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Performance and Emission Characteristics of Diesel Engines Using Biodiesel from Waste Cooking Oil with Cetane Number Improver

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Abstract- **The depletion of fossil fuel reserves has led to a global energy crisis, with increasing demand for alternative energy sources. Diesel fuel shortages, especially in countries like Indonesia, have driven the exploration of biodiesel as a sustainable alternative. This study aims to convert waste cooking oil (WCO) into biodiesel, with the addition of a cetane number improver (CNI) to enhance its performance in diesel engines. The biodiesel was produced through methanolysis, and 2-Ethylhexyl Nitrate (EHN) was added to improve combustion and reduce engine knocking. The results show that the produced biodiesel had a density of 856 Kg/m³ for B0, 872.7 Kg/m³ for B0 with CNI, and 872.1 Kg/m³ for B50CN. Viscosity values were 2.32 cSt for B0, 5.645 cSt for B50, and 4.722 cSt for B50CN. The cetane index was 49.2 for B50 and B50CN, while B0 had a value of 48. The emissions measured included CO levels of 194 mg/Nm³ for B0, 254 mg/Nm³ for B50, and 280 mg/Nm³ for B50CN. NOx emissions were 852 mg/Nm³ for B0, 755 mg/Nm³ for B50, and 825 mg/Nm³ for B50CN. Oxygen content was 15.9% for B0, 14.9% for B50, and 16.2% for B50CN. The findings indicate that adding EHN to WCO biodiesel improves fuel properties but increases emissions of CO and NOx. Overall, WCO-based biodiesel with EHN is a viable alternative fuel that balances performance improvements with environmental considerations.**

Keywords- Biodiesel, Waste Cooking Oil, Cetane Number Improver, Diesel Engine Performance, Emission

I. INTRODUCTION

The global energy crisis, exacerbated by the depletion of fossil fuel reserves and growing energy demand, has intensified the search for alternative and renewable energy sources [1], [2]. Diesel fuel, essential for both industrial and transportation sectors, faces critical shortages, particularly in countries like Indonesia [3], [4], where a heavy reliance on imports exacerbates economic vulnerabilities [5]. This situation has intensified the pursuit of biofuels, particularly biodiesel, as a viable solution to reduce dependence on petroleum-based fuels while addressing environmental issues [6], [7]. Among biodiesel feedstocks, waste cooking oil (WCO) stands out due to its wide availability, cost-effectiveness, and its potential to mitigate waste disposal challenges [8], [9].

Biodiesel produced from WCO offers a promising option as an alternative to conventional diesel fuel, as it not only reduces dependence on fossil fuels but also addresses the problem of waste oil disposal [10]. However, ensuring that biodiesel meets the combustion efficiency and emission standards required by modern diesel engines remains a challenge [11]. To overcome these challenges, Cetane Number Improvers (CNIs) [12], such as 2-Ethylhexyl Nitrate (EHN), are added to enhance combustion properties and reduce the risk of engine knock.[13], [14]. While biodiesel shows potential in reducing pollutants like carbon monoxide (CO) and particulate matter, it also risks increasing nitrogen oxide (NOx) emission [15], making it essential to carefully balance its formulation.

This study addresses the challenge of optimizing WCO-based biodiesel through the use of CNIs, specifically EHN, to improve diesel engine performance, fuel properties characteristics, and emissions. Previous studies have extensively examined the basic properties of biodiesel [16], [17], Although previous research has examined biodiesel production and its properties, little attention has been given to the effects of adding CNIs to WCO-based biodiesel. Additionally [18], the trade-off between reducing CO and particulate emissions while managing NOx emissions remains an area of concern that requires further investigation.

