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- agro-product and food processing engineering;
- physical, chemical and biological changes in the soil caused by tillage and field traffic, soil working machinery and terramechanics;
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PERFORMANCE AND EMISSION OF DIESEL ENGINE FUELLED BY COMMERCIAL BIO-DIESEL FUELS IN INDONESIA

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The performance and emission of a small diesel engine fuelled by commercial diesel fuel in Indonesia are present in this paper. Various commercial diesel fuels in Indonesia are produced and marketed by Pertamina. As the largest oil company in Indonesia, Pertamina has developed various diesel fuels, namely Solar, Biosolar (B30), Dexlite, and Pertadex. This study explains in more detail the performance, fuel consumption, and emission produced by the four types of fuels, and they were investigated experimentally using a single-cylinder diesel engine at various engine speeds, from 1,000 rpm to 4,500 rpm. The result shows the engine fuelled by Pertadex generates the highest power and torque, while the lowest is generated by the Biosolar fuelled engine. The maximum torque and power generated by the Pertadex fuelled engine are about 25.5 Nm and 7200 W, respectively. The engine fuelled by Pertadex has the lowest brake specific fuel consumption (BSFC) of 0.3037 kg·kW·h, compared to the engines fuelled by the Dexlite, Solar, and Biosolar fuels, with values around 0.3127, 0.3215, and 0.3338 kg·kW·h, respectively. At the same time, the measurement of gas emissions, including CO_2, CO, NO_x, and HC was conducted simultaneously.

Keywords: diesel engine; smoke analysis; biofuel; fuel consumption

In Indonesia, vehicles for transportation facilities are dominated by motorcycles, cars, buses, and trucks, estimated at around 126 million (Sub-directorate of Transportation Statistics, 2019). Based on statistics, buses, trucks, and other passenger vehicles are predominantly diesel-engine vehicles in Indonesia. Although diesel engines have numerous advantages, their emission can contribute to increased greenhouse gas emissions and environmental damage (Rai and Sahoo, 2019). As a result, greenhouse gas emissions have climbed by 103.8% over the last four decades. Furthermore, compression ignition (CI) engines consume a considerable amount of fossil fuels and pollute the environment (Hoang et al., 2019). Road transportation's fuel consumption is dominated by road transportation, which accounts for 88% of total fuel oil consumption, primarily diesel and gasoline. In 2020, fuel consumption for transportation in Indonesia is around 15,078,000 kilolitres for diesel fuel and 10,650,000 kilolitres for gasoline (Praptijanto et al., 2015).

Pertamina supplies fuel for vehicles in Indonesia. Pertamina produces several fuels for diesel engines, namely with the brand names Solar, Biosolar, Dexlite, and Pertadex. Solar is a conventional diesel fuel, while Dexlite and Pertadex are higher grade diesel fuels compared with Solar. These various fuel types are made to meet the needs according to the engine technology used, targeted to meet the emission standards currently in effect. In addition, Pertamina is also targeting biodiesel to gradually reduce dependence on fossil fuels, namely with Biosolar or B30 products. B30 is a blend of diesel and biodiesel, with a 30% biodiesel content. The process of transforming raw oil/fat (triglyceride) into biodiesel is known as transesterification (fatty acid methyl-ester, FAME), where the raw material for biodiesel is palm oil. Some of the advantages of biodiesel are low emission, non-toxicity, inherent lubricity, and higher flash point (Devarajan et al., 2017; Devarajan et al., 2018a) However, some disadvantages that need to be considered of using biodiesel are poor viscosity and atomization leading to higher NO_x emission and lower efficiency (Hoekman et al., 2012). Many authors agree to reduce exhaust emissions without reducing engine performance by varying the mixture of diesel fuel with biodiesel (Pullen and Saeed, 2014; Radhakrishnan et al., 2017; Ramanan and Yuvarajan, 2015).

The experimental tests of types of fuel usage need to be carried out to determine their impact on performance and exhaust emissions. Several researchers have researched the performance of diesel engines with a mixture of diesel and biodiesel fuels. Praptijanto et al. (2015) conducted research on the performance of diesel engines by comparing the diesel fuel and a mixture of ethanol and diesel at an engine speed of 1,000–1,500 RPM. The results showed that the power produced by engines using pure diesel fuel (E0) was lower than E2, E5–E10, especially at 1,400 rpm. Mofijur et al. (2015) concluded that studies carried out with the addition of ethanol to biodiesel in diesel engines could significantly reduce the exhaust gas emissions such as hydrocarbon (HC), parts per million (ppm), and smoke, but increase fuel consumption. Meanwhile, Prbakaran and Viswanathan (2016) concluded that brake thermal efficiency (BTE) produced in an engine fuelled by an Ethanol-Solar mixture is the same as pure diesel fuel. There is a reduction in CO and HC exhaust emissions at high loads and an increase at low loads. However, alternative fuels have a crucial issue regarding environmental problems, for example, the use of various additional oil such as waste edible oil (WBO) (Gad and Ismail, 2021), waste cooking oil (WCO) (El-Sawy et al., 2020), and animal fat for biodiesel (Kanth and Debbarma, 2021). Although it does not significantly affect the efficiency, performance, and diesel engine emissions, further research related to the environmental issue is needed.

The Solar, Biosolar, Pertadex, and Dexlite fuels have different characteristics, one of which is cetane number (CN). Pertadex has a higher cetane number than Biosolar and Dexlite, in addition to various other fuel properties. Biosolar's CN is 48, while Pertadex is 53 and Dexlite is 51. Many studies examine the performance of diesel fuel, especially in Indonesia. However, there are still very few more profound into the comparison of diesel fuel in Indonesia, especially on the emissions released. Therefore, this study explains in more detail the performance, fuel consumption, and emissions produced by the four types of fuels using a single-cylinder diesel engine.

Material and methods

The current study assesses the performance, consumption, and emissions of a direct ignition (DI) diesel engine using the commercial diesel fuels such as Solar, Biosolar (B30), Dexlite, and Pertadex. At all loads and a constant speed from 1,000 rpm to 4,500 rpm, the performance measures such as braking torque, brake power (BP), brake specific fuel consumption (BSFC), BTE, and exhaust gas emissions were evaluated. The experiments were conducted at the Institut Teknologi Nasional Bandung's Energy Conversion Laboratory. The engine testbed is shown in Fig 1.

Fuel consumption was measured by determining the time taken by the diesel engine to consume a certain amount of fuel. Engine speed was also monitored using an electronic tachometer connected to data acquisition. The tachometer can measure engine speed up to 20,000 rpm, with a measurement tolerance of 25 rpm and scanning tolerance of 100 rpm. The engine was coupled to a dynamometer, and temperature was measured using a thermocouple. The dynamometer is an eddy current dynamometer measuring the power and torque up to 16 kW and 70 Nm, respectively. The dynamometer cooling system is water cooled, with a pressure and flowrate of 0.3 bar and 6.6 l·min, respectively. The engine cooling temperature, exhaust gas, and air inlet temperature are measured by a T-type thermocouple. While gathering data on diesel engine performance using the computer-based data-acquisition system, Spectrum (MI.3112CA) was installed on a DEWE-5000 portable data-acquisition system to collect and analyse the results. The gas analyser Techno (MODEL 488) was used to measure exhaust gas emissions, especially for NO_x, HC, CO, and CO_2, with an accuracy of 5% of reading; therefore, the voltage and power needed is 230 V (single phase) and 100 W, respectively. Therefore, Table 1 shows the detail of specification of the test engine used in this study. The performance indicators such as BP, BSFC, and BTE of all fuels were calculated as follows:

$$\tau = \frac{F}{l} \quad (1)$$

$$BP(\text{kW}) = \frac{2\pi RPM\,\tau}{60 \cdot 1{,}000} \quad (2)$$

$$BSFC = \frac{\dot{m}_f}{BP} \quad (3)$$

$$BTE(\%) = \frac{3{,}600}{BSFC \cdot LHV} \cdot 100 \quad (4)$$

where: τ – brake torque (Nm); F – load (N); l – the length of crankshaft (m); m_f – fuel consumption rate (kg/s); LHV – the low heating value of each biodiesel

To ensure data accuracy, measurements were repeated three times for each parameter. The data presented are the average of three measurements to decrease the uncertainty of each parameter. The input data for calculation is obtained

