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Optimizing injection pressure for diesel engines fueled with waste cooking oil biodiesel blends

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Abstract

This study examines the effects of used cooking oil biodiesel and injection pressure on diesel engine performance and emissions. Highlights the combined effects of injection pressure and biodiesel blends. The fuel mixtures used were Pertamina Dex (B0), B50 (50% biodiesel), and B65 (65% biodiesel), with injection pressures of 160, 170, and 180 bar. Tests were conducted on a Dongfeng S195 diesel engine with a load of 1000–5000 watts. The parameters tested included fuel characteristics (density, viscosity, flash point, and calorific value), Brake Specific Fuel Consumption (BSFC), Brake Thermal Efficiency (BTE), and exhaust gas opacity. The results show that injection pressure plays a critical role in optimizing biodiesel combustion. The B65 blend at an injection pressure of 170 bar produced the lowest BSFC of 279.30 g/kWh and a high BTE of 25.54%, approaching that of pure diesel. In terms of emissions, the lowest opacity value of 5.88% was achieved with the B65 blend at 180 bar. These findings demonstrate that an optimal injection pressure, particularly 170 bar, can significantly improve fuel efficiency and combustion performance of high-percentage biodiesel blends while reducing exhaust smoke. Thus, used cooking oil biodiesel can improve fuel safety and efficiency as well as reduce emissions, provided it is combined with optimal injection pressure.

Keywords:
Biodiesel, used cooking oil, diesel engine, injection pressure, engine performance, exhaust emissions

1 Introduction

The increasing global energy demand, especially in the transportation sector, is still highly dependent on the availability of fossil fuels such as diesel. This dependence poses two main problems, namely the limitation of non-renewable natural resources and the negative impact on the environment. The burning of fossil fuels produces greenhouse gas emissions that contribute to global warming, air pollution, and reduce the quality of environmental health. In the midst of the energy crisis and increasing awareness of sustainability, the search for alternative energy sources that are environmentally friendly is an urgent need. One of the options that is considered promising is biodiesel, a fuel derived from biological sources such as vegetable oil, animal oil, and cooking oil waste (Arunprasad, *et al.*, 2021; Khayum, *t al.*, 2021).

Biodiesel has renewable properties and is able to reduce emissions of harmful exhaust gases, especially carbon monoxide (CO) and hydrocarbons (HC), compared to conventional diesel fuels. One of the potential raw materials is used cooking oil (WCO). The use of used cooking oil not only reduces environmental pollution due to the disposal of cooking oil waste, but also turns the waste into a valuable source of energy (Elkelawy, *et al.*, 2024; Özgür, 2021). The production process of biodiesel from used cooking oil through the transesterification method produces methyl esters that have physical properties close to fossil diesel. From an economic point of view, the use of used cooking oil is also able to reduce the cost of biodiesel production, while offering effective waste management solutions (Kumar, *et al.*, 2024; Sharma & Sharma, 2025).

Despite its many advantages, the use of biodiesel in diesel engines poses a number of technical challenges. Differences in physical characteristics, such as higher density and viscosity than diesel, have the potential to affect the fuel atomization process, combustion rate, and thermal efficiency of the engine. Previous research has shown that mixing biodiesel with diesel in certain levels is still able to produce competitive engine performance, but it is often accompanied by increased Brake Specific Fuel Consumption (BSFC) and nitrogen oxide (NOx) emissions. Another technical factor that plays an important role in optimizing biodiesel combustion is injection pressure. The right injection pressure can increase the atomization of the fuel, produce a homogeneous air-fuel mixture, and ultimately improve combustion efficiency and reduce emissions.

Several studies, such as those conducted by (Sugiarto, *et al.*, 2021) conducted research on a 1981 Chevrolet LUV diesel engine with injection pressure variations of 110, 120, and 130 kg/cm². The results showed that a standard injection pressure of 120 kg/cm² resulted in optimal power and torque, while an increase or decrease in injection pressure significantly affected performance. (Bakar, *.et al.*, 2008) corroborate these findings by showing that increased injection pressure in direct injection diesel engines can increase brake power and reduce specific fuel consumption (BSFC), despite the potential for increased NOx emissions. (Borugadda, *et al.*, 2018) examined the effect of biodiesel mixtures from used cooking oil (B10 and B15) on diesel engines and found that although thermal efficiency decreased compared to pure diesel, there was a decrease in CO and HC emissions.

Another study by (Senthur Prabu, *et al.*, 2017) tested a mixture of B30 biodiesel from used cooking oil given n-butanol additives. As a result, this blend is able to reduce CO emissions by up to 37.5% but increase NOx by 9%, with thermal efficiency almost equivalent to diesel at high loads. Meanwhile, (Gad & Ismail, 2021) evaluated the mixture of used cooking oil biodiesel with gasoline or kerosene and found that the specific fuel consumption was lower than pure biodiesel, but still higher than diesel. These studies show that biodiesel from used cooking oil has the potential to be used in diesel engines, but its performance and emissions are greatly influenced by the composition of the mixture and the technical parameters of the engine, including injection pressure.

