Assessment of Engine Performance and Emissions Using Palm Oil–Banana Peel Biodiesel Blend in CI Engines

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Abstract- **The global need for renewable energy has encouraged the use of biodiesel from organic waste as an alternative to hydrocarbon fuels. This study focuses on evaluating the performance of a CI diesel engine using a fuel blend made from palm oil and banana peel oil. The objective is to determine the optimal blend in terms of fuel properties, engine performance, and exhaust emissions. The biodiesel is produced using the transesterification method for palm oil and a heating extraction process for banana peel oil. Engine tests are carried out on a Yanmar TF85-ME single-cylinder diesel engine using three fuel types: B0 (Dexlite), BBO-30 (30% banana peel oil and biodiesel), and BBO-50 (50% blend). Fuel characterization showed that BBO-50 had the highest viscosity (4.23 cSt) and density (925 kg/m³), while BBO-30 had the highest calorific value (45.1 MJ/kg). Performance testing revealed that BBO-30 achieved the highest torque (7.26 Nm), lowest SFC (367.4 g/kWh), and highest thermal efficiency (22.4%). Emission tests showed that BBO-50 produced the lowest CO and NOx emissions, while BBO-30 had the highest CO_2 emission, indicating more complete combustion. Based on these results, BBO-30 is recommended for optimal engine efficiency, while BBO-50 is more suitable for lower emissions.**

Keywords- Blended Biodiesel, Banana Peel Oil, Fuel Properties, Engine Performance, Exhaust Emissions

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I. Introduction

The global energy crisis triggered by dwindling fossil fuel reserves and increasing energy demand has driven massive efforts to find alternative and renewable energy sources [1]. Diesel fuel, which is crucial for the industrial and transportation sectors, now faces major challenges in terms of supply sustainability, especially in developing countries like Indonesia, which still relies heavily on imported fuel [2], [3]. This dependence not only burdens the national economy but also increases vulnerability to fluctuations in global energy prices [4]. These concerns are further heightened by simultaneous geopolitical conflicts, such as the Russia–Ukraine war [5] and tensions between Israel and Iran in the Middle East [6], particularly around the Strait of Hormuz—a vital route for global oil distribution [7]. This instability has disrupted the global energy supply chain, increasing the risk of shortages and spikes in oil prices in the near future [8].

Biodiesel has emerged as a promising solution to reduce dependence on petroleum-based fuels and mitigate negative environmental impacts [9]. Various raw materials have been explored in biodiesel production, including virgin vegetable oil, used cooking oil, and animal fat [10], [11]. Palm oil is one of the most widely used raw materials in Indonesia due to its abundant availability [12]. However, the large-scale use of virgin palm oil can raise sustainability issues and competition with the food sector [13].

To address these challenges, a new approach to biodiesel formulation is being developed through the use of biomass waste such as oil from banana peels [14], [15]. Banana peels are a significant source of organic agricultural waste in Indonesia, yet they have not been optimally utilized [16]. The oil produced from the banana peel extraction process contains fatty acids that have the potential to be used as a biodiesel feedstock [15]. By combining palm oil and banana peel oil, it is hoped that a biodiesel formulation can be created that is not only technically efficient, but also environmentally friendly and low-cost.

However, challenges remain in ensuring that these biodiesel blends meet the performance and emission standards of modern diesel engines [17]. Issues such as combustion efficiency, exhaust emissions, and fuel stability remain major concerns in the development of new-generation biodiesel [18], [19]. Therefore, this study was conducted to evaluate the performance and exhaust emission characteristics of diesel engines operating using a blend of biodiesel from palm oil and banana peel oil at a specific concentration (B50).

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This research is expected to make a significant contribution to the development of more sustainable alternative fuels based on biomass waste, while also providing solutions to environmental issues and national energy security. The uniqueness (state-of-the-art) of this research lies in its approach, which combines two different vegetable oil sources, one of which comes from banana peel waste, which has not been widely studied in the context of diesel engine performance and emissions.

II. METHOD

With an experimental method approach in the form of testing the chemical properties of fuel, direct testing of fuel in a single-cylinder diesel engine, and testing exhaust emissions with a gas analyzer, it is hoped that an optimal fuel mixture formulation between palm oil and banana peel oil will be found which is expected to be able to become a reference or benchmark for environmentally friendly alternative fuels [20]. The fuel manufacturing process is also carried out in a way that is commonly used to convert vegetable oil into biodiesel. The transesterification method using methanol and NaOH catalyst is also applied in this study [21], [22].

Various studies have been conducted with the same goal: to find fuels capable of replacing hydrocarbon fuels. However, they often encounter obstacles such as low engine performance, particularly in terms of power, torque, and thermal efficiency. Furthermore, the chemical properties of vegetable oil differ from those of hydrocarbon fuels, making the combustion quality of vegetable oil fuels inferior to those of hydrocarbon fuels [23]. However, the low sulfur content is a key factor in vegetable oil biodiesel's lower emissions compared to conventional fuels. This indicates that this fuel has both advantages and disadvantages, so some research focuses on adding additives so that the quality of the vegetable fuel can match or even surpass that of pure hydrocarbons [24].