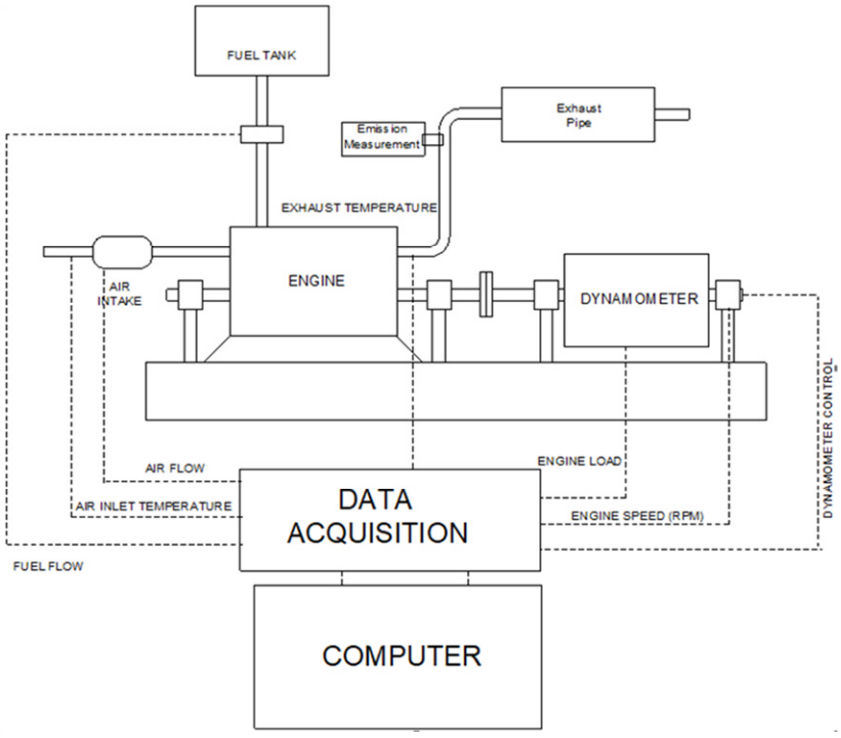

Fig. 1 Experimental scheme

by the load (*F*) of direct measurement from dynamometer load, followed by engine rotation and fuel consumption rate.

Table 1 Diesel engine specification

Items	Specifications
No. of cylinders	1 cylinder
Bore	80.5 mm
Stroke	91 mm
Displacement	460 cm^3
Compression ratio	20:1
Combustion chamber	swirl chamber type
Intake valve open	20° before top dead centre (BTDC)
Exhaust valve open	55° bottom dead centre (BDC)
Intake valve closed	49° after bottom dead centre (ABDC)
Exhaust valve closed	22° after top dead centre (ATDC)
Maximum torque	28 Nm at 2,000 rpm
Maximum power	8 kW at 3,000 rpm

Results and discussion

Diesel engine performance, including torque, power, BSFC, and BTE followed by emission data, is presented in this chapter. These various data were obtained and recorded simultaneously using data acquisition. In this investigation, the diesel engine was operated at various speeds from 1,000 rpm to 4,500 rpm.

Torque and power

Figure 2 shows the identical result of the effect of speed engine on torque, where the four diesel fuels show the highest torque at 2,000 rpm. At that speed, the torque produced by the engine fuelled by Pertadex, Dexlite, Biosolar, and Solar is 25.5 Nm, 25.0 Nm, 24.7 Nm, and 23.0 Nm, respectively. It can be seen in Fig. 2 that Pertadex generates the highest torque, and Biosolar generates the lowest. The high CN of diesel fuel can generate better performance of diesel engines. The greater CN of diesel fuel will speed up the combustion process in a diesel engine. As a result, the engine gets a more substantial increase in torque and power than an engine fuelled by low CN. The results are consistent with the cetane index (CI) engine specifications used in the experiments. These findings are similar to available trend data in open literature (Devarajan et al., 2018b).

Table 2 Diesel fuels specification

No.	Characteristic	Unit	Solar		Biosolar (B30)		Dexlite		Pertadex		Test method
			min	max	min	max	min	max	min	max	
1	cetane number		48			51	51		53		ASTM D613
2	specific gravity	kg·m^{-3}	815	860	815	860	820	860	820	860	ASTM D1298/ D4052
3	viscosity	mm^2·s^{-1}	2	4.5	2	4.5			2	4.5	ASTM D445
4	sulphur content	% m·m^{-1}		0.25		0.05		0.05		0.05	ASTM D2622/ D5453
5	distillation 90% of vaporization	°C		370		370		360		340	ASTM D86
6	flash point	°C	52		55		55		55		ASTM D93
7	pour point	°C	18			18		18		18	ASTM D97
8	carbon residue	% m·m^{-1}		0.1		0.1		0.3		0.3	ASTM D4530/ D189
9	water content	mg·kg^{-1}		500		300		500		500	ASTM D6304
10	calorific value	MJ·kg^{-1}		44.9		44.1		44.4		45.1	ASTM D420
11	fame content	% v/v				30				10	ASTM D7806/ D7371
12	methanol content	% v/v		–		–		–		–	
13	ash content	% v/v		0.01		0.01		0.01		0.01	ASTM D482
14	sediment content	% m/m		0.01		0.01		0.01		0.01	ASTM D473
15	strong acid number	mg KOH·gr^{-1}		0		0		0		0	ASTM D664
16	total acid number	mg KOH·gr^{-1}		0.6		0.6		0.3		0.3	ASTM D664
17	lubricity, high frequency reciprocating rig (HFRR) wear scar diameter at 60 °C	micron		460		460		460		460	ASTM D6079