Although previous studies have examined the effects of used cooking oil, biodiesel, and injection pressure variations separately. No studies tested the combination of B50–B65 with an injection of 160–180 bar on the S195 machine. This study is here to fill this gap by testing three variations of used cooking oil biodiesel blends (B0, B50, and B65) at three injection pressure levels (160, 170, and 180 bar) on diesel engine performance and exhaust emissions. The novelty of this study lies in the integrated evaluation of B50 and B65 biodiesel blend variations with injection pressures of 160, 170, and 180 bar in an S195 diesel engine. This approach enables the identification of the most optimal injection pressure to improve combustion efficiency, reduce specific fuel consumption, and decrease smoke emissions when using used cooking oil–based biodiesel. Therefore, this study not only fills the existing research gap but also provides specific and practical empirical contributions to optimizing the use of high-percentage biodiesel in conventional diesel engines.

This study focuses on the effect of injection pressure variations on the performance and emissions of diesel engines using used cooking oil biodiesel mixtures. The fuel mixture tested included B0 (100% Pertamina Dex), B50 (50% biodiesel + 50% Pertamina Dex), and B65 (65% biodiesel + 35% Pertamina Dex), with injection pressure variations of 160, 170, and 180 bar. The performance parameters analyzed include BSFC, Brake Thermal Efficiency (BTE), and exhaust gas opacity as emission indicators.

The results of this study are expected to contribute to two main aspects. First, theoretically, this study enriches the literature on the performance of diesel engines fueled by used biodiesel cooking oil, especially in relation to injection pressure variations. The resulting empirical data can be a reference for the development of alternative fuel technologies that are efficient and environmentally friendly. Second, practically, this research supports efforts to manage cooking oil waste, reduce dependence on fossil fuels, and provide technical recommendations for the automotive industry and the energy sector related to the optimal use of biodiesel.

2 Research methods

2.1 Research design

This study used laboratory experimental methods to analyze the effect of injection pressure variations on the performance and emissions of diesel engines using used cooking oil-based biodiesel.

2.2 Experimental setup

The test was carried out on a single-cylinder, four-stroke Dongfeng S195 diesel engine, which is operated on three types of fuel: B0 (100% Pertamina Dex), B50 (50% biodiesel + 50% Pertamina Dex), and B65 (65% biodiesel + 35% Pertamina Dex). The injection pressure variations used are 160, 170, and 180 bar, with a load of 1000–5000 watts. The design of this experiment aims to evaluate engine performance through BSFC, BTE, and exhaust gas opacity, as well as measure the physical characteristics of the fuel used.

2.3 Experimental variables

Independent variables: fuel composition (B0, B50, and B65); injection pressure (160, 170, and 180 bar). Dependent variables: BSFC; BTE; exhaust gas opacity (%). Control variables: engine speed maintained at a constant level; engine operating temperature stabilized before data collection; engine type and specifications, as well as the injection system, kept constant; and laboratory environmental conditions were maintained relatively constant.

2.4 Research locations and equipment

The research was carried out at the Automotive Engineering Laboratory of the Madiun State Polytechnic (Campus 2) and SMKN 3 Madiun. The main equipment used is:

1. Dongfeng S195 diesel machine (Table 1)
2. 10 kW single-phase generator as load
3. Opacity Smoke Meter to measure exhaust gas opacity
4. Tachometer to measure engine rotation
5. Bomb Calorimeter to measure the calorific value of fuel
6. Pycnometer to measure density
7. Lamp charging panel and electrical measuring device (multimeter, amperage pliers)
8. Stopwatch to measure fuel consumption time

Table 1. Specification of the Dongfeng S195 diesel engine

Parameter	Specifications
Type	4-stroke, 1 cylinder
Diameter x steps	95 mm x 115 mm
Volume silinder	0.815 L
Compression comparison	17:1
RPM maximum	2200
Oil capacity	3.5 L
Cooling system	Air (hopper)
Lubricating system	Pressure/splash

2.5 Research materials

The fuel used consists of: B0: 100% Pertamina Dex (as control); B50: 50% biodiesel used cooking oil + 50% Pertamina Dex; B65: 65% biodiesel used cooking oil + 35% Pertamina Dex. The production of used cooking oil biodiesel is carried out through a transesterification process, then mixed according to the predetermined composition.

2.6 Measurement procedure

Before testing, the engine was operated for 10–15 minutes to reach a stable operating temperature. Each combination of fuel blend and injection pressure was tested at every load level. To ensure data reliability, each test condition was repeated three times, and the values used in the analysis represent the average of the three repetitions. The tests were conducted sequentially from the lowest to the highest injection pressure, with sufficient time intervals between tests to prevent residual heat effects and operational bias. Exhaust gas opacity was measured after the load and engine speed had stabilized for approximately ±2 minutes. Fuel consumption was recorded based on the time required to consume a specified volume of fuel.

2.6.1 Fuel characteristics testing

Before use, all three types of fuel are tested to determine the density, viscosity, flash point, and calorific value. Density testing was carried out using a pycnometer, viscosity using a viscometer, calorific value with a bomb calorimeter, and flash point with a Pensky-Martens Closed Cup Tester (Table 2).

Table 2. Biodiesel Quality Standard (BSN)

Test Parameters	Unit	Requirement
Density @ 40°C	kg/m³	850–890
Viscosity kinematics @ 40°C	mm²/s	2,3–6,0
The Devil's Numbers	-	Min 51
Flash point	°C	≥100
Calorific value	MJ/kg	37–42

2.6.2 Engine performance testing

The test is carried out by installing the diesel engine on a test frame connected to the generator and the lamp charging panel. The load is given gradually, ranging from 1000 to 5000 watts.

a. BSFC is calculated based on the volume of fuel used in a given time and the engine's output power.
b. BTE is calculated from the ratio of engine output power to the thermal energy of the fuel consumed.

