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Effect of Methanol–NaOH Catalyst Variations on the Properties and Engine Performance of B50 Biodiesel from Waste Cooking Oil

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ABSTRACT

The growing demand for environmentally friendly fuels has encouraged the use of biodiesel as an alternative to fossil diesel. This study explores the production of B50 biodiesel derived from waste cooking oil using the transesterification method, with two catalyst variations: (1) 1000 mL methanol + 25 g NaOH and (2) 1200 mL methanol + 30 g NaOH per 5 liters of feedstock. The research aimed to evaluate the effects of catalyst concentration on the physical properties of biodiesel (density, viscosity, and calorific value), as well as its impact on engine performance metrics, including torque, specific fuel consumption (SFC), thermal efficiency, and exhaust gas opacity. Experimental testing was conducted using a four-stroke diesel engine at varying loads and speeds. Results showed that both fuel blends met the Indonesian standards for density, while only the 1200 mL + 30 g NaOH blend met the standard for viscosity. The biodiesel prepared using 1000 mL methanol and 25 g NaOH demonstrated superior engine performance, with a maximum torque of 8.92 Nm, minimum SFC (406.90 g/kWh), and highest thermal efficiency (21.28%) at 1000 RPM and 4000 W load. Additionally, the biodiesel prepared using 1200 mL methanol and 30 g NaOH produced lower exhaust opacity. In conclusion, while increased catalyst dosage improves fuel cleanliness and compliance with standards, the lower catalyst yields the best balance of performance metrics, making it a promising for biodiesel application in diesel engines.

1. INTRODUCTION

Global efforts to address climate change and reduce greenhouse gas emissions have driven many countries, including Indonesia, to develop environmentally friendly renewable energy sources (Jumah *et al*., 2025; Rahman *et al*., 2025). One increasingly adopted strategy is the use of biodiesel as an alternative fuel to replace fossil diesel fuel (Sathish *et al*., 2024). The Indonesian government has been actively supporting the transition to clean energy since 2025 through the mandatory B35 biodiesel policy and plans to implement B40 (Wirawan *et al*., 2024). In parallel, the thermochemical conversion of palm oil biomass in Indonesia is not only technically feasible but also supports the national transition towards renewable energy and the 2060 net-zero emission target (Haryanto *et al*., 2023). Waste cooking oil, as a byproduct of household and food industry activities, offers great potential as a biodiesel feedstock due to its abundance, low cost, and its contribution to reducing environmental pollution (Suardi *et al*., 2023b; 2024).

Diesel engines (compression ignition or CI engines), as the primary consumers of hydrocarbon fuels, continue to see growing use across the transportation, industrial, and power generation sectors in Indonesia (Suardi *et al*., 2025). These engines are known for their high thermal efficiency and distinct combustion process, which occurs through spontaneous ignition due to high-pressure air compression (Vipavanich *et al*., 2018). However, the increased consumption of diesel fuel has negative consequences, including elevated exhaust emissions and added pressure on the national energy supply (Lakshmaiya *et al*., 2025). Therefore, it is essential to find solutions that are not only environmentally sustainable but also capable of maintaining or enhancing diesel engine performance.

Biodiesel, as an alternative fuel, offers several advantages—it is renewable, produces cleaner emissions, and its carbon output can be reabsorbed by plants via photosynthesis, thereby supporting the carbon cycle balance (Kumar *et al*., 2025). Nevertheless, producing high-quality biodiesel remains a challenge, especially when using waste feedstocks such as used cooking oil. Key fuel characteristics—such as viscosity, density, water content, and oxidative stability—are strongly influenced by the transesterification process, particularly the type and concentration of catalysts employed (Bentil *et al*., 2025).

Transesterification is one of the most widely used methods for biodiesel production. It involves the reaction between triglycerides from vegetable oils or waste oils and alcohol (such as methanol), assisted by a base catalyst like sodium hydroxide (NaOH) (Awogbemi & Desai, 2025). NaOH is commonly chosen for its higher reactivity compared to other catalysts such as potassium hydroxide, enabling a faster reaction rate and higher biodiesel yield (Naseef & Tulaimat, 2025). However, catalyst concentration not only affects production efficiency but also impacts the final quality of the biodiesel, A study conducted by the author showed that the B20 biodiesel blend from castor oil, produced using the same catalyst (methanol and NaOH), achieved the highest torque (17.59 Nm), best thermal efficiency (17.04%), and the most economical specific fuel consumption (470.2 g/kWh) compared to dexlite (B0). (Suardi, 2023a).

Given this background, the present study aims to evaluate the effect of methanol and NaOH catalyst variations on the physicochemical properties of biodiesel derived from waste cooking oil, and to assess their impact on diesel engine performance. The parameters analyzed include engine power, brake specific fuel consumption (BSFC), thermal efficiency, and exhaust gas opacity. Through this approach, the study seeks to identify the optimal biodiesel formulation that ensures high fuel quality and maintains efficient engine performance, thereby contributing to the development of sustainable alternative energy in Indonesia.

