Performance And Emission Characteristics Of Diesel Engines Fueled With Methyl Ester From Waste Cooking Oil

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The increasing dependence on fossil fuels and the environmental impacts associated with diesel engine emissions have driven the development of renewable alternative fuels, including biodiesel derived from waste cooking oil, known as Jelantah Methyl Ester (JME). Although the B30 biodiesel program has been implemented in Indonesia, studies on higher biodiesel blends (B40 and B50) remain limited. Therefore, this study aimed to evaluate the effects of JME biodiesel blends (B30, B40, and B50) on the performance and exhaust emissions of a single-cylinder diesel engine. An experimental study was conducted using a single-cylinder Yanmar TF85MH-di diesel engine (493 cc) diesel engine operated at 1800, 1900, 2000, and 2100 RPM with 25%, 50%, 75%, and 100% loads. Engine performance was evaluated through power, torque, Specific Fuel Oil Consumption (SFOC), thermal efficiency, and Brake Mean Effective Pressure (BMEP), while exhaust emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), carbon dioxide (CO_2), and oxygen (O_2) were measured using calibrated instruments. The results showed that increasing engine load reduced SFOC for all fuel blends, with B50 achieving the lowest SFOC (approximately 360 g/kWh) and the highest thermal efficiency (22–23%) at medium-to-high loads. Torque and BMEP showed only minor differences among the tested fuel blends, whereas B50 produced the lowest HC emission (17 ppm) but higher NOx emissions at maximum load. Overall, B30 provided the most stable engine performance, whereas B50 achieved higher fuel efficiency and lower HC emissions despite producing higher NOx emissions at maximum load. These findings indicate that both blends are promising renewable alternatives for diesel engine applications.

Keywords: Biodiesel Jelantah Methyl Ester, Engine performance, Exhaust emissions, Diesel engine.

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1. Introduction

Air pollution from motor-vehicle exhaust is one of today's most pressing environmental problems [1, 2]. Diesel engines despite their high thermal efficiency emit harmful gases such as carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), carbon dioxide (CO_2), and particulate matter (PM), which adversely affect human health and accelerate climate change [3, 4]. These emissions tend to be more pronounced in developing countries where reliance on conventional fossil fuels remains high [5]. Amid the energy crisis and climate change, the need for renewable, clean, and sustainable energy sources has become urgent [6]. A widely recognized option is biodiesel, an alternative fuel produced from vegetable oils or animal fats via transesterification [7]. Biodiesel's physical and chemical properties are sufficiently similar to petroleum diesel that it can be used directly in conventional diesel engines, either neat or in blends with petroleum diesel [8, 9].

Among potential feedstocks, waste cooking oil stands out for its abundance and relatively low production cost [10, 11]. As a by-product of households and the food industry, improper disposal of waste cooking oil can contaminate soil and waterways; converting it to biodiesel therefore supplies alternative energy while supporting circular-economy waste management [12, 13]. Production typically involves transesterification with methanol and a base catalyst such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) [14, 15]. In Indonesia's policy context, the Ministry of Energy and Mineral Resources has implemented the mandatory B30 program requiring 30% biodiesel in diesel fuel intended to reduce diesel imports, lower emissions, and increase use of domestic energy resources [16]. However, despite broad B30 implementation, the effects of higher biodiesel blends such as B40 and B50 on engine performance and exhaust emissions remain underexplored [17, 18].

Prior work on waste-cooking-oil biodiesel has reported reduced emissions at lower blend ratios. For example, B10 at 20 MPa injection pressure produced the lowest emissions [19, 20], and waste-cooking-oil biodiesel outperformed palm-oil and kepuh seed biodiesel in reducing CO and HC [21]. Nevertheless, most studies focused on blends below B30 and did not comprehensively evaluate performance across different load conditions [22]. Using higher blends (B40, B50) raises crucial questions about engine power, fuel consumption, thermal efficiency, and exhaust-gas characteristics [23, 24]. Addressing these issues is necessary to define an optimal threshold for waste-cooking-oil biodiesel that ensures engine safety and efficiency while delivering environmental benefits particularly relevant amid growing demand for clean energy and global commitments to decarbonization [25, 26].

Accordingly, this study investigates the effects of Jelantah Methyl Ester (JME) waste-cooking-oil methyl ester in blends of B30, B40, and B50 on the performance and exhaust emissions of a single-cylinder diesel engine [27]. Experiments were conducted at a constant 1800 RPM under varying loads [28, 29]. The findings are expected to inform the development of alternative energy derived from waste cooking oil and to provide a scientific reference for biodiesel-based national energy policy implementation.