2.6.3 Exhaust emissions testing

Emissions are measured in the form of opacity using the Opacity Smoke Meter by installing a probe on the engine exhaust duct. The opacity value is expressed as a percentage of smoke darkness.

2.7 Data analysis techniques

The test results data are processed in a quantitative descriptive manner. BSFC and BTE values are compared between fuel variations and injection pressures using graphs to identify performance trends. The opacity results were used to evaluate the influence of a combination of variables on emission levels. The discussion was carried out by relating the findings of the experiment to the results of previous research.

3 Results and discussion

3.1 Fuel characteristics testing

3.1.1 Density

Fig. 1 showed that the fuel density value has changed along with the increase in the percentage of used cooking oil-based biodiesel blends. In B0 fuel, the density was recorded at 833.10 kg/m³, then there was a significant increase in the B50 mixture with a density value of 877.22 kg/m³. Meanwhile, in the blend, the fuel density decreased slightly to 872.61 kg/m³, but it was still higher than B0 fuel. The increase in density value in this biodiesel mixture shows that, in general, biodiesel has a higher density than pure diesel, due to the content of ester compounds and more complex molecular structures in biodiesel. This phenomenon is in accordance with the results of research by (Abed, et al.., 2018) which states that the density of biodiesel tends to be greater than that of conventional fossil fuels, and the higher the percentage of biodiesel, the tendency to increase the density also increases. However, fluctuations in B65 blends that are slightly lower than B50 can be influenced by the characteristics of biodiesel feedstocks, production processes, as well as the homogeneity of the mixture, as also expressed by (Atabani, *et al.*, 2012) that such factors may affect the stability and physical properties of biodiesel mixtures. This change in density has implications for the fuel spraying process, fog formation, and combustion efficiency of diesel engines, so it is an important parameter in the evaluation of the performance of the use of biodiesel mixtures.

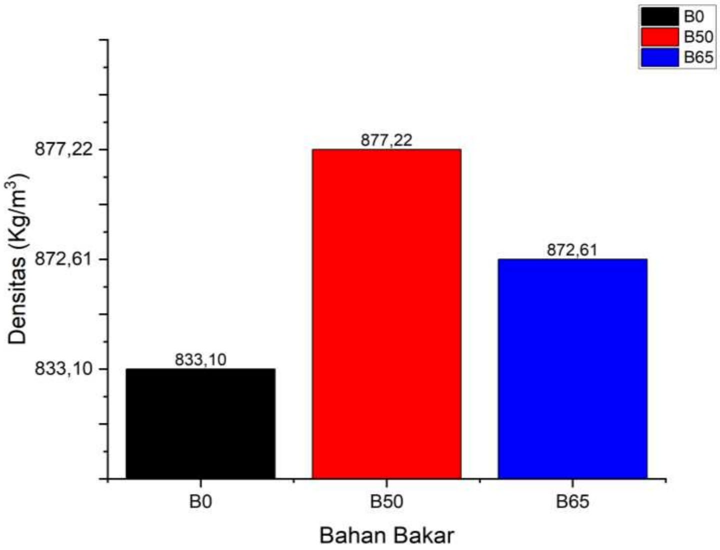

Fig. 1. Density test results

3.1.2 Viscosity

Fig. 2 showed that the viscosity value of fuel tends to increase as the percentage of used cooking oil-based biodiesel blends increases. In B0 fuel, the viscosity value was recorded at 4.69 mm²/s, then there was an increase in the B50 mixture with a viscosity value of 4.84 mm²/s. Furthermore, in the B65 mixture, the viscosity value increases back to 4.91 mm²/s.

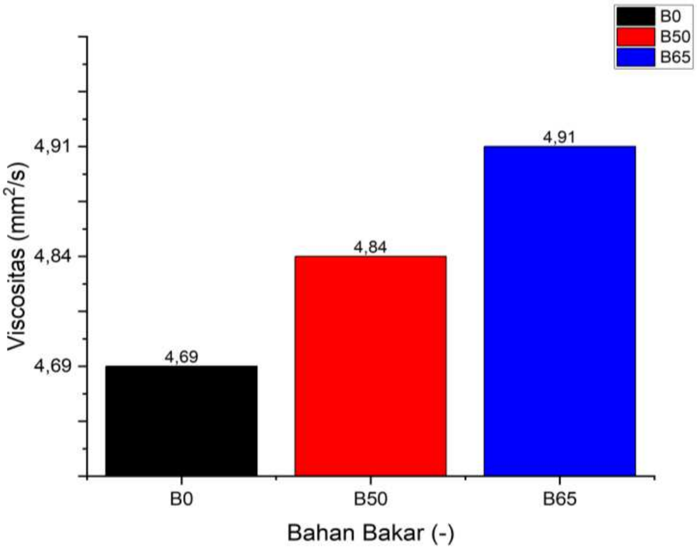

Fig. 2. Viscosity test results

This increase in viscosity value shows that the addition of biodiesel content to the fuel mixture affects the flow properties of the fuel, where biodiesel has higher viscosity characteristics than B0. This is in line with the results of the study by (Abed, *et al.*, 2018) which states that the greater the percentage of biodiesel in the mixture, the viscosity value of the fuel will increase due to the content of the compound ester in biodiesel. This increase in viscosity has implications for the process of fuel mist formation in the combustion chamber, which has the potential to affect the performance and combustion characteristics of diesel engines.

