injection systems (Anastopoulos et al., 2001). On the other hand, changes in fuel properties and injection characteristics specific to CB can affect in-cylinder parameters under different operating conditions and may increase NOx emissions (Manigandan et al., 2019). In this context, it is important to systematically investigate the performance, combustion, and emission behavior of fuel mixtures containing CB under different engine loads and operating conditions. Mahmood et al. investigated the effects of CB blends on diesel engine emissions. The fuel blends were prepared with biodiesel content levels of 7%, 15%, and 20%, and the experiments were conducted at a constant engine speed under various load conditions. The results of the study showed that B20 fuel reduced CO, HC, and smoke emissions by 22.13%, 18.5%, and 25.8%, respectively, while causing increases in NOx and CO_2 emissions by 22.3% and 22%, respectively (Mahmood et al., 2020). Muraganantham et al. investigated the effect of adding cerium oxide (CeO_2) nanoparticles to a diesel-CB blend on engine performance and emissions. The addition of CeO_2 nanoparticles to CB10 fuel improved fuel properties, and the highest brake thermal efficiency (BTE) of 34.7% was achieved at a 50 ppm addition rate. The addition of CeO_2 nanoparticles to the diesel-CB blend resulted in a decrease in CO and HC emissions, while an increase in NOx emissions was observed (Muruganantham et al., 2021).

In this study, biodiesel was produced via transesterification from corn oil, and the resulting biodiesel was blended with neat diesel at 10% and 20% by volume to prepare B10 and B20 fuels. The prepared fuels were tested together with the reference fuel in a single-cylinder diesel research engine. The experiments were conducted at the engine's maximum torque speed and under three different engine loads. Within the scope of this study, performance and combustion parameters such as in-cylinder pressure, heat release rate (HRR), brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), indicated mean effective pressure (IMEP), IMEP coefficient of variation (COV_{IMEP}), combustion phase (CA50), and maximum pressure rise rate (MPRR), as well as CO, HC, and NOx emissions, were examined. Unlike previous studies that mainly focused on conventional performance and emission analyses, the present study provides a comprehensive assessment by combining detailed in-cylinder combustion analysis with performance and emission evaluations under different engine load conditions. Based on the results obtained, the effects of diesel-CB blends on engine performance, combustion characteristics, and emission behavior were investigated, and their potential for use as an alternative fuel was evaluated.

2. Materials and Methods

2.1. Test Fuels

In the first stage of the study, biodiesel was produced via base-catalyzed transesterification of commercial refined corn oil. Prior to the transesterification process, the corn oil was filtered to remove impurities and heated to eliminate any residual moisture. Methanol (CH_3OH) was used as the alcohol, and sodium hydroxide (NaOH) was used as the catalyst in the biodiesel production process. The reaction was carried out under the following conditions: a catalyst-to-oil ratio of 0.5 wt.%, an alcohol-to-oil ratio of 20 wt.%, a reaction temperature of 60 °C, a stirring speed of 600 rpm, and a reaction time of 90 minutes. In this context, NaOH was first completely dissolved in CH_3OH to prepare a sodium methoxide (CH_3ONa) solution, which was then reacted with corn oil at the specified temperature. After the reaction, the mixture was allowed to settle for 24 hours, and the glycerol phase was separated from the biodiesel phase by exploiting their density difference. The resulting biodiesel was washed several times with warm distilled water until a clear wash water was obtained to remove residual catalyst, glycerol, and other undesirable components, and then dried at 105 °C to remove moisture and volatile components. Three different fuel samples were used in the experiments to investigate the effects of the produced CB on engine performance, combustion characteristics, and emission profiles. In this context, B10 and B20 blends containing 10% and 20% CB by volume, respectively, were prepared, while commercial diesel fuel was used as the reference fuel. To achieve a homogeneous structure in the fuel blends, the B10 and B20 samples were mixed for 30 minutes and allowed to stand for 6 hours to examine their physical stability. At the end of the standing period, no phase separation or sedimentation was observed, confirming that the prepared fuels were sufficiently stable. The properties of the neat diesel and CB used in the study are shown in Table 1.

2.2. Experimental Setup and Procedures

The experimental studies were conducted on a comprehensive test setup consisting of a diesel research engine, a regenerative dynamometer, and a control panel. The system is equipped with an in-cylinder pressure sensor for combustion analysis, an encoder for crankshaft angle measurement, a charge amplifier for signal processing, and a data acquisition card. In addition, a precision weighing unit, an exhaust gas analyzer, and temperature-measurement equipment were integrated into the computer-based data-acquisition and monitoring infrastructure. A schematic representation of the experimental setup is presented in Figure 1.

Engine performance and combustion tests were conducted on a single-cylinder Antor AD510 BS diesel research engine. The technical specifications of the research engine used in the experimental studies are given in Table 2. The engine was equipped with a mechanically actuated direct-injection fuel system. The fuel injection timing

Table 1. Fuel properties and measurement details (Uyumaz et al., 2020).

