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Waste Cooking Oil Biodiesel via a Sodium Hydroxide-Catalyzed Transesterification Process: Effects on Diesel Engine Performance and Emissions

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Abstract

This study reports the synthesis of biodiesel from locally sourced Waste Cooking Oil (WCO) using sodium hydroxide (NaOH) catalyst. The main objective of this research is to assess the feasibility of utilizing WCO-based biodiesel as a sustainable alternative fuel by analyzing its physicochemical properties and application in a Yanmar® TF 70 LY-DI diesel engine. The production process involved degumming, acid-catalyzed esterification, and base-catalyzed transesterification to address the high free fatty acid content of WCO. The resulting biodiesel met ASTM D6751 standards, with a kinematic viscosity of 5.06 cSt, a flash point of 164°C, a density of 885 kg/m^3, a FAME yield of 98.17%, and an acid number of 0.12 mg-KOH/g. Engine tests were performed using blends from B10 to B40 and benchmarked against pure diesel. Results showed that B10 and B20 blends maintained comparable engine performance, while higher blends (B30–B40) exhibited reductions in power and torque and increased Specific Fuel Consumption (SFC). CO emissions decreased significantly with increasing biodiesel content, whereas NO and NOx emissions rose due to higher combustion temperatures. These findings demonstrate the technical feasibility and environmental benefits of WCO-derived biodiesel, particularly at lower blend ratios (≤ B20), as a locally available and sustainable fuel. The study is limited to laboratory-scale testing on a single-cylinder engine without long-term durability assessments, which should be addressed in future studies.

Keywords:
Biodiesel; emissions; NaOH catalyst; performance; waste cooking oil

1 Introduction

Fossil fuels, primarily petroleum, coal, and gasoline, remain the dominant global energy sources. The rising demand for these fuels continues annually, raising concerns about energy security across nations due to limited energy resources, a growing population, energy price volatility, and constrained energy supply [1][2]. However, conventional fossil fuels pose significant environmental threats, as their combustion releases substantial amounts of Greenhouse Gases (GHGs), which are major contributors to global warming, climate change, and public health issues [3][4][5]. Based on the latest data, diesel fuel consumption in Indonesia reached approximately 498.23 thousand barrels per day in 2023 [6]. The potential availability of Waste Cooking Oil (WCO) from urban areas in Indonesia is estimated at 157 million liters per year, most of which remains underutilized as a biodiesel feedstock [7]. The Indonesian government has implemented a mandatory biodiesel policy, including B35 (a blend of 35% biodiesel with diesel), with plans to increase the blending ratio to B40 as part of its renewable energy and emission reduction strategy. This situation underscores a gap between the high demand for diesel-based energy and the limited utilization of WCO as an alternative energy source. Optimizing the conversion of WCO into biodiesel would not only reduce Indonesia’s dependence on imported fossil fuels but also mitigate environmental issues associated with improper WCO disposal, which can contaminate soil and water. Consequently, renewable energy sources are increasingly regarded as sustainable and environmentally friendly alternatives [8]. Among these, biodiesel represents a promising substitute due to its renewable origin and lower pollutant emissions [9][10][11].

Biodiesel has emerged as a viable alternative for compression ignition engines [12], primarily due to its versatility in production from various renewable feedstocks. It offers several inherent advantages, including its oxygen content, which enhances combustion efficiency, and its lubricating properties, which contribute to prolonged engine life [13]. Additionally, the absence of sulfur in biodiesel improves its environmental profile. Nevertheless, biodiesel also exhibits certain drawbacks compared to conventional diesel, such as lower calorific value, higher viscosity, and greater density [14][15]. These factors can lead to suboptimal atomization, resulting in larger fuel droplets that hinder adequate fuel-air mixing and vaporization, thereby delaying ignition and reducing thermal efficiency [16]. Consequently, engine performance and emission characteristics are fundamentally influenced by fuel properties, engine design, and operating parameters. Given the property deviations from conventional diesel, biodiesel is typically blended in limited proportions for use in standard diesel engines [17][18][19].

Given the vast untapped potential of WCO, the strategic use of this feedstock for biodiesel production is essential. WCO is a byproduct of repeatedly used vegetable oil, which undergoes chemical degradation due to prolonged heating. It is characterized by high levels of Free Fatty Acids (FFA), affecting both its quality and recyclability. Despite its availability, the issue of WCO has not received adequate public attention, unlike the more widely recognized problem of plastic waste [20]. Converting WCO into biodiesel offers environmental benefits by reducing waste discharge and holds significant economic value, up to 95% yield efficiency, rendering it a valuable and accessible raw material [21].

Ajie et al. [22] conducted performance and emission tests on biodiesel derived from WCO in diesel engines. At 1200 rpm, the Brake Specific Fuel Consumption (BSFC) for B5, B10, B15, B20, B50, B85, and B100 blends was measured at 0.240109, 0.241996, 0.244331, 0.24661, 0.26089, 0.27947, and 0.28798 kg/kWh, respectively, compared to 0.239383 kg/kWh for pure diesel. Brake power and torque decreased under full load across varying speeds, while carbon monoxide (CO) and hydrocarbon (HC) emissions were significantly reduced with increasing biodiesel content. Nitrogen oxides (NOx) emissions declined slightly compared to diesel fuel. Similarly, Mengistu et al. [23] performed experimental investigations on the combustion efficiency of biodiesel-diesel blends in a single-cylinder diesel engine under varying loads at a constant speed of 1500 rpm. Eight blend ratios (B5-B100) were tested. The results indicated reductions of 16.79%, 4.08%, and 27.9% in brake torque, brake power, and brake thermal efficiency, respectively, compared to diesel. Additionally, the average BSFC increased by 4.8%. Exhaust emission analysis revealed reductions in CO and HC emissions of 52.2% and 60%, respectively, alongside increases in carbon dioxide (CO$_2$) and NOx emissions by

28.1% and 45.4%, respectively. These studies confirm that biodiesel derived from WCO is a cost-effective and environmentally favorable alternative to petroleum diesel.