2. materials and methods

This study is a quantitative experimental investigation involving direct testing of a single-cylinder diesel engine under controlled laboratory conditions [30]. An experiment was conducted by blending waste cooking oil with supplementary materials to produce JME biodiesel fuel, which was then tested for its properties in accordance with Indonesian biodiesel standards. The comparative characteristics of JME biodiesel and petroleum diesel are presented in Table 1.

An analysis of the fuel properties demonstrates that JME Biodiesel meets the SNI 7182:2015 standards while presenting clear operational trade-offs regarding engine performance when compared directly to Petroleum Diesel. JME Biodiesel features a density of 873 kg/m^3, which falls within the ideal SNI range $\left(850 - 880\ kg/m^3\right)$ to ensure a consistent energy content per volume, and an exceptionally high flash point of 169°C compared to Petroleum Diesel's 73°C, significantly increasing storage safety. In terms of combustion dynamics, JME Biodiesel has a higher kinematic viscosity (4.63 cSt) than Petroleum Diesel (3.427 cSt), which provides better lubrication for the fuel injection pump but requires optimal injection pressure to achieve proper fuel atomization inside the cylinder. Furthermore, Petroleum Diesel exhibits a higher Cetane Index (51) than JME Biodiesel (48), indicating that Petroleum Diesel offers a slightly shorter ignition delay, resulting in a quicker and more responsive engine combustion process.

Regarding environmental impact and system durability, both JME Biodiesel (0.122% Wt) and Petroleum Diesel (0.09% Wt) maintain sulfur contents well below the 0.2% Wt maximum limit, directly contributing to a reduction in harmful sulfur dioxide (SO_2) emissions that cause acid rain. Exhaust emission quality and long-term engine health are further enhanced by the exceptional purity and low contamination levels of JME Biodiesel. It features minimal water and sediment (<0.05% Vol), a low water content of 97.2 ppm (comparable to Petroleum Diesel's 89 ppm), a low acid number (0.08 mg KOH/g), minimal carbon residue (0.018% Wt), and negligible ash content (0.002% Wt). This combination of clean parameters effectively prevents fuel system corrosion and injector deposits while significantly reducing particulate matter emissions in the exhaust gas, thereby preventing filter clogging and maintaining optimal engine cleanliness.

Subsequently, the test diesel engine, a Yanmar TF 85 MH-di 493 cc capacity, along with several measuring instruments required for performance (Power, Torque, SFOC, and BMEP) and exhaust emission testing (HC, CO, NOx, CO_2, O_2) was prepared. The testing process began with no-load testing, followed by performance testing using JME biodiesel blends of B30, B40, and B50. Data collection was carried out according to the performance test and emission test parameters for each fuel variant. Furthermore, data processing was conducted based on the requirements for analyzing diesel engine performance and exhaust gas emission test results. The objective is to

Table 1. Comparison of Fuel Properties between JME Biodiesel and Petroleum Diesel.

No.	Parameter	Method	Biodiesel Jme			Diesel Petroleum		
			Min	Max	result	Min	Max	Result
1	Density at 15°C (kg/m^3)	ASTM D1298	815	880	873	-	-	-
2	Color	ASTM D1500	-	3.0	1.5	-	3.0	1.0
3	Flash Point (°C)	ASTM D93	52	-	169	52	-	73
4	Kinematic Viscosity at 40°C (cSt)	ASTM D445	2.0	5.0	4.63	2.0	5.0	3.427
5	Water and Sediment Content (%Vol)	ASTM D1796	-	0.05	<0.05	-	-	-
6	Sulfur Content (%Wt)	Sulfur Meter / ASTM D4294	-	0.2	0.122	-	0.2	0.09
7	Distillation Temperature at 90% Vol (°C)	ASTM D86	-	370	355	-	370	338
8	Cetane Index	ASTM D4737	49 (CN)	-	48	48 (CN)	-	51
9	Acid Number (mg KOH/g)	ASTM D664	-	0.16	0.08	-	-	-
10	Carbon Residue (%Wt)	ASTM D189	-	0.1	0.018	-	-	-
11	Ash Content (%Wt)	ASTM D482	-	0.01	0.002	-	-	-
12	Water Content (ppm)	Karl Fischer / ASTM D6304	-	400	97.2	-	380	89
13	Pour Point (°C)	ASTM D97	-	-	-	-	18	3
14	Copper Strip Corrosion (3 h/50°C)	ASTM D130	-	-	-	Class 1	-	1a

determine how different waste-cooking-oil biodiesel blend ratios affect engine performance and exhaust emissions.

This design was selected to yield objective quantitative data amenable to comparative analysis across treatment groups. All tests employed calibrated instruments to ensure valid, reliable, and scientifically defensible results [31].