Properties	Diesel	B100	B10	B20	Standards	Measurement Instruments
Density (kg/m³ @ 15 °C)	831.88	861.6	834.85	837.82	ASTM D4052	Rudolph DDM 2911
Kinematic viscosity (mm²/s @ 40 °C)	3.09	4.42	3.22	3.36	ASTM D445	Omnitek U-VIsc 200
Water content (wt.%)	0.0033	0.017	0.0047	0.006	ASTM D6304	Aquamax KF
Lower heating value (MJ/kg)	44.891	41.834	44.585	44.280	ASTM D240	IKA Werke C2000

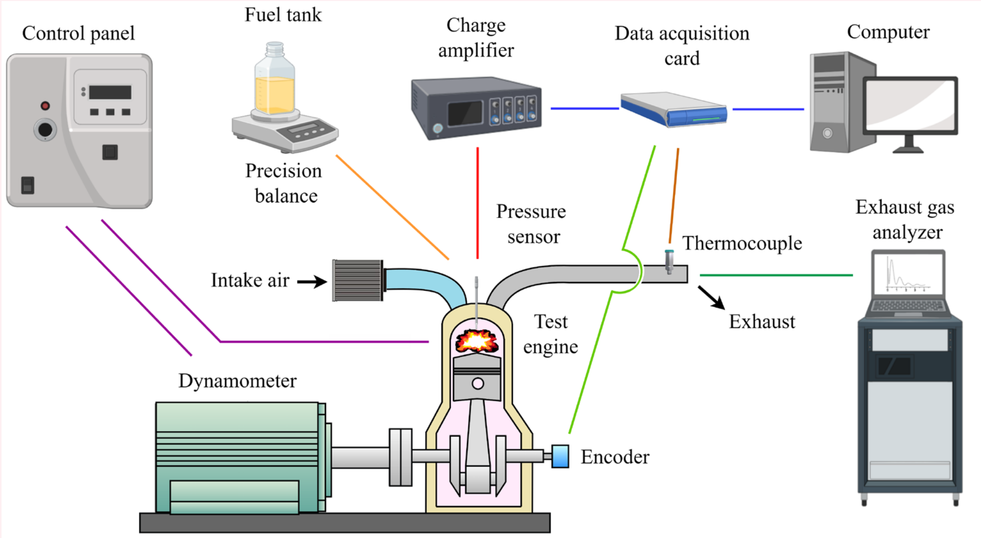

Figure 1. Schematic representation of the experimental setup.

was fixed at 24° BTDC, and the injector opening pressure was maintained within the range of 190-200 kg/cm^2. The experiments were conducted at a constant speed of 1800 rpm—the speed at which the engine produces its maximum torque—and under three different engine loads of 10.98, 16.47, and 21.96 Nm. Before each experiment, the engine was operated with neat diesel fuel for 10 minutes until the nominal operating temperature of 85 °C was reached to ensure thermal stabilization and to eliminate the influence of the previously tested fuel remaining in the fuel supply system. All experiments were performed under ambient laboratory conditions. Load application and speed control were provided by a Kemsan regenerative dynamometer and monitored via an Esit STCS-50 C3 load cell. In-cylinder pressure measurements were performed using an AVL QC34C piezoelectric pressure sensor, while crankshaft angle synchronization was provided by an Opkon PRI 50AR8 encoder. The pressure signals were processed by a Kistler 5018A charge amplifier and transferred to a computer via a National Instruments USB-6351 data acquisition card. Cylinder pressure data were recorded at a resolution of 720 crank-angles per engine cycle, and the average of 200 consecutive cycles was used for evaluation to reduce cyclic variability. Fuel consumption was determined gravimetrically using a precision weighing unit. For thermal measurements, coolant inlet and outlet temperatures were determined using Type K thermocouples, and engine surface temperature was monitored with a TFA ST-490 infrared thermometer. Exhaust emissions were measured using a Bilsa MOD 2210 gas analyzer, and CO, HC, and NOx concentrations were recorded in real time. The gas analyzer was calibrated before each experiment in accordance with the manufacturer's instructions. The measurement ranges and accuracy specifications of the exhaust gas analyzer are presented in Table 3.

Table 2. Technical specifications of the research engine.

Properties	Specifications
Brand and model	Antor AD510 BS
Engine type	4-stroke, direct injection, water cooled
Number of cylinders	1
Cylinder volume (cm^3)	510
Compression ratio	17.5:1
Bore (mm) x Stroke (mm)	85 x 90
Maximum speed (rpm)	3000
Maximum power (kW @ 3000 rpm)	6.6
Maximum torque (Nm @ 1800 rpm)	32.8

Table 3. Measurement specifications of the exhaust gas analyzer.