In biodiesel production, catalysts play a critical role by accelerating reaction rates without undergoing permanent chemical change. Catalyst selection significantly influences production efficiency. In particular, sodium hydroxide (NaOH) is a highly active base catalyst that promotes the transesterification reaction between triglycerides and alcohol (typically methanol) to form methyl esters [24]. NaOH is not only commercially available and inexpensive but also allows high conversion rates at relatively mild conditions (60–65°C) without extreme pressure requirements [25]. Moreover, it shortens reaction times to under one hour [26], making it suitable for large-scale applications. The novelty of this study lies in the use of locally sourced WCO as a biodiesel feedstock, which is abundant yet remains underexploited. A two-step production process (esterification followed by transesterification) was applied to address the high free fatty acid content typically present in WCO. Additionally, this study uniquely evaluates biodiesel blends ranging from B10 to B40 in a Yanmar® agricultural diesel engine, which is widely used in Indonesia's agricultural sector. In the present study, biodiesel will be synthesized from WCO using NaOH as the base catalyst and tested in a Yanmar® TF 70 LY-DI diesel engine. The performance and emission characteristics will be assessed for various blend ratios with pure diesel (B10, B20, B30, and B40), with the specific objective of assessing performance and emission trade-offs to support the adoption of WCO biodiesel in agriculture and light transportation.

2 Research methodology

2.1 Tools and materials

This study used various tools and materials essential to support the biodiesel production process. The equipment involved included a hot plate, an analog balance, a glass beaker, a three-neck flask, a condenser tube, a water pump, a hose, a bucket, a thermometer, a stirrer, a dropper pipette, a stand clamp, a separating funnel, a stir bar, a burette, a stopwatch, a flowmeter, a tachometer, a gas analyzer, and a Yanmar® TF 70 LY-DI diesel engine. The materials used in this process included WCO as the primary feedstock, along with methanol (Merck), sulfuric acid (H2SO4, Smart Lab), phosphoric acid (H3PO4, Merck), and sodium hydroxide (NaOH, Merck) as the catalyst.

2.2 Degumming process

The WCO was initially filtered to remove solid impurities. This was followed by the degumming process, which eliminates phospholipids and other contaminants that may hinder the transesterification reaction and degrade biodiesel quality. Degumming was performed by adding 0.3% (v/v) phosphoric acid (H_3PO_4) to the WCO. The mixture was then heated to 80°C and stirred at 1000 rpm for 15 minutes. The degummed oil was subsequently used for the esterification process.

2.3 Esterification reaction

In this process, the WCO was reacted with methanol in the presence of sulfuric acid (H_2SO_4) as a catalyst at a concentration of 2% (v/v) relative to the oil volume. A molar ratio of oil to methanol of 1:6 was employed. The reaction was carried out at 60°C for one hour with a stirring speed of 600 rpm. Upon completion of the esterification step, the reaction mixture was allowed to settle for 24 hours, yielding two distinct layers. The upper layer was then separated and collected for the subsequent transesterification process.

2.4 Transesterification reaction

Initially, methanol was mixed with sodium hydroxide (NaOH) at 0.5% (w/w) relative to the oil's weight, and the mixture was stirred until a homogeneous solution was obtained. The previously esterified oil was then added to this mixture. The molar ratio of oil to methanol during the transesterification was maintained at 1:9. The reaction mixture was stirred at 800 rpm and heated to 60°C for 2 hours. Once the reaction was completed, the mixture was allowed to settle in a separating funnel for approximately 24 hours. The produced biodiesel was subsequently analyzed for various properties, including kinematic viscosity at 40°C, density, calorific value, flash point, and acid number. These properties were compared with the ASTM D6751 standard. Additionally, the methyl ester content of the biodiesel was determined using a GC–MS instrument. Further tests were conducted to evaluate its fuel properties, performance, and emission characteristics using a Yanmar® TF 70 LY-DI diesel engine. Fig. 1 illustrates the process flowchart for biodiesel production from WCO.

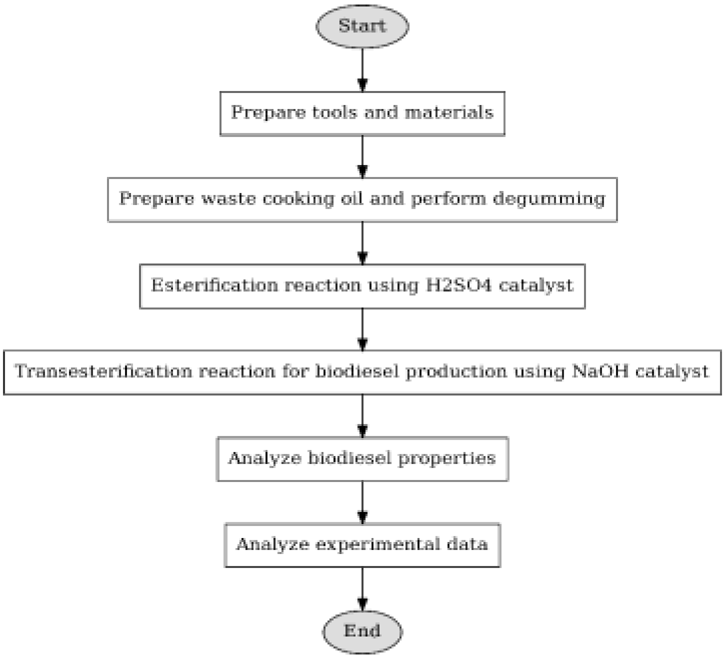

Fig. 1. Flowchart of biodiesel production from WCO

2.5 Performance and emission testing on the Yanmar® TF 70 LY-DI diesel engine

2.5.1 Preparation stage

To evaluate the performance of a diesel engine using biodiesel derived from WCO, a series of experimental procedures was conducted. The initial step involved preparing the required equipment and materials, including a Yanmar® TF 70 LY-DI diesel engine, a burette tube, a stopwatch, a flowmeter, a tachometer, and fuel samples (biodiesel and pure diesel). The specifications of the Yanmar® TF 70 LY-DI diesel engine are presented in Table 1. The following procedure was carried out to collect data on engine performance using biodiesel from WCO:

a. Fuel was filled into the burette tube.
b. The diameter of the intake manifold was measured.
c. The cross-sectional area of the intake manifold was entered into the flowmeter.
d. The Yanmar® engine was started manually using the crank handle.
e. Airflow rate was measured using the flowmeter.

Table 1. Yanmar® TF 70 LY-DI diesel engine specification

Parameter	Value
Cylinder capacity	382 cc
Power output	6.0 DK/2400 Rpm
Bore x stroke (mm)	78 x 80
Generator type	ST-3 Yamamoto
Power	3 Kw
Current	13.6 A
Voltage	220 V
Rotational speed	1500 rpm
Frequency	50 Hz
Power factor (Cosφ)	1.0
Phase	Single phase

2.5.2 Engine performance testing stage

Performance testing was carried out by varying engine speed and fuel blend ratio. The testing procedure comprised the following steps:

a. The first step involved applying a load to the generator by activating a 1250-watt lamp.
b. Fuel consumption was measured by recording the time required for the generator to consume 10 mL of fuel, using a stopwatch for timing.
c. The output voltage from the generator was recorded using a voltmeter.
d. The output current (amperage) of the generator was measured.
e. After all measurements were completed, the load was gradually removed, and both the generator and engine were turned off, followed by closing the fuel supply.
f. Based on the collected data, calculations were performed to determine the power output, torque, and Specific Fuel Consumption (SFC) of the Yanmar® TF 70 LY-DI diesel engine.

SFC was determined from the time required for the fuel in the burette to be consumed at 10 mL increments. The SFC value was then calculated using Eq. (1).

$$SFC = \frac{3600\ x\ fc\ x\ \rho}{P} \qquad 1)$$

Where SFC is specific fuel consumption (kg/HP.h), fc is fuel consumption (m^3/s), ρ is density (kg/L), and P is power (HP).

2.5.3 Emission testing stage

a. The gas analyzer instrument was turned on.
b. The Yanmar® TF 70 LY-DI diesel engine was started.
c. The probe of the gas analyzer was inserted into the engine's exhaust pipe.
d. Emission data were observed and recorded, including the concentrations of NO, NOx, and CO gases for different fuel types: pure diesel, B10, B20, B30, and B40 blends. The experimental setup and flowchart for performance and emission testing on the diesel engine are presented in Fig. 2 and Fig. 3. While the specifications of the Gas analyzer are presented in Table 2.

The calibration standards for the gas analyzer are as follows: when the E8500 Plus is powered on, press OK to start the auto-zero calibration cycle, which lasts 180 seconds. This step must be carried out with the sampling probe and hoses detached from the analyzer, in a clean and dry air environment, ideally outdoors. Once the auto-zero process is finished, the probe can be reattached, and the instrument is ready for testing.

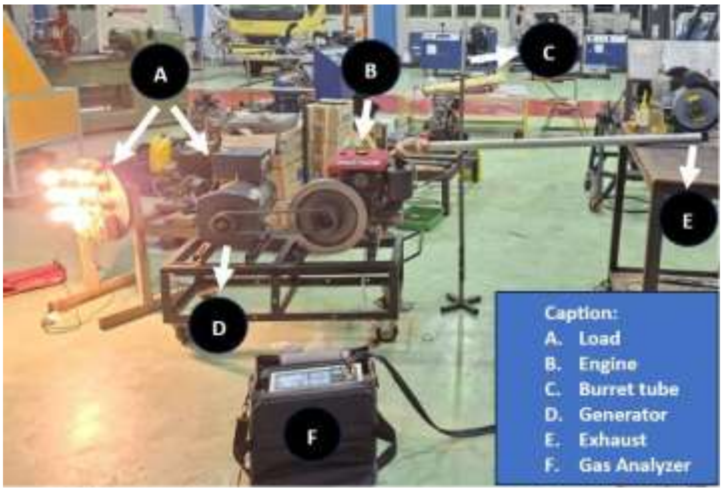

Fig. 2. Set up for performance and emission testing on the diesel engine

Table 2. Gas analyzer instrument specifications

Type	E8500-OCN-0-12
Carbon monoxide range	0 – 8000 ppm
Oxygen range	0 – 25 %
NO/NO_x range	0 – 4000 ppm