Source: Pertamina, 2022

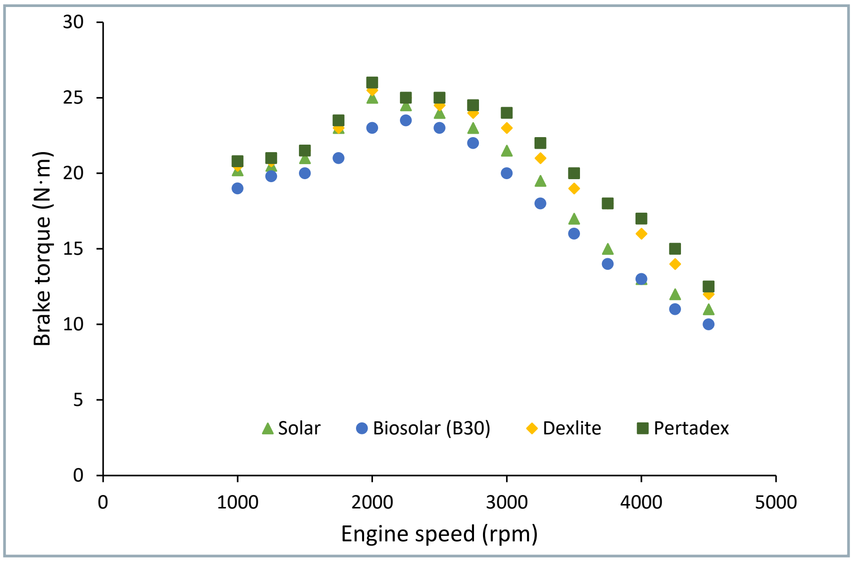

Fig. 2 Effect of engine speed on torque

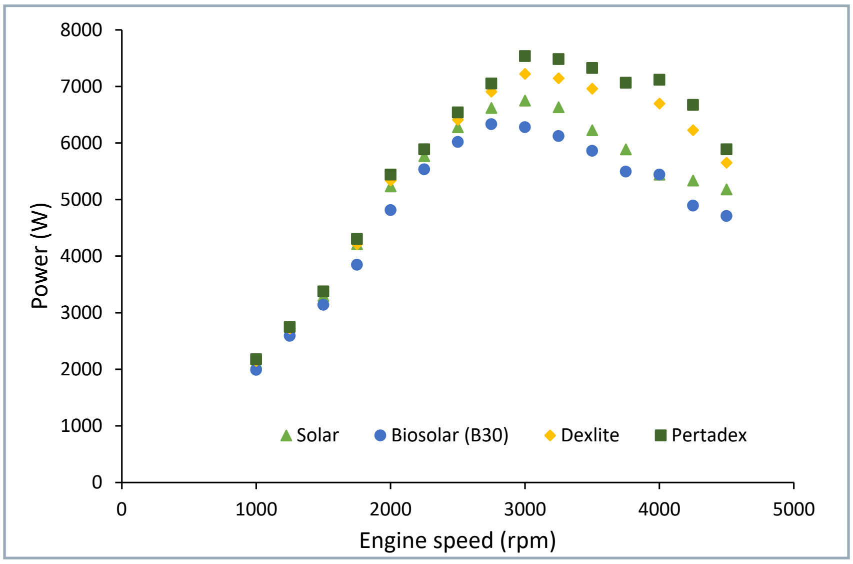

Fig. 3 Effect of engine speed on power

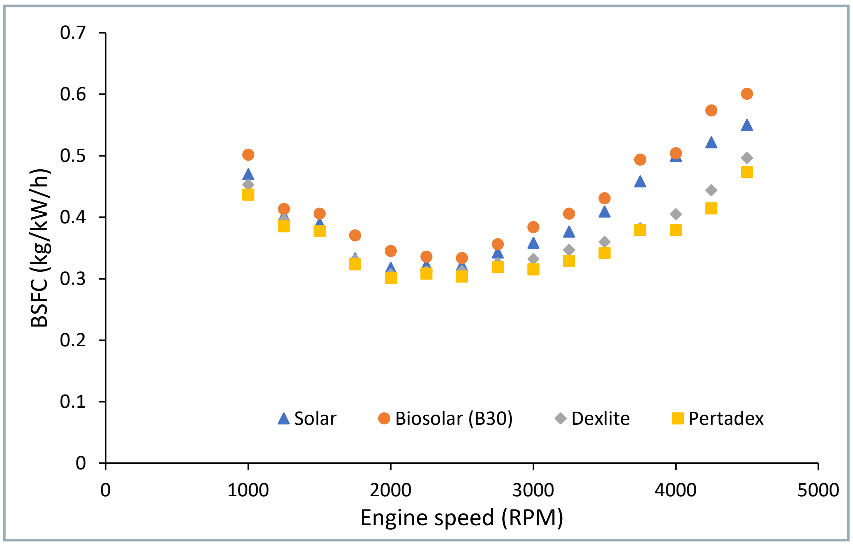

Fig. 4 Effect of engine speed on BSFC

Figure 3 shows that at low speed, engine's performance with all four fuels is similar. At high speed, the performance of the engine is different. The peak points of engine torque could be reached around 2,000 rpm, whereas engine powers are at 3,000 rpm. The engine fuelled by Pertadex generates the highest power, while the lowest is generated by the B30 fuel engine, as shown in Fig. 3. Engines fuelled by Pertadex can produce a maximum power of 7,200 W. In contrast, Dexlite, Solar, and Biosolar fuel engines can produce a maximum power of 7,000 W, 6,500 W, and 6,000 W, respectively. Biosolar has a low calorific value of 44.154 $MJ{\cdot}kg^{-1}$ compared to Solar, Dexlite, and Pertadex with 44.895 $MJ{\cdot}kg^{-1}$, 44.439 $MJ{\cdot}kg^{-1}$, and 45.087 $MJ{\cdot}kg^{-1}$, respectively. However, it can be concluded that an increase of biodiesel percentage in blends decreases the calorific value of diesel fuel. Similar findings were observed by Nguyen et al. (2020) who analysed the biodiesel (B0-B100) blend combustion characteristic under a wide range of thermal condition. The authors state that the high CN of B100 that has more percentage of blends is more reactive and auto-ignites rather than the biodiesel that has low percentage of blends.

Fuel consumption

Other engine performances are presented by BSFC and BTE. The BSFC is the fuel consumed by an engine to generate 1 kW of power in 1 hour. Low BSFC of an engine means low fuel consumption. Figure 4 shows the value of the BSFC of the engine fuelled by various fuels. From 1,000 rpm to 2,000 rpm, the value of BSFC decreases and then increases above 2,000 rpm, experienced by all diesel fuels. When engine speed increases, BSFC will gradually increase to overcome the load in the form of mechanical friction, and the value of BSFC increases with increasing speed (Teoh et al., 2020). The engine fuelled by Pertadex has the lowest BSFC point (0.3037 $kg{\cdot}kW^{-1}{\cdot}h$) compared to the engine fuelled by Dexlite, Solar, and Biosolar with a value around 0.3127, 0.3215, and 0.3338 $kg{\cdot}kW^{-1}{\cdot}h$, respectively. According to Table 2, fuel consumption is influenced by FAME content. It is not surprising that biodiesel (B30), having

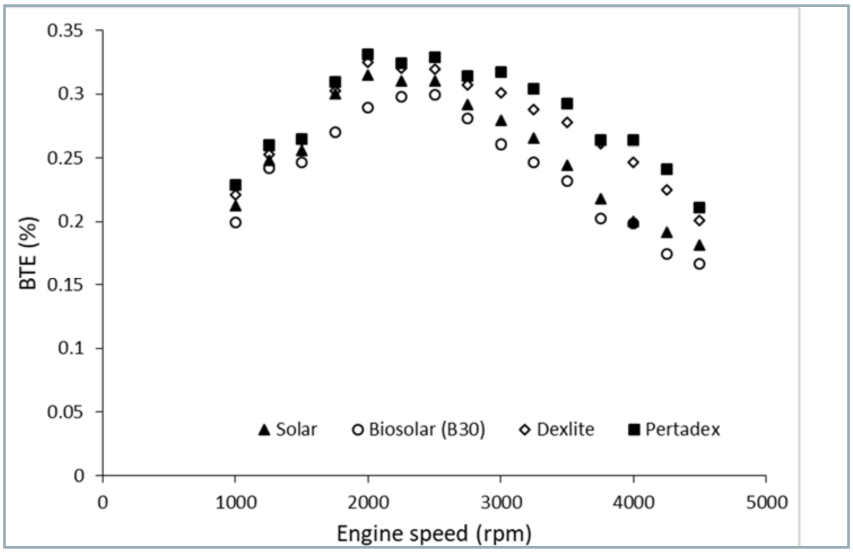

Fig. 5 Effect of the speed engine on BTE

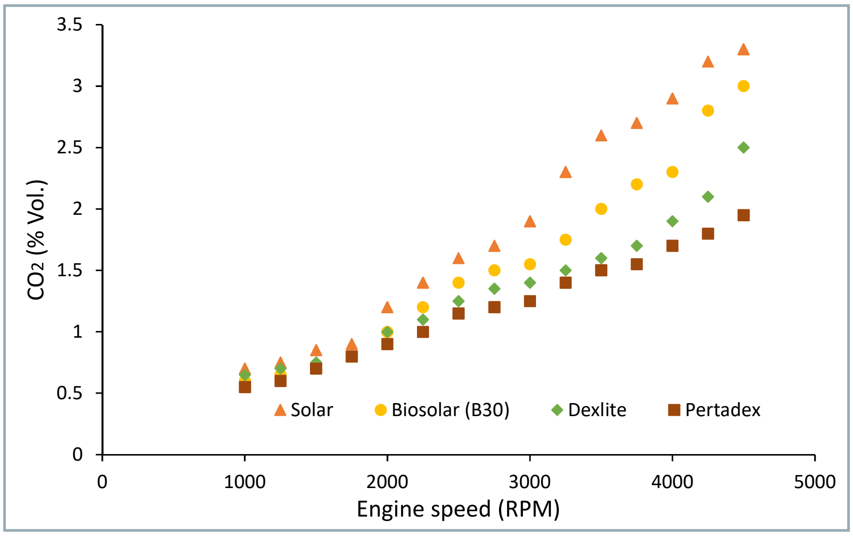

Fig. 6 Effect of the speed engine on CO_2

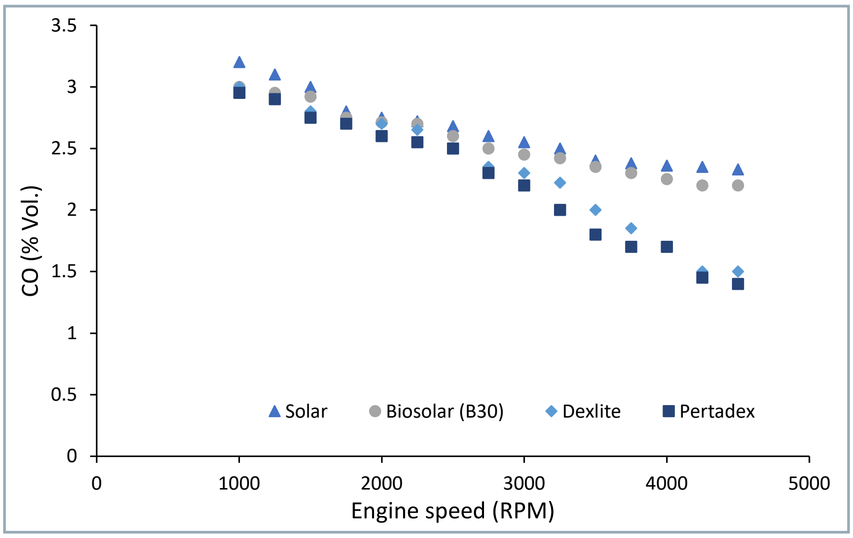

Fig. 7 Effect of the speed engine on CO

the highest FAME content of around 30, shows the highest BSFC increase after 2,000 rpm. Higher specific fuel consumption (FAME content) in case of vegetable oils affected their lower energy content, which led to a higher BSFC result in B30. The same result is achieved by El-Kassaby et al. (2013) who compared the BSFC between B0, B10, B20, and B30.