2.1. Materials and Equipment

The primary feedstock was waste cooking oil collected from household residues and filtered with charcoal and cotton to remove particulates. Biodiesel was then produced via a two-step base-catalyzed transesterification using methanol (CH_3OH) and either NaOH or KOH [32]. After reaction, the mixture separated into biodiesel and glycerol; the biodiesel phase was water-washed to remove residual glycerol, neutralized with a 25% vinegar (acetic acid) solution to quench excess base, and dried at ˜100 °C to eliminate remaining moisture (Fig. 1). The methyl ester derived from vegetable oil is generally referred to as biodiesel and is considered one of the main candidates for alternative diesel fuel. Therefore, the common chemical name for biodiesel produced through this esterification process is Fatty Acid Methyl Ester (FAME) [33]. The reaction equation for producing this biodiesel fuel can be seen in Fig. 2.

Methanol is obtained through a synthesis process involving CO gas and hydrogen gas (H_2). These gases are derived from natural methane gas; therefore, methanol is considered a non-renewable raw material source. Methanol

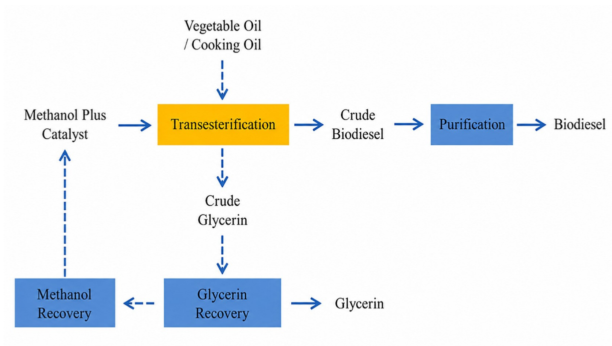

Fig. 1. Transesterification Process Diagram
Source: National Renewable Energy Laboratory

is generally used in the production of formaldehyde, acetic acid, and methyl terephthalate, as well as for fuel applications. Meanwhile, the catalysts used in the process can be acidic, alkaline, or others. Acid catalysts are not widely used because they are less active and may cause corrosion in the processing equipment. The most commonly used catalysts are alkaline catalysts, especially soda and sodium methylate.

2.2. Research Procedure

The experimental procedure began with the collection and purification of waste cooking oil. The oil was filtered through crushed wood charcoal and cotton to remove coarse impurities and solids, minimizing contaminants that could disrupt transesterification. The filtered oil was then

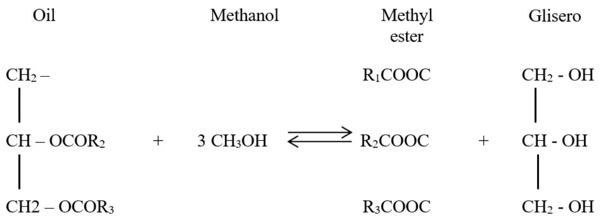

Fig. 2. Reaction Equation for Producing Biodiesel Fuel

preheated to evaporate residual moisture [34].

Next, base-catalyzed transesterification was performed: triglycerides in the oil reacted with methanol in the presence of NaOH, with continuous stirring at approximately 60 °C for ˜30 min. The reaction mixture was then allowed to settle for ˜24 h, yielding two phases biodiesel (upper) and glycerol (lower). The biodiesel phase was separated and purified via three washes using distilled water mixed with a 25% vinegar (acetic acid) solution to remove residual glycerol and neutralize excess base [35]. Finally, the biodiesel was dried at 100 °C for 1 h to eliminate remaining water, producing fuel-grade biodiesel ready for testing.

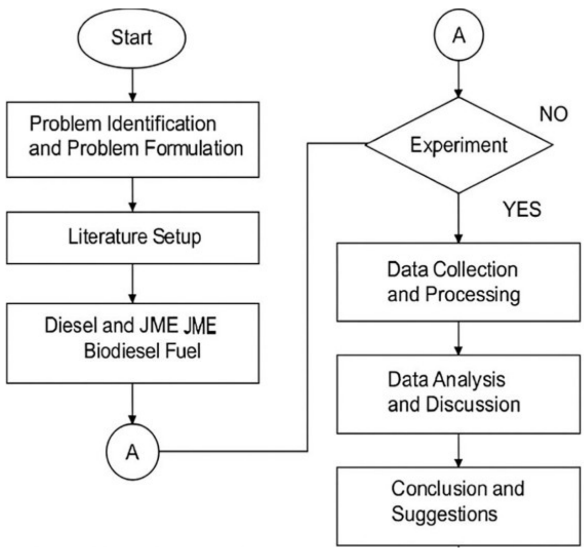

Fig. 3. Research Flow Chart

The produced biodiesel JME was blended with petroleum diesel to obtain three fuels: B30 (30% JME:70% diesel), B40 (40%:60%), and B50 (50%:50%) by volume. Equal volumes of each blend were prepared to ensure consistency across performance and emissions testing. As shown in the block diagram below:

The entire research process was summarized in a flowchart outlining (Fig. 3) the sequential steps: oil filtration, biodiesel production, fuel blending, and engine performance and emission testing. Each stage was carried

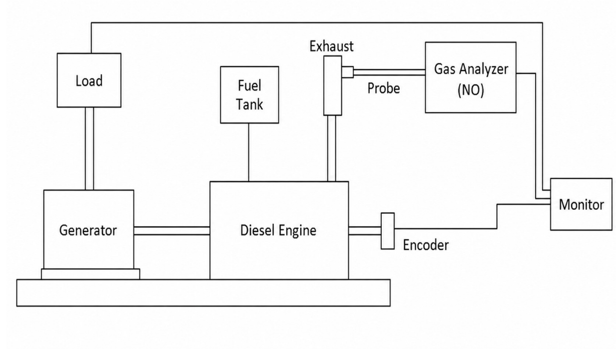

Fig. 4. Engine Setup Block Diagram

out systematically to maintain data validity and reliability.

The tested parameters were grouped into two categories: engine performance and exhaust gas emissions. Tests were conducted on a single-cylinder diesel engine at 25%, 50%, 75%, and 100% load at a constant 1800, 1900, 2000, and 2100 RPM using B30, B40, and B50 blends. All measurements were taken with calibrated instruments. For engine performance, measured variables included brake power, torque, thermal efficiency, SFOC and BMEP (Fig. 4).

For exhaust emissions, the measured constituents were CO, CO_2, HC, NOx, and O_2, analyzed with a gas analyzer capable of real-time readings. In this framework, CO and HC indicate incomplete combustion, CO_2 reflects combustion efficiency, NOx characterizes high-temperature combustion behavior, and O_2 denotes the fraction of unreacted oxygen in the exhaust.

2.3. Data Collection and Analysis Techniques

Data were collected directly through experimental testing using calibrated instruments. Observations were recorded on a single-cylinder diesel engine under four load conditions (25%, 50%, 75%, 100%) at a constant 1800 RPM, with three fuel blends (B30, B40, B50). Each treatment was repeated three times to ensure reliability and minimize experimental error. Performance data were obtained using a digital dynamometer for torque and power, while fuel consumption was measured by recording the fuel volume consumed over time. Thermal efficiency and SFOC were calculated using standard mechanical engineering formulas. BMEP was computed based on cylinder displacement volume and output power. All raw data were tabulated and converted into international standard units (kW, Nm, g/kWh, bar, and %). Exhaust emissions were measured with a portable gas analyzer, which simultaneously CO, CO_2, HC, NOx, and O_2 concentrations. Sampling was conducted after the engine had stabilized for at least three minutes to ensure representative exhaust conditions. Readings were taken digitally and recorded immediately [36].

Data analysis employed a descriptive-comparative approach, comparing parameters across fuel blends under each load condition. Results were processed using technical spreadsheet software and presented in the form of graphs showing the relationship between output power, performance parameters, and emissions. Each graph was interpreted to identify trends, anomalies, and the influence of fuel composition on both performance and environmental impact. Interpretations were made with reference to thermodynamic principles and combustion characteristics of diesel engines.

2.4. Statistical and Descriptive Analysis

The experimental data were analyzed using descriptive statistical methods to compare the effects of B30, B40, and B50 biodiesel blends under different engine operating conditions. Engine performance was evaluated at engine speeds of 1800, 1900, 2000, and 2100 rpm under four load conditions, while exhaust emissions were evaluated at 1800 rpm under four load conditions. The mean, minimum, maximum, standard deviation (SD), and coefficient of variation (CV) were calculated to characterize the variability of the measured parameters across the tested operating conditions. The CV was calculated as the ratio of the SD to the mean value and was used to describe the variation across operating conditions rather than experimental repeatability.

The statistical evaluation in this study was limited to descriptive statistical analysis because the primary objective was to identify and compare the performance and emission trends of each biodiesel blend under controlled operating conditions. Inferential statistical methods, such as analysis of variance (ANOVA), were not applied since the study focused on describing experimental characteristics rather than testing statistical significance among treatment groups. The descriptive results were used to identify the overall trends and differences among the biodiesel blends, as summarized in Table 2. Descriptive statistical analysis of engine performance and exhaust emissions for B30, B40, and B50.

3. Results and discussion

This study evaluated the effects of waste-cooking-oil biodiesel blends (B30, B40, B50) on the performance and exhaust emissions of a single-cylinder diesel engine. All tests were run at a constant 1800 RPM with loads of 25%, 50%, 75%, and 100%. The data were analyzed to assess combustion effectiveness and engine efficiency for each fuel variant.