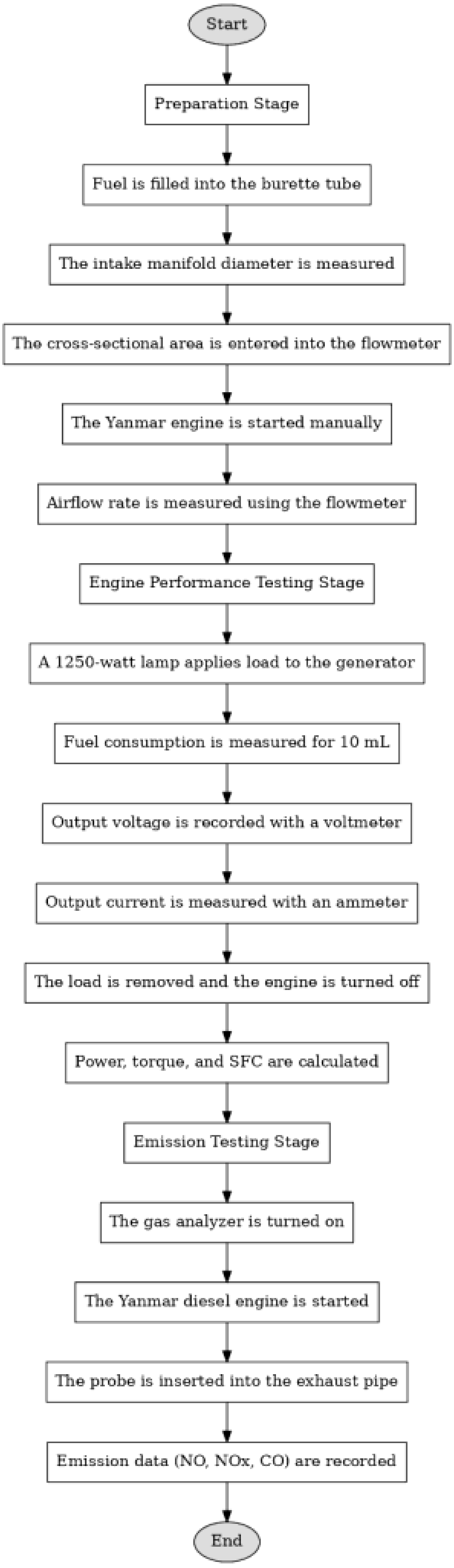

Fig. 3. Flowchart of the engine testing setup

3 Results and discussion

The stages of biodiesel production from WCO using sodium hydroxide (NaOH) as a catalyst are illustrated in Fig. 4. This figure presents the production process for biodiesel from WCO, comprising four main stages: degumming, esterification, transesterification, and biodiesel separation. This multi-step approach is particularly suitable for low-quality feedstocks such as WCO, which often contains high levels of FFA and impurities. The integration of pretreatment and reaction stages ensures higher yield, better purity, and enhanced overall efficiency in biodiesel production.

The first step, degumming, aims to remove impurities such as phosphatides, proteins, and other hydratable or non-hydratable gums present in the oil. These impurities can negatively affect catalyst performance and interfere with subsequent chemical reactions.

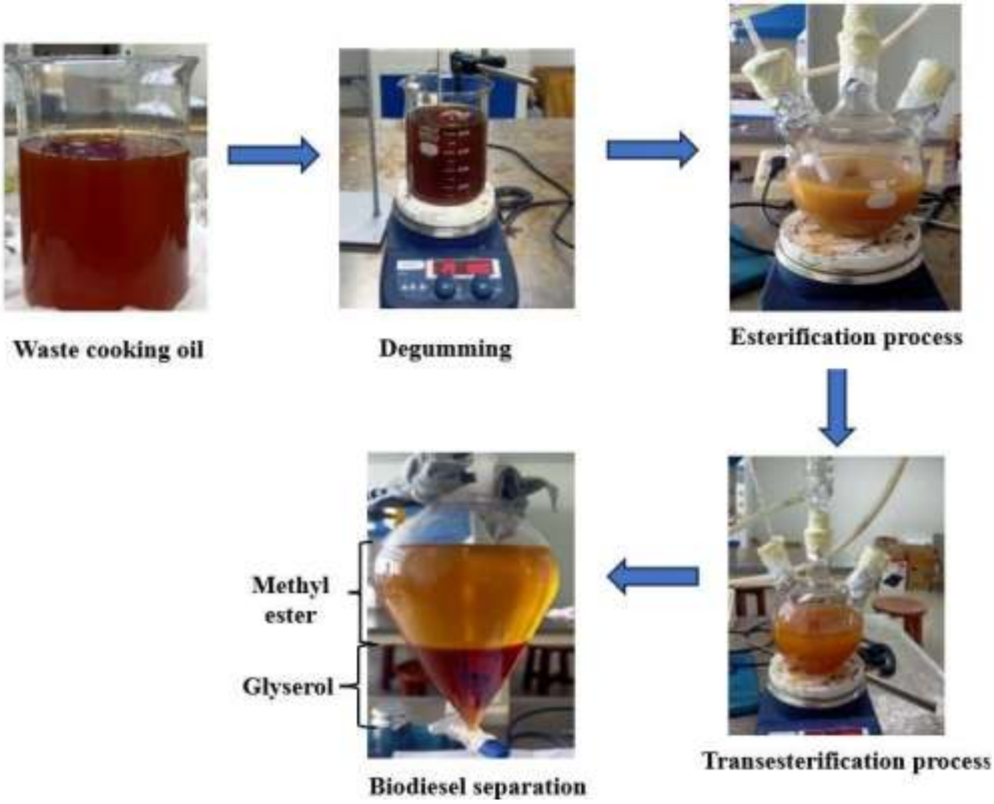

Fig. 4. Process stages of biodiesel production from WCO

Degumming is typically conducted by heating the oil and adding water or a dilute acid solution to facilitate the separation of gums. In the figure, the degumming stage is depicted with the oil being stirred and heated to ensure uniform treatment. This step is crucial for enhancing catalyst efficiency and minimizing soap formation in later processes. Following degumming, esterification is performed to reduce the oil's FFA content. Elevated FFA levels can react with alkaline catalysts to form soap, which hinders the transesterification reaction [27].