2. METHODS

2.1. Catalyst Material

This study was executed in two steps: the transesterification process for biodiesel production and an experiment for evaluating diesel engine performance using the resulting fuel. The transesterification process, also known as methanolysis (Figure 1), was carried out using a catalyst composed of methanol and sodium hydroxide (NaOH) (Pauline *et al*., 2021). Two catalyst composition variations were used: 1000 mL of methanol with 25 grams of NaOH,

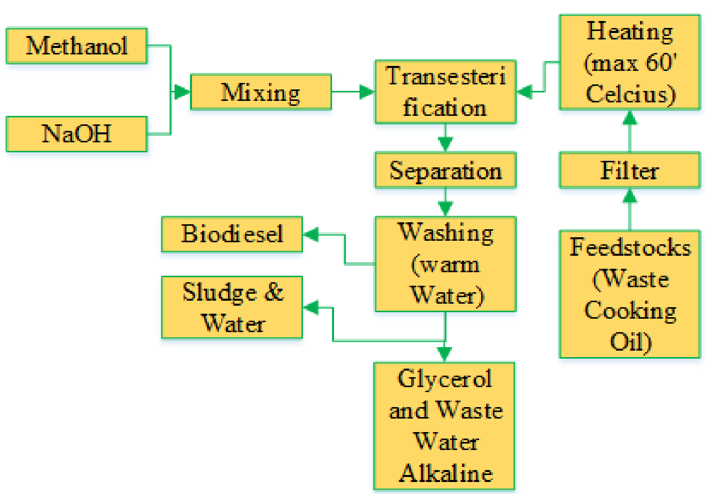

Figure 1. Biodiesel production by transesterification method

and 1200 mL of methanol with 30 grams of NaOH, each applied to 5 liters of waste cooking oil. In this reaction, methanol serves as the alcohol solvent, while NaOH acts as a chemical catalyst to accelerate the conversion of triglycerides into methyl esters (biodiesel).

In addition to producing biodiesel, the transesterification process also yields by-products such as glycerol, residual sludge, and alkaline wastewater (Li *et al*., 2023).

2.2. In-situ Transesterification Method

After the biodiesel was successfully synthesized, it was blended with conventional diesel fuel in various proportions and subsequently tested on a diesel engine using an experimental approach (Mayandi & Suharjito, 2024). The purpose of this testing was to evaluate engine performance parameters such as power output, fuel efficiency, and exhaust emissions. Previous studies have conducted similar experiments using biodiesel derived from vegetable oils, including performance tests on inclined engines to simulate wave-induced motion on ships, aiming to assess engine stability under marine operating conditions (Suardi, 2023c).

This study specifically investigates how the use of methanol and sodium hydroxide (NaOH) as catalysts in the transesterification of waste cooking oil affects the resulting biodiesel's fuel quality and its performance in diesel engines. The transesterification process used in this research is illustrated in Figure 2 (Suardi *et al*., 2023a). The biodiesel production began by heating waste cooking oil to 60 °C using a hot pot mixer, followed by the addition of a methanol and NaOH catalyst solution. Temperature is a critical factor in the biodiesel production process, particularly during the heating stage. Since methanol has a boiling point of approximately 65 °C, heating the oil beyond this temperature may lead to methanol evaporation, potentially reducing the efficiency of the transesterification reaction