During the engine testing stage, previously prepared fuels, consisting of several samples, are tested directly on a diesel engine to compare power, torque, fuel consumption, and thermal efficiency. This performance value is used as a benchmark for determining whether a fuel is suitable for use in an engine. The research and technical assembly scheme of the diesel engine being tested is presented in Figure 1.

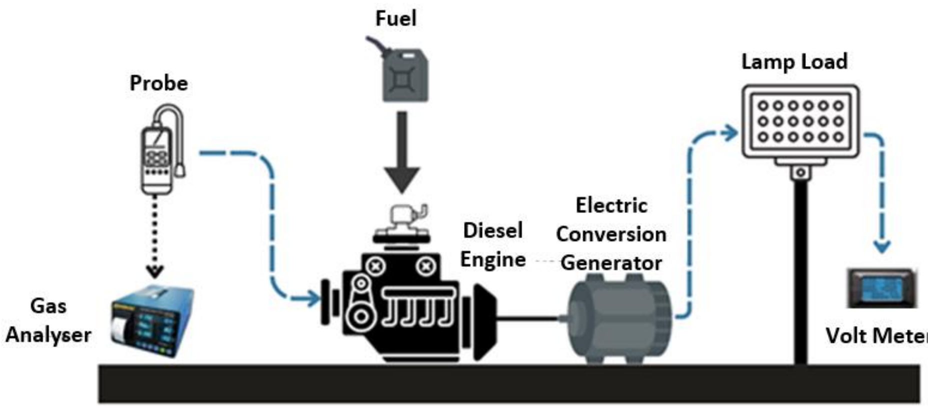

Figure. 1. Assembly scheme of test machine (Diesel Engine, Generator and Lamp loading board) [20]

A. Biodiesel Material

This research focuses on the use of a combination of palm oil and banana peel oil as fuel. Palm oil-based biodiesel is readily available in the environment, for example, from used cooking oil. Furthermore, Indonesia is currently the world's largest palm oil producer [25], [26]. The process for producing biodiesel from palm oil is essentially the same as for other biodiesel products, using the transesterification method, as previously described. The Indonesian government has also adopted a policy of using 40% palm oil in biodiesel blends marketed nationally[27].

Meanwhile, the second raw material, banana peel oil, is also relatively readily available in Indonesia. This is because Indonesia is a tropical country with banana trees growing throughout the archipelago [28]. The process of extracting oil from banana peels begins with collecting and cleaning ripe banana peels to remove dirt and remaining pulp. The cleaned peels are then chopped into small pieces and blended to form a smooth paste. The paste is then heated for approximately five hours with a small amount of cooking oil added to aid in optimal oil extraction. Once finished, the mixture is filtered while warm to separate the oil from the pulp. The extracted oil is stored in a clean container and is ready to be used as raw material for making biodiesel [29].

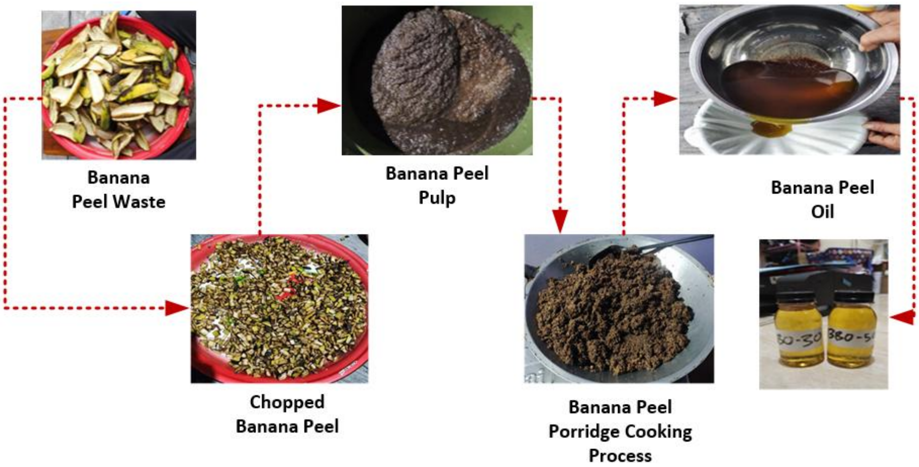

Figure. 2. The Process Of Processing Banana Peels Into Banana Peel Oil

B. Process Of Mixing Two Samples (Palm Oil And BP Oil)

The fuel blending method uses a gravimetric approach to ensure uniformity and accuracy of the mixture composition. The process begins with preparing a clean, dry, closed container, such as a plastic bottle or a chemical-resistant measuring cup, with a pre-calibrated capacity. Next, biodiesel fuel from palm oil and banana peel oil are measured separately using a measuring cup or digital scale according to the predetermined percentages for each fuel mixture variation. The fuels are added one by one into the container, starting with the component with the largest volume to minimize mixing errors. Once all components are mixed, the container is tightly closed and the mixture is homogenized by shaking manually for several minutes or using a magnetic stirrer to ensure even distribution of molecules. The homogenized fuel mixture is then stored in a closed container at room temperature and protected from direct sunlight until ready for use in the diesel engine characteristic and performance testing process.