In esterification, the FFAs are converted into methyl esters using methanol and an acid catalyst, such as sulfuric acid (H_2SO_4). This reaction minimizes side-product formation and prepares the feedstock for the base-catalyzed transesterification [28]. The figure shows esterification conducted in a three-neck flask, allowing precise control of temperature, mixing, and reagent addition under laboratory conditions. The third step is the transesterification reaction, which is the core chemical transformation in biodiesel production. In this stage, the triglycerides in the oil react with methanol in the presence of a fundamental catalyst, such as sodium hydroxide (NaOH), producing methyl esters (biodiesel) and glycerol as byproducts. The final stage, biodiesel separation, involves separating the biodiesel product from the glycerol byproduct using a separatory funnel. Due to their different densities, the two layers naturally separate, with biodiesel (methyl ester) forming the upper layer and glycerol settling at the bottom.

The results of the biodiesel properties tests derived from WCO are presented in The biodiesel sample exhibited a FAME content of 98.17%, exceeding the minimum requirement of 96.5% stipulated by ASTM D6751. FAME content is an essential indicator of biodiesel purity and directly correlates with its performance and stability.

The results of the biodiesel blend from WCO and pure diesel are presented in Fig. 5. The tests were conducted with fuel blends ranging from B10 to B40, as well as pure diesel. The figure shows that increasing the biodiesel content of the blend results in a darker yellow color in the fuel. The engine power test results for various fuel blends are presented in Fig. 6. Engine power increased with engine speed. Pure diesel produced the highest power output, reaching 2.85 HP at 2000 rpm, followed by B10 and B20 blends, which achieved 2.83 HP and 2.80 HP, respectively. In contrast, the lowest power outputs were observed for the B30 and B40 blends, yielding 2.37 HP and 2.33 HP, respectively. These results indicate that pure diesel, with its higher energy content and stable combustion characteristics, delivers optimal power output at higher engine speeds.

Table 3. Biodiesel characterization is critical for determining its suitability as an alternative fuel. The measured kinematic viscosity of 5.06 cSt at 40°C falls within the acceptable ASTM D6751 range (1.9–6.0 cSt), indicating that the fuel exhibits proper flow characteristics for engine injection systems. Viscosity affects atomization during combustion, and excessive values can lead to incomplete combustion or injector fouling. Conversely, values that are too low may result in poor lubrication. The results confirm that the biodiesel possesses appropriate fluidity, balancing fuel delivery performance and engine wear protection. The flash point of 164°C exceeds the minimum requirement of 130°C as per ASTM D6751, suggesting good fuel safety and storage stability. Meanwhile, the calorific value of 9578 kcal/kg, although not specified in ASTM D6751, is within the typical range for biodiesel and suggests a good energy content to support engine performance. Additionally, the acid number of 0.12 mg-KOH/g, as determined by SNI 7182:2015, indicates a low level of FFA and oxidation products. This ensures minimal corrosiveness and long-term fuel stability. Collectively,

these parameters validate the quality and compliance of the biodiesel with international standards, supporting its use in compression-ignition engines. The measured density of biodiesel at 40°C was 885 kg/m³, which falls within the acceptable range specified by ASTM D6751 (869–900 kg/m³). The obtained density indicates that the produced biodiesel has a suitable molecular structure and composition for efficient atomization and combustion. The biodiesel sample exhibited a FAME content of 98.17%, exceeding the minimum requirement of 96.5% stipulated by ASTM D6751. FAME content is an essential indicator of biodiesel purity and directly correlates with its performance and stability.

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Table 3. Properties of biodiesel

No	Parameter	Result	Unit	Test method	Standard (ASTM D6751)
1	Kinematic Viscosity at 40 °C	5.06	cSt	ASTM D445	1.9-6
2	Flash point	164	°C	ASTM D 92	Min 130
3	Calorific value	9578	Kcal/Kg	Bomb calorimeter	-
4	Acid number	0.12	g-I_2/100g	SNI 7182:2015	Max 0.5
5	Density	885	kg/m^3	ASTM D-1298	869-900
6	FAME	98.17	%	GC-MS	Min 96.5

Fig. 5. Pure diesel fuel and biodiesel blends ranging from B10 to B40

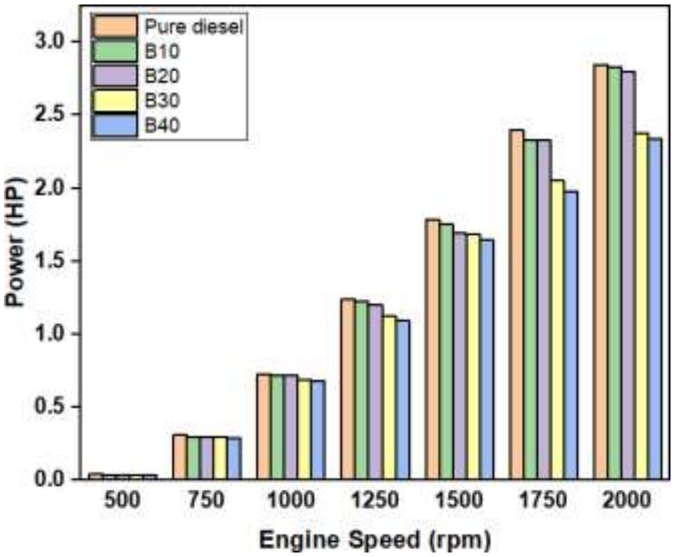

Fig. 6. Power test results

Meanwhile, biodiesel blends up to B20 still demonstrated good and efficient engine performance, with only a minor power reduction of approximately 0.1 HP at 2000 rpm compared to pure diesel. This reduction is relatively insignificant and does not substantially affect the performance of the Yanmar® TF 70 LY-DI diesel engine, suggesting that B20 remains an effective and viable fuel blend for use in conventional diesel engines.

However, higher biodiesel blends such as B30 and B40 exhibited a more pronounced decrease in power output. The B40 blend, for instance, recorded only 2.3 HP at 2000 rpm, representing a reduction of about 0.55 HP or approximately 19.3% compared to pure diesel. This decline highlights the limitations of using high-concentration biodiesel blends, particularly in diesel engines not specifically designed or modified to accommodate biodiesel's distinct characteristics. Technically, this performance reduction is attributed to the physical and chemical differences between biodiesel and conventional diesel, especially the lower calorific value and higher viscosity of biodiesel.