Results are presented as graphs showing the relationship between engine output power and five performance parameters: SFOC, thermal efficiency, torque, BMEP, and output power. Exhaust-emission characteristics (CO, CO2, HC, NOx, and O_2) are also discussed. A descriptive-comparative approach was used to identify the strengths and weaknesses of each blend under the defined test conditions.

3.1. Statistical Analysis and Experimental Repeatability

The descriptive statistical results presented in Table 2. Descriptive statistical analysis of engine performance and exhaust emissions for B30, B40, and B50 show that B30 exhibited relatively low variability in SFOC and thermal efficiency across the tested operating conditions, with CV values of 10.20% and 10.49%, respectively, compared with B40 (19.88% and 19.39%) and B 50 (14.71% and 15.70%). This indicates that B30 provided more consistent performance across the tested engine speeds and loads, while B50 showed intermediate variability. For exhaust emissions at 1800 rpm, B40 produced the lowest mean HC emission (9.50 ppm), whereas B50 produced the highest mean HC emission (21.00 ppm). The mean NO_x emissions were 1006.75, 1087.50, and 986.25 ppm for B30, B40, and B50, respectively. Overall, the descriptive analysis indicates that the effects of biodiesel blending varied depending on the measured parameter and operating condition. B30 showed relatively consistent engine performance, while B50 provided favorable fuel consumption and thermal efficiency under specific operating conditions but exhibited different emission characteristics.

3.2. Engine Performance Analysis

Performance tests examined the engine's response to three JME biodiesel blends: B30, B40, and B50 at 1800, 1900, 2000, 2100 RPM and loads of 25%, 50%, 75%, and 100%. Five key parameters were analyzed: SFOC, thermal efficiency, torque, BMEP, and output power [37]. Results are shown as performance-versus-power plots and discussed comparatively across blends.

3.2.1. *Specific Fuel Oil Consumption (SFOC)*

Figs. 5 and 6 illustrate the relationship between Specific Fuel Oil Consumption (SFOC) and engine power at 1800, 1900, 2000, and 2100 RPM using B30, B40, and B50 fuel blends. Overall, SFOC decreased with increasing engine power across all engine speeds, indicating improved combustion efficiency at higher loads. Among the tested fuels, B30 exhibited the most stable SFOC trend over the entire operating range, whereas B40 showed the greatest fluctuations, particularly at 1900 and 2000 RPM, where SFOC

Table 2. Descriptive statistical analysis of engine performance and exhaust emissions for B30, B40, and B50

Parameter	Fuel	Mean	Minimum	Maximum	SD	CV (%)
SFOC (g/kWh)	B30	405.66	355.92	504.77	41.39	10.20
	B40	453.04	332.18	682.59	90.07	19.88
	B50	424.40	332.81	553.66	62.45	14.71
Thermal efficiency (%)	B30	20.98	16.49	23.39	2.20	10.49
	B40	19.07	12.19	25.06	3.70	19.39
	B50	20.69	15.03	25.01	3.25	15.70
HC (ppm)	B30	17.75	14	21	3.10	17.46
	B40	9.50	8	11	1.29	13.58
	B50	21.00	17	26	3.74	17.80
CO (ppm)	B30	252.00	201	331	56.63	22.47
	B40	268.50	201	350	65.10	24.25
	B50	219.00	23	331	132.40	60.46
NO_x(ppm)	B30	1006.75	768	1189	174.32	17.32
	B40	1087.50	844	1418	241.54	22.21
	B50	986.25	768	1184	181.77	18.43
CO_2 (%)	B30	4.18	3.07	4.77	0.76	18.18
	B40	4.34	3.30	5.67	1.04	23.96
	B50	4.13	3.07	4.81	0.73	17.68
O_2 (%)	B30	15.43	14.62	16.89	0.98	6.34
	B40	15.45	14.42	16.58	0.90	5.84
	B50	15.48	14.56	16.89	0.99	6.38