The mixing composition of the banana peel oil sample with pure hydrocarbon oil (Dexlite) can be seen in Table 1.

Variable	Dexlite%	Palm Oil Biodiesel %	Banana Peel Biodiesel Oil %
Dexlite	100	0	0
BBO-30	70	20	10
BBO-50	50	30	20

III. Results and Discussion

As previously described, this study comprises two main stages. The first stage involves the production of biodiesel derived from used cooking oil, which is subsequently blended with diesel fuel to produce two fuel mixtures: BBO–30 (30% biodiesel banana oil and 70% diesel) and BBO–50 (50% biodiesel banana oil and 50% diesel). Additionally, a control sample, B0, consisting of pure diesel without any biodiesel content, was prepared for comparison purposes.

All fuel samples were tested using a single-cylinder diesel engine to evaluate performance and exhaust emissions. Prior to engine testing, each fuel sample underwent fuel property characterization, including measurements of viscosity, density, calorific value, sulfur content, and cetane number, to assess compliance with applicable fuel standards and to determine the influence of biodiesel blending ratios on fuel quality.

A. Density, Viscosity, Cetane Number Index, Calorific Value, And Sulfur Content

Viscosity is a key parameter in determining fuel quality and performance, particularly in diesel engines. This parameter directly affects the efficiency of the fuel injection system, as well as the atomization and combustion processes in the combustion chamber. Optimal viscosity ensures even fuel distribution and efficient combustion, while inappropriate viscosity can cause various technical problems, such as flame instability, increased fuel consumption, and damage to injection components.

In this study, viscosity measurements were carried out using an Ostwald Viscometer at 40°C, referring to the ASTM D445 standard. The test results showed that the viscosity of B0 fuel (pure diesel) was 2.53 cSt, while the viscosity of the BBO-30 and BBO-50 biodiesel blends was 3.08 cSt and 4.23 cSt, respectively. These values are still within the ASTM D445 standard range (2.0–6.0 cSt) and meet the viscosity limits set in the Pertamina Biosolar specifications (2.0–5.0 cSt). The increase in viscosity in the bio-diesel blend is mainly due to the chemical characteristics of vegetable oil, and is possibly influenced by the use of catalysts during the transesterification process. Viscosity that is too low risks causing premature wear on the injection pump due to lack of lubrication, while viscosity that is too high can clog the fuel filter and disrupt the injector spray pattern, thereby reducing combustion quality.

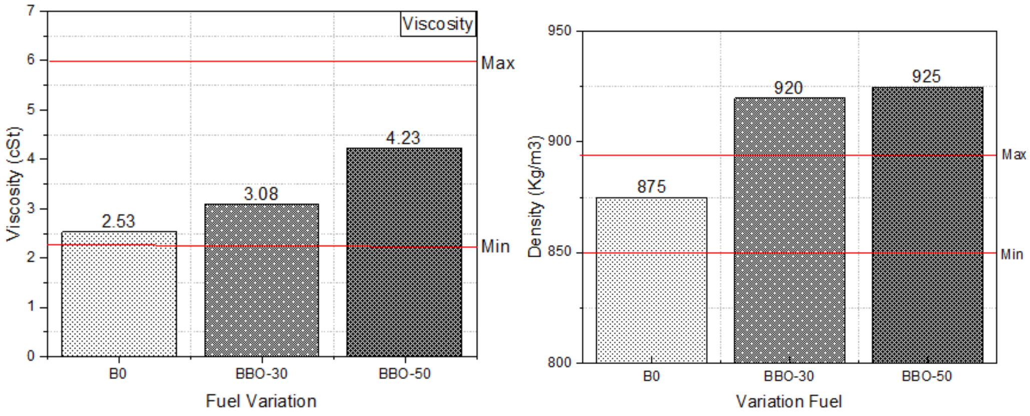

Figure. 3. Viscosity and Density Graphs for Three Fuel Sample Variations

In addition to viscosity, fuel density is an important parameter that affects flow characteristics, fuel spray, and the combustion process in a diesel engine. Density that is too high or too low can impact the volume of energy entering the combustion chamber and the air-fuel ratio, which ultimately affects thermal efficiency and exhaust emissions. In this study, density measurements were conducted using a 5 ml pycnometer, in accordance with ISO 3838 standards. Test results showed that the highest density was found in the BBO-50 blend fuel at 925 kg/m³, followed by BBO-30 at 920 kg/m³, and B0 (pure diesel) at 875 kg/m³. The density values for the BBO-30 and BBO-50 biodiesel blends slightly exceed the upper limit of the biodiesel standard, which is set at 850–890 kg/m³. This high density can lead to deposit formation if not combined with a proper filtration and injection system. However, the high density also contributes to increased energy content per unit volume, thus potentially providing greater thrust to the engine.