The oxygen content in biodiesel supports more complete combustion. However, the presence of oxygen also accelerates fuel consumption in the combustion chamber while providing lower total energy release, resulting in reduced engine power output compared to diesel. In addition, biodiesel generally exhibits a higher cetane number than diesel. A higher cetane number shortens the ignition delay, thereby initiating the combustion process earlier. This effect is beneficial in lower blends such as B10 and B20, where the engine power remains close to that of diesel. Nevertheless, at higher blends (B30 and B40), this advantage cannot compensate for biodiesel's lower specific energy, resulting in a noticeable power reduction. Furthermore, due to its higher viscosity and density, biodiesel tends to produce poorer fuel atomization, resulting in larger fuel droplets and slowing the air–fuel mixing process. Consequently, although the ignition delay is shorter owing to the higher cetane number, the heat release rate becomes less optimal, and the in-cylinder pressure decreases [29]. This condition directly reduces the piston thrust force, thereby lowering the engine power output.

In general, increasing the proportion of biodiesel in fuel blends tends to reduce engine power output. This suggests that the higher the biodiesel content, the lower the engine power produced. These findings are consistent with previous studies by Saputro et al. [30] and Suardi et al. [31], who reported that increasing the biodiesel concentration in the fuel consistently reduces the combustion power output. This reduction is associated with changes in fuel properties resulting from the addition of biodiesel, particularly in energy content.

Furthermore, test results reported by Nghia et al. [32] also demonstrated that engine power declines consistently as the biodiesel ratio in the fuel blend increases. This performance reduction is primarily due to the lower calorific value of biodiesel compared to conventional diesel, resulting in less energy per unit of fuel and, consequently, lower heat release during combustion. As a result, combustion efficiency decreases, and the amount of energy generated per combustion cycle is reduced. Although biodiesel possesses advantages such as a higher cetane number, the reduction in total energy content exerts a more dominant influence on engine power output.

The torque values obtained from diesel engine testing using various fuel blends are presented in Fig. 7. Based on the test results and subsequent analysis, the maximum torque was achieved at

2000 rpm with pure diesel, reaching 10.14 Nm. A slight reduction in torque was observed with B10 and B20 blends, at 10.07 Nm and 9.97 Nm, respectively. The decrease in torque with higher biodiesel concentrations reflects the difference in energy content between biodiesel and pure diesel, indicating that pure diesel possesses higher energy density, thereby enabling greater rotational force output from the engine.

In contrast, higher-concentration biodiesel blends, specifically B30 and B40, exhibited the lowest torque values, recorded at 8.47 Nm and 8.32 Nm, respectively. These blends demonstrated a significant reduction in torque across the entire engine speed range, particularly at 2000 rpm, the peak torque point. This decline is primarily attributed to the lower calorific value of biodiesel compared to pure diesel. A lower calorific value implies reduced thermal energy release during combustion, resulting in suboptimal in-cylinder pressure generation. Lower combustion pressure directly affects the piston thrust force, resulting in a notable reduction in engine torque. These findings are consistent with those reported by Khan et al. [33], who explained that increasing the biodiesel content of the fuel blend reduces the thermal energy released during combustion, thereby contributing to reduced engine performance, particularly torque output.

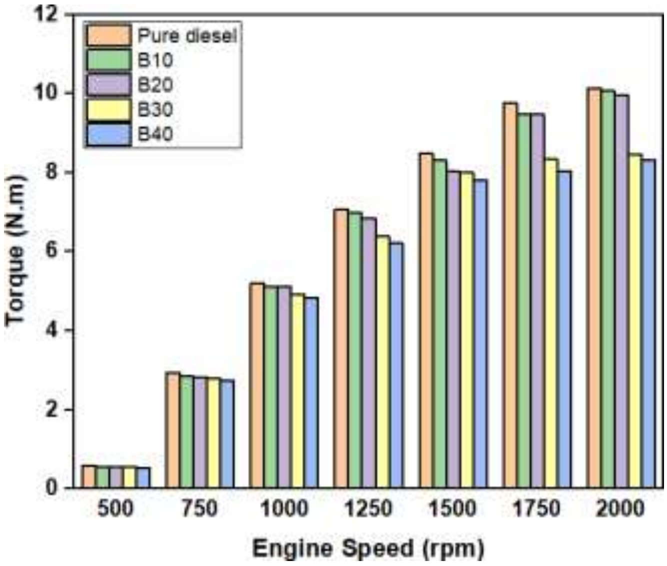

Fig. 7. Torque test results

The analysis of the relationship between SFC and engine speed (rpm) is presented in Fig. 8. Pure diesel fuel exhibited the most efficient performance compared to all tested biodiesel blends. At an engine speed of 1750 rpm, pure diesel had the lowest SFC, approximately 0.00032 kg/HP.h, followed by B10 and B20 blends with values of 0.00034 kg/HP.h, respectively. In contrast, the lowest efficiency was observed with the higher biodiesel concentration blends, namely B30 and B40, which recorded SFC values of 0.00042 and 0.00052 kg/HP, respectively.h, respectively. The low SFC of pure diesel indicates that it requires the least fuel to produce a unit of power, making it superior in both thermal efficiency and fuel economy.