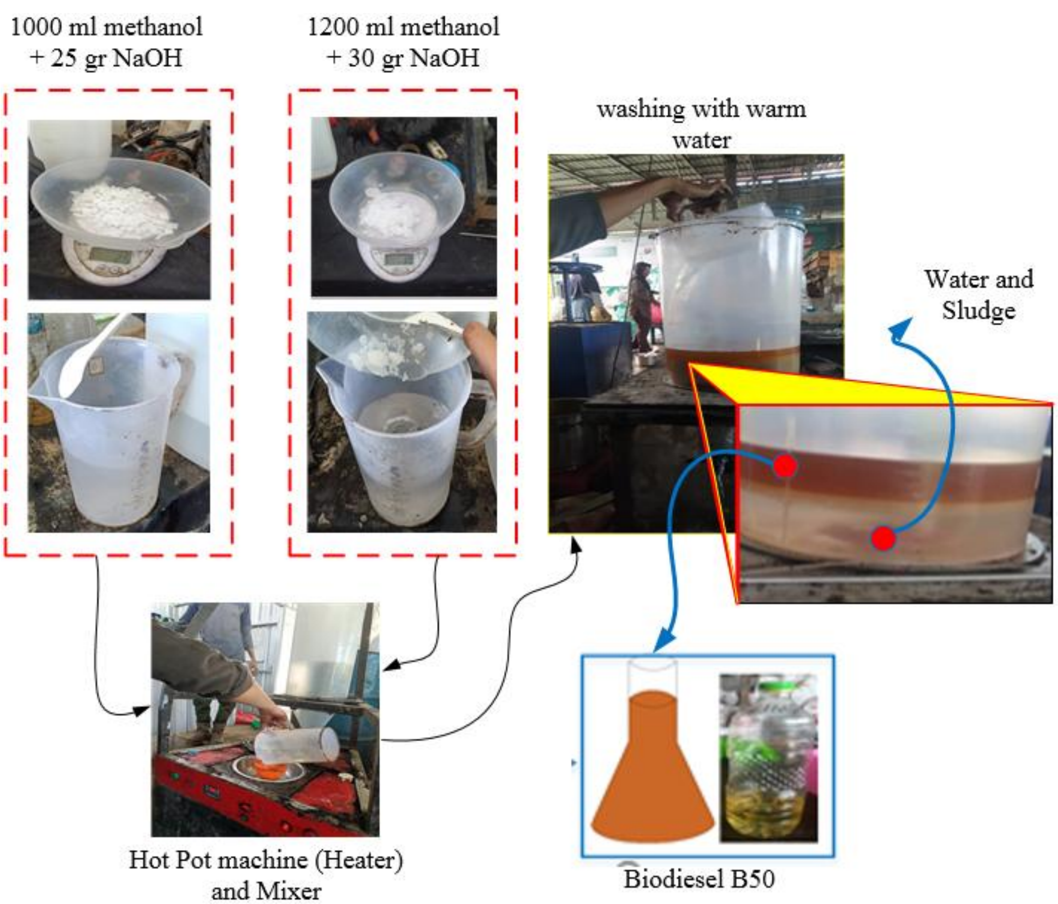

Figure 2. Steps for making biodiesel with two variations of catalyst

(Sinaga *et al*., 2014; Gita *et al.*, 2018). The mixture was stirred for 30 minutes to ensure complete transesterification, then transferred to a container for purification using warm water (80–100 °C) in a 1:1 volume ratio to separate glycerol and residual impurities. The purified biodiesel was then analyzed for its physical properties—density, viscosity, and calorific value—and tested on a diesel engine to evaluate the influence of the methanol-NaOH catalyst on performance, confirming its potential as a clean and efficient alternative fuel.

Following the successful production of biodiesel through the transesterification process, the next step involved blending the biodiesel with conventional diesel fuel to create B50 mixtures, using two different catalyst formulations: (1) 1000 mL methanol + 25 grams NaOH, and (2) 1200 mL methanol + 30 grams NaOH, each for 5 liters of waste cooking oil. This blending process was carried out to evaluate the extent to which the proportion of biodiesel and catalyst composition affect the fuel's physical properties and engine performance.

Prior to engine testing, each fuel blend was subjected to a series of analyses to determine its fundamental physical characteristics. The parameters evaluated included density, viscosity, and calorific value, which are key indicators of fuel quality and safety during use. These tests aimed to ensure that each variation met the necessary technical standards for application in diesel engines.

Once the fuel property tests were completed, the biodiesel blends were tested on a four-stroke diesel engine to assess their impact on engine performance (Figure 3). The performance tests focused on evaluating parameters such as power output, combustion efficiency, and specific fuel consumption (SFC). This approach allowed for a comprehensive analysis of whether increasing the biodiesel proportion along with variations in catalyst quantity has a beneficial or adverse effect on the direct performance of the diesel engine.

3. RESULTS AND DISCUSSION

The discussion is structured into two core areas: the characterization of biodiesel fuel properties and the analysis of diesel engine performance. The study utilized B50 fuel blends synthesized with different methanol and NaOH catalyst concentrations. Rather than reiterating the formulation steps, this section focuses on the resulting variations in physical and combustion-related fuel characteristics, as well as their influence on engine behavior under load.

