# PERFORMANCE, EMISSIONS, AND COMBUSTION IN TURBOCHARGED DIESEL ENGINES
## The Effect of Rapeseed Oil Biodisel-Diesel Blends

by

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*The need for sustainable alternative fuels is becoming increasingly urgent because to the rapidly expanding demand for automobiles and the growing concerns over the fossil fuel diminution. This research looks into how biodiesel, specifically blends made from rapeseed oil (RSO), can fill this new need. The RSO is created through transesterification, which yields a biodiesel with characteristics that meet ASTM requirements. In a 5.1 kW, single-cylinder, turbocharged Diesel engine (Turbo-DE), the performance, emissions, and combustion (P-E-C) characteristics of several RSO-diesel blends (B20, B40, B60, and B80) are examined and contrasted with those of pure diesel. According to the findings, brake thermal efficiency slightly decreases as biodiesel proportion in the blend rises. The environmental advantages of these blends are offset by a sizable decrease in smoke, CO, and hydrocarbon emissions. On the other hand, greater biodiesel ratios result in higher emissions of* $NO_x$ *and* $CO_2$*. The thermal efficiencies of the brakes for diesel, B20, B40, B60, and B80 blends were found to be 29.3%, 28.6%, 27.9%, 27.2%, and 26.9%, respectively, in the detailed results. While smoke emissions decreased from 55% (diesel) to 40% (B80),* $NO_x$ *emissions ranged from 1556 ppm (diesel) to 1718 ppm (B80). The B20 blend's combustion characteristics closely resemble those of diesel, with maximum cylinder pressures and ignition delay of 78 bar, 73 bar, 20%, and 18%, respectively, for diesel and B20. These results offer a good starting point for additional investigation into sustainable alternative fuels by shedding light on the prospective performance and ecological impact of biodiesel-diesel mixes.*

*Key words: combustion characteristics, Diesel engine performance, emissions analysis, alternative fuels, RSO biodiesel*

## Introduction

The ongoing global concern over fossil fuel depletion and escalating environmental pollution has underscored the urgent need for viable and sustainable alternatives to conven-

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tional fuels. This has motivated an increased interest in biodiesel fuels, which are not only renewable but also have a lower environmental impact compared to fossil-based fuels [1, 2]. This review discusses previous literature related to the P-E-C characteristics of biodiesel-diesel blends, particularly focusing on RSO as the biodiesel source.

Biodiesel is produced through the transesterification process from various biofuels. Among vegetable oils, RSO has garnered significant attention due to its relatively low production cost, high oil yield, and compatibility with existing Diesel engine [3, 4]. A research found that RSO biodiesel possesses properties close to those of petroleum-based diesel, thereby making it a promising candidate for use as a biodiesel feedstock [5].

Performance characteristics of biodiesel-diesel blends have been widely explored in recent years. A study determined that the performance of Diesel engine tends not to be significantly affected when biodiesel replaces a portion of conventional diesel fuel [6, 7]. In agreement, an author conducted experiments using different biodiesel-diesel blends and found that blends up to 20% biodiesel (B20) exhibited similar engine performance to pure diesel [8]. However, they noticed that as the biodiesel concentration increased beyond 20%, there was a minor decrease in engine efficiency. This decrement is primarily attributed to the lower heating value of biodiesel compared to diesel fuel [9-11].

In terms of emissions, literature provides mixed insights. While biodiesel and its blends have been credited with reducing PM, CO, and HC emissions, an uptick in $NO_x$ emissions has also been observed [12, 13]. A study conducted using RSO biodiesel blends confirmed these observations, further noting that the rise in $NO_x$ emissions was more prominent with higher biodiesel blend ratios [14, 15].

Combustion characteristics of biodiesel fuels have been extensively studied, providing a better understanding of how these fuels burn in the engine combustion chamber. A study found that biodiesel has a advanced cetane number than diesel, resulting in shorter delay in ignition and therefore, leading to more controlled and complete combustion [16]. A more recent studies demonstrated that RSO biodiesel-diesel blends exhibit similar combustion characteristics to diesel fuel, especially in lower blend percentages, thereby supporting the potential for their use in Diesel engine without major modifications [17, 18].

Despite extensive research, a complete understanding of the implications of using biodiesel, specifically RSO biodiesel in Diesel engine, remains elusive. The impacts on engine P-E-C characteristics still warrant further investigation, especially in the context of higher blend ratios and varying operating conditions. Such research is critical for ascertaining the viability suitable fuel for devising strategies to mitigate any negative impacts [19-21].