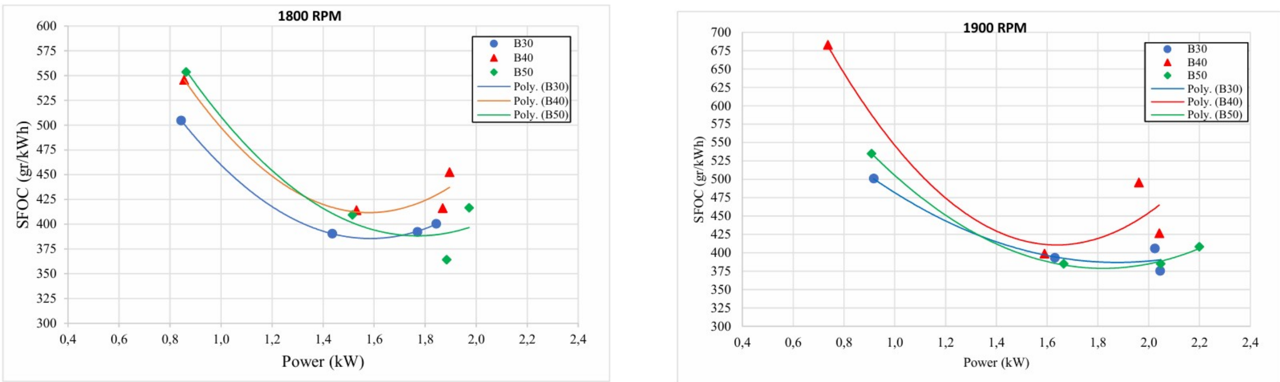

Fig. 5. Comparison between SFOC and Power for fuel types B30, B40, B50 at 1800 and 1900 RPM.

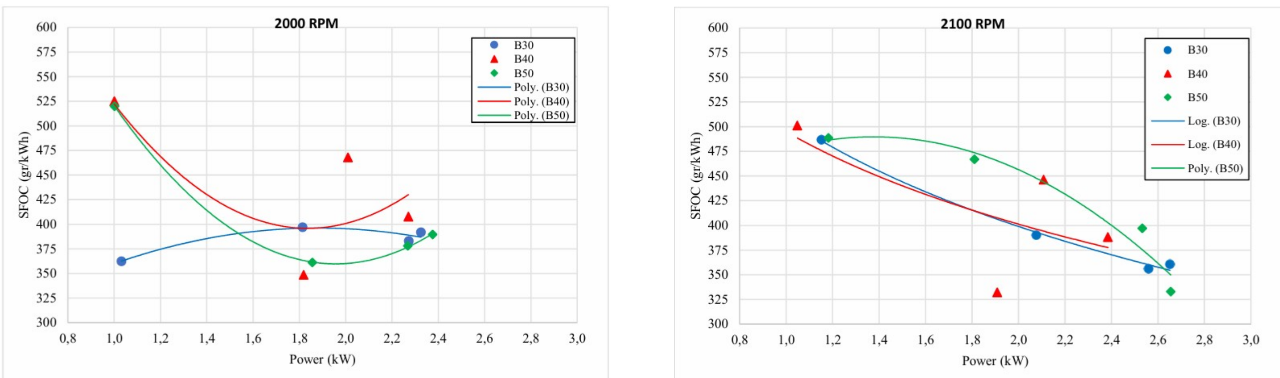

Fig. 6. Comparison between SFOC and Power for fuel types B30, B40, B50 at 2000 and 2100 RPM.

increased again at higher loads, likely due to less favorable fuel atomization and combustion characteristics. In contrast, B50 achieved the lowest SFOC values under several medium-to-high load conditions, especially between 1800 and 2100 RPM, suggesting better fuel economy under optimal operating conditions. Overall, the results indicate that B30 provides the most consistent fuel consumption performance across different engine speeds, while B50 offers superior fuel efficiency at medium-to-high engine loads.

3.2.2. Thermal efficiency

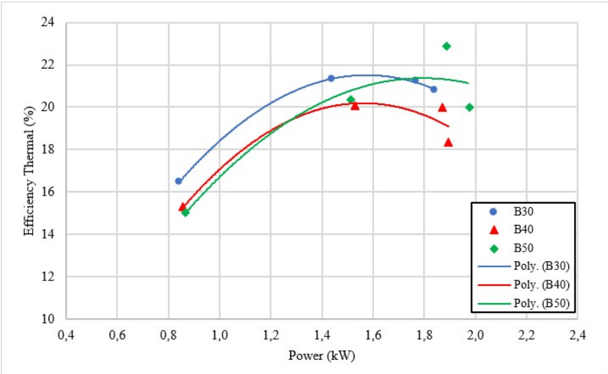

Fig. 7. Thermal Efficiency Vs Power at 1800 RPM.

Thermal efficiency rose with power up to an optimum point, then dipped slightly at maximum power. B50 produced the highest thermal efficiency (approximately 22-23%), especially at 1.8-2.0 kW [38]. The inherent oxygen content of biodiesel likely accelerated combustion and improved energy conversion. B30 delivered consistently even efficiency across loads, albeit slightly below B50 at peak power. B40 again showed a fluctuating profile, with a marked drop at high load. In practice, B50 suits medium-to-high-load applications, while B30 is preferable for lighter, steady operations (Fig. 7).