In addition to viscosity and density, the fuel's calorific value is also an important parameter because it affects the combustion efficiency of a diesel engine. Calorific value testing was conducted using a calorimeter, and the results showed that BBO-30 had the highest calorific value (45.1kJ/kg), followed by B0 (44.8kJ/kg), and BBO-50 (44.7kJ/kg). These values still meet the national minimum biodiesel specification of 43MJ/kg. The difference in calorific value is due to the transesterification process in biodiesel, which reduces energy content due to the release of glycerol, affecting the lower heating value (LHV), and directly impacting combustion efficiency.

Sulfur content was also analyzed because it plays a significant role in determining exhaust emissions, particularly SOx. Testing using the ASTM D4294 method showed that the sulfur content of B0 was 0.12% wt, BBO-30 was 0.056% wt, and BBO-50 was 0.04% wt. While still meeting the global MARPOL limit (0.5% wt), only BBO-50 approaches the maximum sulfur limit according to the biofuel quality standards set by the Indonesian government [30] for biodiesel (0.03% wt). Using low-sulfur fuel is important for maintaining engine performance, extending component life, and reducing air pollution.

Finally, the cetane number was tested using the ASTM D976 standard. The results showed that BBO-30 had the highest cetane number (54.4), followed by B0 (52.2), and BBO-50 (49.24), all of which meet the national minimum standard (48). A high cetane number accelerates fuel ignition, improves combustion stability, and reduces the risk of knocking, which are critical to overall diesel engine performance.

B. Diesel engine performance testing process

Testing was conducted on a TF 85-MLYS four-stroke diesel engine with a focus on torque measurement, specific fuel consumption (SFC), and thermal efficiency. The test data were presented in graphical form and further analyzed. The analysis included the relationship between torque and load, SFC and load, and thermal efficiency with load, where engine performance was evaluated at three engine speed variations:1300 RPM, 1600 RPM, and 1900 RPM.

1. Torque vs load

Based on test results, the highest torque was achieved by the BBO-30 blend fuel, with a maximum value of 7.26 N m at a load of 3,000 Watts. Meanwhile, BBO-50 recorded the highest torque of 6.24 N m, and pure B0 fuel produced a maximum torque of 5.61 N m. At no-load conditions, BBO-30 had the lowest starting torque of 0.17 N m, while BBO-50 and B0 recorded 0.23 N m and 0.26 N m, respectively. These results indicate that the biodiesel blend from banana peel oil and palm oil has the potential to increase diesel engine torque, especially at medium to high loads.