The literature underscores the growing importance of finding sustainable alternatives to fossil fuels due to concerns over fuel depletion and environmental pollution. Biodiesel, specifically RSO biodiesel, has been identified as a promising fuel due to its renewability and lower environmental impact. Previous studies have examined the P-E-C characteristics of biodiesel-diesel blends. These have largely indicated that while blends up to 20% biodiesel have little impact on engine performance, higher biodiesel percentages may slightly reduce engine efficiency. Emission studies reveal a reduction in PM, CO, and HC emissions with biodiesel use, though an increase in $NO_x$ emissions is also noted. Despite extensive research, the entire impacts of increasing RSO biodiesel mix ratios on engine P-E-C characteristics are not fully understood. Furthermore, there is currently insufficient study on how these combinations operate in different operational circumstances.

This study aims to close the gap by analysing the P-E-C parameters of different RSO-diesel mixes in a turbocharged Diesel engine. The study intends to analyse the potential trade-offs in engine performance and emission effects with higher mix ratios to progress a better understanding of RSO biodiesel's viability as a sustainable alternative fuel. The study's findings will provide critical information that will aid in the development of solutions to mitigate any potential negative implications of utilising biodiesel in DE.

## Experiment method and materials

### *Experimental set-up*

The experiments used a 1-cylinder, 5.1 kW turbocharged Diesel engine. Figure 1 depicts the engine's instrumentation required to monitor and manage a variety of operational variables. To control engine load and rpm, a dynamometer was utilised, a fuel flow metre was used to measure fuel consumption, and a temperature sensor was used to monitor coolant temperature. To make the biodiesel used in the experiment, RSO was transesterified. The biodiesel produced was evaluated to ensure that its properties satisfied ASTM biodiesel requirements. The RSO biodiesel was a volumetric blend with conventional fuel to make the biodiesel blends B20, B40, B60, and B80. Furthermore, pure diesel was employed as a norm. For the emission evaluation, modern gas analyzers capable of measuring $NO_x$, CO, and HC emissions were employed. A smoke metre was also used to quantify the smoke opacity of the exhaust gases. An encoder is used to detect the accurate crank position, and a piezoelectric pressure transducer is used to monitor in-cylinder pressure for combustion analysis. The heat release rates were then calculated using the recorded pressure data and known engine characteristics.

Before each test run, the engine was warmed to steady-state temperatures, and the fuel blends were given time to settle in the fuel system. Each test was continual three times to ensure that the results were repeatable. The average results were then obtained in order to conduct additional investigation. Using this thoroughly controlled experimental system, this study intends to provide precise and reliable data on the P-E-C characteristics of RSO biodiesel-diesel mixes in a turbocharged Diesel engine. The knowledge gained will be critical in understanding RSO biodiesel's potential as an alternative fuel source and in directing future endeavours in the biodiesel fuels. The engine specification is displayed in tab. 1.

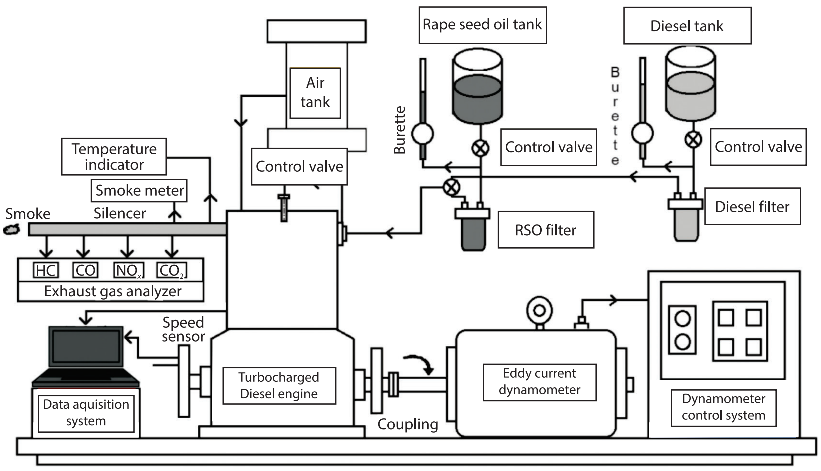


**Figure 1. Engine set-up for experiment**

**Table 1. Engine specification**

| Parameter | Specification |
|---|---|
| Cylinder numbers | Single cylinder |
| Power | 5.1 kW |
| Combustion system | Direct injection |
| Aspiration | Turbocharged |
| Fuel supply type | CRD-I |
| Cylinder diameter | 88.3 mm |
| Cylinder stroke | 115 mm |
| Compression ratio | 18.5:1 |
| Rated speed | 1500 rpm |

### *Oil preparation*

Transesterification is the process used to convert raw RSO into biodiesel. The process involves reacting the RSO with an alcohol, typically methanol or ethanol, in the presence of a catalyst, potassium hydroxide.

