

Investigation of The Use of Biodiesel Produced from Waste Cooking Oil as Fuel for a CI Engine Under Different Operating Parameters

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1. Introduction

Today, although the use of high-performance electric motors in transportation has become widespread in parallel with rapidly advancing technology, internal combustion engines are still widely used in air, road, rail, and sea transportation. CI engines, particularly used in situations requiring high torque and performance, are widely preferred in large ship machinery, railroad vehicles used for freight transport, heavy-duty machinery, high-capacity power generation plants, and many agricultural vehicles. It is predicted that CI engines will not be replaced by electric motors in the near future due to the latter's current inability to achieve the desired performance level.

While low fuel consumption and high efficiency are the most significant advantages of CI engines, the use of petroleum-based fuels and their negative environmental impacts are the biggest disadvantages encountered in the use of CI engines. Researchers have turned to alternatives that can replace oil-based fuels due to predictions of oil reserve depletion in the near future, concerns about oil-rich countries restricting oil use because of political unrest [1]-[3], and the significant contribution of oil to global greenhouse gas emissions [4]-[6].

The most important alternative fuel to petroleum-based diesel is biodiesel. Because biodiesel has similar fuel properties to conventional diesel fuel. Biodiesel can be produced from the oil of plants such as canola, palm, corn, sunflower, safflower, jatropha, and soybeans [7]-[9], as well as from algae [10], [11] and animal fats [12]-[14]. The most common method used in biodiesel production is transesterification [15], [16]. The type and easy availability of the raw material to be used in biodiesel production are very important. This determines the production cost of biodiesel. Waste cooking oils or waste frying oils have come to the forefront as a biodiesel feedstock in recent years due to their easy availability and near-zero cost. These waste oils can be converted into biodiesel using the traditional transesterification method after undergoing a simple filtration process.

Significant research has been conducted on the production of biodiesel from waste cooking or frying oils and its use in CI engines. Patil et al. compared the fuel properties of biodiesel produced from waste cooking oil (WCO) with those of diesel fuel and biodiesel produced from different oils. In conclusion, they stated that the calorific value of WCO biodiesel is closer to that of diesel fuel because it has better oxidation stability, that WCO can remain within acceptable viscosity limits by being adequately filtered and pretreated before transesterification, and that biodiesel

formulations produced from WCO maintain their density within acceptable limits for diesel engine applications. In addition, the WCO stated that the high pour point of biodiesel could be a disadvantage for its use, but that the high cetane number achieved with WCO biodiesel could still provide better combustion characteristics [17]. In their study, El-Shafay et al. examined performance and emission parameters by blending biodiesel produced from WCO with diesel fuel at a 20% ratio. They determined a 5.6% increase in brake specific fuel consumption (BSFC) and a 6% decrease in brake thermal efficiency (BTE) with the addition of biodiesel. However, they stated that there was a 3.5%, 18%, and 12% reduction in CO, HC, and smoke emissions, respectively, and an 8% increase in NO_x emissions due to a 12% increase in exhaust gas temperature. Additionally, they found that the addition of biodiesel reduced the maximum cylinder pressure by 3.5% and the maximum heat release rate (HRR) by 4% [18]. Patra et al. investigated the performance and emission parameters of diesel fuel containing 20% WCO biodiesel at different injection angles. Although the addition of biodiesel decreased the BTE value, they stated that there was some improvement in the BTE value by changing the injection timing. They observed that the BSFC value further increased with the change in advance. They found that changes in injection timing led to noticeable changes in exhaust gas temperature, NO_x, and smoke emissions, while CO and HC emissions worsened further. They determined that increasing the injection advance also increased the maximum cylinder pressure and HRR values [19]. Kumar et al. stated in their study that the addition of 20% WCO biodiesel to diesel fuel reduced the maximum cylinder pressure but increased the HRR value, negatively affecting engine performance, and positively impacting emissions, especially HC, CO, and smoke [20]. In their study, Wei et al. investigated the effects of biodiesel derived from waste cooking oil on the combustion of a diesel engine, irregular gas emissions, and particulate emissions. Experiments were conducted on a direct injection diesel engine operating with B20, B50, B75, and B100. It has been observed that biodiesel increases in-cylinder pressure, shortens ignition delay and combustion duration, and reduces the maximum heat release rate. An increase in brake specific fuel consumption was also observed when biodiesel was used. They stated that there was no significant change in most of the modes tested in terms of brake thermal efficiency. It has been stated that no significant change was observed in the ozone-forming potential of unregulated gas emissions among the tested fuels [21].

It is observed that the studies conducted are

generally focused on the addition of WCO biodiesel to diesel fuel in specific proportions. In addition, there are also studies in which additives such as ethanol [22], methanol [23], and butanol [24] were added to biodiesel-based blends to reduce the high viscosity of biodiesel, cetane improvers [25] were added to improve combustion properties, and different additives (TiO_2 , MgO_2 , 2-butoxyethanol) were added to improve performance.

In this study, the effects of using biodiesel produced from waste cooking oils used entirely for cooking plant-based products as a single fuel at different injection pressures and injection timings on engine performance, exhaust emissions, and combustion characteristics were experimentally investigated. Thanks to this study, it will be demonstrated that biodiesel produced from waste cooking oil can be used directly in CI engines with simple modifications. Thus, the aim is to provide a low-cost and environmentally friendly fuel alternative to petroleum-based diesel fuel while also minimizing the damage waste oils would cause to the environment.

2. Materials and Methods

2.1. Test fuels

In the experiments, different types of oils (sunflower, palm, canola, and hazelnut) used only for cooking vegetable products (potatoes, eggplants, carrots, etc.) from university cafeterias and dining halls were collected to produce biodiesel. The general reuse of oils is between 15 and 25 times.

First, the collected waste cooking oils were filtered through a $0.45 \mu\text{m}$ pore size paper filter to remove sediment and visible foreign matter, and then stored in glass containers. Biodiesel production was carried out in 1-liter batches using the traditional transesterification method. During the production process, methanol (20% of the oil by volume) with a purity of 99.99% was used as an alcohol to precipitate the glycerin in the waste cooking oil. Sodium hydroxide (NaOH) at 3.5 grams per 1 liter of oil was also added to the mixture for the methanol to react. Fig. 1 shows the process of separation in a separatory funnel during biodiesel production. The produced biodiesel has an ester content of 98.22% and an oxygen content of 10.16%. The produced biodiesel was stored in glass containers as shown in Fig. 2 to minimize chemical interaction.