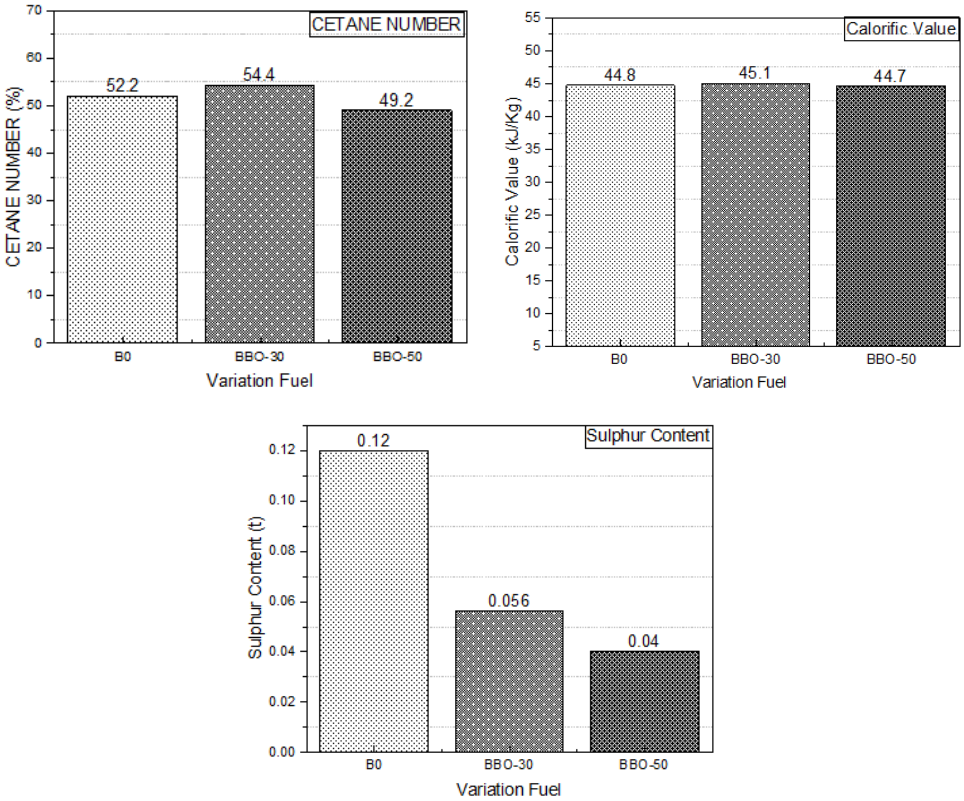

Figure. 4. Cetane Index, Caloric Value and Sulphur Content Graphs for Three Fuel Sample Variation

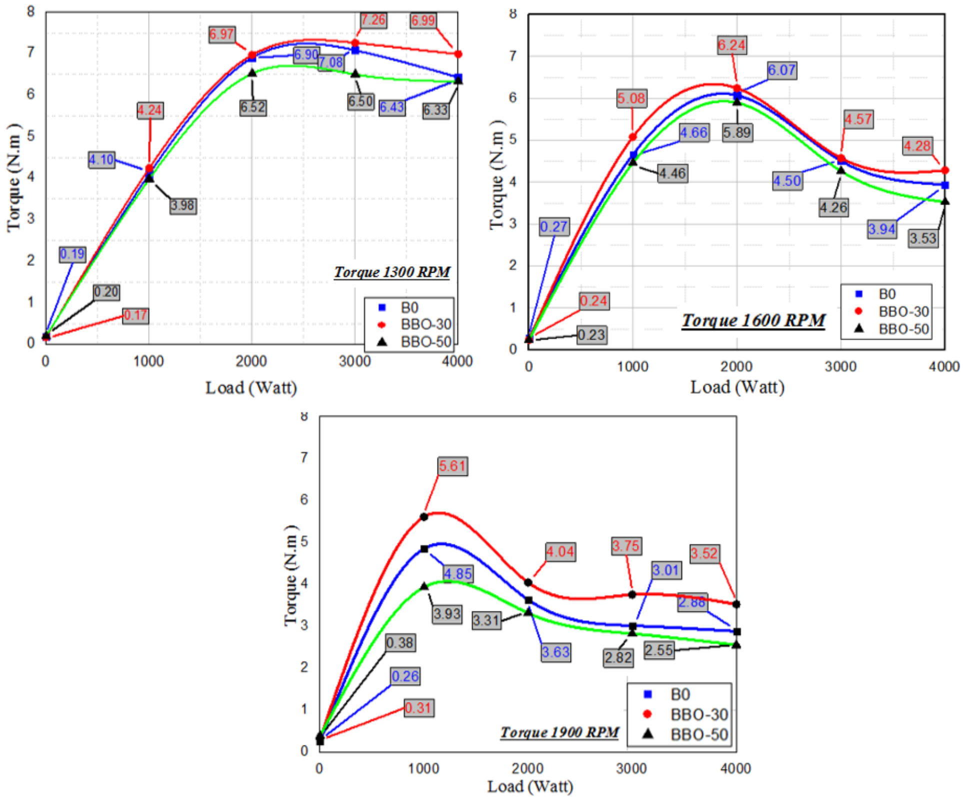

Figure. 5. Torque vs. Load Comparison Chart at 1300 RPM, 1600 RPM, and 1900 RPM

In The increased torque obtained from using BBO-30 is believed to stem from the fuel's physical properties, which better support combustion. Biodiesel has a higher density and viscosity than pure diesel fuel, thus aiding fuel atomization in the combustion chamber and enabling more complete combustion. Although the torque difference between the variations is not too striking, the trend of increasing torque performance with increasing biodiesel content indicates that the use of BBO blends, especially BBO-30, can provide performance benefits for diesel engines, especially in the shipping sector or variable load-based machinery.

2. SFC vs load

The investigation into specific fuel consumption (SFC) relative to engine load aimed to evaluate fuel efficiency across varying loads. The study explored SFC trends at engine speeds of 1300 RPM, 1600 RPM, and 1900 RPM. Interestingly, the SFC displayed a distinct pattern, with B50 fuel consistently showing lower consumption compared to B0 fuel across different load conditions. For example, at 1000 RPM, B50 fuel demonstrated higher fuel efficiency, highlighting its potential to optimize energy use. This analysis of SFC under various loads provides valuable insights into fuel consumption behavior, offering a foundation for improving overall engine performance.