The transesterification process can be briefly described in three main steps:

– *Esterification*: First, any free fatty acids present in the RSO are converted into esters using an acid catalyst to prevent soap formation in the subsequent steps. This is particularly important if the free fatty acid content of the oil is higher.
– *Transesterification*: The purified RSO is then mixed with an alcohol (like methanol) and a catalyst. This mixture is heated at approximately 60-70 °C. The triglycerides present in the RSO react with the alcohol to form esters and glycerol.
– *Separation and purification*: Upon completion of the reaction, two layers form: the top layer consists of biodiesel (esters), and the bottom layer comprises glycerol. The glycerol is drained off, and the biodiesel is eroded to remove any remaining catalyst, alcohol, or soap. The biodiesel is then dried to remove any enduring water.

The resultant product is RSO biodiesel, which has properties very similar to conventional diesel fuel, making it an effective renewable substitute for diesel in various applications. The by-product glycerol can also be utilized in other industries, such as the production of soaps, pharmaceuticals, and cosmetics, further enhancing the sustainability of the process.

**Table 2. Properties comparison of diesel and RSO blends**

| Property | ASTM standard | Diesel | B20 | B40 | B60 | B80 |
|---|---|---|---|---|---|---|
| Density [kgm$^{-3}$] | 820-860 | 830 | 835 | 840 | 845 | 850 |
| Viscosity [mm$^2$s$^{-1}$] | 1.9-6.0 | 2.5 | 2.8 | 3.2 | 3.7 | 4.3 |
| Cetane number | >47 | 49 | 51 | 53 | 55 | 57 |
| Heating value [MJkg$^{-1}$] | >37 | 43 | 42.5 | 42 | 41.5 | 41 |

The tab. 2 provides a comparison between the properties of diesel and various RSO biodiesel-diesel blends (B20, B40, B60, B80), and the standard values as per the ASTM D6751 guidelines for biodiesel fuel. The properties considered include density [kgm$^{-3}$], viscosity [mm$^2$s$^{-1}$], cetane number, and heating value [MJkg$^{-1}$]. These are crucial parameters influencing engine P-E-C characteristics. The density of a fuel impacts its atomization in the combustion chamber. In our table, all fuels meet the ASTM standard for density, falling within the range of 820-860 kg/m³. Viscosity, affecting the fuel injection and atomization process, increases slightly with a higher biodiesel ratio but remains within the ASTM standard range of 1.9-6.0 mm²/s. All fuels exceed the minimum ASTM standard cetane number of 47, implying that biodiesel blends would have even better ignition properties than diesel. Heating value, indicative of the energy capacity of the fuel, decreases slightly with an increase in biodiesel content but stays above the ASTM standard minimum value of 37 MJ/kg. The tabulated data suggest that all the fuel blends, including diesel and RSO biodiesel blends, meet the ASTM standards, confirming their suitability for use in Diesel engines. These findings also set the stage for further investigation into the performance, emission, and combustion characteristics of these blends.

## Result and discussion

### *Performance characteristics*

#### *Brake thermal efficiency*

Figure 2(a) provides a comprehensive overview of how brake thermal efficiency (BTE) varies with brake power [kW] for blends of diesel and RSO biodiesel (B20, B40, B60, B80). BTE is an important factor for evaluating engine performance. As brake power increases, the BTE for all fuels also generally increases, reaching maximum efficiency at the rated power (5 kW). This increase can be attributed to better fuel atomization and more complete combustion at higher loads.

Figure 2(a) clearly shows a decreasing trend in BTE with increasing biodiesel quantity in the blend. For example, the BTE of pure diesel is 29.3% at 5 kW, while for B80, it reduces to 26.9%. However, despite this decrease, the BTE values for the biodiesel blends remain within a reasonable range. This indicates that the engine is able to effectively utilize the biodiesel-diesel blends and convert a substantial portion of the fuel's calorific energy into useful work, thereby demonstrating the viability of these blends as alternative fuels.