Thermal efficiency is the ratio of power generated by the engine to power input by fuel. Figure 5 shows the effect of engine speed from 1,000 rpm to 4,500 rpm on thermal efficiency. It can be seen that the four types of diesel fuels show the same trend, where the value of BTE increases from 1,000 rpm to 2,000 rpm as the peak point and then decreases until 4,500 rpm. Pertadex obtains the highest maximum BTE value with the highest efficiency of 0.33 (or 33.0%), and the lowest maximum efficiency is 0.286 (or 28.6%) obtained in B30. With increased oxygen concentration from the addition of mixes, B30 burns more efficiently with higher rpm until it reaches the maximum rpm (Chaurasiya et al., 2019). However, in terms of BSFC and thermal efficiency, the best performance is in the engine fuelled by Pertadex, while using Biosolar provides the worst performance. This condition is caused by the value of flash point of Biosolar and Solar around 52, and it is lower compared to Dexlite and Pertadex with the value of 55. Thus, flash point is inversely related to the volatility of diesel fuel.

Gas emissions

Diesel engine emission is one of the crucial parameters affecting engine performance. High emission levels generally indicate poor engine performance. In this test, some of the gas emissions were investigated experimentally. These parameters include CO_2, CO, NO_x, and HC emissions. The CO_2 emissions show how much fuel is burnt (the more the fuel burned the more CO_2 emissions are produced). CO_2 is the primary compound in the exhaust emissions of diesel engines that contributes to global warming issues.

Based on Fig. 6, the four fuels show the same trend (the higher the engine speed, the higher the CO_2 produced). The highest CO_2 emissions

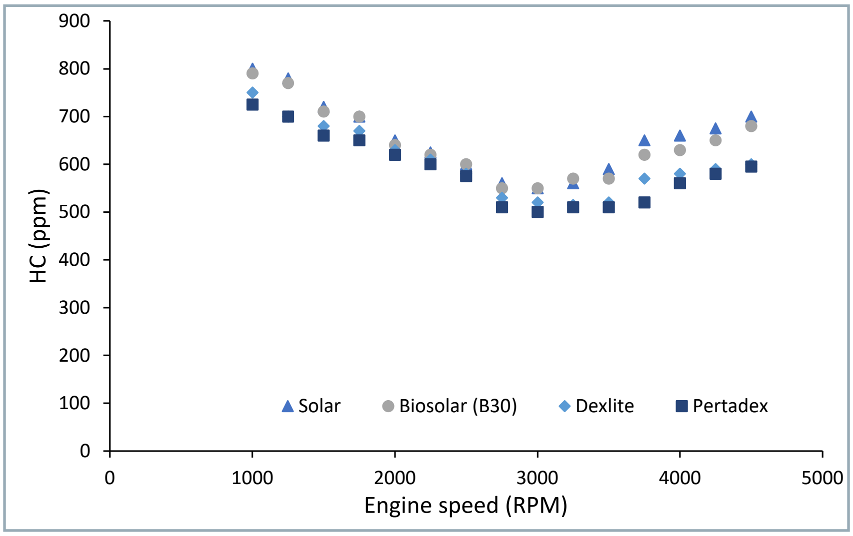

Fig. 8 Effect of engine speed on HC

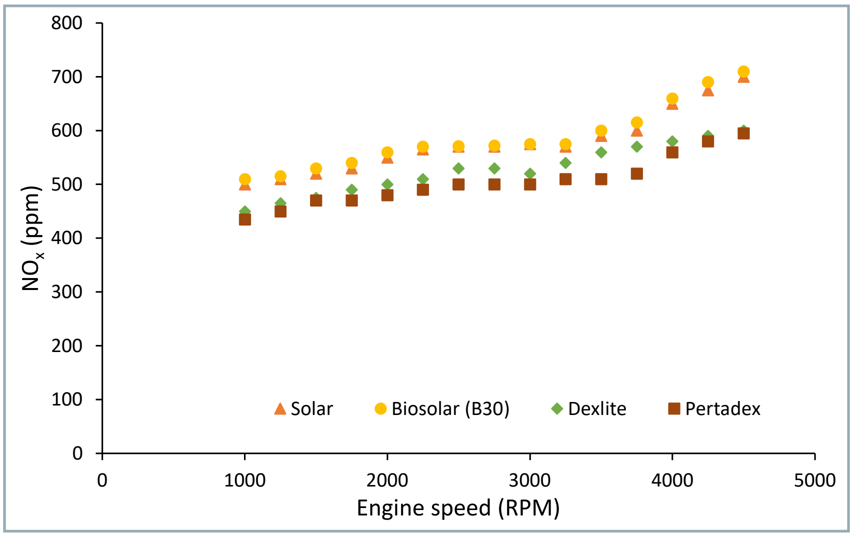

Fig. 9 Effect of engine speed on NO_x

are produced by Solar, while Pertadex produces the lowest CO_2 emissions. This is due to the high sulphur content of Solar with a value of 0.25, compared to other diesel fuels such as B30, Dexlite and Pertadex with a value in all of them 0.05, as shown in Table 2. However, the diesel fuels, especially Solar, with a high sulphur content can damage the engine and produce higher CO_2 emissions. The comparison between the exhaust emissions of Solar and B30 is slightly different from the ratio of torque and power, even though the torque, power, and efficiency of B30 are lower than in Solar. Dexlite, B30, and Pertadex have lower sulphur content than Solar with the values of 0.25 and 0.05% m/m, respectively. The value is still very high with the sulphur content limit in diesel engines with a maximum value of 0.35 %m/m according to the Euro III standard (Xie et al., 2020).

CO is a toxic gas compound that is formed due to incomplete combustion. The measurement of CO emissions is shown in Fig. 7. The four diesel fuels show the same trend, i.e., CO emissions tend to decrease as engine speed increases. The highest CO emissions are produced by Solar at 1,000 rpm with a value of 3.2%vol., compared to Biosolar, Dexlite, and Pertadex with 3%vol., 3%vol., and 2.9%vol., respectively. Thus, oxygen contents in Solar make it easy to burn at higher temperatures in the cylinder. This is due to the lowest distillation of vaporization value of Solar (370 °C), resulting in richer fuel–air blend being ignited; therefore, more CO is produced. The similar result was obtained by Zheng et al. (2017) who investigated the effect of diesel fuels with different distillation temperatures on performance and emission. Lower distillation temperatures produce less soot, but higher distillation temperatures produce more NO_x, HC, and CO emissions.

The effect of engine speed on HC emissions with different fuel types is shown in Fig. 8. The HC emissions indicate how much unburnt fuel is in the combustion process. It can be seen from Fig. 8 that the HC emissions tend to decrease from 1,000 rpm to 3,000 rpm and tend to increase from 3,000 rpm to 4,500 rpm. The lowest HC emission is produced by Pertadex, while the highest is in Solar. The minimum HC emissions at 3000 rpm for Pertadex, Dexlite, Biosolar, and Solar are 490 ppm, 500 ppm, 520 ppm, and 550 ppm, respectively. According to Table 2, sulphur in Solar is the highest among all of them, resulting in an increase in unburnt fuel, which leads to an increase in HC emissions. According to Obeid et al. (2022), the amount of sulphur and nitrogen in the fuel, which may be connected to cylinder temperature and heat release rate, has a significant impact on HC emissions. Low HC emissions are seen for both high and low sulphur values. In contrast, HC emissions are high at high as well as moderate sulphur values. When both sulphur levels are in the middle range, HC emissions are at an intermediate level.