3.1.3 Flash point

Fig. 3 showed that the value of *the flash point* or fuel flash point has increased along with the increase in the percentage of used cooking oil-based biodiesel mixtures. In B0 fuel, the *flash point* value was recorded at 55°C, then increased significantly in the B50 mixture with a *flash point* value of 80.5°C, and there was a further increase in the B65 mixture to 84.5°c.

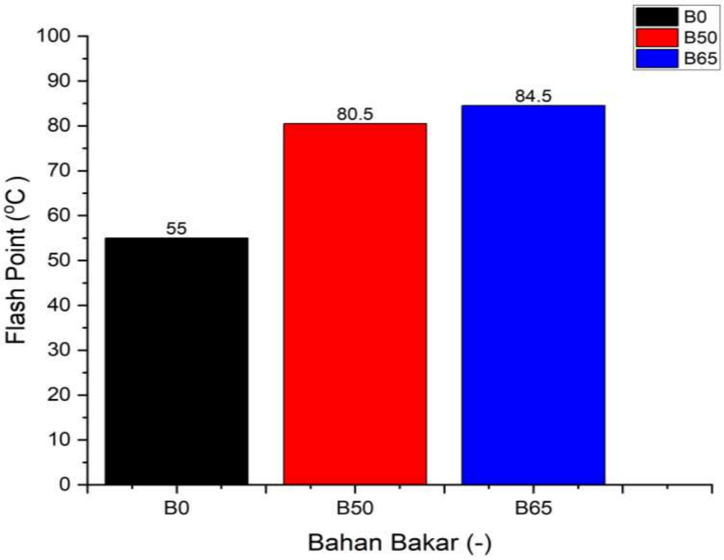

Fig. 3. Point flash test results

Increased value *flash point* This suggests that biodiesel blends have better safety characteristics against the risk of fire than pure diesel, because the higher the flash point, the more difficult it is for the fuel to burn spontaneously at ambient temperature. This is in line with research by (Atabani, *et al.*, 2012)which states that biodiesel has a higher flash point than conventional fossil fuels, due to the chemical structure of biodiesel that contains chains ester and polar compounds, so they require higher temperatures to reach the flash point. This increase in the flash point is one of the advantages of biodiesel in terms of fuel storage and transportation safety, although it is still necessary to consider its implications for the ignition characteristics of diesel engines, especially in low temperature conditions.

The flash point values of B50 and B65, which are lower than the BSN standard (≥100°C), are attributed to the blending of biodiesel with fossil diesel (Pertamina Dex), which inherently has a lower flash point. In addition, the quality of the used cooking oil, including its Free Fatty Acid (FFA) content and the possible presence of residual volatile fractions resulting from repeated heating processes, also affects the flash point of the blend. We have added an explanation that these values are reported as a limitation of the study and do not represent pure biodiesel, but rather the characteristics of biodiesel–diesel blends.

3.1.4 Calorific value

Fig. 4 shows that the calorific value of fuel has increased along with the addition of used cooking oil-based biodiesel mixtures. In B0 fuel, the calorific value was recorded at 44,000 j/g, then increased significantly in the B50 mixture to 53,876 j/g, and decreased slightly but was still higher than pure diesel in the B65 mixture, which was 50,465 j/g.

This increase in calorific value is different from the general trend of biodiesel from various previous studies, but this can be explained through the characteristics of the biodiesel raw materials used, especially the cooking oil, which comes from used cooking oil with a high saturated fat content, as well as an efficient biodiesel production process to produce quality methyl ester compounds. As explained by (Abed, *et al.*, 2018), the variation in the calorific value of biodiesel is highly dependent on the type of raw material and production process, so that under certain conditions, the calorific value of the biodiesel mixture can be higher than that of pure fuel.

This increase in heat value has a positive impact on the combustion process, where higher energy content allows for better power efficiency and thermal energy generation, provided it is supported by optimal injection system settings and combustion conditions.

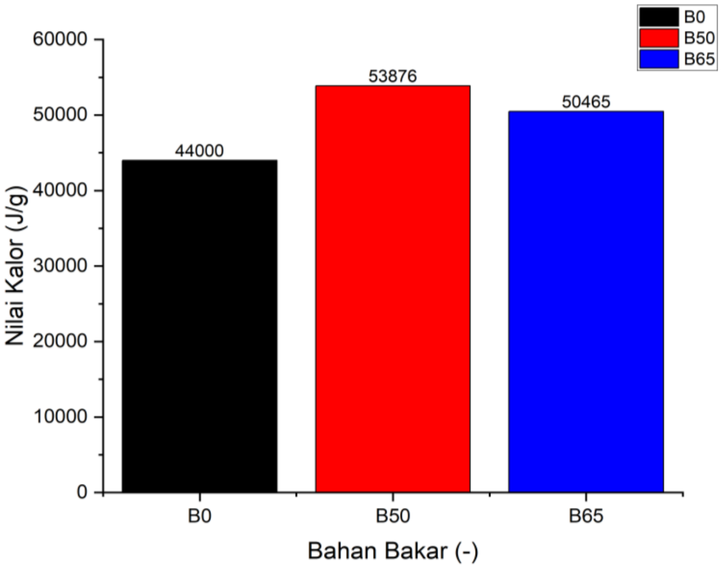

Fig. 4. Heat test results

3.2 Engine performance testing

3.2.1 BSFC

The test is carried out to determine specific fuel consumption based on the data from the test results of the diesel engine on load variations. BSFC calculation using Eq. (1).