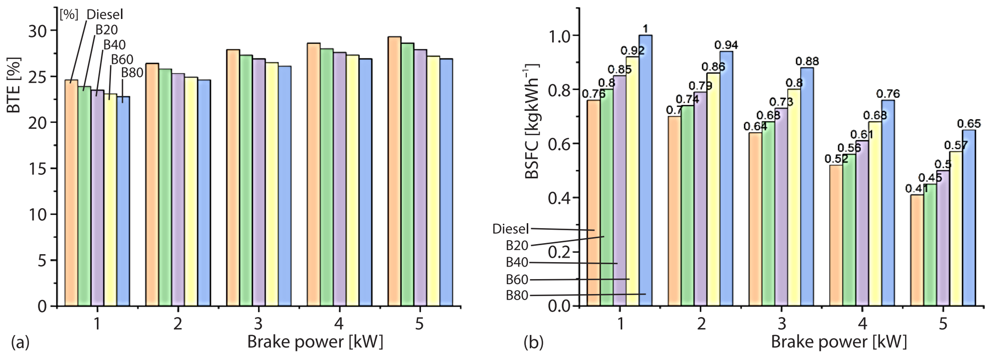


**Figure 2. (a) The BTE and (b) BSFC**

#### *Brake specific fuel consumption*

Figure 2(b) displays the link between braking power and brake specific fuel consumption (BSFC), which includes diesel and biodiesel (B20, B40, B60, and B80). The BSFC assesses the engine's fuel efficiency. It shows how much fuel is needed to generate one unit of electricity. An engine with a lower BSFC is more fuel-efficient because it can produce more power while using less fuel. The BSFC drops as braking power increases for all fuels, indicating that the engine operates better when subjected to higher loads. This is a common occurrence in the majority as a result of increased fuel atomization and more thorough combustion caused by higher loads, which improves fuel economy.

As demonstrated in fig. 2(b), the BSFC rises as the amount of biodiesel in the mixture increases. In comparison B80, which has a BSFC of 0.65 kg/kWh at 5 kW, pure diesel has a BSFC of 0.41 kg/kWh. Despite this increase, BSFC levels in biodiesel blends remain below permitted levels. The engine's ability to successfully burn biodiesel-diesel mixtures highlights its potential for usage as an alternate fuel.

*Exhaust gas temperature*

Figure 3 shows the relationship between brake power and various fuel types, such as diesel and biodiesel-diesel blends (B20, B40, B60, and B80).

Exhaust gas temperature (EGT) has a large influence on how efficiently an engine performs and how its emissions behave increased exhaust gas temperatures, in addition enhancing thermal efficiency, can result in increased concentrations of specific pollutants.

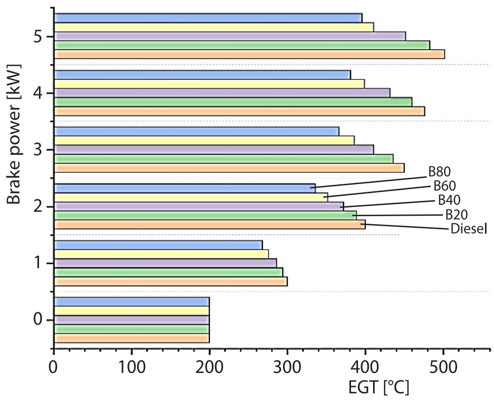


**Figure 3. The EGT**

Figure 3 depicts an increase in EGT for all fuel types as braking power increases. Stronger brakes raise the temperature of exhaust gases, which increases fuel consumption and, eventually, the quantity of heat emitted during combustion. Lower exhaust gas temperatures are obtained because biodiesel, which contains more oxygen than diesel, promotes more complete combustion. Furthermore, because it has a higher specific heat than diesel and a lower heating value than diesel, biodiesel contributes in reversing this reduction. Despite the fact that braking power frequently produces a rise in EGT, using biodiesel-diesel blends can successfully limit the increase in EGT. Decreased EGT can lead to decreased $NO_x$ emissions.