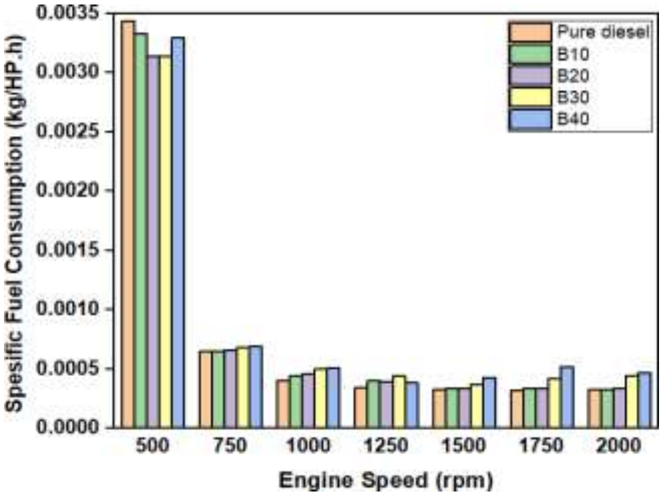

Fig. 8. SFC test results

Meanwhile, the biodiesel blends from B10 to B40 showed an increasing trend in SFC values with increasing biodiesel concentration. The B20 blend still demonstrated relatively good efficiency, with an SFC value of approximately 0.00034 kg/HP.h, only slightly higher than that of pure diesel. However, for the B30 and especially the B40 blends, a significant decrease in efficiency was observed. The B40 blend showed the highest SFC value at around 0.0005 kg/HP.h, indicating an increase in fuel consumption of approximately 56% compared to pure diesel to produce the same power output. The rise in SFC with higher biodiesel content in the fuel blend is closely related to the chemical and physical characteristics of biodiesel. One of the main contributing factors is the lower calorific value of biodiesel compared to pure diesel. This lower energy content results in less energy being released per unit mass of fuel. Consequently, the engine requires more fuel to produce the same amount of power, leading to an overall increase in SFC.

At 2000 rpm, the SFC values for B30 and B40 fuels increased by 36.79% and 44.39%, respectively, compared to pure diesel. This finding is consistent with the study reported by Mengistu et al. [34], which demonstrated that SFC increases with a higher biodiesel proportion in the blend. Mengistu et al investigated BSFC for blends of WCO methyl esters under various engine loads. Their results showed that BSFC decreased with increasing load for all fuel types, with pure diesel recording the lowest BSFC throughout the tests. At low loads, both biodiesel blends and pure diesel exhibited higher BSFC values, whereas at higher loads, fuel consumption decreased slightly. Fuel consumption increased with increasing biodiesel proportion up to 60% engine load, whereas above 60% load, the differences between fuel types became negligible. At low load, the B25 blend produced 0.44% higher power than pure diesel, due to a 4.8% reduction in BSFC, since power is inversely proportional to BSFC. The curve further indicated that BSFC remained relatively high at low loads, mainly due to overcoming engine friction. Overall, the curves for all biodiesel blends followed a similar trend to that of diesel fuel, although BSFC generally increased with increasing biodiesel content.

Other physical properties of biodiesel also contribute to increased fuel consumption. As demonstrated in the study by Nghia et al. [32], the higher flash point of biodiesel blends affects fuel atomization, making the fuel-air mixture less homogeneous during combustion. This condition results in suboptimal combustion, reducing thermal efficiency and increasing the fuel required to achieve the same power output.

Experimental test results further confirmed that, across all fuel types, including biodiesel blends, SFC values increased proportionally with increasing biodiesel concentration. This phenomenon is consistent with findings reported by Wahyudi et al. [35] and Saputro et al. [30] which stated that higher biodiesel content in the fuel blend significantly increases SFC. This is attributed to several physical properties of biodiesel, such as increased density, viscosity, and flash point, as well as its lower calorific value. These combined factors reduce combustion efficiency, resulting in higher fuel consumption.

Carbon monoxide (CO) is a hazardous gas produced from the incomplete combustion of carbon-containing fuels. It poses serious health risks to humans and has detrimental environmental effects. High CO emissions are generally indicative of inefficient combustion in diesel engines, particularly when the air–fuel mixture is suboptimal. Therefore, reducing CO emissions is essential not only for improving energy efficiency but also for mitigating air pollution. In this study, tests on various blends of biodiesel and diesel fuel showed that increasing the biodiesel fraction reduces CO emissions.

Specifically, pure diesel recorded the highest CO emission level at 935 ppm, followed by B10 (840 ppm), B20 (712 ppm), B30 (658 ppm), and B40 (401 ppm), which exhibited the lowest CO emission, as shown in Fig. 7. This downward trend clearly indicates that biodiesel use improves combustion quality in diesel engines. One underlying reason is the viscosity and volatility of biodiesel, which influence its atomization behavior. Biodiesel tends to form finer fuel droplets, resulting in a more homogeneous mixture with air. This improved mixing enhances combustion completeness, thereby reducing carbon monoxide formation. Based on Fig. 9The highest CO emission reduction efficiency was achieved with the B40 blend, reaching 53.9%.

These findings are consistent with those of Kumar et al. [36], who reported that biodiesel blends can effectively reduce CO emissions from diesel engines. They concluded that the emission reduction is primarily due to cleaner biodiesel combustion, without attributing it solely to the fuel's oxygen content. Furthermore, Abed et al. [37]In their research using B10 and B20 blends derived from WCO, jatropha, algae, and palm oil, they also found that CO emissions from all these biodiesel blends were lower than those from pure diesel.