The results of the Specific Fuel Consumption (SFC) test show that the BBO-30 fuel variation consistently produces the lowest SFC value compared to BBO-50 and B0 at various engine speeds and loads. At 1300 RPM, the lowest SFC value was recorded at 367.40 gr/kWh for BBO-30 at a load of 2000 Watts, while the highest SFC of 1.348 gr/kWh occurred in BBO-50 without load. At 1600 RPM, a similar pattern was found with the lowest SFC of 451.60 gr/kWh for BBO-30 and the highest of 1.045 gr/kWh for BBO-50. Similarly, at 1900 RPM, the minimum SFC of 418.10 gr/kWh was achieved by BBO-30 at a load of 1000 Watts, while the maximum SFC of 1.195 gr/kWh was recorded in BBO-50 at a load of 4000 Watts. In general, increasing load tends to decrease the SFC value for all fuel types, but BBO-30 shows the best fuel efficiency.

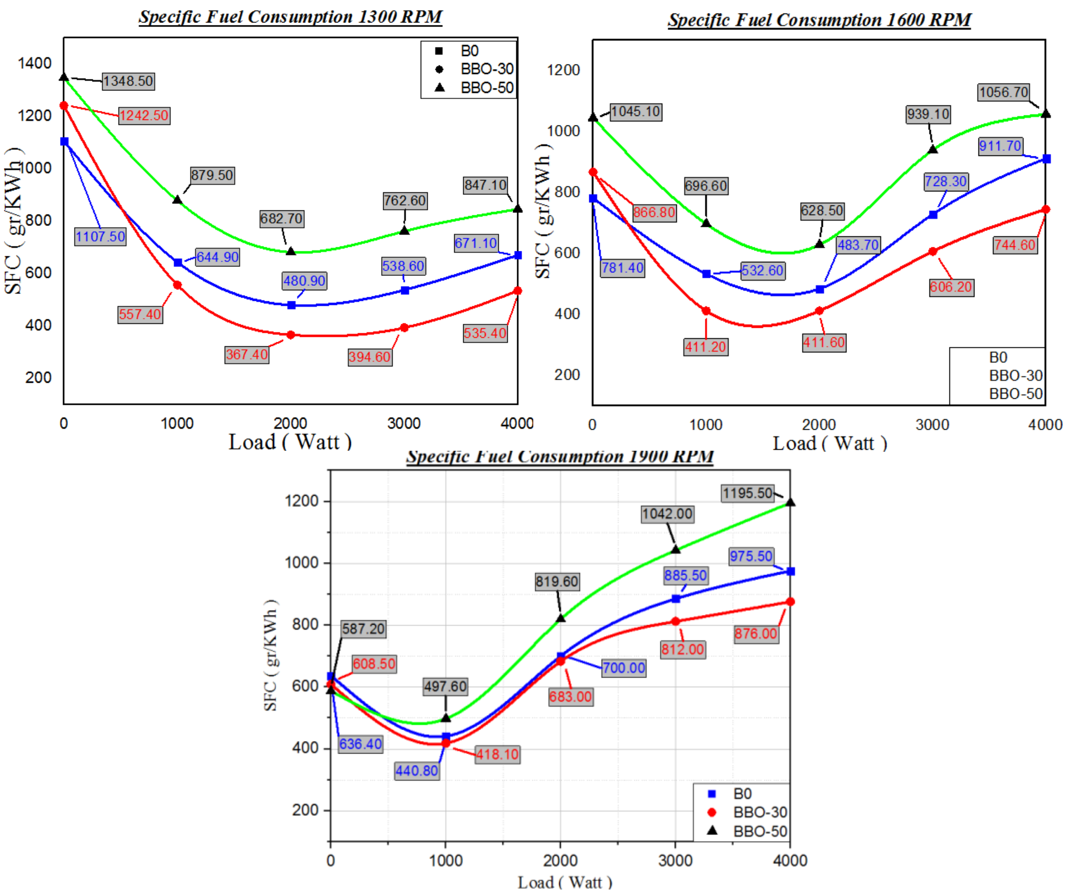

Figure. 6. SFC vs. Load Comparison Chart at 1300 RPM, 1600 RPM, and 1900 RPM

Fuel efficiency is greatly influenced by the physical characteristics of each fuel. The BBO-30 blend, which has a higher viscosity and density than pure diesel, allows for more complete atomization and combustion. This contributes to higher energy efficiency and lower fuel consumption. Conversely, diesel (B0) tends to have a higher SFC value due to less optimal combustion. Therefore, the use of biodiesel blends such as BBO-30 not only reduces fuel consumption but also offers economic and environmental benefits, particularly for diesel engine applications in the transportation and maritime sectors..

1. Thermal efficiency vs load

Thermal efficiency analysis against load provides important insights into engine performance and energy consumption. Thermal efficiency measurements were conducted at various load levels with engine speeds of 1300 RPM, 1600 RPM, and 1900 RPM. The test results show a trend variation, where thermal efficiency changes according to increasing load up to a maximum of 4000 watts. These findings provide key information for improving engine performance and overall energy efficiency, while also supporting the research objective of evaluating the effect of B50 fuel with a cetane number enhancer on diesel engine performance under various operating conditions.