***Emission characteristics***

*Unburned hydrocarbon emissions*

Figure 4(a) depicts the relationship between stopping distance and unburned hydrocarbon (UHC) emissions for diesel and several mixes of RSO biodiesel (B20, B40, B60, and B80). The UHC emissions endanger engine efficiency as well as environmental contamination. The UHC from fuel that enters the engine but is only partially consumed escape into the exhaust as a result of these emissions. The UHC emissions increase with braking power for all fuels. This pattern can be explained when that as engine load grows, so does the amount of fuel required and the possibility of incomplete combustion, both of which result in increasing UHC emissions. Figure 4(a) further shows that as the biodiesel proportion of the blend grows, so do UHC emissions at each braking power level. This is explained by the oxygenation of biodiesel, which promotes more thorough combustion and lowers UHC emissions. These data show that, despite the expected rising trend in UHC emissions with braking power, biodiesel-diesel blends can minimise.

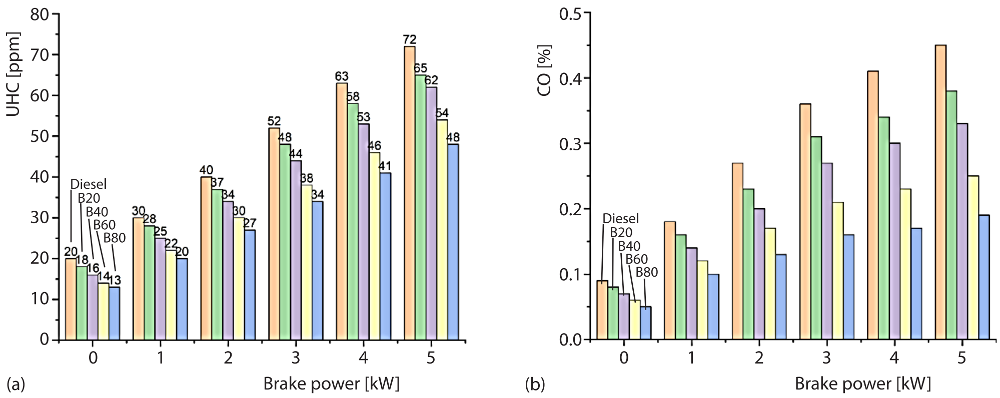


**Figure 4. (a) The UHC and (b) CO emission**

### *Carbon monoxide emissions*

Figure 4(b) depicts the relationship between brake force and CO emissions for diesel and various blends of RSO biodiesel and diesel (B20, B40, B60, and B80). The CO emissions are harmful to human health and a major source of air pollution. Several contaminants are created when inadequate gasoline is consumed in the engine. The CO emissions rise as brake power increases for all fuel types. The most plausible explanation for the increase is that more petrol may enter the engine under higher loads and partially combust, resulting in higher CO emissions. Figure 4(b) shows, however, that as the biodiesel proportion of the mixture increases, CO emissions at each brake power level decrease. This is due to biodiesel's oxygenated composition, which fosters more thorough combustion and thus fewer CO emissions. These findings highlight one environmental advantage of biodiesel-diesel blends over pure diesel fuel. Even if overall CO emissions increase with brake power, the amount of CO emissions can be lowered by using biodiesel in the fuel mixture.

### *Oxides of nitrogen emissions*

Figure 5(a) shows the relationship between braking force and $NO_x$ emissions for diesel and a variety of RSO biodiesel blends (B20, B40, B60, and B80). The $NO_2$ and NO, which account for the vast majority of $NO_x$ emissions, are hazardous pollutants that harm human health and contribute to air pollution.

Figure 5(a) shows how $NO_x$ emissions for all fuels grow as brake power increases. This pattern can be clarified by when heavier loads (and hence greater braking force) boost the temperature at which $NO_x$ combustion occurs, resulting in higher $NO_x$ emissions. The temperature has a large influence on $NO_x$ production. Furthermore, as the proportion of biodiesel blend upsurges, $NO_x$ emissions increase at each level of braking power. This is frequently caused by the increased oxygen content of biodiesel, which can result in higher combustion pressures and temperatures and, as a result, an increase in the amount of $NO_x$ produced. Despite these increases, using biodiesel-diesel blends provides a number of environmental benefits, including lower CO, UHC, and PM emissions. The benefits must be balanced against the little increase in $NO_x$ emissions. Future research could look on ways to lower $NO_x$ emissions when using biodiesel blends.