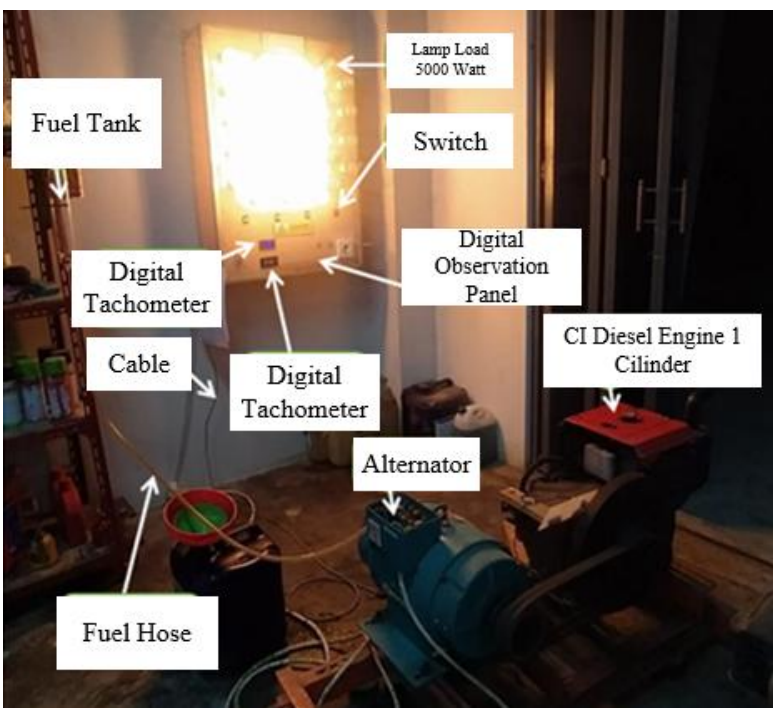

Figure 3. Schematic representation of engine testing setup

The fuel property analysis revealed notable differences in density, viscosity, and calorific value between the two catalyst formulations. These differences played a significant role in determining combustion efficiency and engine compatibility. In parallel, performance testing using a single-cylinder diesel engine highlighted the response of torque, power output, and fuel consumption to the biodiesel blends. Electrical output (current and voltage) and load variation provided further insight into how catalyst composition affects the engine's thermodynamic performance. Overall, the results demonstrate a clear correlation between fuel processing conditions and the operational efficiency of biodiesel-fueled engines.

3.1. Properties of Biodiesel Fuel

The evaluation of B50 biodiesel characteristics aimed to ensure compliance with Indonesian government standards, focusing on both engine performance and fuel properties. High-quality fuel must deliver optimal power, torque, SFC, and thermal efficiency, while also meeting criteria for density, viscosity, and calorific value. This study analyzed B50 biodiesel produced with two catalyst variations to assess its suitability for diesel engines and its potential to support efficient combustion and engine performance.

The viscosity test results for B50 fuel with a catalyst composition of 1000 mL methanol + 25 grams NaOH yielded a value of 8.07 cSt, while the B50 with 1200 mL methanol + 30 grams NaOH showed a value of 3.95 cSt. According to the Indonesian National Standard (Kementerian ESDM, 2019), which specifies an acceptable viscosity range of 2.3–6.0 cSt, the first variation exceeds the upper limit and therefore does not meet the standard set by the Government of Indonesia, whereas the second variation complies with the established criteria.

In terms of density, the B50 fuel blend synthesized with 1000 mL methanol and 25 grams of NaOH recorded a density of 886 kg/m³, while the blend using 1200 mL methanol and 30 grams of NaOH showed a slightly lower density of 876 kg/m³. Both values fall within the acceptable range of 850–890 kg/m³ as specified by the Indonesian National Standard, confirming compliance with national fuel quality criteria. The observed decrease in density with the higher catalyst concentration can be attributed to the enhanced transesterification reaction facilitated by the increased amount of NaOH. A higher concentration of NaOH improves the conversion of triglycerides into methyl esters, thereby reducing the presence of unreacted or heavier components that typically increase fuel density. This correlation suggests that catalyst concentration plays a significant role in determining the physical characteristics of the resulting biodiesel.

Beyond viscosity and density, this study also evaluated the calorific value of the biodiesel, as it directly influences the fuel's lower heating value (LHV) and, subsequently, the fuel consumption rate per unit time. The calorific value was measured using the ASTM D5865 method, and the results are presented in the Figure 4.

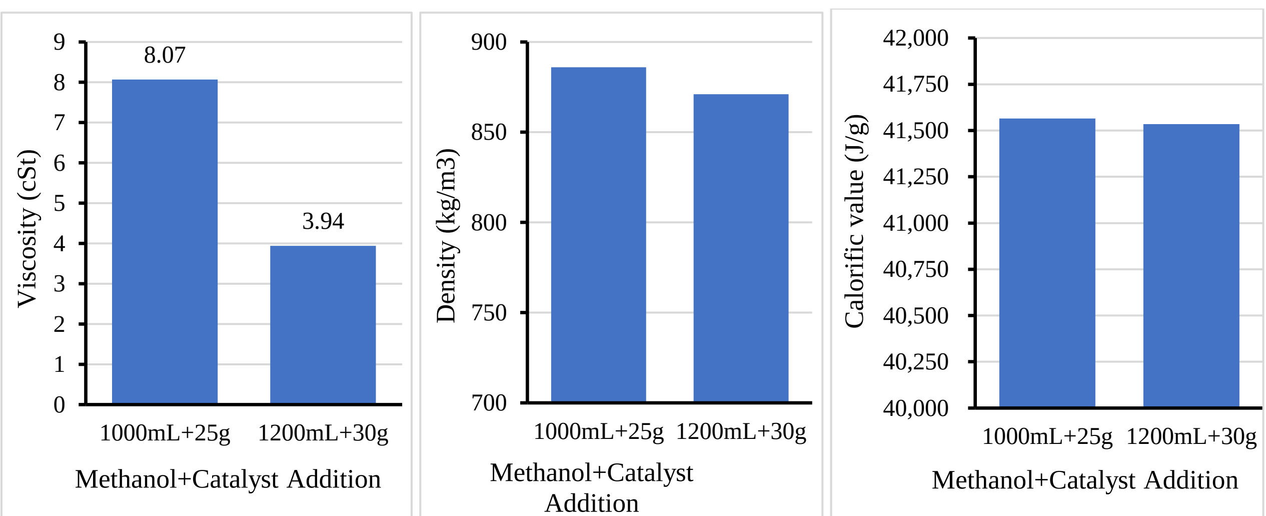

Figure 4. Graph of biodiesel property values, a) Density, b) Viscosity, c) Calorific value

3.2. Engine Performance

The engine performance obtained in this study is the value of torque, specific fuel consumption (SFC), and thermal efficiency.

