Selcuk Journal of Agriculture and Food Sciences
https://dergipark.org.tr/tr/pub/selcukjafsci
Research Article

(2026) 40 (2), 319-335 DOI:10.15316/selcukjafsci.1933412 e-ISSN: 2458-8377 Selcuk J Agr Food Sci

Effect Of Camellia Sinensis Oil Methyl Ester on Engine Performance and Exhaust Emissions Under Varied Fuel Injection Pressures

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HIGHLIGHTS

- Camellia Sinensis seed oil was converted into biodiesel Camellia Sinensis Oil Methyl Ester and blended with diesel at different ratios ($B_{20}D_{80}$, $B_{50}D_{50}$, B_{100}, D_{100}).
- Engine tests were performed at full load and injector pressures of 175–200 kg/cm².

Abstract

Oil obtained from *Camellia sinensis* seeds was transesterified to produce Camellia sinensis oil methyl ester (CSOME). The experimental fuels were prepared by volumetrically blending CSOME with conventional diesel fuel, as presented in Table 1. During the experiments, the test engine was operated under full-load conditions using each fuel type, and the engine performance parameters, including torque, brake power, specific fuel consumption, and exhaust emission characteristics, were evaluated at injector pressures ranging from 175 to 200 kg/cm². The experimental results demonstrated that carbon monoxide (CO) emissions of the $B_{50}D_{50}$, $B_{20}D_{80}$, and B_{100} fuel blends were lower than those of neat diesel fuel (D_{100}). In contrast, unburned hydrocarbon (HC) emissions were higher for the biodiesel-containing blends compared with D_{100}. Carbon dioxide (CO_2) emissions increased for the $B_{50}D_{50}$, $B_{20}D_{80}$, and B_{100} blends, whereas oxygen (O_2) concentrations in the exhaust gases decreased relative to diesel fuel. Furthermore, nitrogen oxides (NO_x) emissions were found to be higher for all biodiesel blends than for pure diesel fuel. Among the tested fuels, the maximum torque value of 54.570 Nm was obtained with D_{100} at an injector pressure of 200 kg/cm² and an engine speed of 1100 rpm. The highest brake power output, 9.556 kW, was achieved using the $B_{20}D_{80}$ blend at 1900 rpm under the same injector pressure condition. In addition, the minimum specific fuel consumption was recorded as 344.512 g/kWh for the $B_{50}D_{50}$ blend at 1400 rpm and an injector pressure of 175 kg/cm².

Keywords: Alternative fuels; Biodiesel; Diesel engine; Transesterification.

Citation: Aydın, F., & Çalışkan, Özden, S. (2026). Effect Of Camellia Sinensis Oil Methyl Ester on Engine Performance and Exhaust Emissions Under Varied Fuel Injection Pressures. *Selcuk Journal of Agriculture and Food Sciences*, 40 (2), 319-335. https://doi.org/10.15316/selcukjafsci.1933412
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Received date: 18/04/2026
Accepted date: 11/05/2026

1. Introduction

Today, with the increase in the usage of motor vehicles, the risk of air pollution problems have reached significant levels (Uyaroğlu et al., 2022). Reliance on fossil-based energy resources has become a significant issue in recent years (Zullaikah et al., 2021). Growing concerns over the depletion of petroleum reserves, recurring energy crises, and heightened environmental awareness have led to an increased interest in renewable energy alternatives (Aydın and Caliskan, 2020). Scientific community has diverted the focus towards the diversification of vehicular fuels for the development of versatile solutions that are in complete conformity with environmental protection and alleviation in the use of fossils-based fuels. In this regard, biodiesels have been identified as an efficient substitution for reduction in carbon-based emissions (Iram et al., 2022). In recent years, biodiesel utilization has gained considerable significance (Şahin et al., 2023). The volume of research aimed at identifying alternative fuels for internal combustion engines has expanded markedly due to the depletion of petroleum reserves and increasing concerns over climate change (Adhikesavan et al., 2022). Moreover, the direct application of biodiesel in engines has been demonstrated to be practicable (Ropandi et al., 2022). With the exception of hydropower and nuclear energy, a substantial portion of global energy demand continues to be satisfied by fossil-based resources, including coal, natural gas, and petroleum (Akgün et al., 2009). As global energy consumption continues to rise, efforts to develop and adopt alternative energy sources have intensified accordingly. The use of biodiesel as a renewable fuel alternative to petroleum diesel is seen as an important transition strategy in the search for new energy sources (Monteiro et al. (2018). Biodiesel is regarded as one of the most promising biofuel alternatives, as it does not significantly affect engine performance characteristics when compared with conventional diesel fuel (Elkelawy et al., 2020). Biodiesel is a renewable and sustainable liquid bioenergy source that can serve as a viable substitute for conventional diesel fuel (Malabadi et al., 2023a). Due to its low emission values and biodegradability, biodiesel not only promotes environmental sustainability but also reduces dependency on fossil fuels (Şahin et al., 2025). Biodiesel can be widely used in Diesel engines with little or no alteration, and it has been demonstrated that B_{20} biodiesel can be used in diesel engines without modifying their specifications (Aydın & Serin, 2025). Biodiesel is among the contemporary renewable and environmentally benign energy sources with the potential to satisfy growing energy demands (Jan et al., 2023).

Biodiesel is a renewable, non-toxic, and environmentally benign fuel that represents an economically viable alternative to mitigate the depletion of fossil resources and their adverse environmental impacts (Keneni & Marchetti, 2017). In addition, it exhibits high combustion efficiency along with a shorter ignition delay (Jan et al., 2023). It can be utilized either in its pure form or in blends with conventional diesel with minimal engine modifications. Furthermore, owing to its relatively lower carbon content compared to fossil fuels, biodiesel contributes to the reduction of greenhouse gas emissions from transportation sources (Malabadi, 2023b). Non-edible plant oils, waste cooking oils, and by products of the edible oil industry are considered promising biodiesel feedstocks, as non-edible sources do not compete with food resources intended for human consumption (Brahma et al., 2022). Biodiesel is also recognized as a contemporary renewable and environmentally sustainable energy source with the capacity to meet increasing energy demands (Jan et al., 2023). There are so many biodiesels that can be produced from the different kinds of seeds of eatable and non-eatable vegetable oils. Among them, transesterification is one the easiest and best method to extract the biodiesel. B_{100} (Pure Biodiesel) contains 8% less energy content than its petroleum counterpart. On the other hand, biodiesel fuels exhibit superior engine cleaning effect since they act as solvents and can be used to clean the deposits accumulated in the engine due to petrol diesel use (Malabadi, 2023b). With the development in the energy crisis and environmental problems, the effective control of energy saving and the reduction of emissions in engines is a primary area of focus for scholars (Yu et al, 2021). The direct use of biodiesel on the engine is feasible (Nguyen et al, 2023). The use of biofuels in internal combustion engines has a direct influence on exhaust emission characteristics (Zare et al., 2021). Biodiesel can be produced not only from vegetable oils but also from animal fats and waste edible oils, and it may be utilized either in pure form or in blends with petroleum derived diesel fuels (Erdoğan, 2019). Consequently, there is a growing research focus on identifying novel non-edible feedstocks, particularly for biodiesel production (Serin et al., 2013).