The aim of this research is to convert WCO into biodiesel through methanolysis and investigate the effects of adding EHN as a cetane number improver on the performance and emissions of diesel engines. By examining the influence of EHN on WCO-based biodiesel, this study seeks to determine whether the enhanced biodiesel can serve as a more sustainable and efficient fuel for diesel engines, with a focus on reducing harmful emissions such as CO and NOx.The novelty of this study lies in its focus on the combined use of WCO-based biodiesel with EHN, offering new insights into optimizing biodiesel for modern diesel engines. This research not only aims to improve

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engine performance but also contributes to the broader discourse on renewable energy by addressing environmental concerns related to waste oils and plastics. Through this work, the study fills an important gap in the literature, demonstrating how waste-derived biodiesel can be optimized with advanced additives to achieve both enhanced engine performance and environmental sustainability.

II. METHOD

This study employs a laboratory experimental design to evaluate the effects of adding Cetane Number Improver (CNI) on the performance of biodiesel produced from used cooking oil, focusing on diesel engine performance and emission characteristics. The addition of a cetane number improver can enhance combustion quality and improve engine performance [19], [20].The research encompasses several stages, including the production of biodiesel through methanolysis, the addition of CNI, testing diesel engine performance using the produced fuel, and analyzing exhaust emissions [21]. The experimental design is structured to compare the performance of pure biodiesel, biodiesel blended with CNI, and conventional diesel fuel as a control.

The engine characteristics used as fuel testing objects can be seen in Table 1.

TABLE 1.
DETAILED TECHNICAL SPECIFICATIONS OF THE ENGINE

Engine Model	TF 85 Series
Engine Type	TF 85MH Yanmar
Cylinders Count	1 Cylinder 4 Stroke
Engine Capacity	493 cc
Continuous Power Rating	7.5 Kw/2200 rpm
Compression Ratio	1:18
Fuel Efficiency per Unit	171 gr/HP h

Source: Yanmar 2022 [22]

The engine test experimental flow can be seen in Figure 1

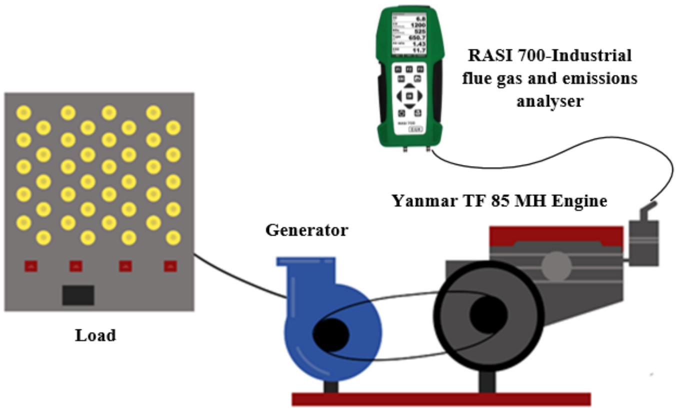

Figure 1. Configuration of the Experimental Engine Setup [23]

This study does not involve human participants but focuses on samples of biodiesel fuel derived from used cooking oil. The used cooking oil samples were collected from various local food industry sources in Indonesia. Conventional diesel fuel was used as a control, while the produced biodiesel was tested in a four-stroke internal combustion diesel engine to evaluate its performance and emissions characteristics. The primary materials used in this research include used cooking oil as the biodiesel feedstock, methanol as the transesterification agent, and Cetane Number Improver (2-Ethylhexyl Nitrate or EHN). Transesterification is a widely used method for producing biodiesel, as it simplifies the process and effectively removes glycerol from vegetable oil [24], [25]. Key instruments include a transesterification reactor for biodiesel production, a four-stroke diesel engine for fuel performance testing, and exhaust gas analyzers for measuring CO, NOx, and O_2 emissions. Additionally, a viscometer, densitometer, and fuel quality testing equipment were utilized to assess the physicochemical properties of the produced biodiesel.

Figure 2. a) Raw Material: Used Cooking Oil. b) Cetane Number Improvement (2-Ethylhexyl Nitrate).