$$BSFC = \frac{mf}{\text{P}} \tag{1}$$

$$mf = \frac{\text{volume(L)} \times Densitas(g/L)}{Waktu\ (Jam)} = \frac{0.025\text{L} \times 833.1\ g/L}{0.0224 Jam} = 929.7991$$

$$P = \frac{V \times I \times PF}{1000} = \frac{226 \times 6 \times 1}{1000} = 1.356$$

$$BSFC = \frac{mf}{P} = \frac{929.7991}{1.356} = 685.6925$$

The results of BSFC data collection have been calculated Eq. (1), and the results are obtained in Table 3.

Table 3. BSFC Results

Fuel	Injection pressure	1000watt	2000watt	3000watt	4000watt	5000watt
B0	160	685.6925	431.4470	350.2340	313.4381	322.0586
	170	673.6497	417.8101	348.6911	319.9243	319.9801
	180	688.8220	417.8101	348.6911	319.9243	329.4710
B50	160	738.3891	470.0791	376.4134	329.9923	358.6652
	170	725.2847	444.7878	374.7979	336.8594	336.9182
	180	728.5665	468.0616	382.7724	336.8594	359.8730
B65	160	734.6008	467.6673	379.7566	328.2992	336.6344
	170	604.8733	372.8906	309.8375	279.3010	310.0632
	180	738.1053	457.6253	378.0837	340.8210	378.3591

Based on BSFC data in Table 3, it can be seen that the BSFC value tends to decrease as the load on all types of fuel increases and the injection pressure varies. B0 (pure diesel) fuel shows the lowest BSFC at most loads, particularly at an injection pressure of 170 bar, which reaches 348.69 g/kWh at a load of 3000 watts and 319.92 g/kWh at a load of 4000 watts. B50 mixtures generally have higher BSFCs than B0 under all conditions, indicating lower combustion efficiency due to higher viscosity. Interestingly, the B65 mixture at an injection pressure of 170 bar showed excellent performance, with the lowest BSFC of 279.30 g/kWh at a load of 4000 watts, which is even lower than B0. In contrast, at injection pressures that are too high (180 bar) or too low (160 bar), BSFCs tend to increase in all mixtures, suggesting that 170 bar is the most optimal injection pressure to improve the fuel consumption efficiency of used cooking oil biodiesel.

Fig. 5 shows that an increase in specific fuel consumption (BSFC) occurred in the B50 and B65 biodiesel mixtures, especially at low loads (1000 watts) of 738.3891 g/kWh and 734.6008 g/kWh, respectively, higher than the B0 pure fuel of 685.6925 g/kWh.

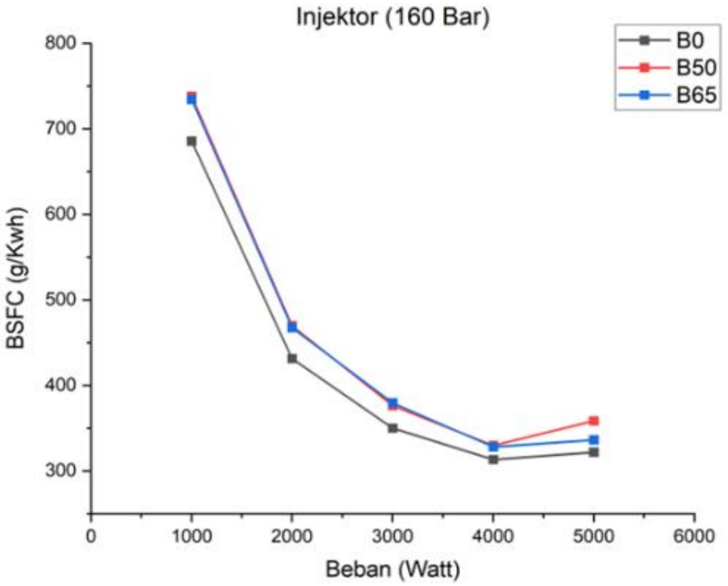

Fig. 5. BSFC at an injection pressure of 160 Bar

The decrease in fuel consumption is seen as power increases, but at all load levels, the biodiesel blend still shows higher BSFC than B0, indicating that combustion efficiency is not optimal. This is in line with the findings (Abed, *et al.*, 2018; Bakar, *et al.*, 2008) which states that biodiesel has a higher viscosity than diesel, so that at low injection pressure, the fuel atomization is less perfect and increases fuel consumption.

Fig. 6 shows that at an injection pressure of 170 bar, there is a significant increase in efficiency in the B65 mixture, where BSFC is the lowest at almost all power levels. For example, at 4000 watts, it reaches 279.3010 g/kWh, lower than B0 (319.9243 g/kWh) and B50 (336.8594 g/kWh).