However, the sustained and large-scale production of biodiesel from edible oils may lead to significant food security concerns unless affordable and feasible alternatives are developed (Olatundun et al., 2024). In this context, *Camellia sinensis* seed oil emerges as a promising feedstock. As a non-edible raw material, *Camellia sinensis* seed oil is suitable for biodiesel production and exhibits properties closely comparable to those of conventional diesel fuel. Moreover, biodiesel derived from *Camellia sinensis* oil does not differ markedly from biodiesels produced from other vegetable oil sources (Serin & Yıldızhan, 2018).

The production of CSOME is based on a transesterification reaction, in which the triglycerides contained in the oil are converted into fatty acid methyl esters (FAMEs) through reaction with methanol, typically in the presence of a catalyst such as sodium hydroxide or potassium hydroxide (Sairam et al., 2015). This conversion process is essential, as it modifies the physical and chemical properties of the original oil, thereby enhancing its suitability for diesel engine applications. The obtained biodiesel can subsequently be blended with conventional diesel fuel in different ratios, providing flexibility in fuel composition (Serin & Akar, 2013). Furthermore, the characterization of CSOME indicates a distinct fatty acid composition, primarily consisting of oleic acid, linoleic acid, and palmitic acid (Kim et al., 2013).

Camellia Sinensis oil is one of the cheapest vegetable oil raw materials, with a lower pour point, low viscosity and an average price of $514 per tonne compared to other vegetable oils (Serin & Akar, 2013). According to Food and Agriculture Organization of the United Nations, tea cultivation is carried out in 48 countries in the world. 21 of these countries are in the African continent, 18 in the Asian continent, 7 in the Americas, 1 in the European continent and 1 in the Australian continent (Türkyılmaz, 2015). Moreover, the economic viability of CSOME as a biodiesel feedstock is supported by the availability of Camellia sinensis seeds, which are often considered a by-product of tea production. Utilizing these seeds for biodiesel production not only adds value to agricultural waste but also promotes sustainable practices in the tea industry (Seyis et al., 2019).

Biodiesel is produced via the transesterification process, in which triglycerides present in vegetable oils are converted into methyl esters. Although transesterification constitutes the principal stage in biodiesel production, additional processing steps are necessary to obtain a final product that complies with international quality standards. Accordingly, once the chemical reaction is completed and phase separation has occurred, the resulting methyl ester mixture must undergo purification to reduce impurity levels to acceptable limits (Durmuş & Koçer, 2017). For biodiesel to be applicable in diesel engines, its physicochemical properties must satisfy specified regulatory standards. In this context, the European diesel fuel standard TS EN 590 is also applicable in Türkiye. This standard defines several critical parameters, including ester content, density, kinematic viscosity, flash point, cetane number, sulfur content, water content, and iodine value. Similarly, the European biodiesel standard EN 14214 is also valid in Türkiye and sets the quality requirements for biodiesel fuels (Akgün et al., 2009).

There are some studies on tea seed in the literature.

Serin et al. (2014) conducted experimental investigations on a four-cylinder, four-stroke, direct-injection diesel engine. Their findings indicated that a blended fuel composed of tea seed (20%), soybean (20%), cottonseed (20%), and diesel (40%) exhibited satisfactory fuel properties for engine application. The results showed that while carbon monoxide (CO) and carbon dioxide (CO_2) emissions decreased, nitrogen oxides (NO_x) emissions increased with rising biodiesel content in the fuel blends. Additionally, the proportion of diesel fuel was reduced to 40% through blending with the biodiesel mixture.

According to the experimental outcomes, it was further observed that mixed fuels led to an increase in NO_x emissions and brake specific fuel consumption compared to conventional diesel fuel, whereas engine power output, torque, and emissions of CO, CO_2, and hydrocarbons (HC) were reduced (Aydın et al., 2023). The study highlights contemporary literature on biodiesel combustion strategies aimed at enhancing engine performance and mitigating exhaust emissions. The application of such strategies in compression ignition engines is recognized as an effective approach for reducing harmful emissions, with literature indicating that biodiesel can substantially decrease CO, HC, and particulate matter (PM) emissions (Azad et al., 2023).

In another study, Serin and Yıldızhan (2018) investigated a glow-plug assisted direct-injection diesel engine and reported that when diesel *Camellia sinensis* seed oil biodiesel blends (B_{10} and B_{20}) were used instead of neat diesel fuel, higher brake specific fuel consumption and lower torque values were obtained.

This study provides an original contribution by comprehensively investigating the effects of biodiesel derived from tea seed oil (tea oil methyl ester) when blended with diesel fuel at various ratios on engine performance and emission characteristics. Although biodiesel produced from a wide range of vegetable oils has been extensively examined in the literature, the utilization of tea seed oil in this context remains relatively limited. In this respect, the study highlights the potential of tea seed oil as an alternative feedstock.

Furthermore, the simultaneous evaluation of engine performance, specific fuel consumption, and exhaust emissions under different injector pressures (175 and 200 kg/cm²) and blend ratios broadens the scope of the research and provides novel data to the existing literature. Overall, the study offers new and original insights into both alternative fuel research and diesel engine performance analysis.

2. Materials and Methods

Camellia Sinensis oil methyl esters were obtained from Camellia Sinensis seed oil by transesterification, then mixed with diesel fuel in certain proportions by volume and engine performance and exhaust emission tests were carried out on the diesel engine at different nozzle pressures. In the experiments, one-cylinder, water-cooled, Super Star 11015 brand diesel engine with 15 HP power and connected to a hydraulic dynamometer was used. BİLSA MOD 2210 brand exhaust emission device was used to measure the waste gases resulting from the combustion of fuels. To produce Camellia Sinensis oil methyl ester, a methyl ester(biodiesel) production reactor located in the Energy Systems Engineering Laboratory of Necmettin Erbakan University Engineering Faculty was used. Experimental fuel was obtained by mixing the methyl ester(biodiesel) fuel obtained from Camellia Sinensis oil with diesel oil at a rate of 20% and 50% by volume. The names and mixing ratios of the fuel mixtures created are given in Table 1. Euro diesel required for fuel mixtures was obtained from OPET Petroleum Company. The lubricating oil of the diesel engine to be used in the experiments is OPET 20W-50 engine oil recommended by the manufacturer.

Table 1. Names and mixing ratios of fuel mixtures

Fuels	Eurodiesel	CSOME
D_{100}	100	0
B_{100}	0	100
$B_{50}D_{50}$	50	50
$B_{20}D_{80}$	80	20

The technical specifications and measurement data of the exhaust emission measuring device are given in Table 2.

Table 2. Technical specifications of exhaust emission device

Parameters	Boundary	Sensitivity
CO	0-%10	0,01%
CO_2	0-%20	0,01%
HC	0-10000	1 ppm
O_2	0-%25	0,01%
NO_x	0-5000	1 ppm
Lambda	0-5	0,001

The experimental setup is given in Figure 1. The properties of the test fuels are given in Table 3.