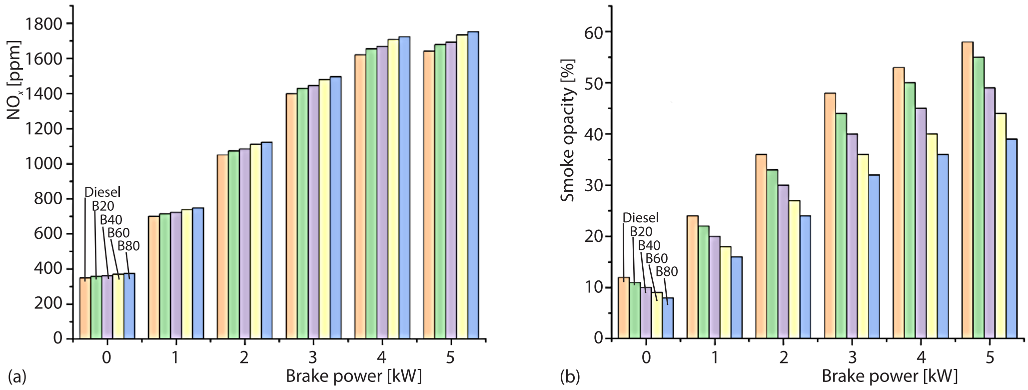


**Figure 5. (a) The $NO_x$ and (b) smoke emission**

### *Smoke emissions*

Figure 5(b) depicts several biodiesel-diesel blends (B20, B40, B60, and B80) made from RSO and diesel fuel, as well as their relationship to brake power and smoke opacity emissions. The figure illustrates that smoke opacity emissions rise in direct proportion braking power for all fuels. Heavy loads, as expected, increase fuel consumption, and incomplete combustion may increase particulate matter emissions, which are visible as thicker smoke.

Figure 5(b) also clearly depicts how smoke opacity emissions decrease as the biodiesel in the fuel mixture grows at each braking power level. This could be because biodiesel is oxygenated, which encourages more complete combustion and so lowers particle emissions. These data show that, despite an increase in overall smoke opacity emissions with braking power, using biodiesel in fuel blends can significantly lower smoke emissions, emphasising the environmental benefits of doing so over using pure diesel fuel.

### *Combustion characteristics*

### *Cylinder peak pressure*

Figure 6 depicts the relationship between brake power and cylinder peak pressure (CPP) for diesel and three RSO biodiesel blends (B20, B40, B60, and B80). The CPP is an important aspect in evaluating the combustion characteristics. The figure illustrates that for all fuels, CPP increases as braking power increases. Higher loads (brake power) cause more fuel-air combination burn, which increases cylinder pressure as expected.

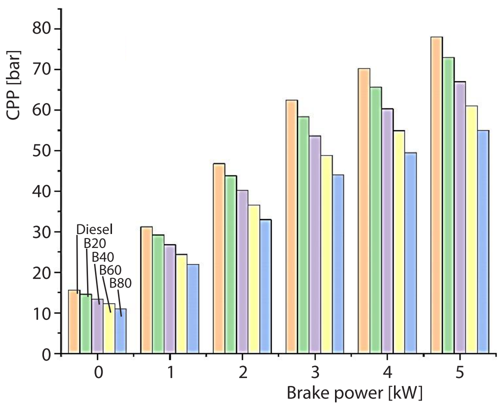


**Figure 6. Cylinder peak pressure**

Figure 6 also demonstrates how CPP decreases with increasing biodiesel proportion of the blend at each braking power level. This is due to the fact that biodiesel burns slower and produces less energy during combustion than diesel, resulting in a lower peak pressure for biodiesel. These findings highlight the trade-offs that must be made when using biodiesel-diesel mixes, where benefits like lower emissions must be balanced against changes to engine performance characteristics like CPP.

*Cylinder pressure*

Figure 7 provided is a representation of how cylinder pressure in a Diesel engine vary with the crank angle for different fuel blends. The blends considered here are pure diesel, B20 (20% biodiesel, 80% diesel), B40 (40% biodiesel, 60% diesel), B60 (60% biodiesel, 40% diesel), and B80 (80% biodiesel, 20% diesel). Each metric represents a specific crank angle (CA), ranging from –30° to +30°, where 0° is considered as the point of maximum compression (and ignition). The negative degrees denote the compression stroke (piston moving up, compressing the fuel-air mixture before combustion), and the positive degrees denote the expansion or power stroke (piston moving down after combustion).