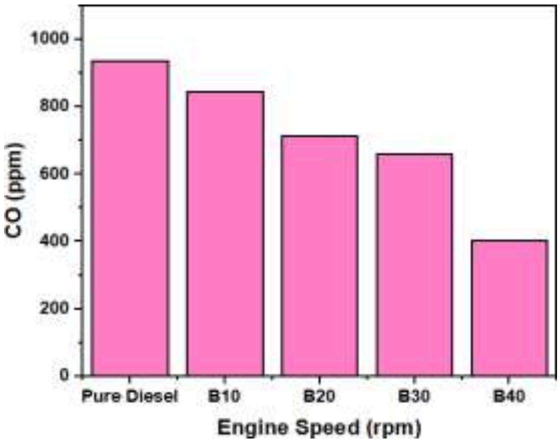

Fig. 9. CO emission test results

The emission profiles of nitrogen monoxide (NO) and nitrogen oxides (NO_x) from different fuel blends reveal a clear trend of increasing concentrations as the proportion of biodiesel in the blend increases (Fig. 10). Pure diesel exhibited the lowest emission values, with NO and NO_x concentrations of 122.45 ppm and 128.92 ppm, respectively. This indicates that conventional diesel combustion under controlled engine conditions tends to produce lower levels of nitrogen-based pollutants than biodiesel-diesel blends.

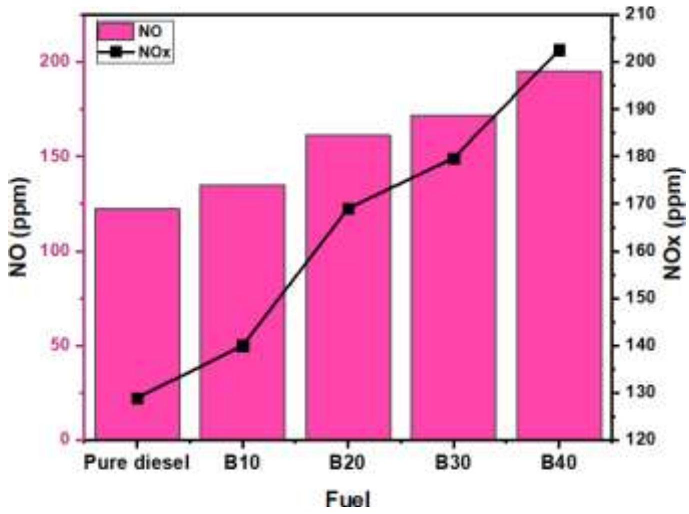

Fig. 10. NO and NO_x emissions test results

As the biodiesel content increases from B10 to B40, both NO and NOx emissions rise significantly. For instance, NO emissions increased from 134.66 ppm for B10 to 195.06 ppm for B40, representing an approximate 59% increase. Similarly, NO_x emissions rose from 140 ppm to 202.55 ppm over the same blending range. This trend is consistent with existing literature, which attributes the increase in NO_x emissions in biodiesel combustion to the higher oxygen content of biodiesel, leading to elevated combustion temperatures and enhanced thermal NO formation [37] . The elevated combustion temperature and the more complete combustion associated with oxygenated fuels such as biodiesel enhance the formation of thermal NO_x, which is primarily produced at high temperatures. Although biodiesel has the advantage of lower hydrocarbon and particulate emissions, its propensity to elevate NOx emissions remains a critical challenge.

Based on the CO and NO_x emission test results, it can be concluded that higher biodiesel content leads to lower CO emissions, whereas NOx emissions tend to increase. The reduction in CO emissions is generally attributed to the higher oxygen content of biodiesel, which enhances fuel oxidation and reduces incomplete combustion. However, the additional oxygen also raises the in-cylinder peak temperature, thereby promoting NO_x formation through the thermal NOx mechanism. This pattern has been consistently reported across various experimental studies, in which CO decreases while NO_x increases with higher biodiesel fractions. These findings are in agreement with the work of Ali et al. [38], who demonstrated that biodiesel–diesel blends significantly affect engine emission profiles. For instance, CO emissions were reduced by 20% with B5 compared to pure diesel, and by as much as 60% with B10, due to the improved oxidation resulting from biodiesel's oxygen content. Conversely, NO and NO_x emissions increased by 21.6% and 21.5% for B5 and by 16.3% and 15.6% for B10, respectively. Similarly, Mengistu et al. [34] reported the effects of biodiesel blends on CO and NO_x emissions. Compared with pure diesel, NO_x emissions from WCO biodiesel–diesel blends exhibited a mixed trend, with one blend showing a slight reduction of about 1.02%, while other blends recorded increases of 9.7%, 16.7%, 22.4%, 28.8%, 33.4%, 37.9%, 40.9%, and 45.4% for B10, B15, B20, B25, B30, B35, B40, and B100, respectively. In contrast, CO emissions consistently decreased across all blends, with reductions of 9.4%, 16.6%, 23.3%, 25.0%, 30.0%, 33.3%, 39.4%, 46.6%, and 52.2% relative to neat diesel fuel for B5 through B100, respectively.

4 Conclusions

Biodiesel synthesized from WCO using NaOH as a catalyst exhibits fuel properties that meet the ASTM D6751 standard, making it suitable for use in diesel engines. Blending biodiesel up to a B20 ratio results in only a minor decline in engine power and torque and low increases in specific fuel consumption, suggesting it is a viable alternative to conventional diesel engines without modification. B30 and B40 tend to significantly reduce engine performance due to the lower calorific value and higher viscosity of biodiesel. Emission testing showed that CO emissions decreased consistently with increasing biodiesel content, with the B40 blend achieving the most reduction of up to 53.9% compared to pure diesel, demonstrating significant environmental benefits. However, NO and nitrogen oxides (NOx) emissions increased with higher biodiesel concentrations, by approximately 59% for NO and 40 % for NOx at the B40 blend compared to pure diesel. From a practical perspective, B20 is recommended as the most balanced blend, offering a compromise between maintaining engine performance and reducing harmful emissions, while avoiding the significant efficiency losses associated with higher blends. This study was limited to laboratory-scale testing on a single-cylinder diesel engine. Therefore, it is recommended to test WCO-derived biodiesel blends in multi-cylinder engines, investigate the influence of injection timing, compression ratio, and other combustion parameters, and exploring the use of heterogeneous catalysts to enhance biodiesel production efficiency.

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