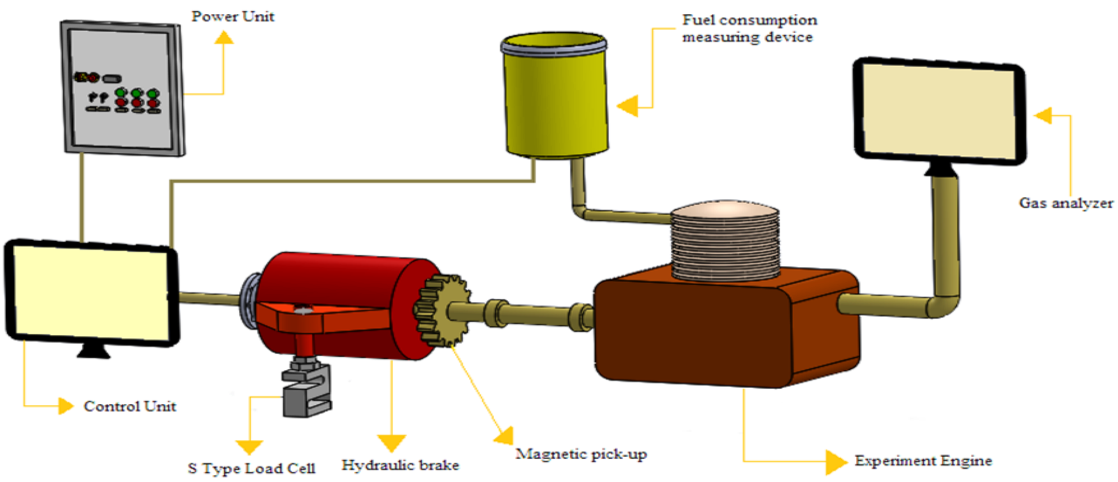


Figure 1. Test set-up

The fuel properties of the experimental fuels were compared with TSEN590 for diesel fuel and TSEN14214 for methyl ester (biodiesel) standards measured in laboratory conditions. Engine tests were carried out under EN 1231 standard conditions.

Table 3. Analysis Results of Test Fuels (Çalışkan, 2021)

Characteristic Property	Unit	Camellia Sinensis Oil	D_{100}	B_{100}	$B_{50}D_{50}$	$B_{20}D_{80}$	Limiting Values	
							Diesel	Biodiesel
Density (15 ºC)	g/cm³	0.913	0.827	0.893	0.857	0.841	0.82- 0.84	0.86-0.90
Kinematic Viscosity (40 ºC)	mm²/s	36.507	2.929	8.813	5.036	3.173	2-4.5	3.5-5
Cetane Number	---	65	52.9	68.1	59.2	54.1	51	---
pH	---	7.58	5.12	6.83	6.41	5.95	---	---
Cloud Point	ºC	-10.7	-4	-2.3	-3.1	-3.76	---	---
Pour Point	ºC	-17.3	-15	-4.5	-8.1	-11.2	---	---
Freezing point	ºC	-22.1	-21	-12.6	-15.7	-18.3	---	---
Calorific Value	Cal/gr	-------	10399	9582	10234	10344	---	---
Color	ASTM	0.5	0.6	0.5	0.5	0.5	---	---
Flash Point	ºC	188	61	123	82	73	55	120
CFPP	ºC	-------	-14	-3.8	-7	-9.5	-20	-15

3. Results

3.1.1. Torque (engine)

Camellia Sinensis oil methyl ester (CSOME)- Diesel fuel mixtures using 175 and 200 kg/cm² fuel nozzle pressure, the changes in torque values depending on speed in the experiments performed at different speeds in full load condition are shown in Figure 2.

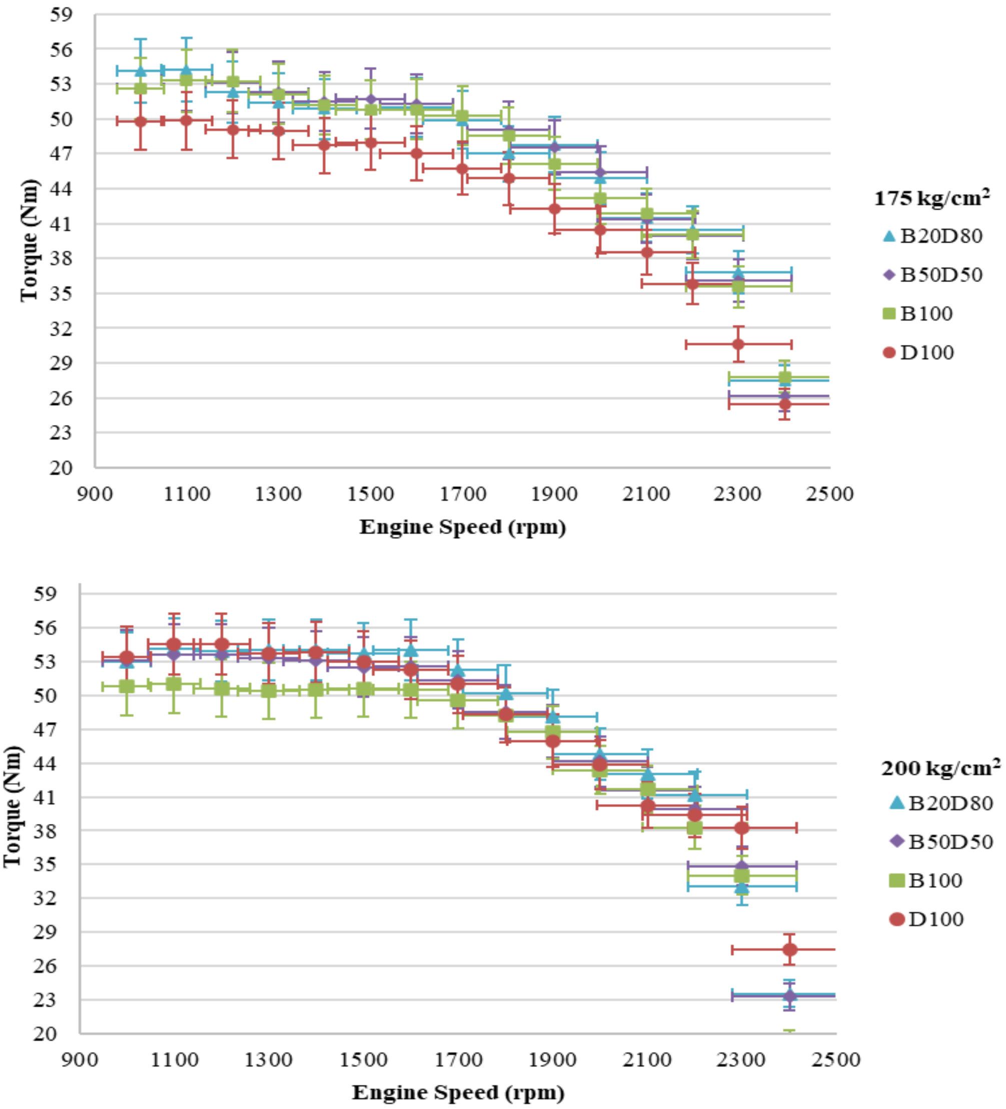


Figure 2. Moment changes of test fuels at 175 and 200 kg/cm² injector(nozzle) pressure

Maximum torque was measured as 54,235 Nm at 1100 revolutions per minute with $B_{20}D_{80}$ fuel at 175 kg/cm² nozzle pressure. Compared to the D_{100} fuel, an increase of 6.99%, 8.85% and 6.94% was observed in the fuels in the form of $B_{50}D_{50}$, $B_{20}D_{80}$ and B_{100}. Working with D_{100} fuel at 200 kg/cm² nozzle pressure, it was measured as 54.570 Nm at 1100 revolutions per minute. Compared to the D_{100} fuel, a decrease of 1.67%, 0.76% and 6.49% was observed in the fuels in the form of $B_{50}D_{50}$, $B_{20}D_{80}$ and B_{100}.