Figure 9 shows the variation of NO_x emission with engine speed. The NO_x concentration increases with engine speed for all the fuels. Compared with other diesel fuels, the NO_x emission of Pertadex is the lowest. The peak concentrations for Pertadex, Dexlite, Biosolar, and Solar at 4,500 rpm are 520 ppm, 525 ppm, 640 ppm, and 650 ppm, respectively. The NO_x emissions for diesel engines are affected by CN. It can be seen from the measurement results shown in Fig. 9 that the higher the CN, the smaller the NO_x emission. Several studies reported the effect of CN on resulting emissions and concluded that NO_x decreased when CN increased in diesel fuel (Chacko et al., 2021; Kumar et al., 2019; Labeckas et al., 2021).

Conclusion

In this study, the performance and emissions of a single-cylinder diesel engine by Solar, Biosolar, Dexlite, and Pertadex fuels at various engine speed from 1,000 rpm to 4,500 rpm have been carried out experimentally. It can be concluded from the experimental result that:

- The engine fuelled by Pertadex generates the highest brake torque of 26 Nm at 2,000 rpm and the highest power of 7,536 W at 3,000 rpm compared to other diesel fuels. This is due to differences in the CN of diesel fuels.
- The lowest fuel consumption and the highest thermal efficiency are achieved by Pertadex, indicated by the thermal efficiency of 33% and BSFC of 0.03037 $kg \cdot kW^{-1} \cdot h$. This is due to differences in the FAME content and flash point of diesel fuels.
- There is an increase in the amount of gas emissions (CO_2 and NO_x) and an increase in engine speed, whereas Pertadex is a diesel fuel that produces the lowest emissions compared to others.
- On the other hand, gas emissions (CO and HC) are decreasing with increasing engine speed, and Pertadex is a diesel fuel that produces the lowest emissions.
- Although B30 has a lower sulphur concentration than Dexlite and Pertadex (with levels of 0.25 and 0.05 %m/m, respectively), the value is still relatively high according to Euro III, with a maximum value of 0.35 %m/m for sulphur content in diesel engines.

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Performance and Emission of Diesel Engine Fuelled by Commercial Bio-Diesel Fuels in Indonesia

By tarsisius kristyadi

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PERFORMANCE AND EMISSION OF DIESEL ENGINE FUELLED BY COMMERCIAL BIO-DIESEL FUELS IN INDONESIA

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The performance and emission of a small diesel engine fuelled by commercial diesel fuel in Indonesia are present in this paper. Various commercial diesel fuels in Indonesia are produced and marketed by Pertamina. As the largest oil company in Indonesia, Pertamina has developed various diesel fuels, namely Solar, Biosolar (B30), Dexlite, and Pertadex. This study explains in more detail the performance, fuel consumption, and emission produced by the four types of fuels, and they were investigated experimentally using a single-cylinder diesel engine at various engine speeds, from 1,000 rpm to 4,500 rpm. The result shows the engine fuelled by Pertadex generates the highest power and torque, while the lowest is generated by the Biosolar fuelled engine. The maximum torque and power generated by the Pertadex fuelled engine are about 25.5 Nm and 7200 W, respectively. The engine fuelled by Pertadex has the lowest brake specific fuel consumption (BSFC) of 0.3037 kg·kW·h, compared to the engines fuelled by the Dexlite, Solar, and Biosolar fuels, with values around 0.3127, 0.3215, and 0.3338 kg·kW·h, respectively. At the same time, the measurement of gas emissions, including CO_2, CO, NO_x, and HC was conducted simultaneously.

Keywords: diesel engine; smoke analysis; biofuel; fuel consumption

In Indonesia, vehicles for transportation facilities are dominated by motorcycles, cars, buses, and trucks, estimated at around 126 million (Sub-directorate of Transportation Statistics, 2019). Based on statistics, buses, trucks, and other passenger vehicles are predominantly diesel-engine vehicles in Indonesia. Although diesel engines have numerous advantages, their emission can contribute to increased greenhouse gas emissions and environmental damage (Rai and Sahoo, 2019). As a result, greenhouse gas emissions have climbed by 103.8% over the last four decades. Furthermore, compression ignition (CI) engines consume a considerable amount of fossil fuels and pollute the environment (Hoang et al., 2019). Road transportation's fuel consumption is dominated by road transportation, which accounts for 88% of total fuel oil consumption, primarily diesel and gasoline. In 2020, fuel consumption for transportation in Indonesia is around 15,078,000 kilolitres for diesel fuel and 10,650,000 kilolitres for gasoline (Praptijanto et al., 2015).

Pertamina supplies fuel for vehicles in Indonesia. Pertamina produces several fuels for diesel engines, namely with the brand names Solar, Biosolar, Dexlite, and Pertadex. Solar is a conventional diesel fuel, while Dexlite and Pertadex are higher grade diesel fuels compared with Solar. These various fuel types are made to meet the needs according to the engine technology used, targeted to meet the emission standards currently in effect. In addition, Pertamina is also targeting biodiesel to gradually reduce dependence on fossil fuels, namely with Biosolar or B30 products. B30 is a blend of diesel and biodiesel, with a 30% biodiesel content. The process of transforming raw oil/fat (triglyceride) into biodiesel is known as transesterification (fatty acid methyl-ester, FAME), where the raw material for biodiesel is palm oil. Some of the advantages of biodiesel are low emission, non-toxicity, inherent lubricity, and higher flash point (Devarajan et al., 2017; Devarajan et al., 2018a) However, some disadvantages that need to be considered of using biodiesel are poor viscosity and atomization leading to higher NO_x emission and lower efficiency (Hoekman et al., 2012). Many authors agree to reduce exhaust emissions without reducing engine performance by varying the mixture of diesel fuel with biodiesel (Pullen and Saeed, 2014; Radhakrishnan et al., 2017; Ramanan and Yuvarajan, 2015).

The experimental tests of types of fuel usage need to be carried out to determine their impact on performance and exhaust emissions. Several researchers have researched the performance of diesel engines with a mixture of diesel and biodiesel fuels. Praptijanto et al. (2015) conducted research on the performance of diesel engines by comparing the diesel fuel and a mixture of ethanol and diesel at an engine speed of 1,000–1,500 RPM. The results showed that the power produced by engines using pure diesel fuel (E0) was lower than E2, E5–E10, especially at 1,400 rpm. Mofijur et al. (2015) concluded that studies carried out with the addition of ethanol to biodiesel in diesel engines could significantly reduce the exhaust gas emissions such as hydrocarbon (HC), parts per million (ppm), and smoke, but increase fuel consumption. Meanwhile, Prbakaran and Viswanathan (2016) concluded that brake thermal efficiency (BTE) produced in an engine fuelled by an Ethanol-Solar mixture is the same as pure diesel fuel. There is a reduction in CO and HC exhaust emissions at high loads and an increase at low loads. However, alternative fuels have a crucial issue regarding environmental problems, for example, the use of various additional oil such as waste edible oil (WBO) (Gad and Ismail, 2021), waste cooking oil (WCO) (El-Sawy et al., 2020), and animal fat for biodiesel (Kanth and Debbarma, 2021). Although it does not significantly affect the efficiency, performance, and diesel engine emissions, further research related to the environmental issue is needed.

The Solar, Biosolar, Pertadex, and Dexlite fuels have different characteristics, one of which is cetane number (CN). Pertadex has a higher cetane number than Biosolar and Dexlite, in addition to various other fuel properties. Biosolar's CN is 48, while Pertadex is 53 and Dexlite is 51. Many studies examine the performance of diesel fuel, especially in Indonesia. However, there are still very few more profound into the comparison of diesel fuel in Indonesia, especially on the emissions released. Therefore, this study explains in more detail the performance, fuel consumption, and emissions produced by the four types of fuels using a single-cylinder diesel engine.

Material and methods

The current study assesses the performance, consumption, and emissions of a direct ignition (DI) diesel engine using the commercial diesel fuels such as Solar, Biosolar (B30), Dexlite, and Pertadex. At all loads and a constant speed from 1,000 rpm to 4,500 rpm, the performance measures such as braking torque, brake power (BP), brake specific fuel consumption (BSFC), BTE, and exhaust gas emissions were evaluated. The experiments were conducted at the Institut Teknologi Nasional Bandung's Energy Conversion Laboratory. The engine testbed is shown in Fig 1.