The fuel properties of the produced biodiesel are shown in Table 1. It is observed that the produced biodiesel meets both the ASTM D6751 and TS EN 14214 standards.

Table 1
Physical and chemical properties of test fuels

Properties	Unit	Diesel	Biodiesel
Density, at 15°C	kg/m^3	837.6	880.1
Kinematic viscosity, at 40°C	mm^2/s	3.211	4.656
Lower heating value,	MJ/kg	44.52	38.8
Cold filter plugging point	$^\circ\text{C}$	-17	-2
Flash point	$^\circ\text{C}$	>120	>120
Water content	mg/kg	48.612	268.28
Cetane index		48.75	49.86

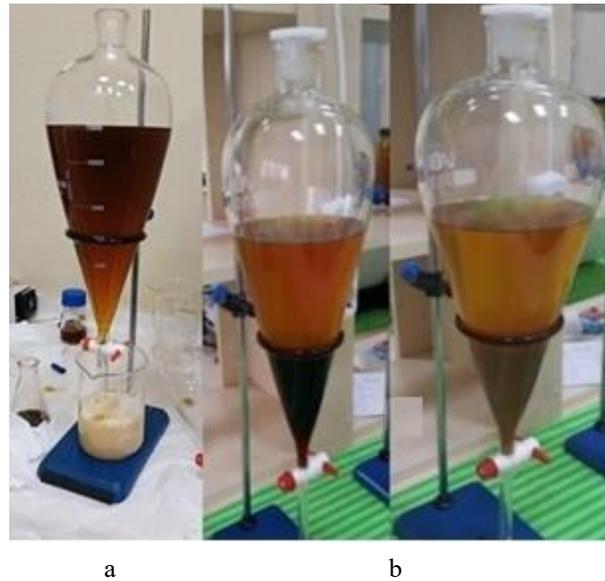


Fig. 1 Biodiesel separation process: a – resting in the separating funnel, b – settling



Fig. 2 WOC biodiesel

2.2. Experimental setup

Engine tests were conducted on a Lombardini, four-stroke, naturally aspirated a diesel engine with the specifications given in Table 2.

Table 2
Technical specifications of the test engine

Model	LDW 1003
Type	Direct injection
Number of Cylinders	3
Cylinder volume, cm^3	1028
Bore \times Stroke, $\text{mm} \times \text{mm}$	75 \times 77.6
Compression ratio	22.8:1
Max. engine torque, Nm	67
Injection pressure, bar	150
Cooling type	Water cooling

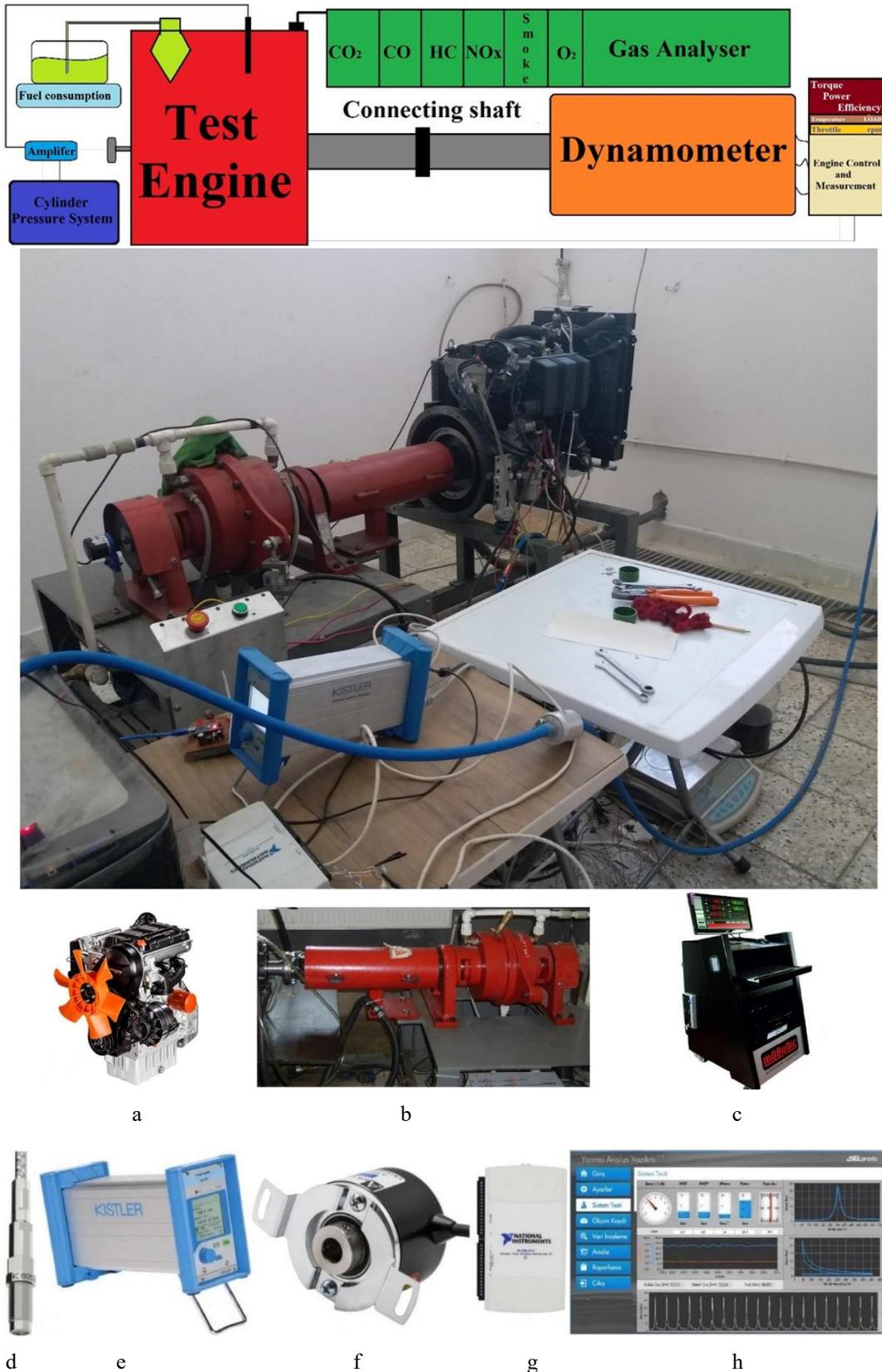


Fig. 3 Experimental setup: a – test engine, b – hydraulic dynamometer, c – gas analyser, d – in-cylinder pressure sensor, e – amplifier, f – encoder, g – data-logger, h – interface of combustion software