3.1.2. Power (engine)

Camellia Sinensis oil methyl ester (CSOME) - The changes in the power values depending on the speed in the experiments carried out in full load condition at different speeds in the use of 175 and 200 kg/cm² fuel nozzle pressures of diesel fuel mixtures are shown in Figure 3. Maximum power was measured as 9.477 kW at 175 kg/cm² nozzle pressure at 1900 revolutions per minute with $B_{20}D_{80}$ fuel. Compared to the D_{100} fuel, an increase of 11.88%, 11.84% and 8.48% was observed in the fuels in the form of $B_{50}D_{50}$, $B_{20}D_{80}$ and B_{100}. In the operating condition at 200 kg/cm² nozzle pressure, it was measured as 9.556 kW in $B_{20}D_{80}$ fuel at 1900 revolutions per minute. Compared to the D100 fuel, an increase of 0.9%, 4.19% and 1.52% was observed in the fuels in the form of $B_{50}D_{50}$, $B_{20}D_{80}$ and B_{100}.

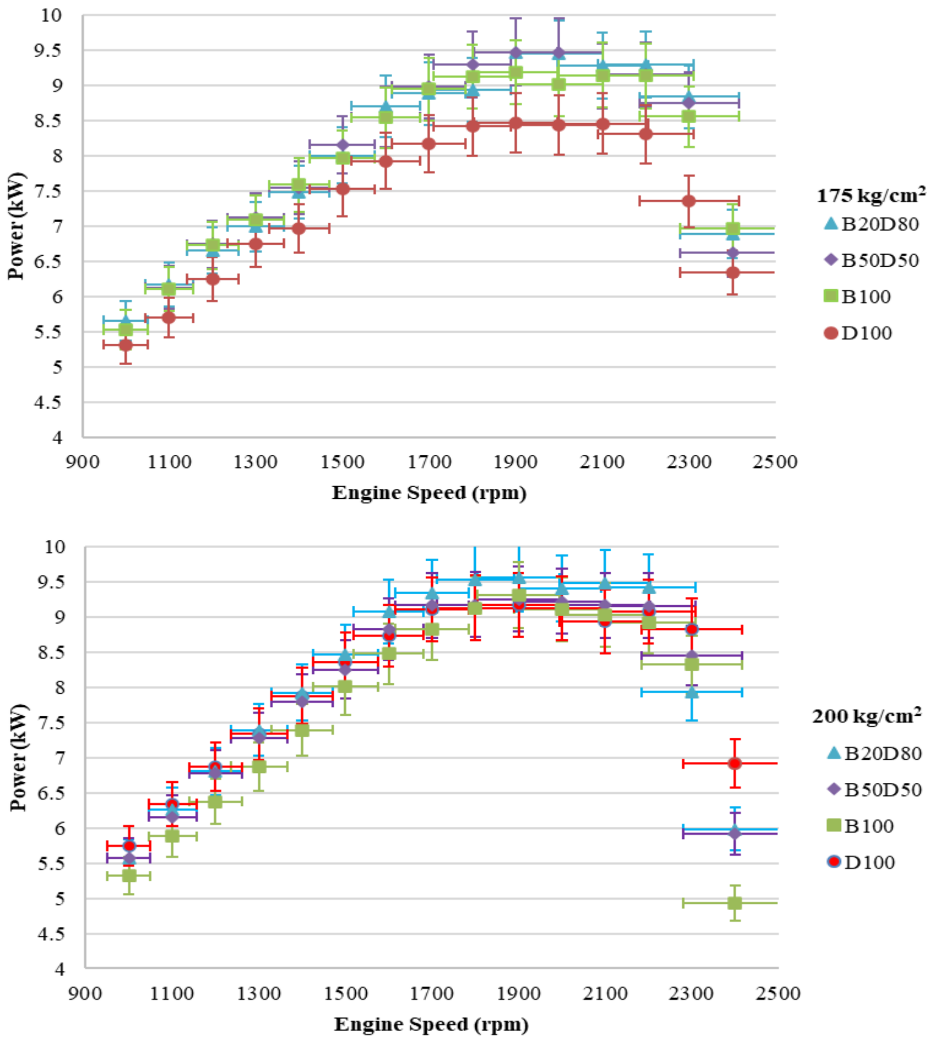


Figure 3. Power changes of test fuels at 175 and 200 kg/cm² injector(nozzle) pressure

3.1.3. Fuel consumption (specific)

Camellia Sinensis oil methyl ester (CSOME) - The changes in specific fuel consumption values depending on the speed in the experiments carried out in full-load condition at different speeds in the use of 175 and 200 kg/cm² fuel nozzle pressures of diesel fuel mixtures are shown in Figure 4. The minimum specific fuel consumption was measured as 344.512 g/kWh in $B_{50}D_{50}$ fuel at 175 kg/cm² nozzle pressure and 1400 revolutions per minute operating condition. Compared to D_{100} fuel, there is a 4.67%, 4.19% and 3.98% decrease in $B_{50}D_{50}$, $B_{20}D_{80}$ and B_{100} fuels. In the operating condition at 200 kg/cm² nozzle pressure, it was measured as 350,213 g/kWh in $B_{50}D_{50}$ fuel at 1400 revolutions per minute. Compared to D100 fuel, there is 1.06% decrease, 0.33% decrease and 4.72% increase in $B_{50}D_{50}$, $B_{20}D_{80}$ and B_{100} fuels.