Components	Measurement ranges	Accuracies
NO (ppm)	0-5000	±1
CO (vol.%)	0-10	±0.01
CO_2 (vol.%)	0-20	±0.01
HC (ppm)	0-9999	±1
O_2 (vol.%)	0-25	±0.01
Lambda (λ)	0.5-2	±0.001

2.3. Combustion Analysis

While some of the data obtained from the experimental studies were evaluated directly, other data were derived using various equations. Cylinder pressure values and CO, HC, and NOx emissions were measured using sensors and used directly in the analyses. On the other hand, fundamental engine and combustion characteristics, such as net work (W_N), HRR, BTE, BSFC, IMEP, COV_{IMEP}, CA50, and MPRR, were derived from the measurement results. A specialized calculation tool developed specifically for this study was used to process the measurement data and calculate the derived parameters.

HRR, one of the key parameters in the analysis of combustion characteristics, was calculated using Equation 1 based on the first law of thermodynamics (Uyumaz et al., 2020).

$$HRR = \frac{\gamma}{\gamma - 1} \cdot P \cdot \frac{dV}{d\theta} + \frac{1}{\gamma - 1} \cdot V \cdot \frac{dP}{d\theta} + \frac{dQ_W}{d\theta} \quad (1)$$

Here, P is the cylinder pressure, V is the cylinder volume, θ is the crankshaft angle, γ is the specific heat ratio, and Q_W is the heat transfer occurring through the cylinder walls.

In determining the HRR, the heat flow between the cylinder wall and the external environment was modeled using Equation 2 (Polat et al., 2020a). Equation 3, proposed by Hohenberg, was used to calculate the instantaneous heat transfer coefficient (Hohenberg, 1979).

$$\frac{dQ_W}{d\theta} = \frac{1}{6n} \cdot h_g \cdot A \cdot (T_W - T_A) \quad (2)$$

$$h_g = 130 \cdot V^{-0.06} \cdot P^{0.8} \cdot {T_W}^{-0.4} \cdot w^{0.8} \quad (3)$$

Here, n is the engine speed, h_g is the heat transfer coefficient, A is the heat transfer surface area, T_W is the wall temperature, T_A is the ambient temperature, and w is the mean piston speed.

The BTE parameter, which is an indicator of internal combustion engine efficiency, and the BSFC parameter, which represents the engine's fuel economy performance, are defined by Equations 4 and 5, respectively (Yang et al., 2014; Uyumaz et al., 2024a).

$$BTE = \frac{P_b}{\dot{m}_f \cdot LHV_f} \quad (4)$$

$$BSFC = \frac{\dot{m}_f}{P_b} \quad (5)$$

Here, P_b is the brake power, $\dot{m}_f$ is the mass flow rate of the fuel, and LHV_f is the lower heating value of the fuel.

The W_N value, which indicates the mechanical work capacity of the engine, was calculated using Equation 6 based on the engine's in-cylinder pressure and volume values (Ali et al., 2026).

$$W_N = \int P \cdot dV \quad (6)$$

The IMEP, which is an indicator of the in-cylinder work capacity, was calculated using Equation 7 based on the values of W_N and stroke volume (V_H) (Arslan et al., 2025).

$$IMEP = \frac{W_N}{V_H} \quad (7)$$

The COV_{IMEP}, a statistical parameter commonly used to quantify cycle-to-cycle variations and assess combustion stability in internal combustion engines, was calculated using Equation 8 (Polat et al., 2020b).

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{\overline{IMEP}} \cdot 100 \quad (8)$$

Here, σ_{IMEP} is the standard deviation of the IMEP values and $\overline{IMEP}$ is the mean IMEP value of 100 consecutive cycles.

The MPRR parameter, which indicates the pressure-rise severity and potential combustion noise in internal combustion engines, was determined using Equation 9 (Babagiray et al., 2023).

$$MPRR = \left(\frac{dP}{d\theta}\right)_{max} \quad (8)$$

2.4. Uncertainty Analysis

An uncertainty analysis was performed to evaluate the accuracy and reliability of the experimental measurements. The uncertainty associated with each measured parameter was determined based on the accuracy specifications provided by the respective instrument manufacturers, and the calculated uncertainties are presented in Table 4. The overall uncertainty of the experimental system was determined by combining the individual measurement uncertainties using the standard error propagation method. The combined uncertainty of the experimental setup was calculated to be ±1.93%, demonstrating the high accuracy and repeatability of the experimental measurements.

Table 4. Uncertainty of the measured parameters.