Fuel consumption was measured by determining the time taken by the diesel engine to consume a certain amount of fuel. Engine speed was also monitored using an electronic tachometer connected to data acquisition. The tachometer can measure engine speed up to 20,000 rpm, with a measurement tolerance of 25 rpm and scanning tolerance of 100 rpm. The engine was coupled to a dynamometer, and temperature was measured using a thermocouple. The dynamometer is an eddy current dynamometer measuring the power and torque up to 16 kW and 70 Nm, respectively. The dynamometer cooling system is water cooled, with a pressure and flowrate of 0.3 bar and 6.6 l·min, respectively. The engine cooling temperature, exhaust gas, and air inlet temperature are measured by a T-type thermocouple. While gathering data on diesel engine performance using the computer-based data-acquisition system, Spectrum (MI.3112CA) was installed on a DEWE-5000 portable data-acquisition system to collect and analyse the results. The gas analyser Techno (MODEL 488) was used to measure exhaust gas emissions, especially for NO_x, HC, CO, and CO_2, with an accuracy of 5% of reading; therefore, the voltage and power needed is 230 V (single phase) and 100 W, respectively. Therefore, Table 1 shows the detail of specification of the test engine used in this study. The performance indicators such as BP, BSFC, and BTE of all fuels were calculated as follows:

$$\tau = \frac{F}{l} \tag{1}$$

$$BP(\text{kW}) = \frac{2\pi RPM\,\tau}{60 \cdot 1{,}000} \tag{2}$$

$$BSFC = \frac{\dot{m}_f}{BP} \tag{3}$$

$$BTE(\%) = \frac{3{,}600}{BSFC \cdot LHV} \cdot 100 \tag{4}$$

where: τ – brake torque (Nm); F – load (N); l – the length of crankshaft (m); m_f – fuel consumption rate (kg/s); LHV – the low heating value of each biodiesel

To ensure data accuracy, measurements were repeated three times for each parameter. The data presented are the average of three measurements to decrease the uncertainty of each parameter. The input data for calculation is obtained

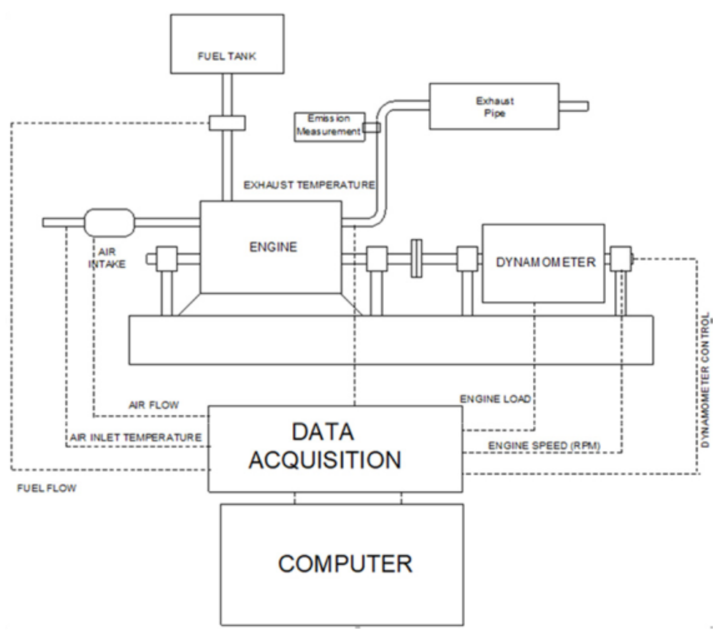

Fig. 1 Experimental scheme

by the load (*F*) of direct measurement from dynamometer load, followed by engine rotation and fuel consumption rate.

Table 1 Diesel engine specification

Items	Specifications
No. of cylinders	1 cylinder
Bore	80.5 mm
Stroke	91 mm
Displacement	460 cm^3
Compression ratio	20:1
Combustion chamber	swirl chamber type
Intake valve open	20° before top dead centre (BTDC)
Exhaust valve open	55° bottom dead centre (BDC)
Intake valve closed	49° after bottom dead centre (ABDC)
Exhaust valve closed	22° after top dead centre (ATDC)
Maximum torque	28 Nm at 2,000 rpm
Maximum power	8 kW at 3,000 rpm

Results and discussion

Diesel engine performance, including torque, power, BSFC, and BTE followed by emission data, is presented in this chapter. These various data were obtained and recorded simultaneously using data acquisition. In this investigation, the diesel engine was operated at various speeds from 1,000 rpm to 4,500 rpm.

Torque and power

Figure 2 shows the identical result of the effect of speed engine on torque, where the four diesel fuels show the highest torque at 2,000 rpm. At that speed, the torque produced by the engine fuelled by Pertadex, Dexlite, Biosolar, and Solar is 25.5 Nm, 25.0 Nm, 24.7 Nm, and 23.0 Nm, respectively. It can be seen in Fig. 2 that Pertadex generates the highest torque, and Biosolar generates the lowest. The high CN of diesel fuel can generate better performance of diesel engines. The greater CN of diesel fuel will speed up the combustion process in a diesel engine. As a result, the engine gets a more substantial increase in torque and power than an engine fuelled by low CN. The results are consistent with the cetane index (CI) engine specifications used in the experiments. These findings are similar to available trend data in open literature (Devarajan et al., 2018b).

Table 2 Diesel fuels specification

No.	Characteristic	Unit	Solar		Biosolar (B30)		Dexlite		Pertadex		Test method
			min	max	min	max	min	max	min	max	
1	cetane number		48			51	51		53		ASTM D613
2	specific gravity	$kg \cdot m^{-3}$	815	860	815	860	820	860	820	860	ASTM D1298/ D4052
3	viscosity	$mm^2 \cdot s^{-1}$	2	4.5	2	4.5			2	4.5	ASTM D445
4	sulphur content	$\% m \cdot m^{-1}$		0.25		0.05		0.05		0.05	ASTM D2622/ D5453
5	distillation 90% of vaporization	°C		370		370		360		340	ASTM D86
6	flash point	°C	52		55		55		55		ASTM D93
7	pour point	°C	18			18		18		18	ASTM D97
8	carbon residue	$\% m \cdot m^{-1}$		0.1		0.1		0.3		0.3	ASTM D4530/ D189
9	water content	$mg \cdot kg^{-1}$		500		300		500		500	ASTM D6304
10	calorific value	$MJ \cdot kg^{-1}$		44.9		44.1		44.4		45.1	ASTM D420
11	fame content	% v/v				30				10	ASTM D7806/ D7371
12	methanol content	% v/v		–		–		–		–	
13	ash content	% v/v		0.01		0.01		0.01		0.01	ASTM D482
14	sediment content	% m/m		0.01		0.01		0.01		0.01	ASTM D473
15	strong acid number	$mg KOH \cdot gr^{-1}$		0		0		0		0	ASTM D664
16	total acid number	$mg KOH \cdot gr^{-1}$		0.6		0.6		0.3		0.3	ASTM D664
17	lubricity, high frequency reciprocating rig (HFRR) wear scar diameter at 60 °C	micron		460		460		460		460	ASTM D6079