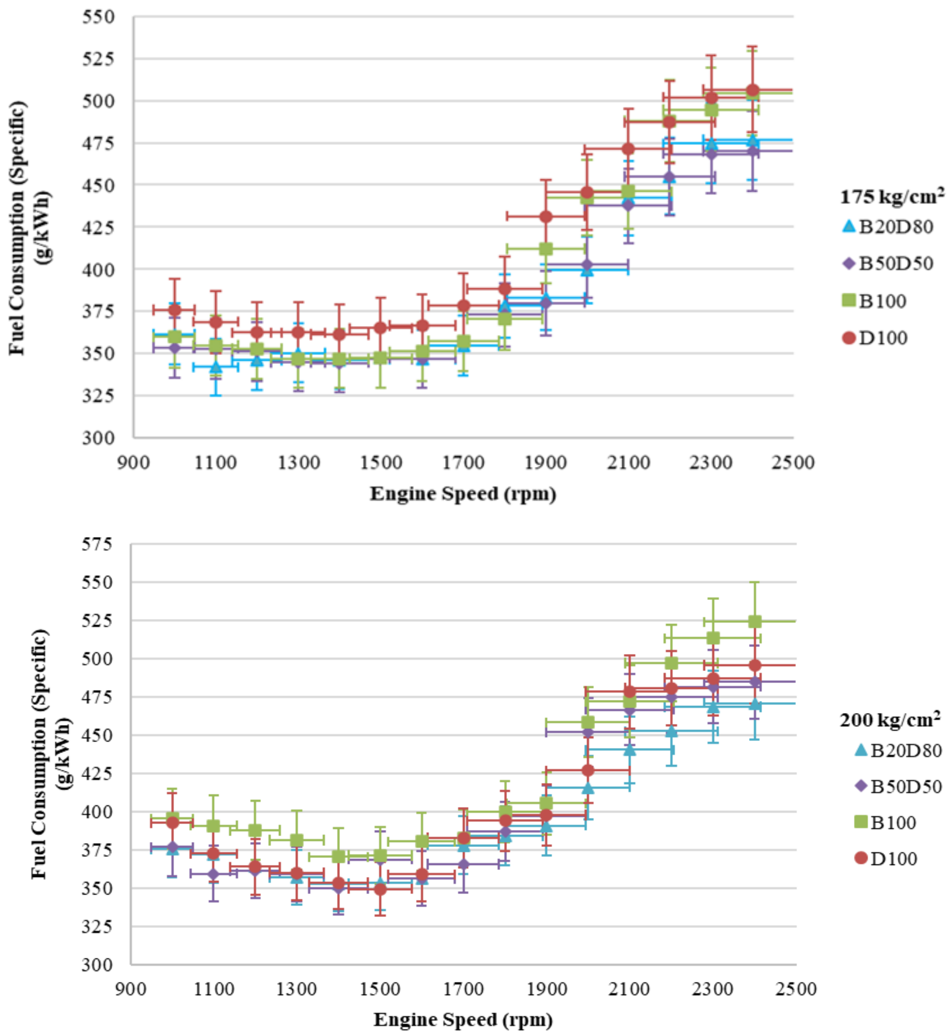


Figure 4. Specific fuel consumption changes of test fuels at 175 and 200 kg/cm^2 injector(nozzle) pressure

When the torque, effective power and specific fuel consumption values were examined because of the experiments, the results obtained by Canakci et al., 2009) and Öğüt et al. (2013) is like the studies done.

3.1.4. Carbon monoxide (CO)

Carbon monoxide (CO) is a product of incomplete fuel combustion. Ideally, the carbon content in fuel is fully oxidized to carbon dioxide (CO_2); however, due to insufficient oxygen availability in the intake air, complete oxidation may not occur. As a result, incomplete combustion of carbon-containing compounds leads to the formation of CO (Zhang et al., 2022).

The changes in the CO values depending on the speed in the experiments carried out in full load condition at different speeds in the use of 175 and 200 kg/cm^2 fuel nozzle pressures of the Camellia Sinensis oil methyl ester (CSOME) - diesel fuel mixtures are shown in figure 5.

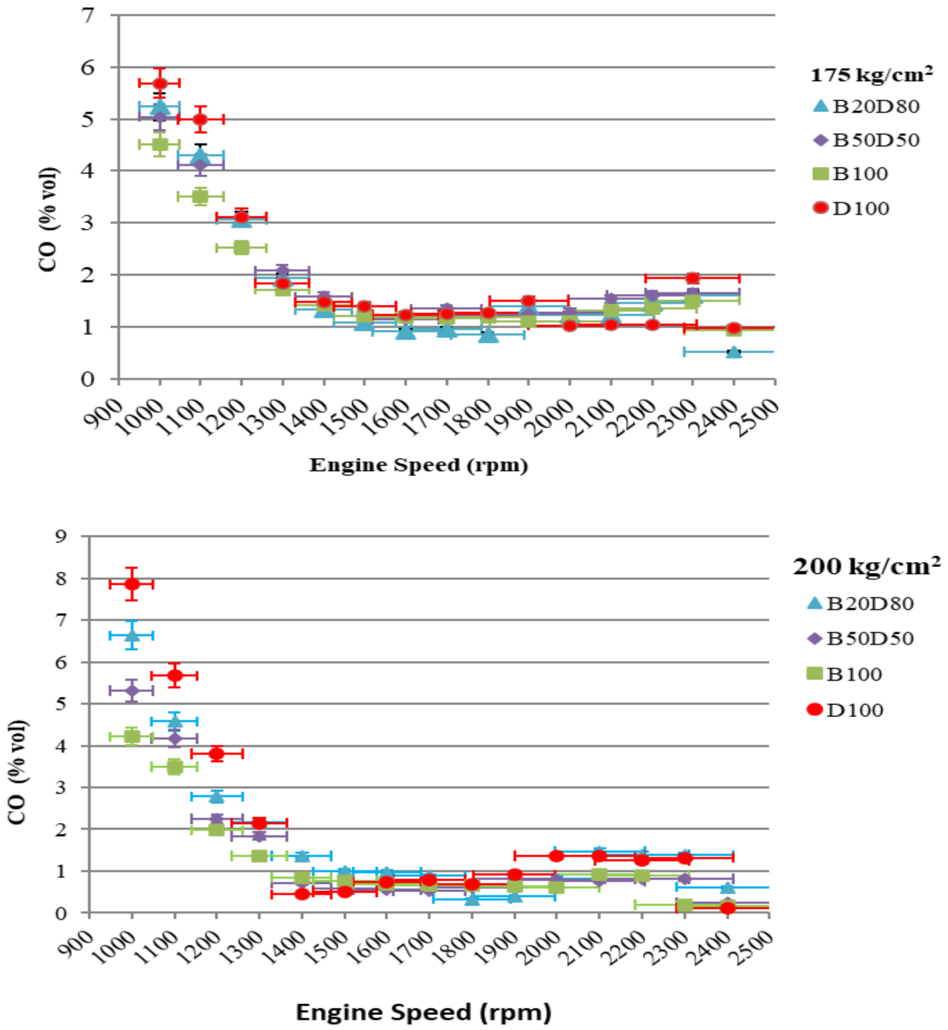


Figure 5. Carbon monoxide emission changes of test fuels at 175 and 200 kg/cm^2 injector(nozzle) pressure

Carbon monoxide emissions are reduced by 13.84%, 17.67% and 29.69%, respectively, in fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} at maximum torque at 1100 revolutions per minute for an injector(nozzle) pressure of 175 kg/cm^2 when compared to D_{100} fuel. At the maximum power at 1900 revolutions per minute, fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show a decrease of 6.91%, 17.28% and 27.32%, respectively, when compared with D_{100} fuel. In the operating condition at 200 kg/cm^2 injector(nozzle) pressure, a decrease of 19.31%, 26.45% and 38.43% is observed, respectively, in fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} at maximum torque at 1100 revolutions per minute, when compared to D_{100} fuel. At the maximum power at 1900 revolutions per minute, a decrease of 56.93%, 10.71% and 30.38% is observed in $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} fuels, respectively, when compared with D_{100} fuel.

3.1.5. Hydrocarbon (HC)

They reported that hydrocarbon (HC) emissions are dependent on both the oxygen availability and the temperature within the combustion chamber. Increased oxygen concentration and elevated combustion temperatures promote more complete fuel oxidation, thereby contributing to a reduction in HC emissions (Nguyen et al., 2020).

Camellia Sinensis oil methyl ester (CSOME) - The changes in hydrocarbon (HC) emission values depending on the speed in the experiments carried out in full load condition at different speeds in the use of 175 and 200 kg/cm^2 fuel nozzle pressures of diesel fuel mixtures are shown in figure 6. For the hydrocarbon emission operating condition at a nozzle pressure of 175 kg/cm^2, at maximum torque at 1100 revolutions per minute in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} fuels, an increase of 31.50%, 52.73% and 74.65% is observed, respectively, when compared to D_{100} fuel.

At the maximum power at 1900 revolutions per minute, there is an increase of 27.88%, 45.19% and 39.42%, respectively, when compared with D_{100} fuel in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} fuels. In the operating condition at 200 kg/cm^2 nozzle pressure, an increase of 2.46%, 4.69% and 17.89% is observed, respectively, when compared to D_{100} fuel in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} fuels at maximum torque at 1100 revolutions per minute. At the maximum power at 1900 revolutions per minute, fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show an increase of 32.38%, 38.57% and 47.61%, respectively, when compared to D_{100} fuel.