In this scenario, as the biodiesel blend fraction increases, the peak pressure decreases. This is based on that biodiesel has a lower energy content related to diesel, leading to a slightly lower peak cylinder pressure. For example, the maximum cylinder pressure when using pure diesel is 75 bars (at 0° CA), but it reduces to 70 bars for B20, 65 bars for B40, 60 bars for B60, and 55 bars for B80.

The shape of the curve generally remains the same for all fuels, reflecting the rapid rise in pressure during the compression stroke, attaining a peak around the point of ignition, and then decreasing during the expansion stroke.

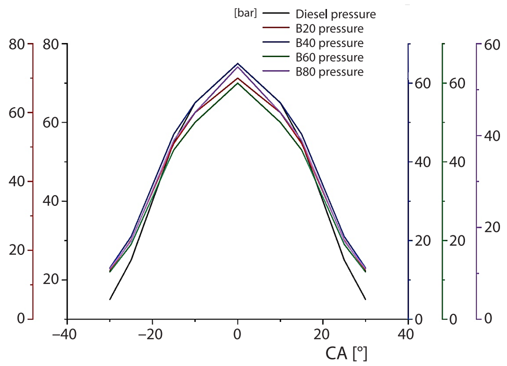


**Figure 7. Cylinder pressure with respect to CA**

*Ignition delay (% crank angle)*

Figure 8 depicts the relationship between diesel and numerous biodiesel blends generated from RSO (B20, B40, B60, and B80), ignition delay (% CA), and braking power. The ignition delay is an important factor to consider when researching engine combustion because it can affect both the efficiency of combustion and the amount of pollutants produced.

Figure 8 shows how the ignition delay is decreasing while the brake power is increasing for all fuels increased loads result in increased cylinder temperatures and pressures, which can shorten the time it takes for fuel to ignite following injection. The figure also shows how the ignition delay decreases with increasing biodiesel percentage for each braking power level. This could be because biodiesel has a higher cetane number than diesel, which can minimise the igniting delay.

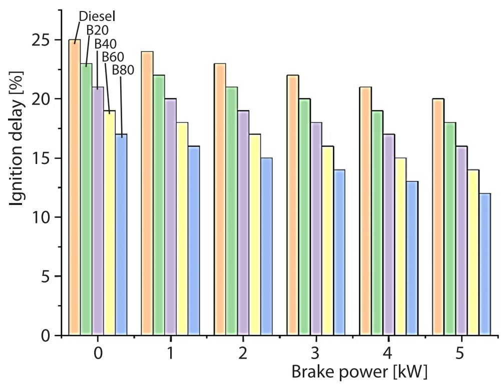


**Figure 8. Ignition delay**

These results indicate that using biodiesel-diesel blends can improve the ignition characteristics of the fuel, which can have benefits for engine performance and emissions.

## Conclusions

In light of the escalating demand for automobiles, diminishing fossil fuel reserves, and growing environmental concerns, the need for sustainable alternative fuels has never been more pressing. The current study explores the potential of biodiesel, specifically blends derived from RSO, to meet this emerging need. The RSO, produced through transesterification, yields a biodiesel with properties that align with ASTM standards. This research investigated into the P-E-C characteristics of RSO-diesel blends (B20, B40, B60, B80), compared to pure diesel, in a 5.1 kW, 1-cylinder, turbocharged Diesel engine. The findings suggest that while BTE marginally declines with an increase in the biodiesel proportion of the blend, the environmental benefits of these blends are pronounced, demonstrated by a substantial decrease in smoke, CO, and HC emissions. Contrarily, higher biodiesel ratios led to increased emissions of $NO_x$. The BTE for diesel, B20, B40, B60, and B80 blends were found to be 29.3%, 28.6%, 27.9%, 27.2%, and 26.9%, respectively. Smoke emissions decreased from 55% for diesel to 40% for B80, while $NO_x$ emissions increased from 1556 ppm for diesel to 1718 ppm for B80. The maximum cylinder pressures and ignition delays for diesel and B20 are 78 bar, 73 bar, 20%, and 18%, respectively. These values are very similar to one another. These findings point to biodiesel-diesel blends as a more sustainable alternative to fossil fuels. Despite a slight decrease in BTE and an increase in $NO_x$ emission, the significant reductions in smoke, CO, and HC emissions demonstrate the environmental benefits of biodiesel. Furthermore, because its combustion qualities are comparable to those of diesel, B20 presents a potential substitute. This research improves biodiesel-diesel blends' potential to diminish the environmental impact of transportation by establishing the framework for future research on sustainable alternative fuels.

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