Source: Pertamina, 2022

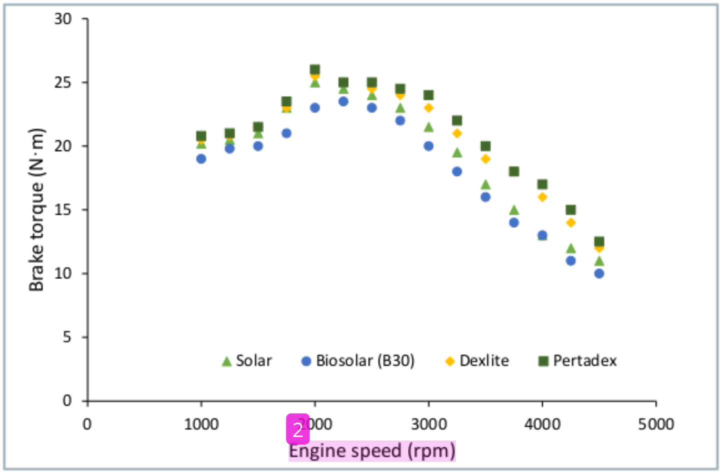

Fig. 2 Effect of engine speed on torque

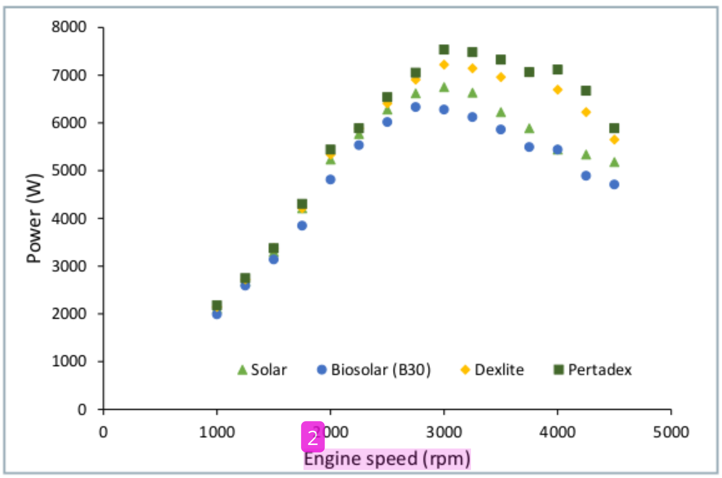

Fig. 3 Effect of engine speed on power

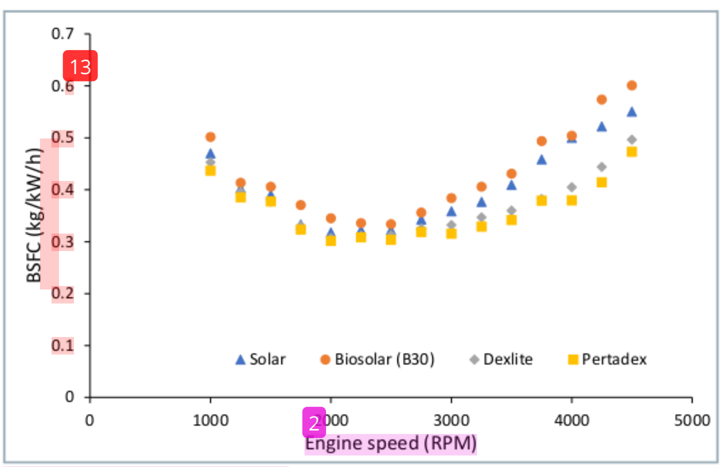

Fig. 4 Effect of engine speed on BSFC

Figure 3 shows that at low speed, engine's performance with all four fuels is similar. At high speed, the performance of the engine is different. The peak points of engine torque could be reached around 2,000 rpm, whereas engine powers are at 3,000 rpm. The engine fuelled by Pertadex generates the highest power, while the lowest is generated by the B30 fuel engine, as shown in Fig. 3. Engines fuelled by Pertadex can produce a maximum power of 7,200 W. In contrast, Dexlite, Solar, and Biosolar fuel engines can produce a maximum power of 7,000 W, 6,500 W, and 6,000 W, respectively. Biosolar has a low calorific value of 44.154 MJ·kg^{-1} compared to Solar, Dexlite, and Pertadex with 44.895 MJ·kg^{-1}, 44.439 MJ·kg^{-1}, and 45.087 MJ·kg^{-1}, respectively. However, it can be concluded that an increase of biodiesel percentage in blends decreases the calorific value of diesel fuel. Similar findings were observed by Nguyen et al. (2020) who analysed the biodiesel (B0-B100) blend combustion characteristic under a wide range of thermal condition. The authors state that the high CN of B100 that has more percentage of blends is more reactive and auto-ignites rather than the biodiesel that has low percentage of blends.

Fuel consumption

Other engine performances are presented by BSFC and BTE. The BSFC is the fuel consumed by an engine to generate 1 kW of power in 1 hour. Low BSFC of an engine means low fuel consumption. Figure 4 shows the value of the BSFC of the engine fuelled by various fuels. From 1,000 rpm to 2,000 rpm, the value of BSFC decreases and then increases above 2,000 rpm, experienced by all diesel fuels. When engine speed increases, BSFC will gradually increase to overcome the load in the form of mechanical friction, and the value of BSFC increases with increasing speed (Teoh et al., 2020). The engine fuelled by Pertadex has the lowest BSFC point (0.3037 kg·kW^{-1}·h) compared to the engine fuelled by Dexlite, Solar, and Biosolar with a value around 0.3127, 0.3215, and 0.3338 kg·kW^{-1}·h, respectively. According to Table 2, fuel consumption is influenced by FAME content. It is not surprising that biodiesel (B30), having

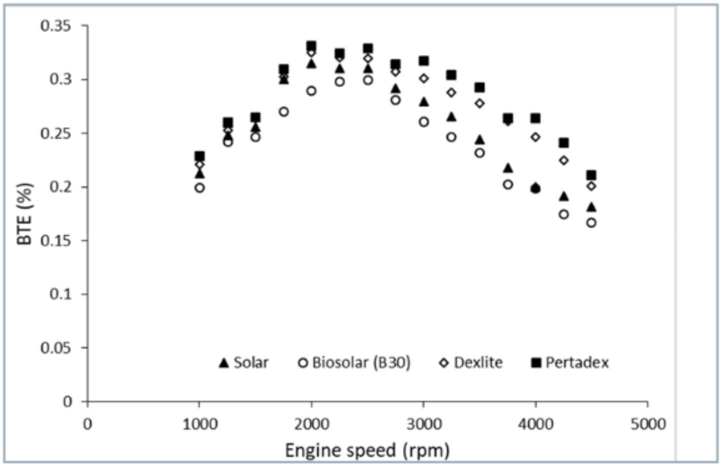

Fig. 5 Effect of the speed engine on BTE

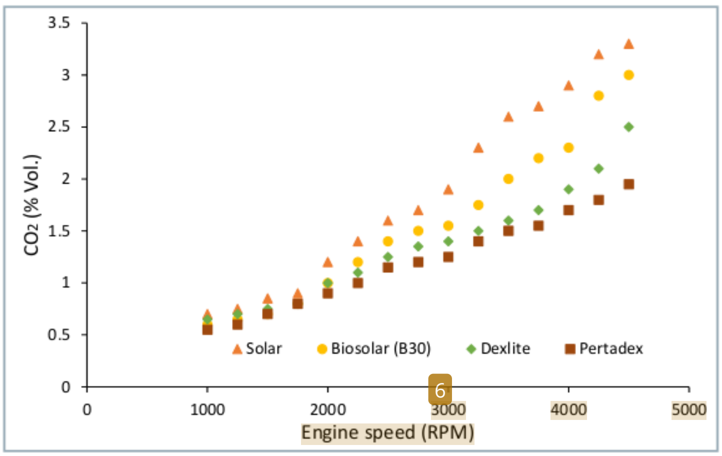

Fig. 6 Effect of the speed engine on CO_2

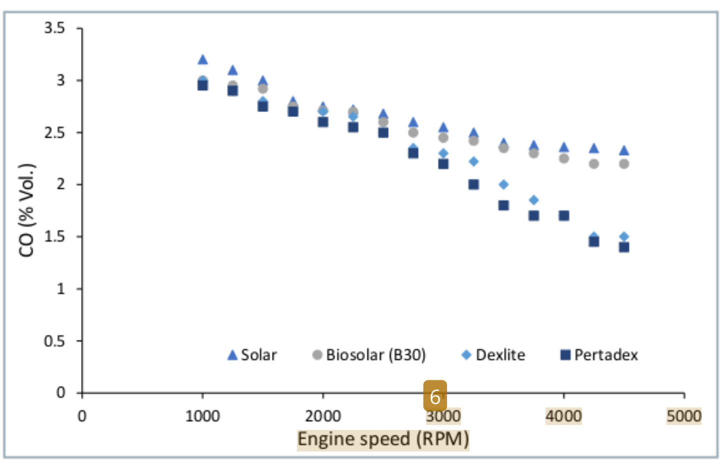

Fig. 7 Effect of the speed engine on CO

the highest FAME content of around 30, shows the highest BSFC increase after 2,000 rpm. Higher specific fuel consumption (FAME content) in case of vegetable oils affected their lower energy content, which led to a higher BSFC result in B30. The same result is achieved by El-Kassaby et al. (2013) who compared the BSFC between B0, B10, B20, and B30.