Parameters	Units	Uncertainties (%)
In-cylinder pressure	bar	±0.5
Crank angle	°CA	±0.1
Fuel mass	g	±0.001
CO	vol.%	±0.84
CO_2	vol.%	±0.84
HC	ppm	±0.83
NOx	ppm	±0.83
O_2	vol.%	±0.83
Overall	-	±1.93

3. Results and Discussion

The in-cylinder pressure and HRR results for the test fuels as a function of engine load are shown in Figure 2. For all fuels, significant increases in in-cylinder pressure and HRR values were observed as engine load was increased. For neat diesel fuel, the maximum in-cylinder pressure was measured at 63.69 bar at a load of 10.98 Nm; when the load was increased to 21.96 Nm, this value rose to 68.68 bar. This increase is attributed to the rise in the amount of fuel injected into the cylinder with increasing engine load and, consequently, to the increase in the energy released during combustion (Ge et al., 2023). Furthermore, the rise in cylinder temperature under increased load conditions shortened the ignition delay and made the effect of the diffusion-controlled combustion phase more pronounced during the combustion process. Under a 10.98 Nm load condition, the maximum pressure and HRR values were observed to follow the order of diesel, B10, and B20. This can be explained by the decrease in the fuel's lower heating value due to the addition of CB, as well as the negative impact of increased viscosity on injection and atomization quality (Uyumaz et al., 2025). At an engine load of 16.47 Nm, however, the B10 blend produced the highest maximum pressure and HRR values. This result indicates that a suitable balance has been achieved between the high energy content of diesel and the combustion-promoting effect of the oxygen present in the CB's composition. Conversely, when the biodiesel blend ratio was increased to 20%, the negative effects caused by viscosity and low volatility became apparent, leading to a partial decline in combustion performance. At an engine load of of 21.96 Nm, the in-cylinder pressure and HRR values were in the order of diesel, B20, and B10. In the high-temperature environment, the additional oxygen present in the B20 fuel was effective in promoting combustion reactions, thereby contributing to more efficient combustion. However, due to its higher lower heating value and rapid energy release, the highest in-cylinder pressure and HRR were again achieved with neat diesel fuel.

The BTE results for the test fuels as a function of engine load are presented in Figure 3. A general upward trend in BTE values was observed as engine load increased across all fuel types. This phenomenon was associated with the increase in mean effective pressure and the decrease in heat losses as the load increased, resulting in a greater proportion of the cycle energy being converted into useful work (Sunaryo et al., 2021). Under low-load conditions of 10.98 Nm, diesel and B10 fuels exhibited similar BTE values of approximately 31.1%, whereas B20 fuel demonstrated lower efficiency. The decreasing lower heating value and deteriorating atomization characteristics associated with the increased CB ratio in B20 fuel limited the cycle efficiency. The maximum BTE value of 33.59% was obtained with B10 fuel at an engine load of 16.47 Nm. This result, similar to the in-cylinder pressure and HRR results, indicates that a low-ratio CB additive creates a balanced combustion characteristic in the diesel fuel composition (Uyumaz et al., 2024b). At an engine load of 21.96 Nm, the highest BTE value of 34.39% was obtained with diesel fuel, followed by B10 and B20 fuels. At this load level, while diesel's high lower heating value and faster energy release capability became decisive factors alongside increased combustion intensity, the low energy density in CB-blended fuels became the dominant factor limiting thermal efficiency. The BTE results confirmed that the B10 blend offers optimal energy conversion performance, particularly in the medium-load range, while for B20 fuel, the negative effects associated with biodiesel were found to begin to dominate thermal efficiency.

The BSFC results for the test fuels as a function of engine load are given in Figure 4. As engine load increased, a significant decrease in BSFC was observed across all fuel types. This phenomenon is explained by improvements in thermal efficiency and reductions in the proportion of losses in total energy consumption as load increases in diesel engines (Chaurasiya et al., 2019). It was determined that the lowest BSFC values were obtained with