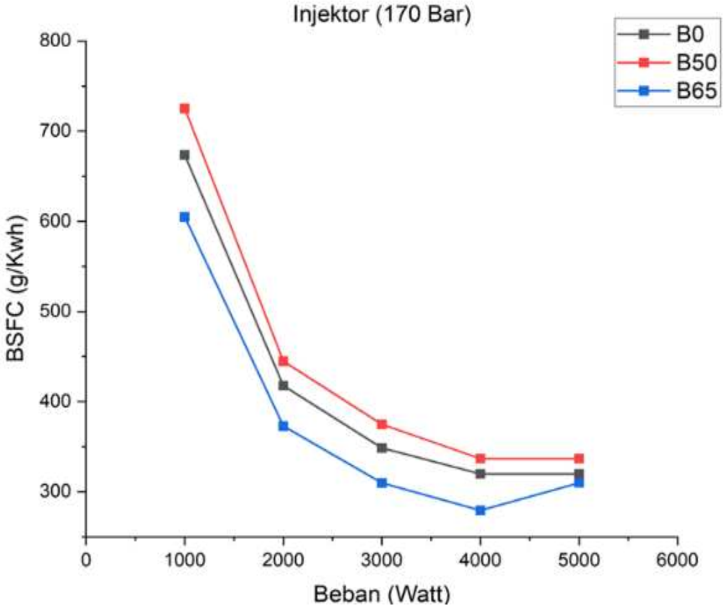

Fig. 6. BSFC at an injection pressure of 170 Bar

This decrease in BSFC indicates that the increase in injection pressure improves the atomization of the fuel, resulting in more perfect combustion even though the biodiesel mixture has a higher viscosity. The natural oxygen content in biodiesel also helps to improve the thermal efficiency of the engine. These findings are in line with research (Atabani, *et al.*, 2012; Bakar, *et al.*, 2008; Hossain & Davies, 2010), who reported that higher injection pressures improve the combustion efficiency of biodiesel by improving fuel spread.

Fig. 7 shows that at an injection pressure of 180 bar, the consumption of specific fuels tends to increase again, especially in biodiesel blends. For example, at a load of 1000 watts, BSFC blended B65 was recorded at 738.1053 g/kWh, higher than pure B0 fuel (688.8220 g/kWh).

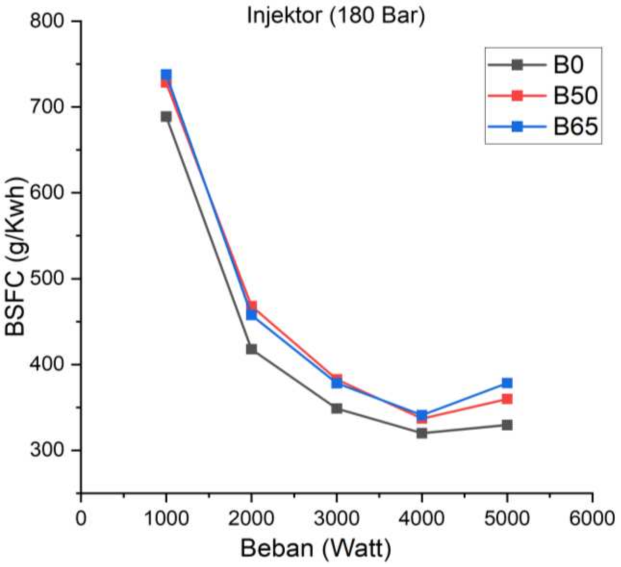

Fig. 7. BSFC at an injection pressure of 180 Bar

This phenomenon suggests that too high an injection pressure can disrupt the fuel spraying pattern, causing over-penetration or excessive penetration of fuel into the combustion chamber, so that the air-fuel mixture is not homogeneous and combustion is not optimal. It is also reported that an increase in injection pressure above the optimal point can have a negative effect on fuel consumption and engine efficiency.

3.2.2 BTE

The test was carried out to find out how efficiently the engine converts chemical energy into mechanical energy based on test results on diesel engines with load variations. The BTE calculation using Eq. (2), where P is 1.356, mf is 929.7991 g/L = 0.9297991 Kg/L = 0.0002583 Kg/s, and Qhv is 44000 kJ/kg. The results of the BTE calculation can be seen in Table 4.

$$BTE = \frac{P}{(mf \times Qhv)} \tag{2}$$

$$BTE = \frac{1.356}{(0.0002583 \times 44000)} = 0.119322 = 11.9322\%$$

Table 4. BTE calculation results

Fuel	Injection pressure	1000watt	2000watt	3000watt	4000watt	5000watt
B0	160	11.93%	18.96%	23.36%	26.10%	25.40%
	170	12.14%	19.58%	23.46%	25.57%	25.56%
	180	11.87%	19.58%	23.46%	25.57%	24.83%
B50	160	9.049%	14.21%	17.75%	20.24%	18.63%
	170	9.212%	15.02%	17.82%	19.83%	19.83%
	180	9.171%	14.27%	17.45%	19.83%	18.56%
B65	160	9.710%	15.25%	18.78%	21.72%	21.19%
	170	11.79%	19.13%	23.02%	25.54%	23.00%
	180	9.664%	15.58%	18.86%	20.93%	18.85%

Based upon data on BTE in Table 4, it can be seen that the BTE value increases with increasing load on all types of fuel and variations in injection pressure. B0 (pure diesel) consistently recorded the highest BTE, with a maximum value of 26.10% at an injection pressure of 160 bar and a load of 4000 watts. The B50 blend showed the lowest BTE in all conditions, with a relatively moderate increase despite the increased load. Meanwhile, B65 showed a more competitive performance, especially at an injection pressure of 170 bar, where the BTE reached 25.54% at a load of 4000 watts, close to the efficiency of B0 under the same conditions. This phenomenon shows that the right injection pressure setting, particularly at 170 bar, can optimize the combustion of used cooking oil biodiesel so that its efficiency is close to fossil fuels, although at pressures that are too low (160 bar) or too high (180 bar), the efficiency tends to decrease.