3.2.3. Torque

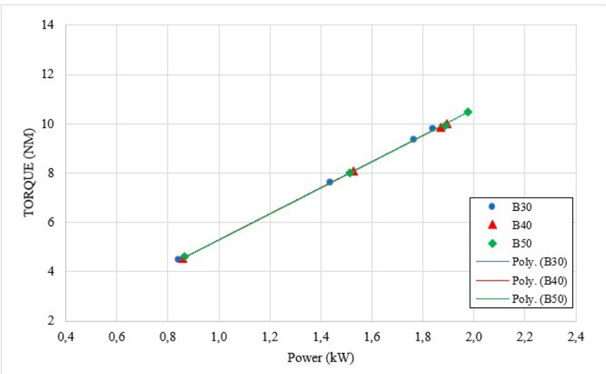

Fig. 8. Torque VS Power at 1800 RPM

Torque increased nearly linearly with power and showed minimal differences across blends: ˜4.2 Nm at 25% load up to ˜10.3 Nm at 100% load. This indicates that using up to 50% biodiesel does not significantly affect the engine's torque-producing capability; combustion still generated adequate mean gas pressures to drive the crankshaft despite fuel-property differences (Fig. 8).

3.2.4. Brake Mean Effective Pressure (BMEP)

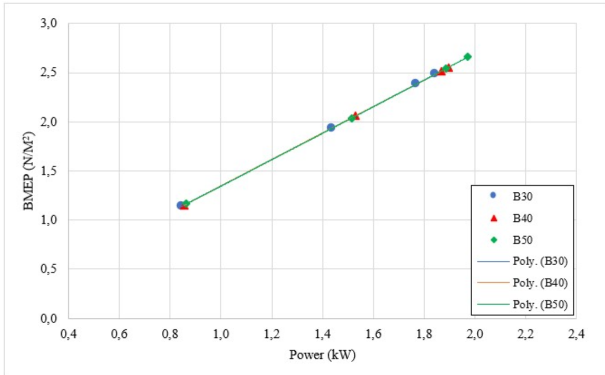

Fig. 9. BMEP vs Power at 1800 RPM

BMEP rose proportionally with power for all blends and largely overlapped across fuels, ranging from ˜1.1 bar to ˜2.4 bar. Thus, average in-cylinder working pressure was not materially influenced by biodiesel fraction [39]. Despite biodiesel's lower heating value relative to diesel, mean effective pressure remained within an efficient band, suggesting stable combustion (Fig. 9).

3.2.5. Output power

Output power increased with load, but declined slightly as biodiesel fraction increased [40]. B30 achieved a maximum of ˜2.2 kW, while B50 produced ˜2.0-2.1 kW. The reduction is consistent with biodiesel's lower heating value, yielding less released energy per unit fuel. Even so, B50's output remained within acceptable operational limits and did not compromise core engine function.

3.3. Exhaust Emissions Analysis

Emission testing assessed how JME blends (B30, B40, B50) affect combustion quality in a single-cylinder diesel engine at 1800 RPM and loads of 25%, 50%, 75%, and 100% [41]. Emissions evaluated were CO, HC, NOx, CO_2, and O_2. Results showed complex dynamics driven by engine load and fuel-blend characteristics (Table 3).

3.3.1. Carbon monoxide (CO)

CO decreased from low to medium loads, then rose slightly at full load. For B30, CO fell from 331 ppm (25%) to 201 ppm (75%), then increased to 240 ppm (100%). B40 and B50 showed similar trends, though initial CO was higher for

Table 3. Exhaust Gas Emission Test Results for Diesel Engines with B30, B40, and B50 Variants at 1800 RPM

No	Fuel Type	RPM	Load %	Emission Types				
				HC	CO	NOx	**CO_2**	**O_2**
1	B30	1800	25	21	331	768	3,07	16,89
		1800	50	19	236	1024	4,61	14,88
		1800	75	17	201	1046	4,26	15,34
		1800	100	14	240	1189	4,77	14,62
2	B40	1800	25	11	350	844	3,30	16,58
		1800	50	10	270	1042	4,14	15,46
		1800	75	9	201	1046	4,26	15,34
		1800	100	8	253	1418	5,67	14,42
3	B50	1800	25	26	331	768	3,07	16,89
		1800	50	22	286	969	4,04	15,60
		1800	75	19	236	1024	4,61	14,88
		1800	100	17	43	1184	4,81	14,56

Source: Marine Engine Laboratory Results FTIK Hang Tuah University Surabaya

B40 (350 ppm) and B50 (331 ppm). Lower CO at medium loads indicates more complete combustion, whereas the rise at maximum load may reflect mixture enrichment or turbulence that hinders complete oxidation.

3.3.2. *Hydrocarbons (HC)*

HC declined progressively for all blends. For example, B50 dropped from 26 ppm (25%) to 17 ppm (100%), while B30 decreased from 21 ppm to 14 ppm over the same load range. This suggests increasingly complete combustion and fewer unburned hydrocarbons with rising load; minor fluctuations imply stable biodiesel combustion chemistry.