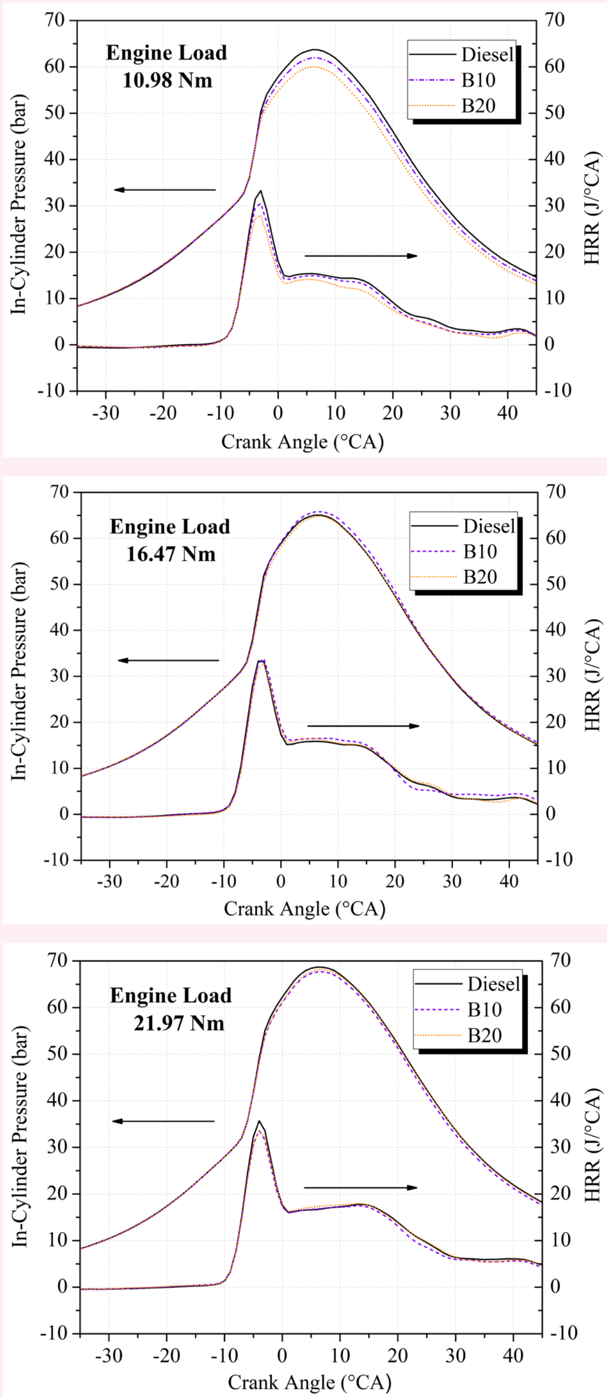

Figure 2. Effect of engine load and fuel type on in-cylinder pressure and HRR.

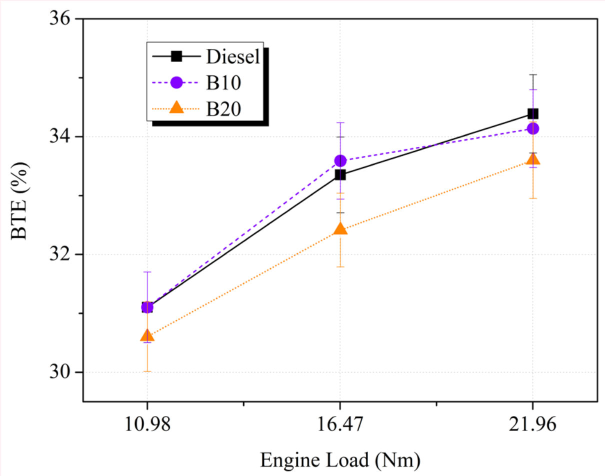

Figure 3. Effect of engine load and fuel type on BTE.

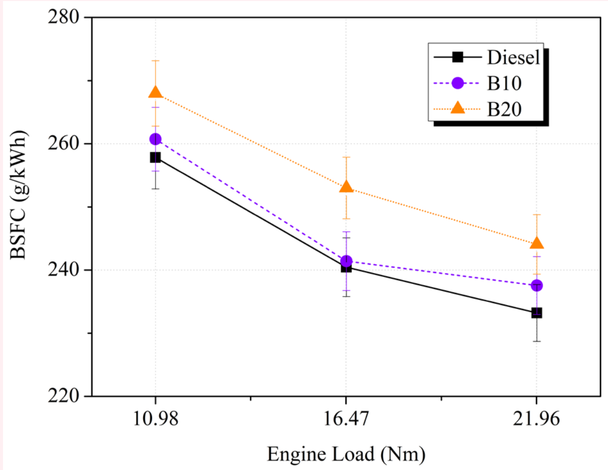

Figure 4. Effect of engine load and fuel type on BSFC.

neat diesel fuel under all load conditions; diesel's high energy content enabled the same power output to be achieved with lower fuel consumption. The BSFC value for diesel fuel was measured at 257.83 g/kWh at an engine load of 10.98 Nm, while increasing the load to 21.96 Nm reduced this value to 233.21 g/kWh. B10 fuel exhibited BSFC values very close to those of diesel fuel under all load conditions. In particular, the fact that the BSFC values of B10 and diesel fuel were very close at a load of 16.47 Nm indicates that the oxygen content derived from CB improved the combustion process while partially offsetting the negative fuel properties. B20 fuel, on the other hand, produced the highest BSFC values under all load conditions, with a maximum BSFC value of 267.97 g/kWh determined for this blend at a low load of 10.98 Nm. This situation is explained by the fact that biodiesel has a lower heating value than diesel fuel, while the increase in viscosity due to the increased CB ratio reduces the quality of injection and atomization, which is an additional factor that increases fuel consumption.