The test setup, in its most basic form, consists of the engine where the tests are conducted, the dynamometer where performance measurement is performed, the in-cylinder pressure measurement system where combustion analysis is carried out, and exhaust emission measurements. A schematic diagram of the test setup is presented in Fig. 3.

In the experiments, a hydraulic brake dynamometer with a torque measurement capacity of 150 Nm at a shaft speed of 6500 rpm and an accuracy of ± 0.1 was used to determine the engine performance parameters. A scale with 0.01 precision was also used for fuel consumption

In the experiments, the cylinder internal pressure

was measured with a Kistler-6052C model piezoelectric sensor. The signal produced by the sensor is amplified by the Kistler-5018A amplifier. The system has a measurement capacity of 250 bar and an accuracy of 10.69 pC/bar. The bottom and top dead centers of the piston were determined using an encoder. Cylinder pressure was determined using software that records and averages the pressure every 100 cycles. The heat release rate was calculated using the following one-dimensional combustion model in Eq. (1)

$$\frac{dQ_{net}}{d\theta} = \frac{\gamma}{\gamma-1} P \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dP}{d\theta}. \quad (1)$$

The time of injection, injection duration, start of combustion, ignition delay, end of combustion, and total combustion duration were evaluated as combustion characteristics. These parameters are determined by calculating the cumulative heat release using the normalization method described in Eq. 2. Fig. 4 shows an example graph of the cumulative heat release calculated from the test results.

$$X_{normalized} = \frac{(X - X_{minimum})}{(X_{maksimum} - X_{minimum})}. \quad (2)$$

In the experiments, a mOByDic-5000 combined/model 4 gas analyzer was used. This device, used for analyzing exhaust gases, can measure CO emissions with an accuracy of $\pm 0.01\%$ by volume, CO₂ emissions with an accuracy of $\pm 0.1\%$ by volume, O₂ emissions with an accuracy

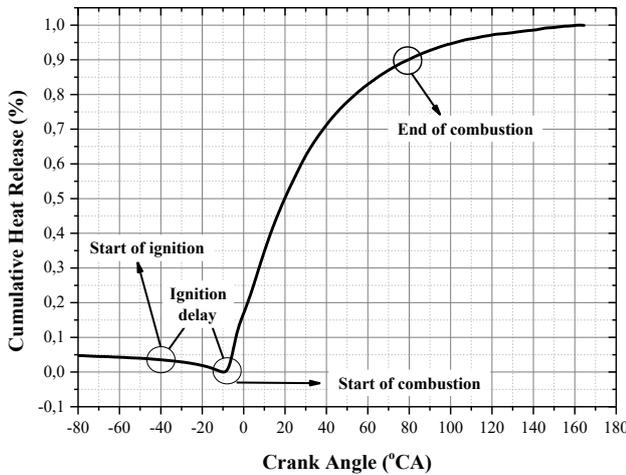


Fig. 4 Cumulative heat release graph

of $\pm 0.01\%$ by volume, and HC and NO_x emissions with an accuracy of ± 1 ppm. Smoke opacity measurements can also be made with an Automotive Microbench II analyzer adapted to the device, with an accuracy of $\pm 0.1\%$ by weight.

2.3. Test procedure

Partial load tests were conducted so that the data obtained from the tests could yield results more suitable for real-world operating conditions. Therefore, the maximum engine torque and the engine speed at which this value is achieved were determined as a priority. Subsequently, partial load tests were performed using the standard parameters of the engine. Partial load tests were also conducted to determine the optimal injector pressure and injection timing values for biodiesel. Four different partial load ratios have been determined for the tests: 25%, 50%, 75%, and 100%. Each test was repeated three times, and the average was taken. The results of experimental measurements and calculations were determined using the model in Eq. 3. The accuracy of the experimental results and the uncertainty of the calculated parameters are given in Table 3.

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2}. \quad (3)$$

R is a given function that depends on the independent variables such as $x_1, x_2, x_3, \dots, x_n$. Besides, w_R is defined as the total percentage uncertainty of the experimental values in the results, and w_1, w_2, \dots, w_n are given uncertainties of the independent variables.

Tests were performed under 3 different engine operating parameters. These parameters are: BD-S, which represents the standard operating condition where no engine operating parameters were modified. BD-P, which represents the operating condition where the injector pressure is 200 bar. This value is explained in Fig. 6. BD-A, which represents the operating condition where the injection advance is -4. This value is also explained in Fig. 7.