3.2.1.Torque vs Load

The torque test results revealed that B50 fuel blended with 1000 mL methanol and 25 grams of NaOH consistently delivered higher torque across all engine speeds and load variations. At 1000 RPM, the highest torque recorded was 8.92 Nm under a 4000-watt load, while the lowest was 2.99 Nm using B50 with 1200 mL methanol and 30 grams NaOH at 1000 watts. Similar trends were observed at 1200 RPM and 1400 RPM, where the lower catalyst concentration in B50 fuel resulted in peak torque values of 8.50 Nm and 8.40 Nm, respectively, at higher loads.

These findings suggest that engine torque tends to increase with load but is also significantly affected by catalyst concentration in the biodiesel blend. There is a slight difference in the torque values produced by the two fuel samples. At higher engine speeds (RPM), it was observed that the B50 sample with 1200 mL of methanol and 25 grams of NaOH produced higher torque compared to the sample with a higher catalyst concentration. This suggests that exceeding the optimal catalyst threshold—specifically more than 1200 mL of methanol and 25 grams of NaOH—may lead to diminished engine performance. Therefore, the maximum effective catalyst concentration should be limited to these values to maintain optimal torque output.

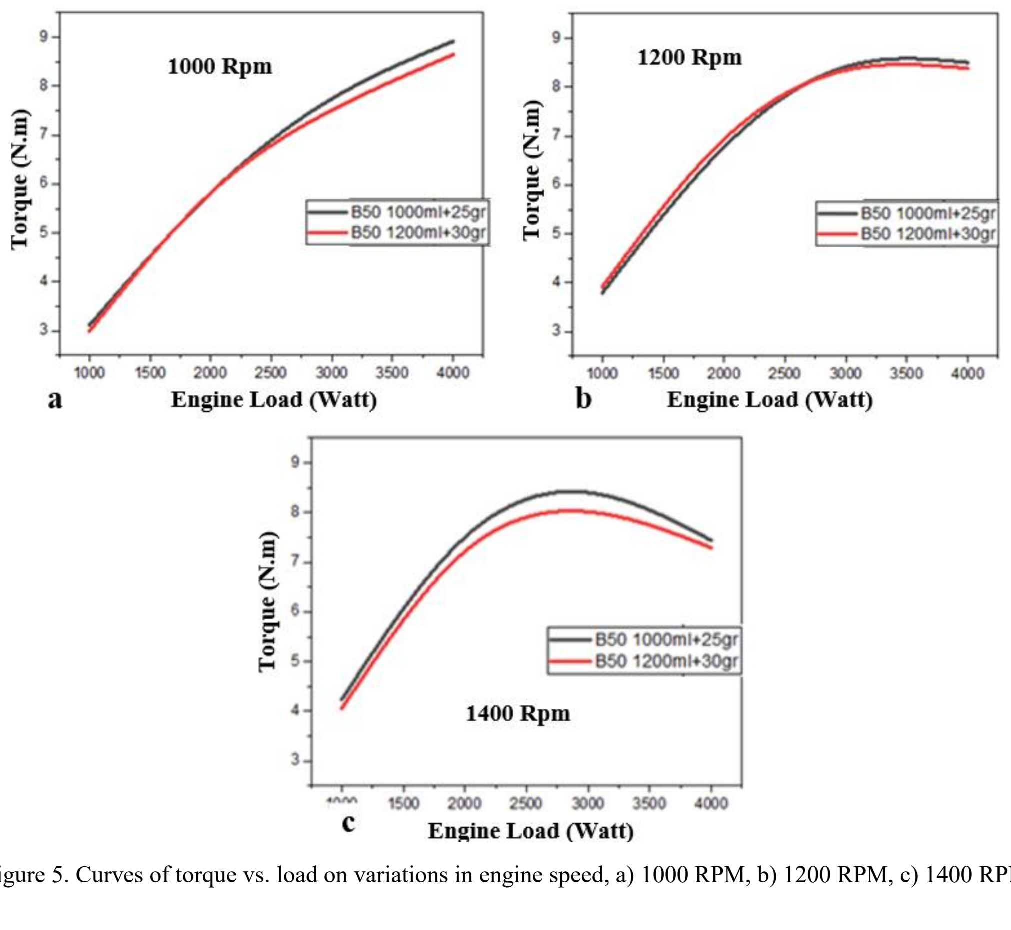

Figure 5. Curves of torque vs. load on variations in engine speed, a) 1000 RPM, b) 1200 RPM, c) 1400 RPM