Based on the displayed thermal efficiency graph, BBO-30 fuel shows the best performance with an efficiency value reaching 22.40% at a load of 2000 Watts, while the lowest thermal efficiency of 0.60% is achieved by BBO-50 without load. B0 fuel (pure diesel) shows an efficiency value that is between the two. This efficiency value is influenced by several factors, such as the power generated, fuel flow rate, and the calorific value of each fuel. The higher the power and calorific value, the higher the thermal efficiency. Conversely, under no-load conditions, thermal efficiency tends to be low because combustion is less than optimal.

Increased thermal efficiency is also observed as engine speed increases, leading to more complete combustion due to more even mixing of air and fuel. Biodiesel blends such as BBO-30 and BBO-50 have higher viscosity and density than diesel, thus supporting better fuel atomization and increasing combustion efficiency. Although biodiesel has a slightly lower calorific value, its natural oxygen content helps produce cleaner and more efficient combustion. Therefore, in general, biodiesel blends, especially BBO-30, show the potential for higher thermal efficiency compared to pure diesel under typical diesel engine operating conditions.

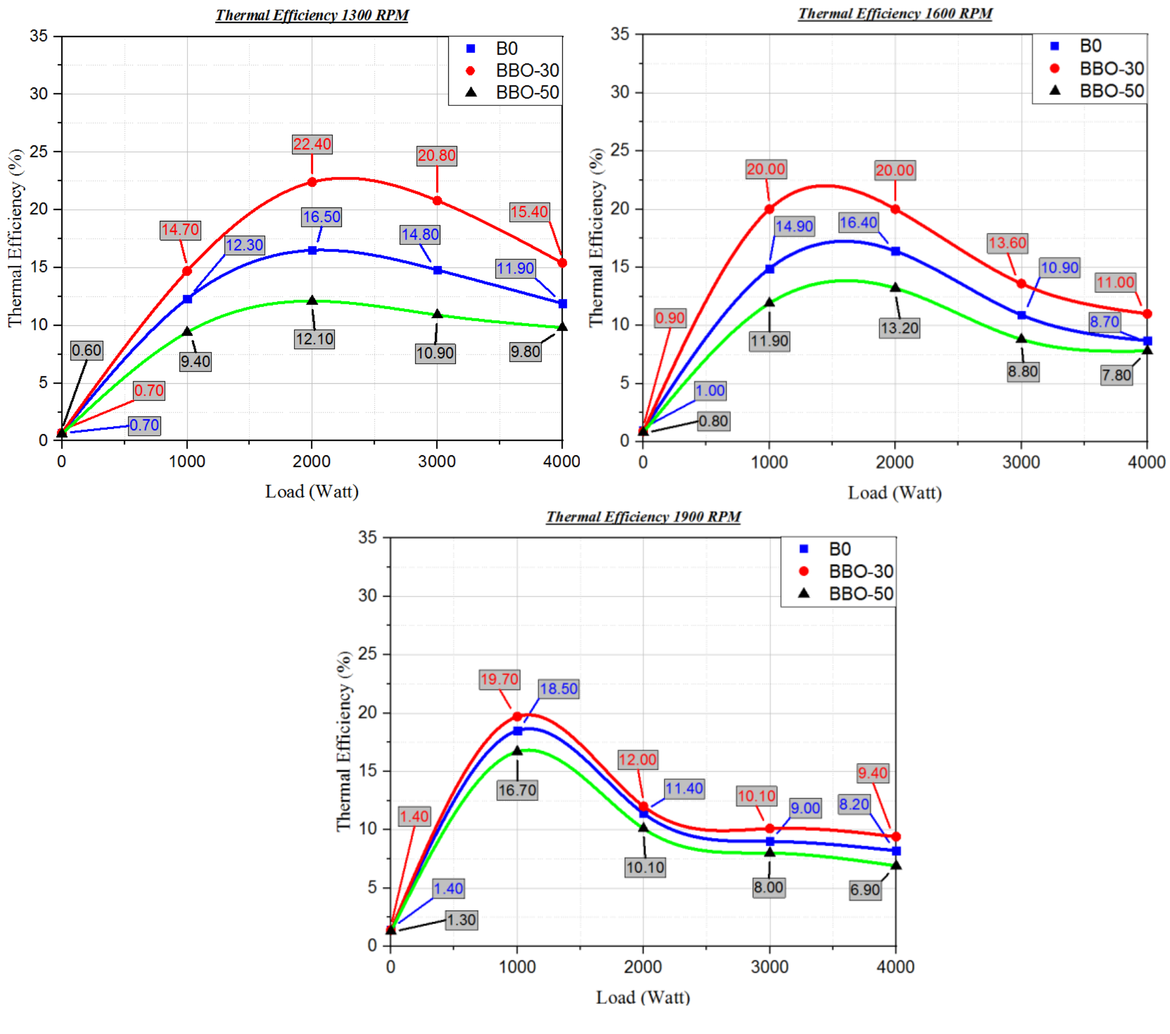

Figure. 7. Thermal Efficiency vs. Load Comparison Chart at 1300 RPM, 1600 RPM, and 1900 RPM