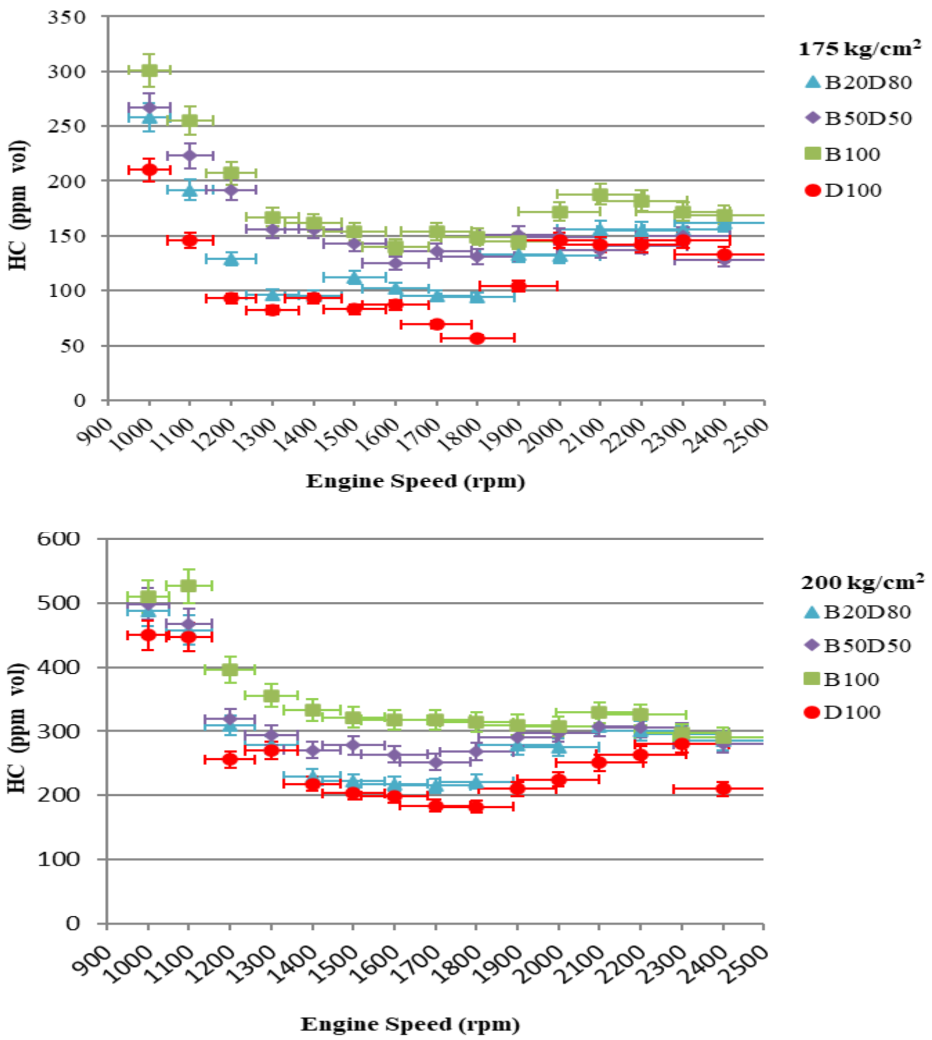
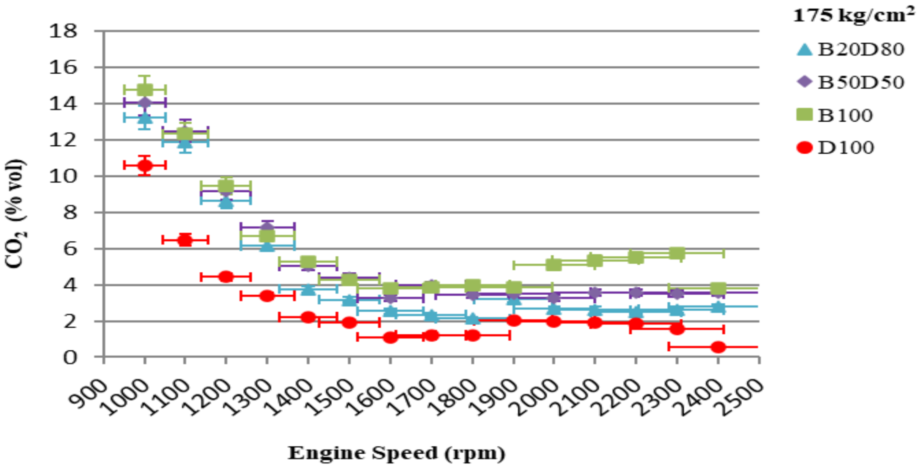


Figure 6. Hydrocarbon emission changes of test fuels at 175 and 200 kg/cm^2 injector(nozzle) pressure

3.1.6. Carbon dioxide (CO_2)

Camellia Sinensis oil methyl ester (CSOME) - Carbon dioxide (CO_2) emissions, depending on speed, were determined in the experiments carried out in full load condition at different speeds in the use of 175 and 200 kg/cm^2 fuel nozzle pressures of diesel fuel mixtures.

Carbon dioxide (CO_2) is a primary product of complete combustion within the combustion chamber and is recognized as a greenhouse gas. Therefore, CO_2 emissions from diesel engines operating with biodiesel blends must be carefully regulated and controlled (Zhang et al., 2022). In contrast, carbon monoxide (CO) emissions serve as an indicator of incomplete combustion and the presence of unoxidized carbon species in the exhaust gases (Bouighi et al., 2026). Changes in the values can be seen in Figure 7.



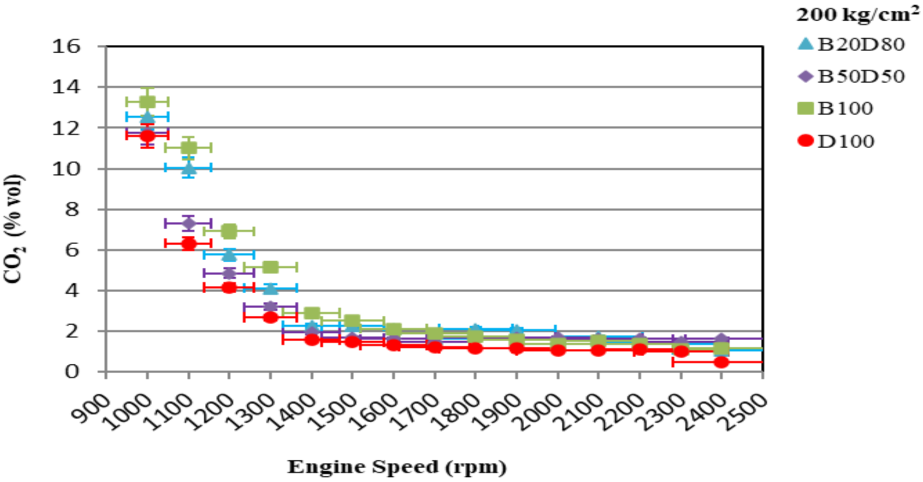


Figure 7. Changes in carbon dioxide emissions of test fuels at 175 and 200 kg/cm^2 injector pressure

Maximum torque at 1100 revolutions per minute for carbon dioxide emission 175 kg/cm^2 nozzle pressure; Fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show an increase of 83.48%, 92.94% and 90.72%, respectively, when compared to D_{100} fuel. At the maximum power at 1900 revolutions per minute, fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show an increase of 57.39%, 71.59% and 90.53%, respectively, when compared with D_{100} fuel. In case of operation at a nozzle pressure of 200 kg/cm^2, the maximum torque is at 1100 revolutions per minute; $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} fuels show an increase of 58.81%, 15.40% and 74.24%, respectively, when compared to D_{100} fuel. At the maximum power at 1900 revolutions per minute, fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show an increase of 78.74%, 48.43% and 37.97%, respectively, when compared with D_{100} fuel.