The research procedure begins with the conversion of used cooking oil into biodiesel through a methanolysis process. In this process, used cooking oil is mixed with methanol and a base catalyst (NaOH) in the reactor at specified temperature and time conditions. After the process is completed, biodiesel is separated from glycerol and purified. The resulting biodiesel is then divided into several variations, including blends with and without the addition of EHN. Once the biodiesel and its blends are ready, the diesel engine performance tests are conducted using each fuel sample. The diesel engine operates under the same conditions for each type of fuel, and performance data such as engine power, fuel efficiency, and exhaust gas emission characteristics (CO, NOx, O2) are recorded.

The collected data are analyzed using both descriptive and inferential statistical methods. Statistical analysis is performed to assess significant differences between the performance and emissions of the engine running on biodiesel with and without EHN compared to conventional diesel. Viscosity, density, cetane index, and emission data are analyzed to identify relevant patterns. Statistical test results are used to determine whether the addition of EHN leads to a significant improvement in biodiesel performance and combustion efficiency, as well as its impact on the reduction of harmful emissions.

III. Results and Discussion

As previously described, this study involves two primary phases: first, the production of biodiesel from used cooking oil, and then the blending of this biodiesel with diesel oil to create a B50 mixture. Two samples of B50 were prepared, with one sample having Cetane Number Improver added. The next phase involves testing the biodiesel in a diesel engine. Additionally, a comprehensive evaluation was conducted to assess the characteristics of the biodiesel, including measurements of viscosity, density, and calorific value.

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

The density test is crucial for determining the quality of fuel, particularly in assessing fuel viscosity. The performance of the fuel injection system, which impacts diesel engine performance, is influenced by one of the fuel properties, namely viscosity. The cetane index is an indicator of a diesel fuel's is capability to ignite rapidly after being injected into the combustion chamber. This test is important to ensure that diesel fuel has ignition properties that meet established standards, thereby improving combustion efficiency, reducing emissions, and preventing engine damage.