2.4. Determining the maximum engine torque value

A full load test was conducted to determine the engine's maximum torque value. The engine was braked up to an engine speed of 1000 rpm using an engine dynamometer while the engine throttle was fully open. Subsequently,

Table 3

The accuracy of the measurements and the uncertainty analysis

Measurement	Accuracy	Calculated quantity	Uncertainty, %	
Hydraulic Dynamometer	$\pm 0.02\%$	Brake Torque	0.4766	
Piezoelectric Pressure Sensor	$\pm 1\%$	Brake Power	0.093	
Digital Rotary Encoder	± 0.01 rpm	BSFC	4.1774	
Cylinder Volume	$\pm 1\%$	BMEP	0.1941	
Cylinder Pressure	$\pm 1\%$	Thermal Efficiency	0.022	
Exhaust Gas Analyzer	CO ₂	$\pm 0.1\%$	Total Engine Performance	4.3316
	CO	$\pm 0.01\%$	HRR	1.7125
	HC	± 1 ppm	Emissions	0.0014
	NO _x	± 1 ppm	Total System	4.692
	Smoke Opacity	$\pm 0.01\%$		

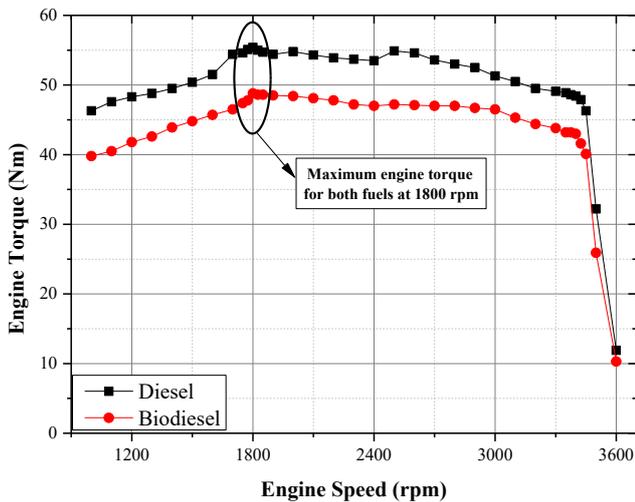


Fig. 5 Maximum torque value according to full load test

torque measurements were taken at intervals of 100 rpm each. These intervals have been slightly tightened only to clearly determine the maximum torque and maximum power values. Fig. 5 shows the maximum torque value and the engine speed at which these values are obtained.

When the engine torque values obtained from the full load test were examined, it was observed that the maximum value was 55.4 Nm at an engine speed of 1800 rpm with diesel fuel, and 48.8 Nm at an engine speed of 1800 rpm with biodiesel. To see if these values are correct, the torque value was also measured at engine speeds of 1750-1775-1825 and 1850 rpm. The tests were repeated 5 times to ensure the accuracy of the results. As a result, partial load tests were conducted at an engine speed of 1800 rpm and according to the maximum torque values of the fuels.

3. Results and Discussion

The research results were analyzed in terms of engine performance, combustion analysis, and exhaust emissions. First, the effect of using biodiesel without any modifications to the engine on the determined parameters was examined. Then, tests and inspections were carried out at different injector pressure and injection timing values, respectively, and presented in comparison to diesel fuel. Test fuels were defined as diesel, the results of using biodiesel at standard engine operating parameters (BD-S), the results of using biodiesel at an injector injection pressure of 200 bar (BD-P), and the results of using biodiesel at an injection timing of -4°CA (BD-A).

3.1. Injector pressure achieved of maximum torque

This study also investigated the effect of injector pressure on the use of biodiesel as fuel. Therefore, the injection pressure that provides the best torque value at different injector pressures was determined through a full-load test of the injection pressure. Fig. 6 shows the torque values of biodiesel at different injector pressures under full load conditions.

The injection pressure value determined by the manufacturer of the injector is 150 bar. Due to biodiesel already having a high viscosity value, higher injection pressures were preferred during the tests, and torque values

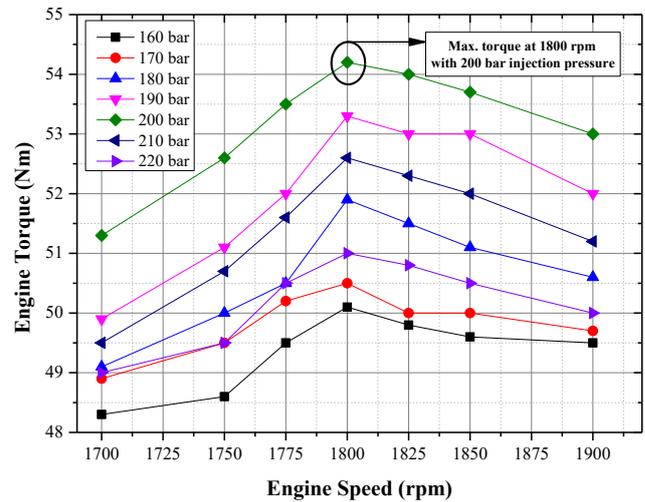


Fig. 6 Injector pressure at which maximum torque is achieved

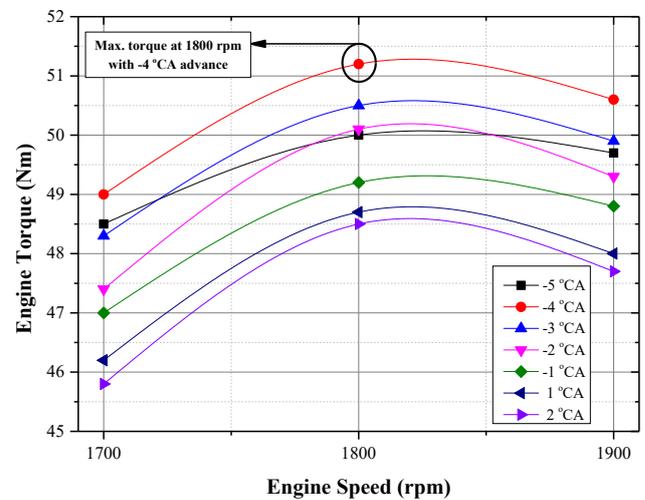


Fig. 7 Injection advance achieved of maximum torque

were determined with every 10 bar increase. It can be seen that the highest torque value of 54.2 Nm is achieved at an injector pressure of 200 bar and an engine speed of 1800 rpm.

3.2. Injection advance achieved of maximum torque

Full load tests were conducted at the original injection pressure of 150 bar to determine the optimal injection advance value for achieving the best torque with biodiesel fuel. Fig. 7 shows the torque values obtained with biodiesel at different injection timings.

The high cetane number of biodiesel allowed for a slight retardation of the injection timing, which increased performance somewhat. The highest torque value was obtained at an engine speed of 1800 rpm and 51.2 Nm, with the fuel injected -4° before the original advance value.