3.2.2. Specific Fuel Consumption (SFC) vs Load

The comparison of Specific Fuel Consumption (SFC) for B50 biodiesel with two catalyst variations—1000 mL methanol + 25 g NaOH and 1200 mL methanol + 30 g NaOH—at engine speeds of 1000, 1200, and 1400 RPM is shown in Figures 6.a, 6.b, and 6.c. At 1000 RPM (Fig. 6.a), the blend with 1000 mL methanol and 25 g NaOH demonstrated lower SFC values, indicating better fuel economy. In contrast, at 1200 RPM (Fig. 6.b) and 1400 RPM (Fig. 6.c), the lowest SFC was observed in the 1200 mL + 30 g NaOH catalyst variant at higher loads (3000 W), while the highest SFC occurred in the 1000 mL + 25 g variant at lower loads (1000 W).

These results indicate that catalyst ratio, engine speed, and load play a critical role in determining the fuel efficiency of biodiesel These results indicate that the catalyst ratio, engine speed, and load significantly influence the fuel efficiency of biodiesel blends. The catalyst ratio affects the quality of the transesterification process, which directly impacts the physical properties of the biodiesel, such as viscosity and calorific value—both of which are crucial for combustion performance. A proper balance in catalyst concentration ensures complete reaction and minimizes the formation of by-products that can reduce engine efficiency. Engine speed, on the other hand, determines the combustion duration and mixing of air-fuel, where higher speeds may reduce combustion completeness, affecting efficiency. Likewise, engine load alters the engine's operating condition, influencing fuel consumption rate and thermal conversion. The interaction of these parameters collectively shapes how effectively the biodiesel blend performs in real engine conditions.

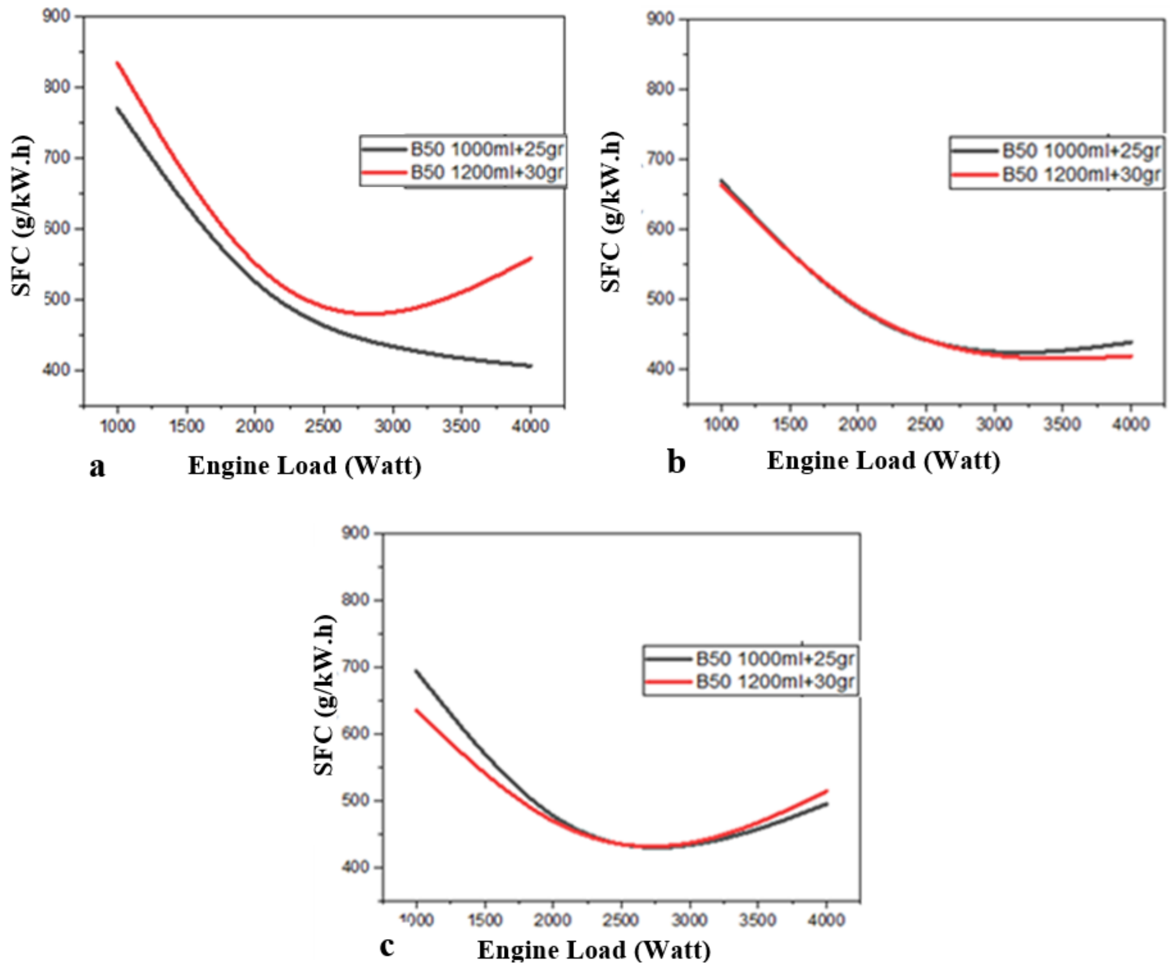

Figure. 6. Curves of SFC vs. load on variations in engine speed, a) 1000 RPM, b) 1200 RPM, c) 1400 RPM