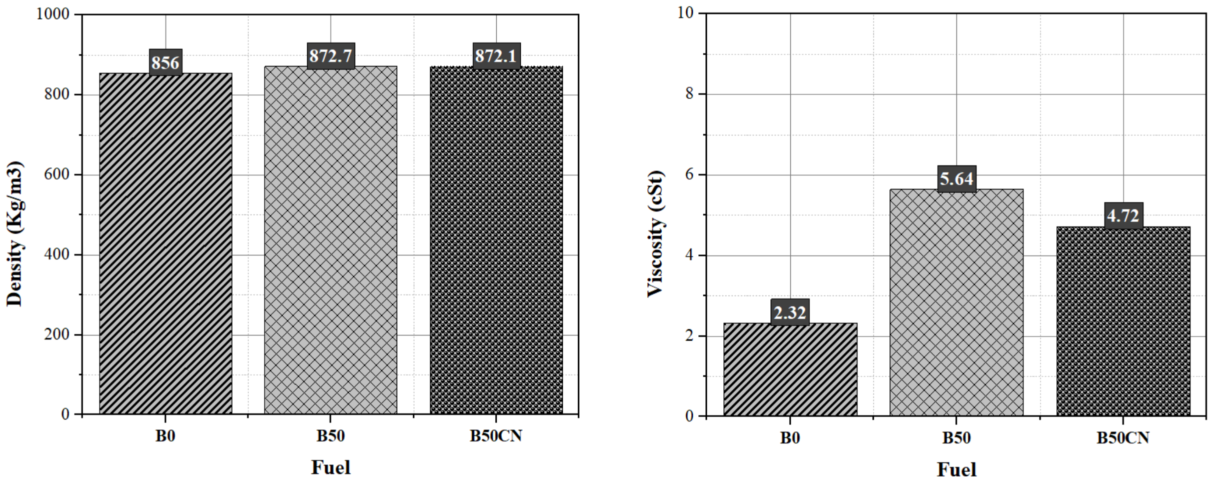

Figure 3. Viscosity and Density Graphs for Three Fuel Sample Variations

From the viscosity and density graphs shown in Figure 3, it can be observed that the lowest density value is found in the B0 variant, with a density of 856 kg/m³, while the highest density is in the B0 variant with a value of 872.7 kg/m³, and the B50CN variant has a density of 872.1 kg/m³. All fuel density values meet the standard biodiesel density range of 850–890 kg/m³. The graph also shows that the lowest viscosity value is in the B0 fuel, with a viscosity of 2.32 cSt. The highest viscosity is in the B50 fuel, with a value of 5.645 cSt, while the B50CN fuel has a viscosity of 4.722 cSt. Viscosity is measured based on the fluid's thickness, indicating the degree of friction within the fluid. If the viscosity value is below the standard, some injection pumps may experience wear. Conversely, if it exceeds the standard, filters may be damaged, and the fuel spray pattern in the combustion chamber may be affected.