3.3. Combustion analysis

The formation of pressure acting on the head of the piston due to the combustion of fuel compressed within the cylinder at the end of the compression stroke continues to affect the piston until the end of the working stroke. The pressure change that occurs during this process is important

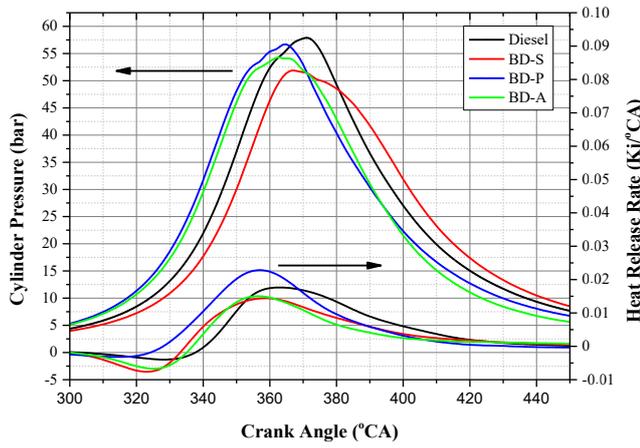


Fig. 8 Pressure and HRR curves of test fuels at full load

because it directly affects the engine's power. Fig. 8 shows the variation of pressure and HRR values generated by fuel combustion inside the cylinder with respect to crank angle. These values were measured at the moment of maximum torque, which is achieved at full load.

It is generally observed that the use of biodiesel, in particular, reduces the maximum cylinder pressure value. The most important reason for this is that due to the high density of biodiesel, less fuel by volume is injected into the cylinder during injection, resulting in lower combustion pressure. In addition, the low end of combustion energy has also led to a decrease in the maximum cylinder pressure value. It has been observed that increasing the injection pressure improves combustion by reducing the droplet diameter of the fuel injected into the high-pressure and high-temperature air in the cylinder at the end of the compression stroke, increasing its speed, and allowing it to penetrate the air better, thus leading to a slight increase in the maximum pressure value. With the retraction of the injection timing, the maximum pressure value both increased slightly and approached top dead center even further compared to the BD-S condition. For the most efficient combustion and best performance, it is generally desired that the maximum cylinder pressure value occur 3-6 degrees after top dead center. It can be seen that the maximum cylinder pressure also falls within these angles as the values of injection pressure and advance change. Therefore, it can be said that better combustion is achieved and combustion efficiency is improved through changes in injection pressure and advance.

The heat release rate is an important parameter that allows for investigation of the combustion phases. Sudden changes in the heat release rate indicate external heat input or output into the cylinder. At the end of compression, there is a sudden change in the rate of heat release when fuel is injected into the high-temperature air, resulting in a negative decrease, while at the beginning of combustion, there is a sudden positive increase.

The approximate 10.16% oxygen content of biodiesel has caused a slightly faster combustion rate from the moment it started burning. Subsequently, due to its high density and viscosity, it was observed that the combustion rate slowed down during injection because it could not fully penetrate the compressed air inside the cylinder. However, it is observed that this slowdown in the combustion rate disappears as the injection pressure increases, allowing for better penetration into the air, and the combustion rate further increases.

3.4. Combustion characteristics

The phases of combustion occurring within the cylinder can be explained thanks to certain characteristics. The combustion phase is generally characterized by features such as the time of injection, injection duration, start of combustion, ignition delay, end of combustion, and total combustion duration. Table 4 presents the combustion characteristics identified in this study.

Table 4

Combustion characteristics

	Diesel	BD-S	BD-P	BD-A
P_{max} , bar	57.93	51.88	56.66	54.24
θP_{max} , °CA	371	367	365	363
HRR_{max} , kJ/°CA	0.0176	0.0144	0.0228	0.015
θHRR_{max} , °CA	363	359	357	356
θSoI , °CA	327	323	320	319
θSoC , °CA	341	335	329	329
ID , °CA	14	12	9	10
θEoC , °CA	423	408	395	401
DoC , °CA	82	85	66	72

P_{max} ; Maximum cylinder pressure, θP_{max} ; Angle of max. cylinder pressure, HRR_{max} ; Maximum heat release rate, θHRR_{max} ; Angle of max. heat release rate, θSoI ; Start of ignition, θSoC ; Start of combustion, ID ; Ignition delay (duration of the crank angle), θEoC ; End of combustion, DoC ; Duration of combustion (duration of the crank angle).

Upon examining Table 4, it is evident that biodiesel's high cetane number shortens ignition delay, increases combustion speed due to its oxygen content, and extends combustion duration. However, particularly the increase in injection pressure and the high density of biodiesel have caused the high-pressure pump to compress more quickly and start injecting earlier. Additionally, it appears that an increase in injection pressure significantly shortens the ignition delay and total combustion duration. Because the increase in pressure, along with the oxygen content of the biodiesel, increased the combustion efficiency and ensured that combustion was completed in a shorter time.

3.5. Engine performance parameters

As for engine performance parameters, the effects of biodiesel use on brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) parameters were investigated.

Specific fuel consumption refers to the amount of fuel consumed per unit of time to obtain a unit of power. Using BSFC data will provide a more objective result when comparing the performance parameters of different engines or fuels. The ratio of fuel energy used to obtain power in an engine to the net power output is indicated by thermal efficiency. Since not all of the fuel energy can be converted into power due to mechanical and heat losses, the effects of engine operating parameters on thermal efficiency are particularly prominent. The effect of biodiesel use on BSFC and BTE under different operating conditions is shown in Fig. 9. According to the test results, the BSFC values of BD-S, BD-P, and BD-A fuels are on average 14.32%, 6.61%, and 10.42% higher than that of diesel fuel, respectively. Increasing the injector pressure resulted in a 6.74% improvement

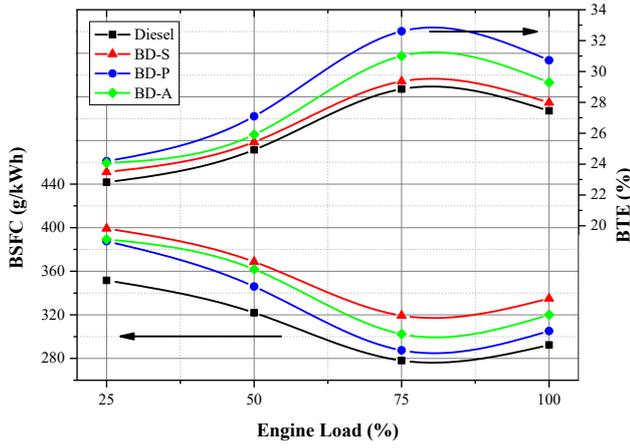


Fig. 9 Effect of biodiesel use on BSFC and BTE at different engine operating parameters

in BSFC compared to using biodiesel under standard operating conditions, while advancing the injection timing reduced BSFC by 3.41% compared to BD-S. It was also calculated that the BSFC values obtained with BD-B were on average 3.45% better than those with BD-A.