Thermal efficiency is the ratio of power generated by the engine to power input by fuel. Figure 5 shows the effect of engine speed from 1,000 rpm to 4,500 rpm on thermal efficiency. It can be seen that the four types of diesel fuels show the same trend, where the value of BTE increases from 1,000 rpm to 2,000 rpm as the peak point and then decreases until 4,500 rpm. Pertadex obtains the highest maximum BTE value with the highest efficiency of 0.33 (or 33.0%), and the lowest maximum efficiency is 0.286 (or 28.6%) obtained in B30. With increased oxygen concentration from the addition of mixes, B30 burns more efficiently with higher rpm until it reaches the maximum rpm (Chaurasiya et al., 2019). However, in terms of BSFC and thermal efficiency, the best performance is in the engine fuelled by Pertadex, while using Biosolar provides the worst performance. This condition is caused by the value of flash point of Biosolar and Solar around 52, and it is lower compared to Dexlite and Pertadex with the value of 55. Thus, flash point is inversely related to the volatility of diesel fuel.

Gas emissions

Diesel engine emission is one of the crucial parameters affecting engine performance. High emission levels generally indicate poor engine performance. In this test, some of the gas emissions were investigated experimentally. These parameters include CO_2, CO, NO_x, and HC emissions. The CO_2 emissions show how much fuel is burnt (the more the fuel burned the more CO_2 emissions are produced). CO_2 is the primary compound in the exhaust emissions of diesel engines that contributes to global warming issues.

Based on Fig. 6, the four fuels show the same trend (the higher the engine speed, the higher the CO_2 produced). The highest CO_2 emissions

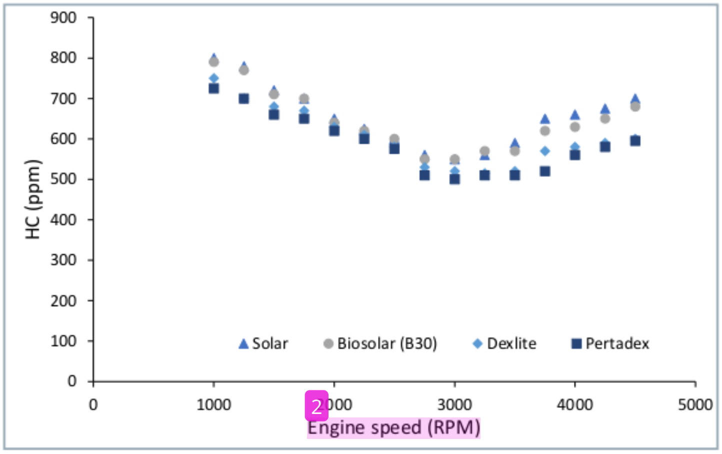

Fig. 8 Effect of engine speed on HC

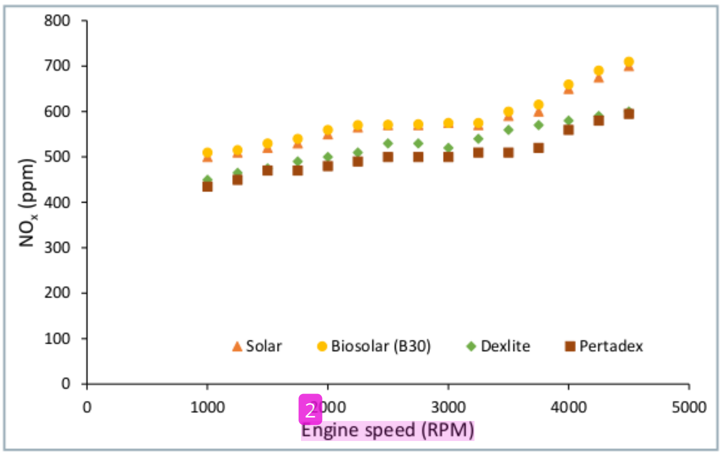

Fig. 9 Effect of engine speed on NO_x

are produced by Solar, while Pertadex produces the lowest CO_2 emissions. This is due to the high sulphur content of Solar with a value of 0.25, compared to other diesel fuels such as B30, Dexlite and Pertadex with a value in all of them 0.05, as shown in Table 2. However, the diesel fuels, especially Solar, with a high sulphur content can damage the engine and produce higher CO_2 emissions. The comparison between the exhaust emissions of Solar and B30 is slightly different from the ratio of torque and power, even though the torque, power, and efficiency of B30 are lower than in Solar. Dexlite, B30, and Pertadex have lower sulphur content than Solar with the values of 0.25 and 0.05% m/m, respectively. The value is still very high with the sulphur content limit in diesel engines with a maximum value of 0.35 %m/m according to the Euro II standard (Xie et al., 2020).

CO is a toxic gas compound that is formed due to incomplete combustion. The measurement of CO emissions is shown in Fig. 7. The four diesel fuels show the same trend, i.e., CO emissions tend to decrease as engine speed increases. The highest CO emissions are produced by Solar at 1,000 rpm with a value of 3.2%vol., compared to Biosolar, Dexlite, and Pertadex with 3%vol., 3%vol., and 2.9%vol., respectively. Thus, oxygen contents in Solar make it easy to burn at higher temperatures in the cylinder. This is due to the lowest distillation of vaporization value of Solar (370 °C), resulting in richer fuel–air blend being ignited; therefore, more CO is produced. The similar result was obtained by Zheng et al. (2017) who investigated the effect of diesel fuels with different distillation temperatures on performance and emission. Lower distillation temperatures produce less soot, but higher distillation temperatures produce more NO_x, HC, and CO emissions.

The effect of engine speed on HC emissions with different fuel types is shown in Fig. 8. The HC emissions indicate how much unburnt fuel is in the combustion process. It can be seen from Fig. 8 that the HC emissions tend to decrease from 1,000 rpm to 3,000 rpm and tend to increase from 3,000 rpm to 4,500 rpm. The lowest HC emission is produced by Pertadex, while the highest is in Solar. The minimum HC emissions at 3000 rpm for Pertadex, Dexlite, Biosolar, and Solar are 490 ppm, 500 ppm, 520 ppm, and 550 ppm, respectively. According to Table 2, sulphur in Solar is the highest among all of them, resulting in an increase in unburnt fuel, which leads to an increase in HC emissions. According to Obeid et al. (2022), the amount of sulphur and nitrogen in the fuel, which may be connected to cylinder temperature and heat release rate, has a significant impact on HC emissions. Low HC emissions are seen for both high and low sulphur values. In contrast, HC emissions are high at high as well as moderate sulphur values. When both sulphur levels are in the middle range, HC emissions are at an intermediate level.

Figure 9 shows the variation of NO_x emission with engine speed. The NO_x concentration increases with engine speed for all the fuels. Compared with other diesel fuels, the NO_x emission of Pertadex is the lowest. The peak concentrations for Pertadex, Dexlite, Biosolar, and Solar at 4,500 rpm are 520 ppm, 525 ppm, 640 ppm, and 650 ppm, respectively. The NO_x emissions for diesel engines are affected by CN. It can be seen from the measurement results shown in Fig. 9 that the higher the CN, the smaller the NO_x emission. Several studies reported the effect of CN on resulting emissions and concluded that NO_x decreased when CN increased in diesel fuel (Chacko et al., 2021; Kumar et al., 2019; Labeckas et al., 2021).

Conclusion

In this study, the performance and emissions of a single-cylinder diesel engine by Solar, Biosolar, Dexlite, and Pertadex fuels at various engine speed from 1,000 rpm to 4,500 rpm have been carried out experimentally. It can be concluded from the experimental result that:

- The engine fuelled by Pertadex generates the highest brake torque of 26 Nm at 2,000 rpm and the highest power of 7,536 W at 3,000 rpm compared to other diesel fuels. This is due to differences in the CN of diesel fuels.
- The lowest fuel consumption and the highest thermal efficiency are achieved by Pertadex, indicated by the thermal efficiency of 33% and BSFC of 0.03037 $kg \cdot kW^{-1} \cdot h$. This is due to differences in the FAME content and flash point of diesel fuels.
- There is an increase in the amount of gas emissions (CO_2 and NO_x) and an increase in engine speed, whereas Pertadex is a diesel fuel that produces the lowest emissions compared to others.
- On the other hand, gas emissions (CO and HC) are decreasing with increasing engine speed, and Pertadex is a diesel fuel that produces the lowest emissions.
- Although B30 has a lower sulphur concentration than Dexlite and Pertadex (with levels of 0.25 and 0.05 %m/m, respectively), the value is still relatively high according to Euro III, with a maximum value of 0.35 %m/m for sulphur content in diesel engines.

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