In Fig. 8, the highest thermal efficiency value (BTE) is recorded in B0 fuel, especially at a load of 4000 watts, which is 26.10%. Meanwhile, B50 and B65 biodiesel blends showed lower BTE, at 20.24% and 21.72%, respectively. The low BTE in biodiesel blends is due to the higher viscosity and density properties, so combustion does not take place optimally at this injection pressure. (Abed, *et al.*, 2018)reports that high viscosity in biodiesel can affect the atomization process, causing thermal efficiency to decrease, especially at low injection pressures.

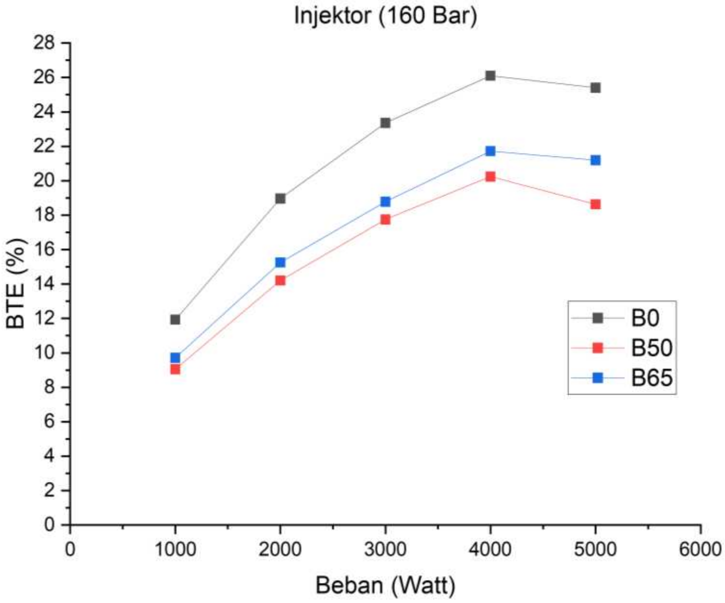

Fig. 8. BTE on 160 Bar injector

In Fig. 9, it can be seen that the increase in thermal efficiency in biodiesel blends, especially B65, which reached 25.54% at a load of 4000 watts, is close to the efficiency of B0 of 25.57%. This increase shows that the injection pressure of 170 bar is able to optimize the atomization of the fuel, so that even though it uses a biodiesel mixture with a higher viscosity, the combustion process still runs more perfectly. (Atabani, *et al.*, 2012; Hossain & Davies, 2010)explains that the increase in injection pressure improves the spread of fuel within the combustion chamber, improving the thermal efficiency of the engine, especially when using a biodiesel mixture.

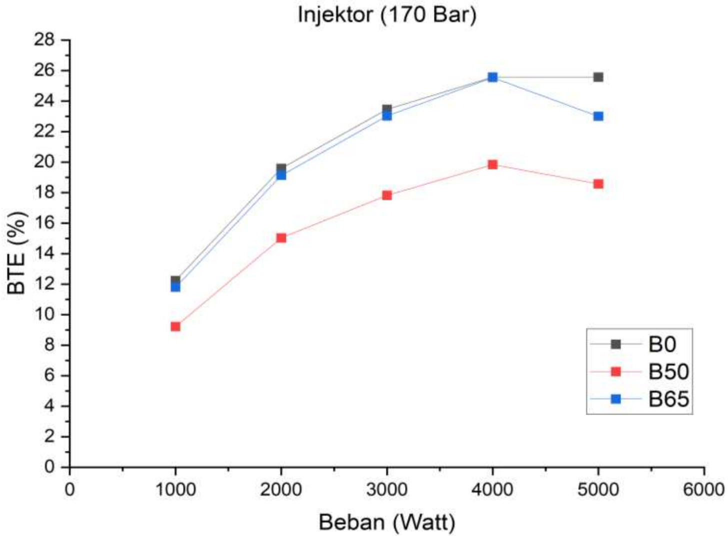

Fig. 9. BTE on 170 bar injectors

In Fig. 10, the BTE values for B50 and B65 biodiesel mixtures decreased again at several load levels. For example, at a load of 1000 watts, the BTE for B65 is 9.664%, lower than at a pressure of 170 bar. This decrease in efficiency indicates that too high an injection pressure can cause *over-penetration* fuel into the combustion chamber, so that the fuel distribution pattern becomes suboptimal, causing uneven combustion. This is in accordance with research (Borugadda, *et al.*, 2018) which states that injection pressure above the optimal point can negatively impact the thermal efficiency of diesel engines that use biodiesel.