2. Emission

After the Yanmar TF85ME diesel engine was run using three types of fuel: B0, BBO-30, and BBO-50, the next step was to collect exhaust emission data. This test aimed to determine the extent to which variations in biodiesel blends affected the engine's emissions characteristics. Measurements were taken using a gas analyzer after the engine reached stable operating conditions at 1900 rpm.

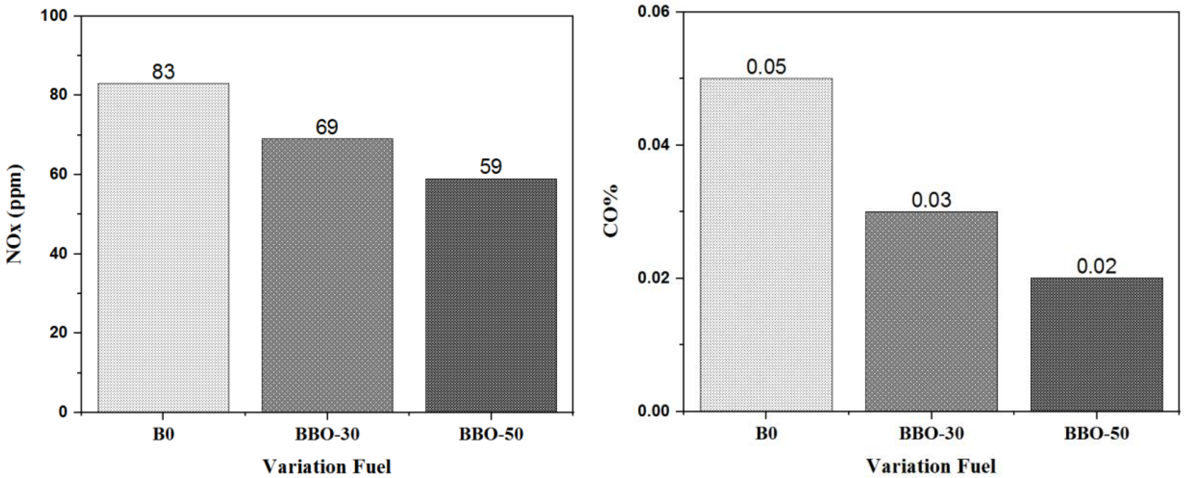

Figure. 8. Graph of Emission Test Results for Fuel: Carbon Monoxide (CO) and Nitrogen Oxide (Nox)

Emissions testing results showed that the B0 fuel blend produced the highest carbon monoxide (CO) emissions at 0.05%, while the BBO-30 and BBO-50 blends produced lower emissions at 0.03% and 0.02%, respectively. This reduction in CO emissions is due to the higher natural oxygen content in biodiesel compared to pure diesel, which increases combustion efficiency and results in more complete oxidation of carbon to CO_2.

Meanwhile, the highest nitrogen oxide (NOx) emissions were recorded in the B0 fuel at 83 ppm, and the lowest in the BBO-50 at 59 ppm. The reduction in NOx emissions in biodiesel blends is due to the high cetane number and the presence of polar compounds that accelerate the combustion process and lower the peak combustion chamber temperature. This lower temperature inhibits NOx formation, so the higher the biodiesel content, the lower the NOx emissions.

IV. Conclusion

This study successfully developed and tested a biodiesel blend made from palm oil and banana peel oil (BBO) as an alternative renewable fuel for diesel engines. The main objective—to evaluate fuel properties, engine performance, and exhaust emissions—was achieved through systematic testing of B0 (pure diesel), BBO-30, and BBO-50 fuel blends. The results showed that the BBO-30 blend provided the best engine performance, as indicated by its highest torque (7.26 Nm), lowest specific fuel consumption (367.40 g/kWh), and highest thermal efficiency (22.4%). In terms of emissions, the BBO-50 blend demonstrated superior environmental performance by producing the lowest CO (0.02%) and NO_x (59 ppm) levels due to its higher oxygen content that promotes cleaner combustion. These findings confirm that BBO-30 offers an optimal balance between power output and energy efficiency, while BBO-50 is more suitable for reducing pollutant emissions. Therefore, BBO-30 is recommended for applications that prioritize performance and fuel economy, whereas BBO-50 is preferable for scenarios focused on emission control. Overall, this research contributes to the advancement of sustainable and environmentally friendly biofuel alternatives for diesel engines, especially in the transportation and marine sectors.

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