Thanks to the increase in injection pressure, the droplet diameter of the injected biodiesel has decreased, thereby improving combustion characteristics and leading to a reduction in fuel consumption. Shehata et al. [30], Jamrozik et al. [32], and Du et al. [32] also obtained similar results in their studies. However, by advancing the injection timing and utilizing biodiesel with a high cetane number, which results in a shorter ignition delay, more controlled combustion was achieved, causing maximum cylinder pressure to occur at a more ideal crank angle. This improvement in combustion characteristics has increased engine performance and reduced fuel consumption.

It is observed that the use of biodiesel increases the BTE of BD-S by 2.11% compared to diesel fuel, and the BTE improves by 10.14% and 5.98%, respectively, compared to diesel fuel under high pressure and early advance conditions.

It is observed that biodiesel has a higher BTE value because the reduction in power output obtained with biodiesel compared to diesel fuel is less than the reduction in the calorific value of biodiesel. However, increasing both the injection pressure and the advance value further improved the BTE of biodiesel. Sastry et al. [33], as well as Taymaz and Coban [34] and Yarrapathruni et al. [35], have also presented very similar results.

3.6. Exhaust emission parameters

Exhaust emissions are one of the important factors indicating combustion quality in internal combustion engines. However, there is also a requirement for exhaust gas emission values to be world-class and within certain norm limits. In this study, CO₂, CO, HC, NO_x, smoke density, and exhaust gas temperature values were measured.

The gas temperature formed after combustion has a significant impact, especially on the formation of emission values. Additionally, the exhaust gas temperature value is also an indicator of combustion inside the cylinder. Fig. 10 shows the exhaust gas temperature values obtained from the test results. Biodiesel's longer duration of combustion resulted in an exhaust gas temperature that was 9.30% higher

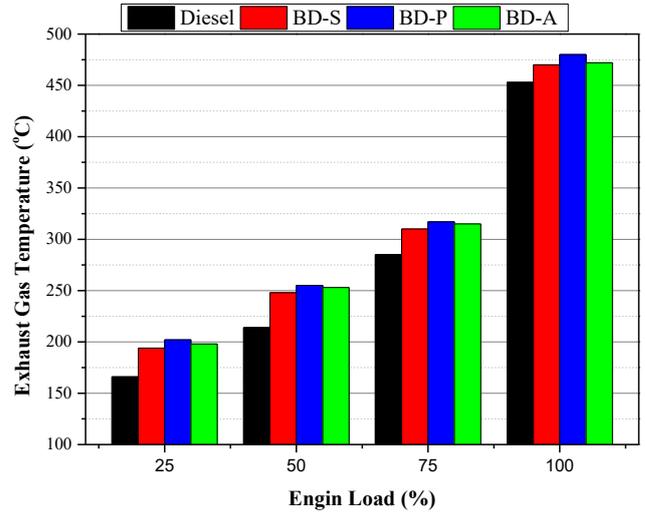


Fig. 10 Effect of biodiesel use on exhaust gas temperature at different engine operating parameters

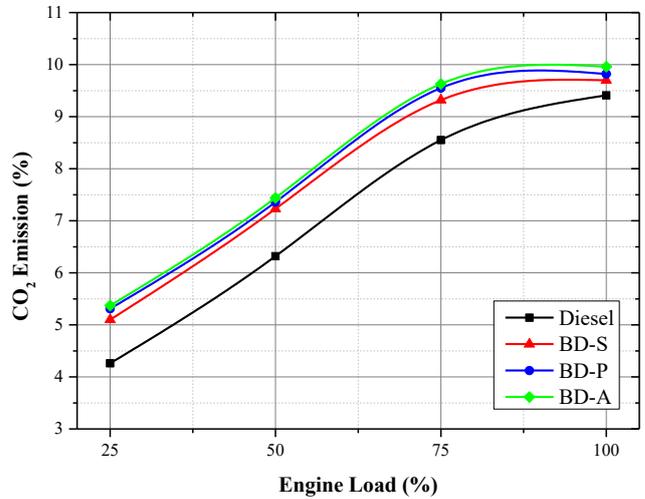


Fig. 11 Effect of biodiesel use on CO₂ emission at different engine operating parameters

than that of diesel fuel. Increasing the injection pressure resulted in a higher rate of fuel combustion, further increasing the combustion end temperature by 2.62% compared to BD-S. As the advance increased, combustion started earlier, resulting in the formation of high temperatures at high pressure. Therefore, the exhaust gas temperature value for BD-A is 1.31% higher than for BD-S. Yılmaz et al. [36] presented similar results in their studies as researchers such as Atmanlı [37], and Prabakaran and Udhoji [38].

CO₂ gas is produced as a normal combustion product from the burning of hydrocarbon-containing fuels. The number of carbon atoms in the fuel is one of the most important factors affecting CO₂ emissions. Fig. 11 shows the CO₂ emission data obtained from the test results.

It is observed that CO₂ emissions increase with the use of biodiesel because the number of carbon atoms in biodiesel is approximately 1.5 times greater than in diesel fuel. Additionally, the increased combustion efficiency due to the oxygen content is also a reason why biodiesel has higher CO₂ emission values. The CO₂ emission value obtained with the use of biodiesel under standard engine parameters is 9.84% higher than that of diesel fuel. With an increase in injection pressure, the CO₂ ratio increased by 12.26%, while advancing the timing and slightly extending the combustion

duration resulted in 13.52% higher CO₂ formation compared to diesel fuel. These results are also consistent with the studies conducted by Ranjan et al. [39] and Noorollahi et al. [40].