3.2.3. Thermal Efficiency vs Load

Figure 7.a, 7.b, and 7.c illustrate the comparison of thermal efficiency for B50 biodiesel with two catalyst variations—1000 mL methanol + 25 g NaOH and 1200 mL methanol + 30 g NaOH—at engine speeds of 1000, 1200, and 1400 RPM. At 1000 RPM (Fig. 8.a), the blend using 1200 mL methanol and 30 g NaOH exhibited better thermal efficiency

compared to the 1000 mL + 25 g variant. At 1200 RPM (Fig. 8.b), the lowest efficiency was recorded for the 1000 mL + 25 g blend at 13.331%, while the highest was 21.808% for the 1200 mL + 30 g blend at 3000 W load. Similarly, at 1400 RPM (Fig. 8.c), thermal efficiency ranged from 12.854% (B50 with 1000 mL + 25 g at 1000 W) to 21.418% (B50 with 1200 mL + 30 g at 3000 W). These variations are influenced by output power, fuel flow rate, and the calorific value of the fuel. A lower heating value leads to higher fuel consumption, while higher viscosity reduces fuel injection efficiency, thereby affecting thermal performance.

The significant difference between the red and black lines at the ends of the graph indicates that the B50 mixture with 1000 ml methanol and 25 g NaOH has a higher thermal efficiency than the mixture with 1200 ml methanol and 30 g NaOH, especially at high loads. This is due to the better fuel quality of the mixture with lower methanol and catalyst content. Excess methanol and NaOH can produce residual compounds such as soap, increase viscosity, and reduce the effective calorific value of the fuel, which ultimately disrupts the atomization and combustion processes. As a result, combustion efficiency decreases significantly at high loads.