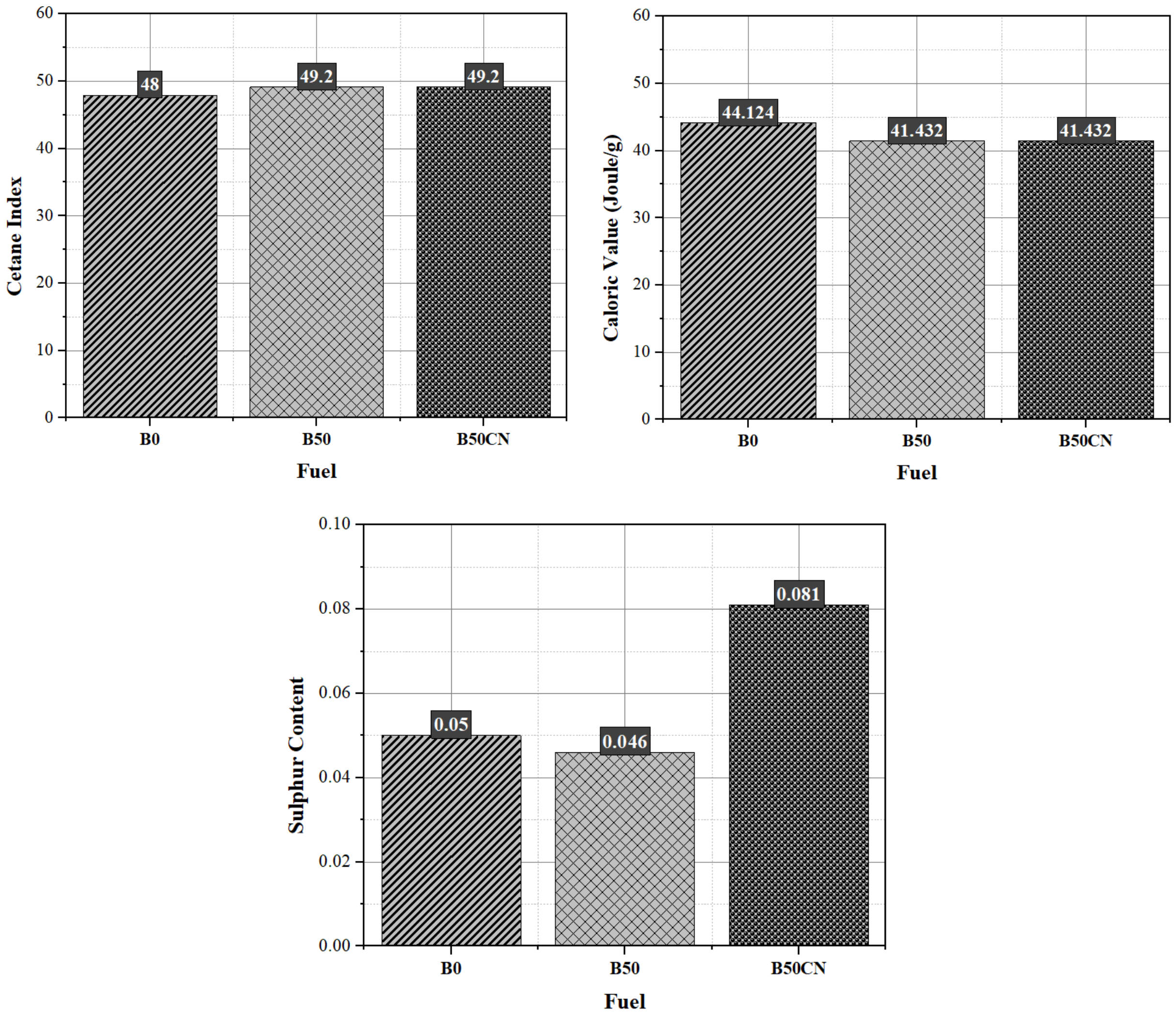

Figure 4. Cetane Index, Caloric Value and Sulphur Content Graphs for Three Fuel Sample Variations

From the graph, it can be observed that the lowest cetane index values are found in the B50 and B50CN fuels, with values of 49.2 and 48 respectively, while the B0 fuel has a cetane index of 48. A higher cetane index indicates that the fuel ignites more easily, which can lead to smoother and more efficient combustion. The calorific values from the graph show that the lowest value is in the B0 variant with 44.124 Joule/g, while the highest calorific value is in the B50CN variant with 41.432 Joule/g. The B50 variant has a calorific value of 41.543 Joule/g. Regarding sulfur content, the lowest sulfur level is in the B50 variant at 0.046% wt, and the highest sulfur content is in the B50CN variant with a sulfur level of 0.081% wt. All tested fuels meet the standards set by MARPOL in the SOx Regulation 14 of Marine Pollution Annex VI - Regulations for the Prevention of Air Pollution from Ships, which applies to both ECA (Emission Control Areas) with a standard of 0.10% wt and non-ECA areas with a standard of 0.50% wt [26].

B. Diesel engine performance testing process

The tests were conducted on a four-stroke diesel engine, model TF 85-MLYS, focusing on torque, Specific Fuel Consumption (SFC), thermal efficiency, and Brake Mean Effective Pressure (BMEP). The data was presented in graphical form and subsequently analyzed. The analysis covers the relationship between torque and load, SFC and load, as well as thermal efficiency and load, with the engine's performance evaluated at different speeds: 1000 RPM, 1200 RPM, and 1400 RPM.

1. Torque vs load

The relationship between torque and load was thoroughly examined to understand the engine's performance under different loading conditions. This investigation involved altering the loads (1000 watts, 2000 watts, 3000 watts, and 4000 watts) at engine speeds of 1000 RPM, 1200 RPM, and 1400 RPM. The results revealed significant patterns in torque in response to the varying loads.