CO emissions occur when the amount of oxygen during combustion is less than required, or when the combustion rate is too high, causing carbon atoms in the fuel to not fully react with oxygen, resulting in the formation of CO molecules instead of CO₂. The change in CO emissions for the test fuels at different operating parameters is shown in Fig. 12. Thanks to the oxygen content, CO emissions have decreased by an average of 37.97% with the use of biodiesel. However, the increase in injection pressure had a positive effect on combustion efficiency, resulting in a 3.69% improvement in CO emissions compared to the standard injection pressure. Thanks to the increased advance, the combustion duration is extended, allowing more time for carbon and oxygen atoms to react during combustion, which leads to a 42.88% reduction in CO emissions compared to diesel fuel. This reduction is 7.92% at a high injection pressure value. Emiroğlu and Şen [41], Kumar and Raj [42], Shen et al. [43], and Mojifur et al. [44] have also obtained similar results.

The low amount of oxygen in the environment during combustion is not only a significant cause of CO emissions but also of HC emissions. Due to insufficient oxygen atoms, carbon atoms will find hydrogen atoms for the reaction, thus increasing unburned hydrocarbon (HC) emissions. In addition, the low combustion temperature is another important reason for the formation of HC emissions. Fig. 13 also shows the formation of HC emissions for the test fuels. The oxygen content of biodiesel again increased the fuel's combustion efficiency, triggering an increase in water molecule formation due to more oxygen atoms being present in the combustion chamber for hydrogen atoms. Thus, a 34.14% reduction in HC emissions was observed with the use of biodiesel. Through optimization of pressure and advance values, it was determined that HC emissions were further reduced by 35.52% and 37.96%, respectively, with biodiesel. These results are consistent with those presented in the studies by Kumar and Raj [42], and Pan et al. [45].

It is an inevitable phenomenon that nitrogen and oxygen react at the end of combustion, leading to the

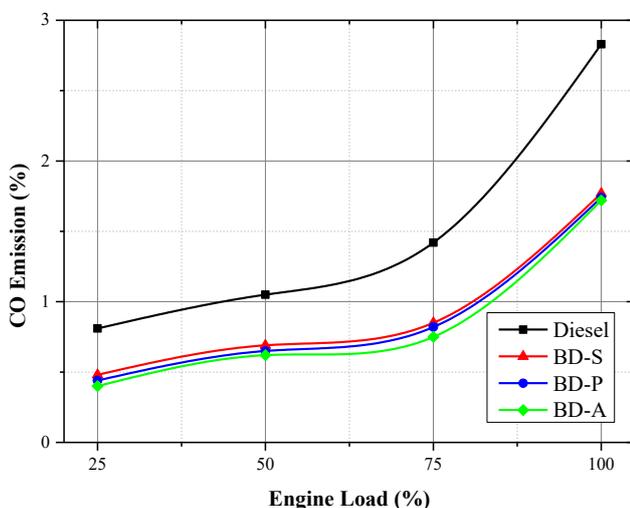


Fig. 12 Effect of biodiesel use on CO emission at different engine operating parameters

formation of NO_x (NO and NO₂) emissions. The reaction of nitrogen and oxygen at very high temperatures, and the operation of diesel engines with a high air excess ratio, significantly affect the formation of NO_x. The negative effects of these gasses include acid rain caused by the combination of NO_x gases with raindrops, and the serious damage they cause to human respiratory systems, especially the lungs. The high exhaust gas temperature of biodiesel has caused a 13.15% increase in NO_x emissions, as shown in Fig. 14. The high combustion efficiency of high injection pressure increased NO_x formation by 15.66% compared to diesel fuel, and this rate was calculated to be 14.13% with increased advance. The studies by Attia and Hassaneen [28], Jamrozik et al. [31], Emiroğlu and Şen [41], Hulwan and Joshi [46], Pradelle et al. [47], and Valente et al. [48] also support these findings.

The increased NO_x emissions associated with biodiesel use can be seen as a significant drawback. However, EGR systems [51] and catalytic converters [52] used to reduce NO_x emissions have been largely successful, particularly in reducing vehicle-related NO_x emissions to near zero.

The insufficient number of oxygen atoms reacting during combustion in the combustion chamber leads to the

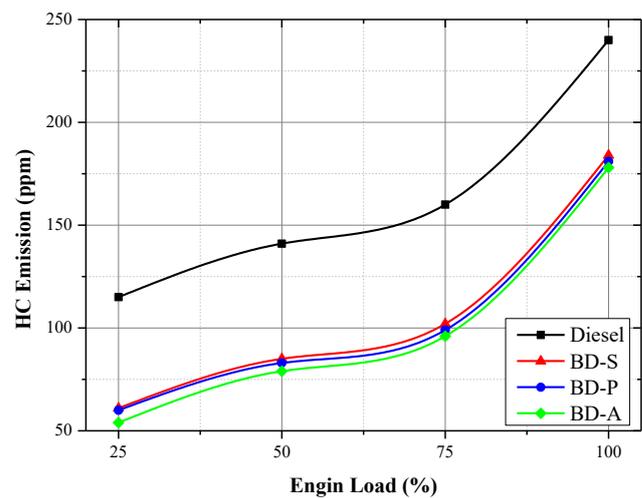


Fig. 13 Effect of biodiesel use on HC emission at different engine operating parameters