The IMEP distributions obtained at an engine load of 21.96 Nm for the test fuels and their variation across cycles are shown in Figure 5. It was determined that IMEP values for all fuel types exhibited a distribution within a specific range across cycles. The average IMEP values at the 21.96 Nm load were 6.08, 5.72, and 5.99 bar for diesel, B10, and B20 fuels, respectively. The fact that neat diesel fuel produces the highest IMEP values is attributed to its high energy density. The reason why B20 fuel exhibits IMEP values close to those of diesel fuel can be attributed to the fact that CB partially offsets the decrease in energy content by supporting the combustion process. In contrast, the lower IMEP values observed in B10 fuel stem from the limited oxygen support provided by the low CB content, which is insufficient to adequately compensate for the reduced energy density under these load conditions. The results for the COV_{IMEP}, which represents cyclic stability, were obtained as 3.55%, 4.18%, and 3.63% for diesel, B10, and B20 fuels, respectively. The fact that neat diesel fuel has the lowest COV_{IMEP} value is related to its more homogeneous spray characteristics and, consequently, more stable combustion processes. In biodiesel blends, however, the negative impact on blend formation quality increases combustion variability between cycles (Sharma et al., 2023). The higher COV_{IMEP} value observed, particularly in B10 fuel, has been attributed to mixture heterogeneity and irregularities in the premixed combustion phase. In contrast, the increased oxygen content in B20 fuel has partially stabilized combustion, resulting in a lower COV_{IMEP} value than with B10.

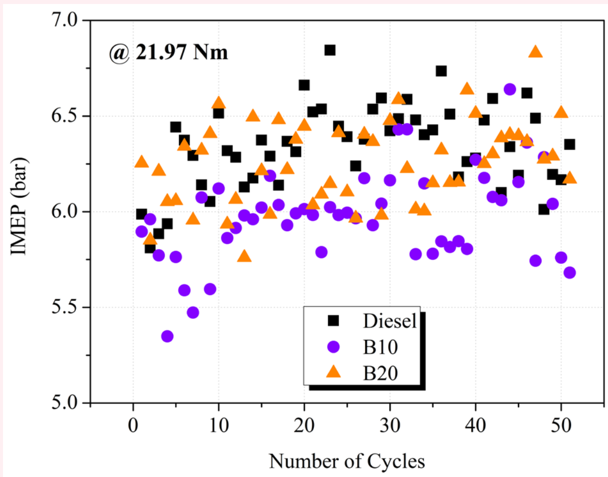

Figure 5. Effect of engine load and fuel type on IMEP distribution and cycle-to-cycle variation at 21.96 Nm engine load.

The CA50 results for the test fuels as a function of engine load are presented in Figure 6. For all fuel types, a steady increase in CA50 values was observed as engine load increased. This phenomenon is attributed to the increase in fuel quantity due to the rise in load and the combustion process becoming largely diffusion-controlled (Solmaz et al., 2016). The dominance of diffusion combustion caused the total heat release to be spread over a longer crankshaft angle range, resulting in the CA50 point shifting to later crankshaft angles. On the other hand, it was determined that the CA50 ranking across all load regions was diesel, B10, and B20. The higher CA50 values observed in diesel fuel stemmed from the heat release process being concentrated in later phases due to a longer ignition delay. Conversely, the decrease in CA50 values associated with an increasing biodiesel blend ratio is explained by the fuel's higher cetane number and the oxygen present in its molecular structure, which improves combustion kinetics, resulting in the combustion phase occurring at earlier crankshaft angles (Piloto-Rodríguez et al., 2013). In B20 fuel, where the CB ratio was increased to 20%, this effect became pronounced, leading to earlier completion of mass combustion and, consequently, the lowest CA50 values. The obtained CA50 results demonstrate that diesel-CB fuel blends shift the combustion process to earlier phases, thereby accelerating combustion timing.

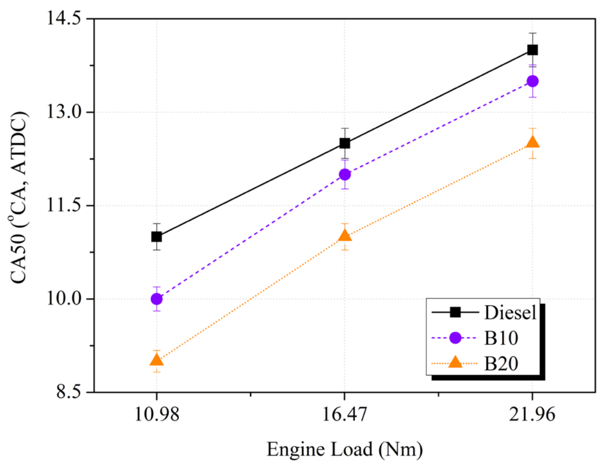

Figure 6. Effect of engine load and fuel type on CA50.