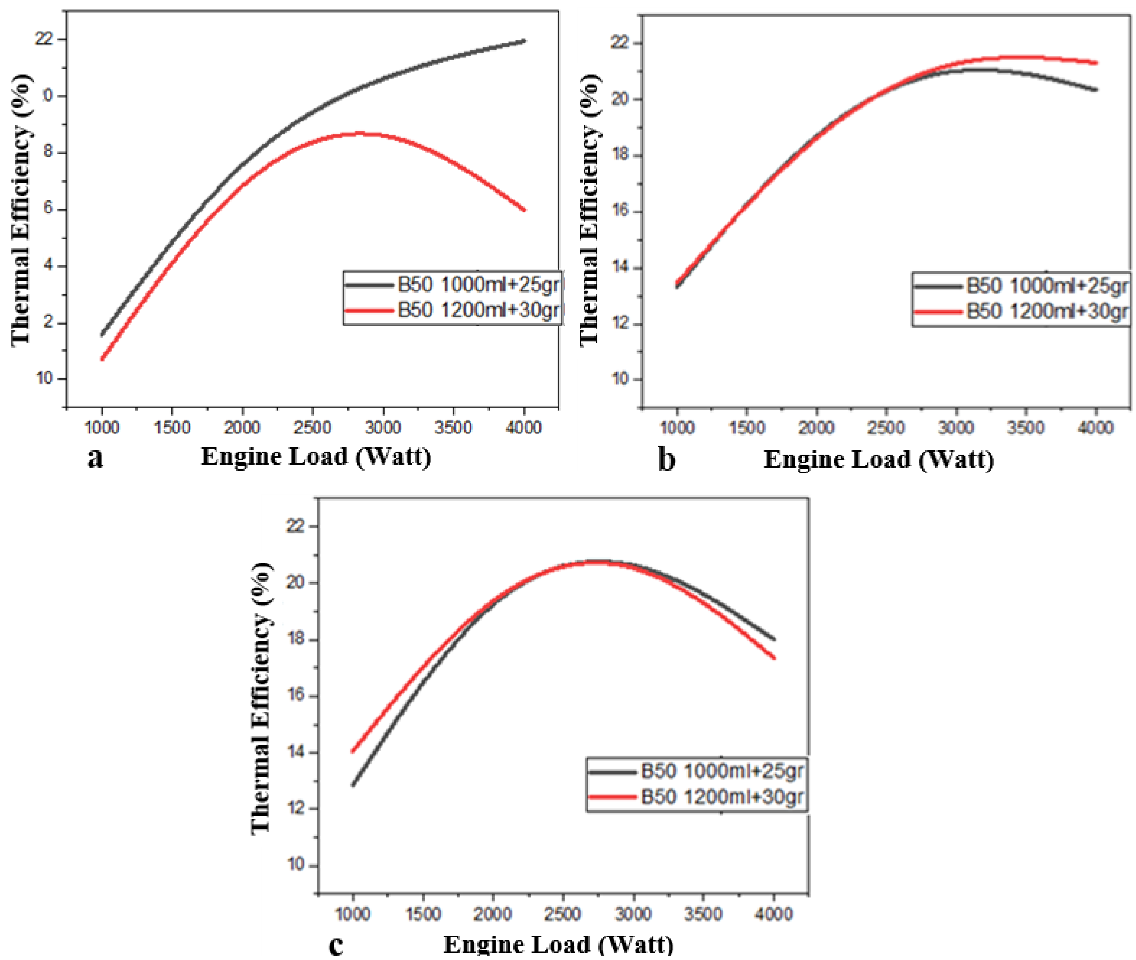

Figure. 7. Curves of thermal efficiency vs. load on variations in engine speed, a) 1000 RPM, b) 1200 RPM, c) 1400 RPM

3.2.4. Exhaust Gas Opacity Analysis

In this experimental study, opacity measurements were also conducted to evaluate the visual particulate emissions resulting from combustion using two B50 biodiesel fuel variants: one with 1000 mL methanol + 25 g NaOH and the other with 1200 mL methanol + 30 g NaOH. The testing employed the NHT6 Opacimeter, which is used to assess the visible contaminants present in the exhaust emissions of diesel engines.

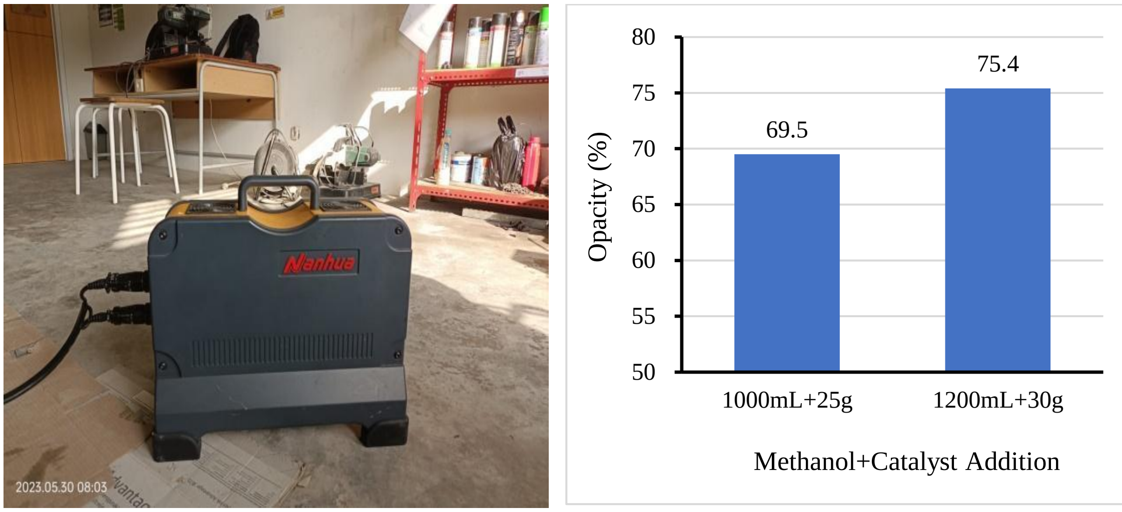

Figure. 9. Opacity measuring tool and graph of test results

The results of the opacity tests are presented in graphical form. A lower opacity level is theoretically attributed to the fact that fatty acids in biodiesel are more readily oxidized, allowing for more complete combustion. During the biodiesel production process, as the amount of catalyst increases, the fatty acid content in the biodiesel tends to decrease due to the more efficient separation of glycerol. This improved separation contributes to cleaner combustion characteristics, thereby reducing visible particulate emissions.

4. CONCLUSION

This study investigated the effect of methanol and NaOH catalyst variations on the properties and performance of B50 biodiesel made from waste cooking oil. The fuel produced using 1200 mL methanol + 30 g NaOH met the Indonesian fuel standards for density (876 kg/m³) and viscosity (3.95 cSt), while the 1000 mL + 25 g NaOH blend exceeded the viscosity limit. A slight decrease in calorific value was observed with increased catalyst dosage. Engine testing showed that the 1000 mL + 25 g NaOH blend delivered the best performance, achieving a maximum torque of 8.92 Nm, lowest SFC of 406.904 g/kWh, and highest thermal efficiency of 21.28% at 1000 RPM and 4000 W load. In contrast, the 1200 mL + 30 g NaOH blend exhibited better emission characteristics with lower opacity, indicating cleaner combustion. Overall, catalyst concentration significantly influenced both fuel quality and engine performance. Optimizing the catalyst ratio is essential to balance power output, fuel efficiency, and emissions in biodiesel-fueled diesel engines.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Sua	✓	✓	✓		✓		✓	✓	✓	✓	✓			
Har		✓												
FM										✓				
MRA				✓										
MUP	✓								✓					
Ala		✓								✓				
WS	✓	✓	✓											

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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