3.3.3. *Nitrogen oxides (NOx)*

NOx increased sharply with load. For B30, NOx rose from 768 ppm (25%) to 1189 ppm (100%); B50 increased from 768 ppm to 1184 ppm. Higher combustion temperatures at heavy loads drive thermal NOx formation. This finding has environmental implications, as NOx contributes to acid rain precursors and respiratory irritation.

3.3.4. *Carbon dioxide* (CO_2)

As a proxy for combustion completeness, CO_2 increased at medium loads ($50 - 75\%$) and then declined at full load. B30 peaked at 15.34% CO_2 at 75% load, dropping to 14.62% at 100%. B40 and B50 followed similar patterns. The CO_2 drop at maximum load, accompanied by higher CO and O_2, points to suboptimal air-fuel conditions and reduced combustion efficiency under extreme load.

3.3.5. *Oxygen* (O_2)

Exhaust O_2 reflects unreacted oxygen. Across all blends, O_2 was lowest at medium load and highest at full load. For instance, B50 registered 3.07% O_2 (25%), fell toward 4.61% (75%), then rose to 4.81% (100%). Elevated O_2 suggests incomplete utilization of available oxygen (excess air or incomplete combustion). Thus, even as high temperatures elevate NOx at full load, oxygen utilization efficiency may decline at the extremes.

Overall, the experimental results indicate that each biodiesel blend offers distinct advantages under different operating conditions. B50 exhibited superior fuel economy and higher thermal efficiency, particularly under medium-to-high engine loads, whereas B30 demonstrated more stable engine performance across the entire operating range with relatively consistent fuel consumption characteristics. Although the emission characteristics varied among the biodiesel blends depending on engine load, no single blend consistently outperformed the others for all emission parameters. Therefore, from a practical engineering perspective, B30 represents a more balanced biodiesel blend by providing an appropriate compromise between engine performance, operational stability, fuel economy, and exhaust emission characteristics, making it more suitable for general diesel engine applications.

4. Conclusions

Based on the experimental investigation of diesel engine performance and exhaust emissions using biodiesel derived from waste cooking oil (Jelantah Methyl Ester, JME) blends of B30, B40, and B50, the following conclusions can be drawn. Based on the experimental results demonstrated distinct performance characteristics depending on the operating conditions. B50 achieved the lowest Specific Fuel Oil Consumption (SFOC) and the highest thermal efficiency, particularly under medium-to-high engine loads, indicating its potential for improving fuel economy. However, B30 consistently provided more stable engine performance across the entire operating range while maintaining balanced fuel consumption and exhaust emission characteristics. Considering the overall balance between engine performance, operational stability, fuel efficiency, and emission characteristics, B30 is recommended as the most suitable biodiesel blend for practical diesel engine applications.

4.1. Diesel Engine Performance Analysis

The test results showed that all fuel blend variations experienced an increase in engine performance as the engine load increased. The SFOC decreased with increasing engine power, with B50 producing the lowest value of approximately 360 g/kWh at medium load, indicating the best fuel efficiency. B30 demonstrated more stable fuel consumption and efficiency across the entire power range. Meanwhile, B40 exhibited fluctuating performance, indicating instability in the combustion process.

The torque and BMEP parameters showed no significant differences among the fuel variations, indicating that biodiesel blends up to 50% did not significantly affect the basic mechanical performance of the diesel engine. The experimental results indicate that B30 is the most suitable biodiesel blend for practical diesel engine operation under varying load conditions, whereas B50 is more appropriate for medium-to-high load applications requiring improved fuel efficiency.

4.2. Exhaust Emission Analysis

The use of biodiesel blends significantly affected the exhaust gas emission characteristics of the diesel engine. CO and HC emissions decreased at medium loads, indicating a more complete combustion process. The B50 blend produced the lowest HC emissions (17 ppm), indicating cleaner combustion, particularly under high-load operating conditions. However, nitrogen oxide (NOx) emissions increased as the engine load increased.

NOx emissions increased with increasing engine load for all biodiesel blends due to higher combustion temperatures. Although the NOx values differed slightly among the fuel blends, all biodiesel variants exhibited the same increasing trend at higher loads. Overall, B30 provided the best balance between engine performance and exhaust emission characteristics, whereas B50 achieved superior fuel economy and cleaner combustion under specific operating conditions. Therefore, the selection of biodiesel blends should consider the intended engine operating conditions and emission requirements.

The findings of this study demonstrate that waste-cooking-oil biodiesel has considerable potential as a renewable alternative fuel capable of improving diesel engine sustainability while maintaining acceptable engine performance and emission characteristics. However, this study was limited to short-term performance testing using a single-cylinder diesel engine under controlled laboratory conditions. Future studies are recommended to investigate long-term engine durability, higher biodiesel blend ratios, multi-cylinder diesel engines, and advanced NOx reduction technologies to support wider biodiesel implementation in accordance with international environmental regulations.

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