The MPRR results for the test fuels as a function of engine load are given in Figure 7. As engine load increased, the rise in in-cylinder pressure and heat release rate led to more severe pressure development, thereby increasing the MPRR values for all fuel types. However, it was determined that under all load conditions, the MPRR values followed the order of diesel, B10, and B20. The minimum MPRR value of 4.16 bar/°CA was obtained for B20 fuel at a load of 10.98 Nm, while the maximum value of 5.09 bar/°CA was determined for diesel fuel at a load of 21.96 Nm. The fact that neat diesel fuel produces higher MPRR values is attributed to the release of energy over a shorter period during combustion and a sharper pressure rise profile. In contrast, the addition of CB gradually altered this trend. Particularly in B20 fuel, it was observed that energy release was spread over a wider time interval along the crankshaft angle, and the pressure increase followed a smoother trajectory. This indicates that the combustion process becomes more controlled as the biodiesel content increases (Balasubramanian and Subramanian, 2021). In the literature, MPRR values below approximately 10 bar/°CA for diesel engines are considered to be within acceptable limits in terms of combustion noise and mechanical stress (Ardebili et al., 2021). In this context, it has been concluded that fuel blends containing CB can be used without adversely affecting the engine's combustion stability and mechanical reliability, and that they can provide more controlled combustion characteristics, particularly at high biodiesel blends.

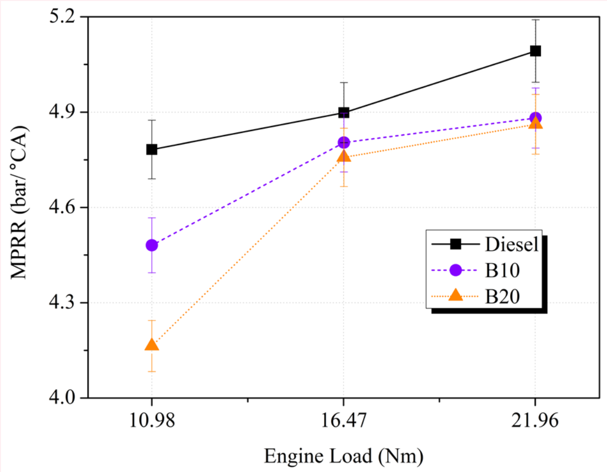

Figure 7. Effect of engine load and fuel type on MPRR.

The CO, HC, and NOx concentrations as a function of engine load for the test fuels are shown in Figure 8. When the results are evaluated together, it is observed that engine load and fuel type exert distinct and complementary effects on emission characteristics. A general upward trend in CO, HC, and NOx emissions was observed with increasing engine load across all fuel types. As the load increased, the amount of fuel injected per cycle also increased, leading to the formation of localized rich mixture regions; the oxygen deficiency in these regions increased CO and HC emissions. In particular, the dominance of diffusion-controlled combustion under high load conditions hinders the completion of oxidation reactions in some regions, leading to increased unburned combustion products (Yuvenda et al., 2022). The increase in NOx emissions, meanwhile, is associated with rising combustion temperatures and a more intense heat release profile accompanying the increased engine load. When evaluated by fuel type, it was determined that CO and HC emissions reached their maximum values with diesel fuel, while these emissions decreased with the addition of biodiesel and an increased CB ratio. In contrast, NOx emissions exhibited an opposite trend, following the order B20, B10, and diesel. The CB additive limited CO and HC formation and improved combustion quality by supporting local oxidation processes through the oxygen content in the fuel (Kuş, 2011). While this improvement also indicates more efficient energy conversion, the increased combustion efficiency and localized temperature increases have promoted NOx formation. Compared to neat diesel fuel, B20 fuel resulted in average decreases of 17.6% and 8.9% in CO and HC emissions, respectively, while NOx emissions increased by an average of 10.9%.