3.1.7. Oxygen (O_2)

Camellia Sinensis oil methyl ester (CSOME) - The changes in oxygen (O_2) values depending on the speed in the experiments carried out in full load condition at different speeds in the use of 175 and 200 kg/cm^2 fuel nozzle pressures of diesel fuel mixtures are shown in figure 8. Oxygen values are reduced by 16.23%, 15.76% and 4.70% in fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} at maximum torque at 1100 revolutions per minute for the operating condition at 175 kg/cm^2 nozzle pressure, when compared to D_{100} fuel. At the maximum power at 1900 revolutions per minute, there is a 0.57%, 4.98% and 5.90% decrease in fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B100 compared to D100 fuel. In the case of operating at 200 kg/cm2 nozzle pressure, a decrease of 28.72%, 11.85% and 34.04% is observed in fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} at maximum torque at 1100 revolutions per minute compared to D_{100} fuel. At the maximum power at 1900 revolutions per minute, a decrease of 12.24%, 5.07% and 2.56% is observed in fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100}, when compared with D_{100} fuel.

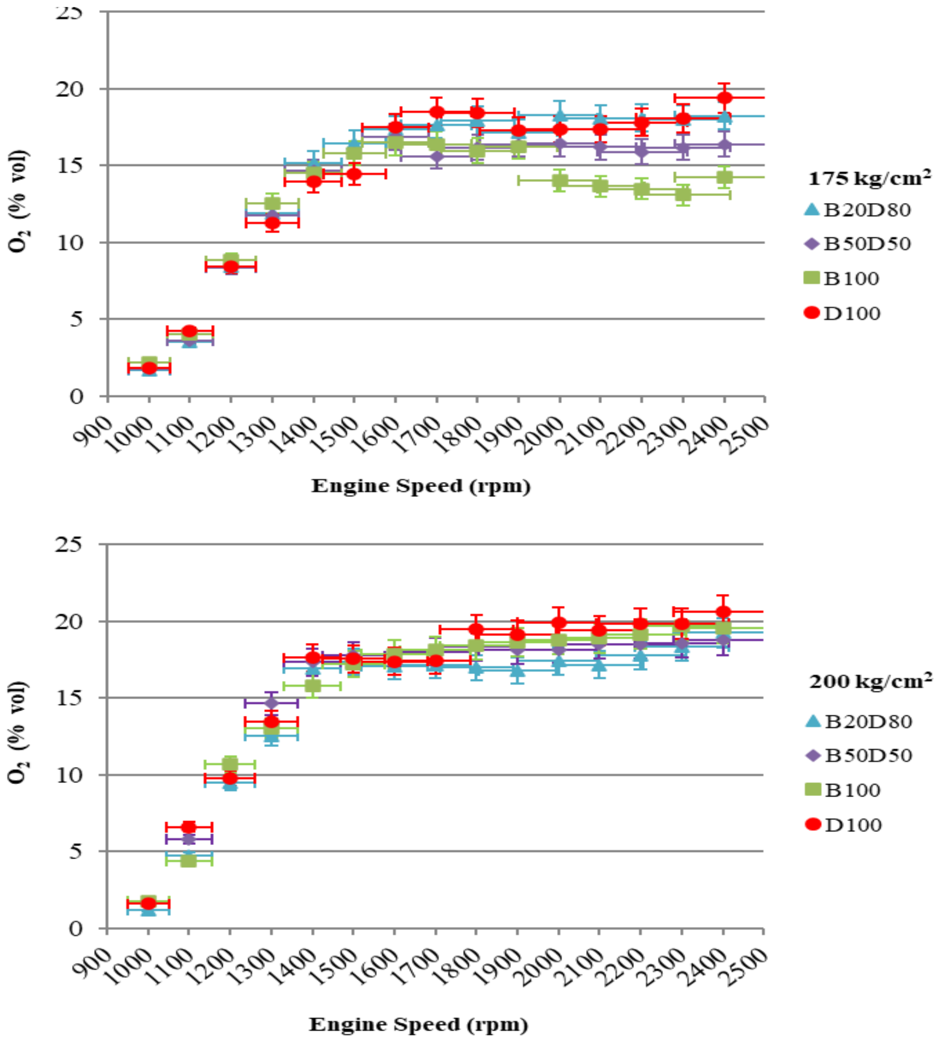


Figure 8. Oxygen changes of test fuels at 175 and 200 kg/cm^2 injector(nozzle) pressure

3.1.8. Nitrogen (NO_x)

According to the majority of published studies, biodiesel generally produces higher nitrogen oxides (NO_x) emissions compared to conventional fossil diesel. The formation of NO_x is a complex phenomenon influenced by multiple factors, including engine operating conditions, combustion chamber geometry, fuel injection system characteristics, in cylinder combustion temperature, oxygen availability, residence time, and overall thermal conditions in biodiesel fueled diesel engines (Zhang et al., 2022). The changes in nitrogen oxide (NO_x) emission values depending on the speed in the experiments carried out in full load condition at different speeds in the use of 175 and 200 kg/cm^2 fuel nozzle pressures of the Camellia Sinensis oil methyl ester (CSOME) – diesel fuel mixtures are shown in figure 9. Nitrous oxide emission at 175 kg/cm^2 nozzle pressure, maximum torque at 1100 revolutions per minute; Fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show an increase of 94.84%, 92.43% and 97.25%, respectively, when compared to D_{100} fuel. At the maximum power at 1900 revolutions per minute, fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show an increase of 4.54%, 68.18% and 77.27%, respectively, when compared to D_{100} fuel. In case of operation at a nozzle pressure of 200 kg/cm^2, the maximum torque is at 1100 revolutions per minute; Fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show an increase of 4.68%, 6.92% and 27.49%, respectively, when compared to D_{100} fuel. At the maximum power at 1900 revolutions per minute, fuels in the form of $B_{20}D_{80}$, $B_{50}D_{50}$ and B_{100} show an increase of 4.49%, 8.98% and 57.30%, respectively, when compared to D_{100} fuel.