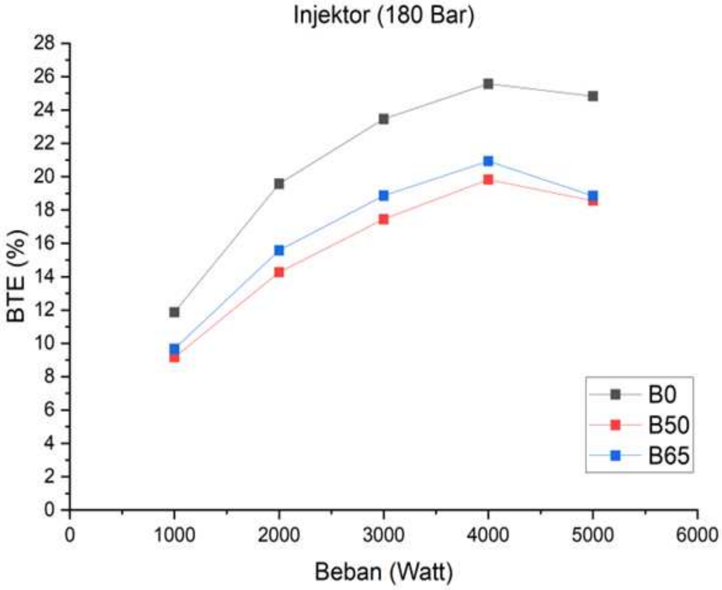

Fig. 10. BTE on 180 Bar injectors

3.3 Exhaust emissions testing

3.3.1 Combustion opacity

In Fig. 11, it can be seen that the addition of biodiesel and an increase in injection pressure lead to a decrease in exhaust gas opacity. At an injection pressure of 160 bar, the highest opacity occurred in B0 fuel at 14.58%, then decreased to 12.92% for B50, and 10.36% for B65.

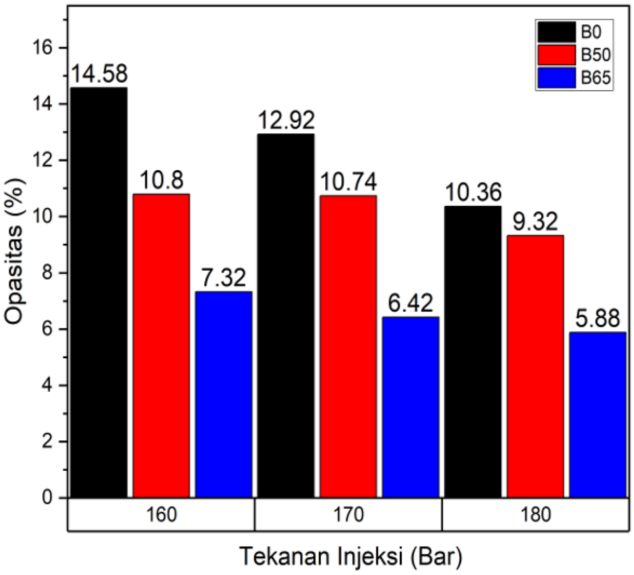

Fig. 11. Opacity test results

At a pressure of 170 bar, there was a further decrease in the opacity of B0 of 10.80%, B50 of 10.74%, and B65 of 9.32%. At a pressure of 180 bar, the opacity values are lower: 7.32% for B0, 6.42% for B50, and 5.88% for B65.

This decrease in opacity indicates that the oxygen content in biodiesel and the increase in injection pressure improve the atomization of the fuel, resulting in more perfect combustion, thereby reducing exhaust fumes. These findings are in line with research by (Khannan, *et al.*, 2022)which states that the use of biodiesel, especially with higher injection pressures, is effective in reducing smoke emissions in diesel engines.

4 Conclusions

The research concluded that the highest calorific value was obtained in the B50 mixture of 53,876 J/g, followed by B65 of 50,465 J/g, and B0 of 44,000 J/g. In terms of engine performance, the results indicate that while biodiesel blends tend to increase BSFC at lower injection pressures due to higher viscosity, optimization of injection pressure significantly improves performance. At 170 bar, B65 achieved the lowest BSFC (279.30 g/kWh at 4000 W), outperforming B0, and produced a BTE (25.54%) comparable to diesel fuel. Biodiesel use consistently reduced exhaust opacity, with the lowest value recorded for B65 at 180 bar (5.88%), substantially lower than B0. In terms of exhaust emissions, the use of biodiesel consistently lowers exhaust gas opacity at all injection pressure variations. The lowest opacity value was obtained for the B65 mixture at a180 bar injection pressure of 5.88%, much lower than B0 at 160 bar pressure (14.58%).

The findings of this study have practical implications for the application of used cooking oil biodiesel in conventional diesel engines. The recommended operating condition of B65 at 170 bar can be implemented without major engine modifications, offering a feasible pathway to improve fuel efficiency and reduce dependence on fossil diesel while maintaining emission performance. Nevertheless, this study has several limitations. The experiments were conducted on a single-cylinder S195 diesel engine under steady-state conditions, and only smoke opacity was evaluated as an emission parameter. In addition, the physicochemical properties of biodiesel were influenced by the quality of the used cooking oil and the transesterification process, which may limit the generalizability of the results. Transient operating conditions, long-term engine durability, and other exhaust emissions such as NOx, CO, and HC were not investigated.

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