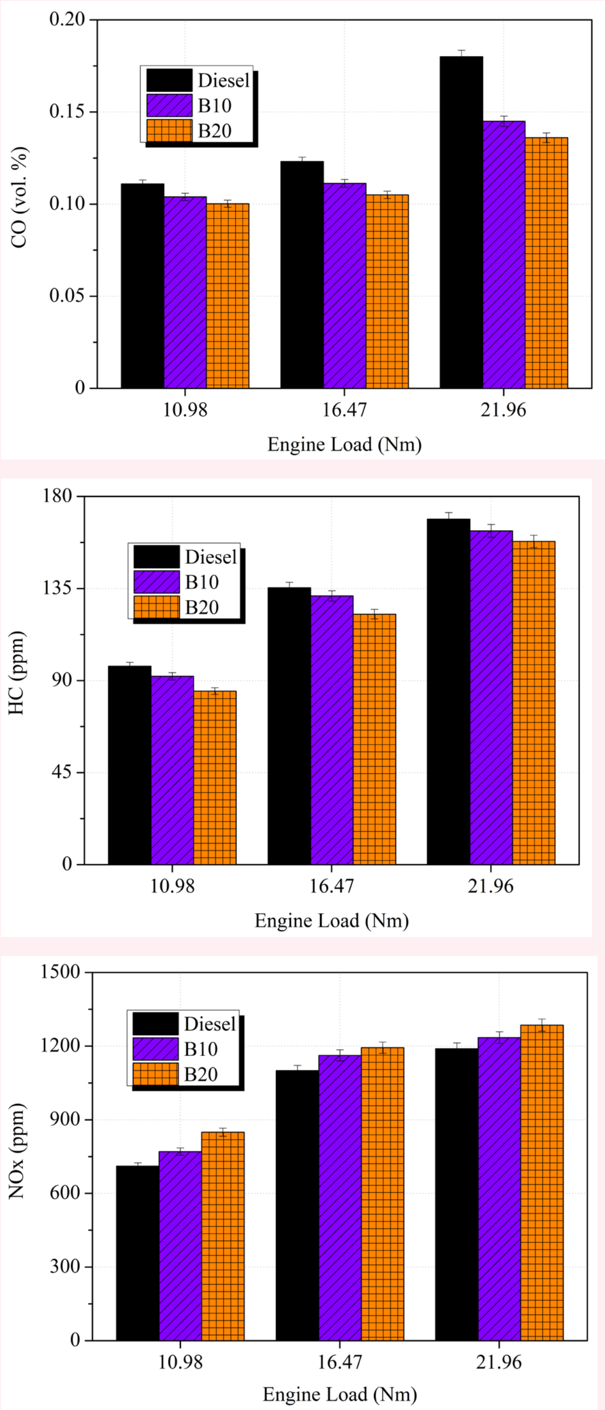

Figure 8. Effect of engine load and fuel type on CO, HC, and NOx emissions.

4. Conclusion

In this study, biodiesel was produced from corn oil to evaluate the feasibility of using biodiesel in diesel engines, and the performance, combustion, and emission characteristics of B10 and B20 fuels—prepared by blending biodiesel with diesel fuel at different ratios—were experimentally investigated. The findings indicate that the addition of biodiesel has a significant effect on engine characteristics. In particular, the B10 fuel yielded results very close to those of neat diesel fuel for BTE and BSFC, and produced the highest BTE value under medium-load conditions. When evaluated in terms of combustion characteristics, fuels containing CB exhibited lower CA50 and MPRR values, demonstrating more controlled combustion behavior. The emission results showed that CB blends reduced CO and HC emissions, while a certain increase in NOx emissions was observed. Considering the combined effects on engine performance, fuel economy, combustion characteristics, and emission behavior, B10 provided more balanced results compared with the other investigated fuel blends. On the other hand, it is evaluated that the increase in NOx emissions observed in CB-blended fuels can be effectively controlled using exhaust gas aftertreatment systems commonly used today, such as exhaust gas recirculation (EGR) and selective catalytic reduction (SCR). The findings of this study are limited to the investigated single-cylinder diesel engine, operating speed, load conditions, and corn oil biodiesel-diesel fuel blends. For future studies, it is recommended to investigate the wear and material interactions that diesel-CB blends may cause in fuel systems and engine components, to examine the effects of different blend ratios and injection parameters on engine performance, and to evaluate the long-term durability behavior of these fuel blends under extended operating conditions.

Nomenclature

A	Heat transfer surface area
BSFC	Brake specific fuel consumption
BTDC	Bottom top dead center
BTE	Brake thermal efficiency
CA	Crank angle
CA50	Combustion phase
CB	Corn oil biodiesel
CI	Compression-ignition
CeO_2	Cerium oxide
CH_3OH	Methanol
CH_3ONa	Sodium methoxide
CO	Carbon monoxides
CO_2	Carbon dioxides
COV_{IMEP}	IMEP coefficient of variation
EGR	Exhaust gas recirculation
h_g	Heat transfer coefficient
HC	Hydrocarbons
HRR	Heat release rate
IMEP	Indicated mean effective pressure
$\overline{IMEP}$	Mean IMEP value of 100 consecutive cycles
ITE	Indicated thermal efficiency
$\overline{LHV_f}$	Lower heating value of the fuel
$\dot{m}_f$	Mass flow rate of the fuel
MPRR	Maximum pressure rise rate
n	Engine speed
NaOH	Sodium hydroxide
NOx	Nitrogen oxides

O_2	Oxygen
P	Pressure
P_b	Brake power
PM	Particulate matter
Q_W	Heat transfer through the cylinder walls
SCR	Selective catalytic reduction
SFC	Specific fuel consumption
SI	Spark-ignition
T_A	Ambient temperature
T_W	Wall temperature
V	Volume
V_H	Stroke volume
$\overline{w}$	Mean piston speed
W_N	Net work
γ	Specific heat ratio
θ	Crankshaft angle
σ_{IMEP}	Standard deviation of the IMEP values

Research Ethics

The authors hereby state that the present work is in compliance with ethical standards.

Author Contributions

All authors equally contributed to Conceptualization, Investigation, Methodology, Software, Visualization, and Writing – original draft.

Competing Interests

The authors states no conflict of interest.

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The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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