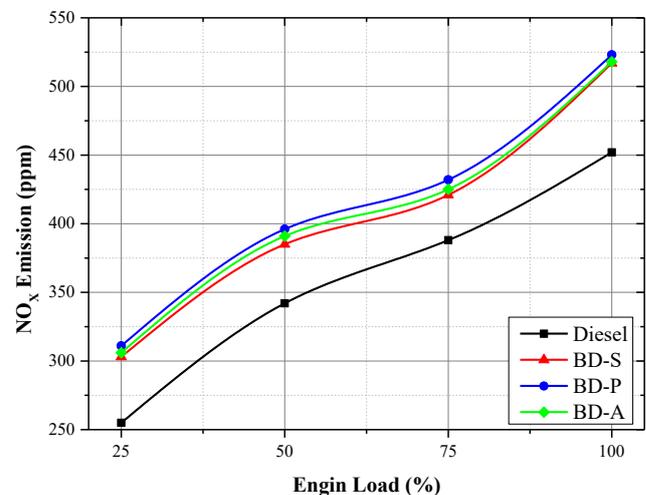


Fig. 14 Effect of biodiesel use on NO_x emission at different engine operating parameters

formation of solid carbon particles. Because these carbon particles are dark, they affect the color of the exhaust gas. Smoke opacity can be expressed as a percentage based on the gas color. Fig. 15 shows the changes in smoke opacity measured as a result of the tests. It is observed that biodiesel burns cleaner than diesel fuel, resulting in a significant average reduction of 43.52% in smoke opacity values. This decrease increased somewhat with increasing injection pressure and feed rate. Abed et al. [49], and Qi et al. [50] have reported similar results.

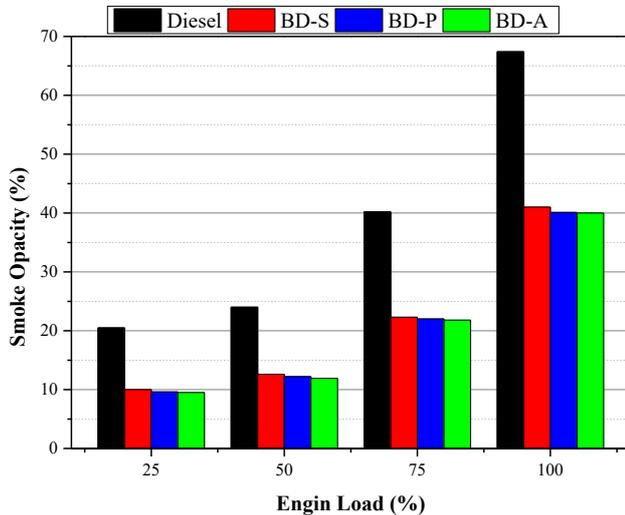


Fig. 15 Effect of biodiesel use on smoke opacity at different engine operating parameters

4. Conclusions

When the obtained data is analyzed separately as combustion, performance, and emission analyses, the following results can be presented.

Due to the high density and viscosity of biodiesel, poor injection characteristics have negatively impacted combustion efficiency. However, increasing the injection pressure, in particular, has led to better atomization of the injected fuel and a reduction in droplet diameter. This has also improved the combustion characteristics. Especially the shortening of the ignition delay will provide an important opportunity for controlled combustion. However, the increase in advance has extended the combusting time, increasing the fuel's combustion rate and improving combustion efficiency.

Biodiesel engines, which have lower thermal energy compared to diesel fuel, result in a 14.32% reduction in specific fuel consumption in terms of engine performance. However, the increase in injection pressure resulted in better atomization of the injected fuel, improved penetration into the compressed air with high homogeneity, and enhanced combustion efficiency. Thus, an increase in the injection pressure value resulted in a 6.74% reduction in BSFC compared to the BD-S test condition. According to the combustion analysis results, increasing the advance caused the combustion process to start earlier and the maximum cylinder pressure was achieved at the ideal crank angle. This also resulted in a 3.41% decrease in BSFC according to BD-S. Similarly, increasing the injection pressure resulted in 10.14% better thermal efficiency compared to diesel fuel, while changing the advance improved thermal efficiency by 5.98%.

The use of biodiesel as fuel has significantly reduced the values of harmful exhaust emission parameters such as CO, HC, and smoke opacity. Increasing the injection pressure resulted in an additional 3.69% improvement in CO emissions, 2.1% in HC emissions, and a 2.33% reduction in smoke opacity. The advanced timing increase further reduced CO emissions by an extra 7.92%, HC emissions by 5.79%, and smoke opacity by 3.14%. As combustion efficiency increased, the end of combustion temperature rose, resulting in higher NO_x emissions from biodiesel compared to diesel fuel.

To use biodiesel as a single fuel, increasing the injector pressure positively affected performance and emission parameters as it improved combustion characteristics. While increasing the advance also caused a slight increase in performance, it provided better results, especially in emission parameters.

In conclusion, the use of biodiesel produced from waste cooking oil as the primary fuel in at least agricultural vehicles and equipment, as well as in generators used for electricity production, is completely suitable. Thus, the damage that waste cooking oil would cause to the environment will also be minimized.

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INVESTIGATION OF THE USE OF BIODIESEL PRODUCED FROM WASTE COOKING OIL AS FUEL FOR A CI ENGINE UNDER DIFFERENT OPERATING PARAMETERS

S u m m a r y

The environmentally responsible disposal of waste cooking oil is a significant concern for numerous nations. One method to repurpose waste cooking oil is to employ it as diesel fuel. This approach diminishes both the expense of fuel feedstocks and the ecological repercussions of waste cooking oil. In this study, the use of waste cooking oil as fuel was achieved by converting it into biodiesel thru the transesterification method. The negative thermos-physical properties of biodiesel, due to its high density and viscosity, have been improved by increasing the injector injection pressure. Furthermore, the optimal injection advance value for engine torque was established, and combustion properties were enhanced. The impact of varying injection pressures and timings of biodiesel on engine performance, combustion characteristics, and exhaust emission parameters was examined in a three-cylinder, naturally aspirated direct injection diesel engine. Consequently, increasing both injection pressure and advance favorably affected combustion characteristics such as ignition delay, combustion duration, and the crank angle at which maximum pressure was achieved. Thanks to an increase in injection pressure, the specific fuel consumption improved by 6.74% and thermal efficiency by 10.14% compared to using biodiesel into regular engine parameters. The impact of injection advance was more significant in the exhaust emission parameters. Extra reductions of 7.92%, 5.79%, and 3.14% were established for CO, HC, and smoke opacity emissions, respectively. Enhanced combustion efficiency, leading to elevated end of combustion temperatures, resulted in a rise of up to 15.66% in NO_x emissions.

Keywords: biodiesel, diesel engine, engine performance, exhaust emissions, combustion analysis.

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