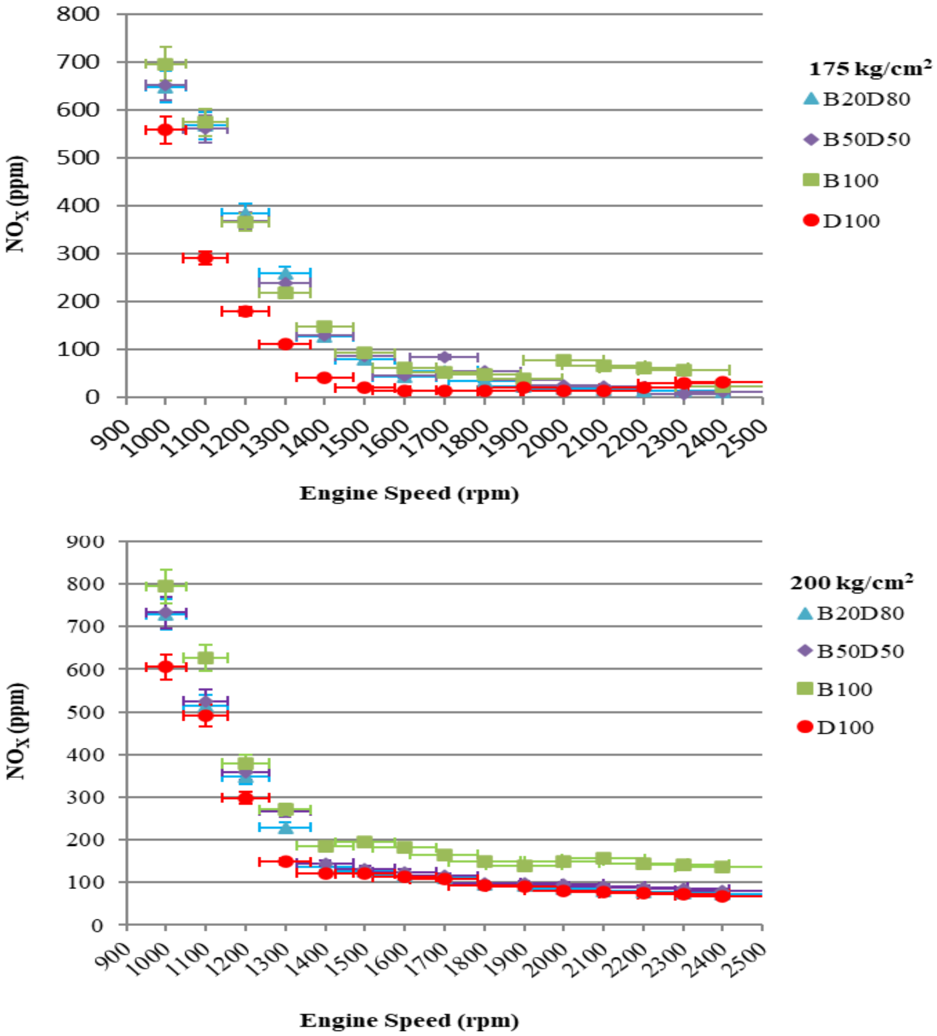


Figure 9. Nitrogen oxide emission changes of test fuels at 175 and 200 kg/cm² injector(nozzle) pressure

When the exhaust emissions (CO), (HC), (CO2), (O_2) and (NO_x) values obtained because of the experiments are examined, the results obtained are like the studies of (Özdemir, 2011), (Aydın & Öğüt, 2017) and Şahin (2019).

4. Conclusions

The experimental results demonstrate that injector nozzle pressure and fuel composition significantly influence the performance and emission characteristics of the test engine. Under full-load operating conditions, the engine was fueled with diesel fuel (D_{100}), Camellia Sinensis oil methyl ester (B_{100}), and their blends, while torque, brake power, specific fuel consumption (SFC), and exhaust emissions were evaluated at injector pressures of 175 and 200 kg/cm².

At an injector pressure of 175 kg/cm², the maximum torque values for Camellia Sinensis oil methyl ester and its blends were obtained at approximately 1100 rpm, despite their lower heating values compared to diesel fuel. This behavior can be attributed to the oxygenated structure of biodiesel, which enhances combustion efficiency, particularly at low engine speeds where combustion duration is relatively longer. The additional oxygen content in biodiesel contributes to improved oxidation reactions, resulting in slightly higher torque characteristics under low-speed operating conditions. However, when the injector pressure was increased to 200 kg/cm², the fuel spray became finer and more atomized, leading to improved fuel–air mixing and more stable combustion. Although combustion quality improved with higher injector pressure, the lower calorific value of biodiesel still caused the torque values of B_{100}, and its blends remain below those of diesel fuel.

A similar trend was observed in brake power characteristics. At 175 kg/cm² injector pressure, the higher cetane number and superior lubricity properties of Camellia Sinensis oil methyl ester contributed positively to combustion quality, especially at higher engine speeds. Consequently, biodiesel blends exhibited competitive and, in some cases, higher power outputs compared to diesel fuel. Increasing the injector pressure to 200 kg/cm² further enhanced atomization and combustion regularity, resulting in improved power production at elevated engine speeds. These findings indicate that higher injector pressures can partially compensate for the lower energy content of biodiesel fuels by improving spray characteristics and combustion efficiency.

Specific fuel consumption results revealed that biodiesel fuels generally exhibited higher consumption values than diesel fuel because of their lower heating values. Nevertheless, at 175 kg/cm² injector pressure, the oxygenated structure of Camellia Sinensis oil methyl ester promoted more efficient combustion at lower engine speeds, thereby reducing SFC under certain operating conditions. At 200 kg/cm² injector pressure, improved atomization and combustion stability were observed; however, the inherently lower calorific value of biodiesel continued to increase fuel consumption relative to diesel fuel.

Exhaust emission analyses showed that carbon monoxide (CO) emissions decreased for biodiesel blends at both injector pressures. This reduction is associated with the oxygen-containing molecular structure of biodiesel, which facilitates the oxidation of CO into carbon dioxide (CO_2) during combustion. Conversely, hydrocarbon (HC) emissions tended to increase, particularly at lower engine speeds. This increase may be explained by relatively low in-cylinder temperatures and delayed fuel evaporation characteristics, which contribute to incomplete combustion. At higher engine speeds, the formation of locally lean air–fuel mixtures further intensified HC emissions.

Carbon dioxide (CO_2) emissions were generally higher for biodiesel blends than for diesel fuel at both injector pressures. The elevated CO_2 levels are attributed to the higher excess air coefficient and improved oxidation processes resulting from the oxygen content of biodiesel fuels. Additionally, because diesel fuel possesses lower density than biodiesel blends, it occupies a greater effective volume within the combustion chamber, thereby reducing the amount of fresh air available for combustion. Oxygen (O_2) emission trends indicated lower oxygen concentration at reduced engine speeds; however, with increasing engine speed, the oxygenated nature of biodiesel improved combustion efficiency and enhanced oxidation reactions.

Nitrogen oxide (NO_x) emissions increased at both 175 and 200 kg/cm² injector pressures for biodiesel-containing fuels. The higher oxygen availability in biodiesel blends promotes elevated in-cylinder combustion temperatures, which accelerate thermal NO_x formation mechanisms. This behavior is consistent with findings reported in the literature for oxygenated alternative fuels.

Overall, the results indicate that increasing injector pressure improves spray atomization, combustion stability, and engine performance characteristics for biodiesel fuels. Although biodiesel blends exhibit disadvantages in terms of lower heating value and increased fuel consumption, their oxygenated structure contributes positively to combustion efficiency and reductions in CO emissions. Therefore, Camellia Sinensis oil methyl ester appears to be a promising alternative fuel for diesel engines, particularly when optimized injector pressures are employed.

Error bars presented in the graphs represent the confidence intervals of the experimental measurements and are used to illustrate the uncertainty and variability associated with the obtained data. These error bars provide a visual indication of the reliability and repeatability of the experimental results.

Funding: This research received no external funding.

Acknowledgments: This study is prepared as a part of Sena Çalışkan's Ms. thesis (Advisor: Dr. Fatih AYDIN)

Conflicts of Interest: The authors declare no conflict of interest.

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