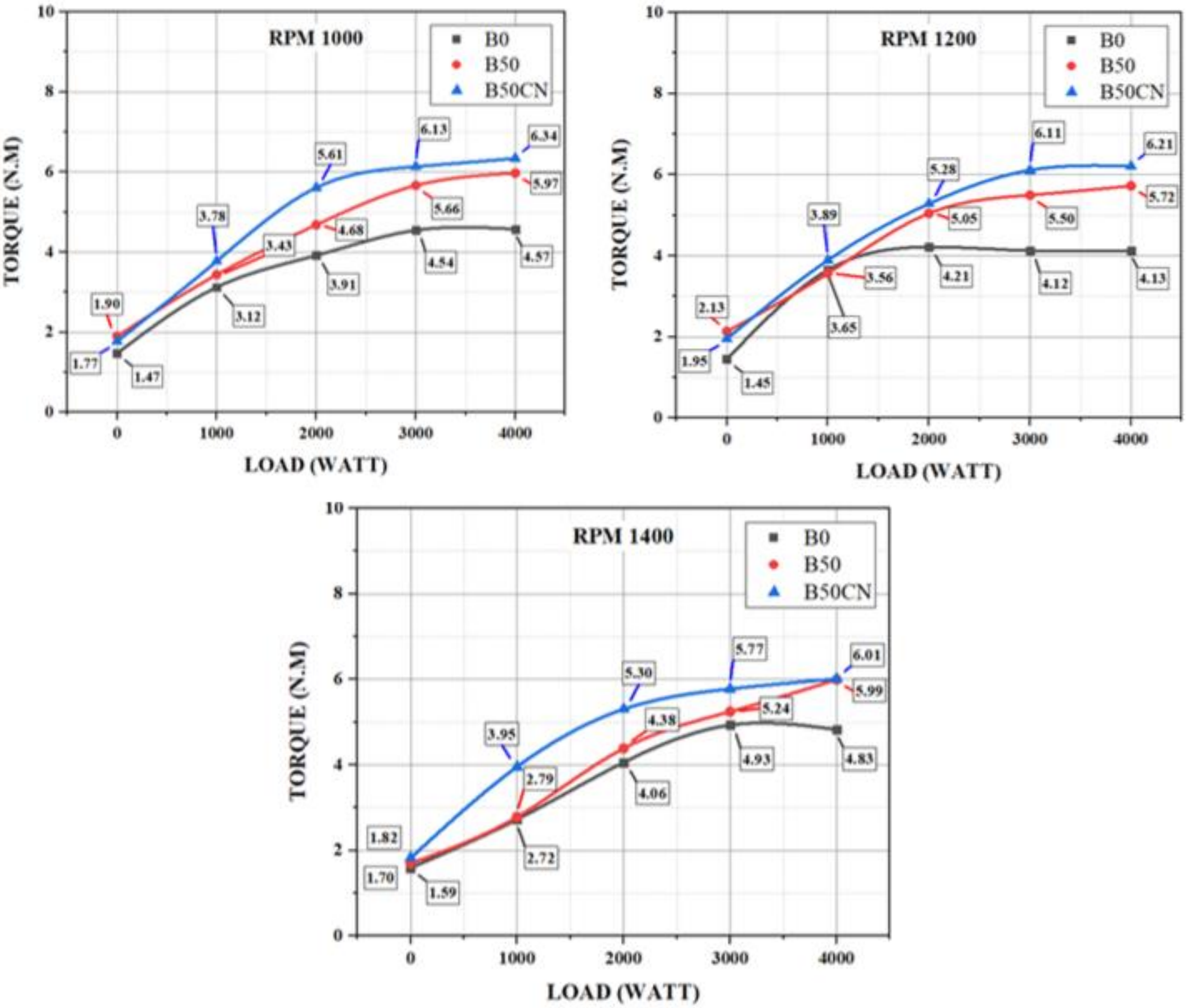

Figure 5. Torque vs. Load Comparison Chart at 1000 RPM, 1200 RPM, and 1400 RPM

In Figure 5, the graph shows a comparison of torque between fuels B0, B50, and B50CN at a 1000 RPM variation. The data reveals that torque is influenced by the power generated by the diesel engine, which is determined by the combination of voltage (volts) and current (amperes), as well as variations in engine speed at 1000 RPM and lamp load. As the power output (watts) and engine speed increase, along with the lamp load, the resulting torque decreases. For 1200 RPM, the lowest torque was observed with fuel B0 during the no-load test, with a value of 1.44975 N.m. Conversely, the highest torque was recorded with fuel B50CN under a 4000 Watt load, reaching 6.20793 N.m. This variation in torque is influenced by the voltage and current generated by the diesel engine when using different fuel variables.

At the highest RPM of 1400, the lowest torque was again observed with fuel B0 during the no-load test, with a value of 1.47 N.m. The highest torque was recorded with fuel B50CN under a 4000 Watt load, reaching 6.01 N.m. Similar to the previous RPM levels, the variation in torque is influenced by the voltage and current generated by the diesel engine for each tested fuel.

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 1000 RPM, 1200 RPM, and 1400 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.

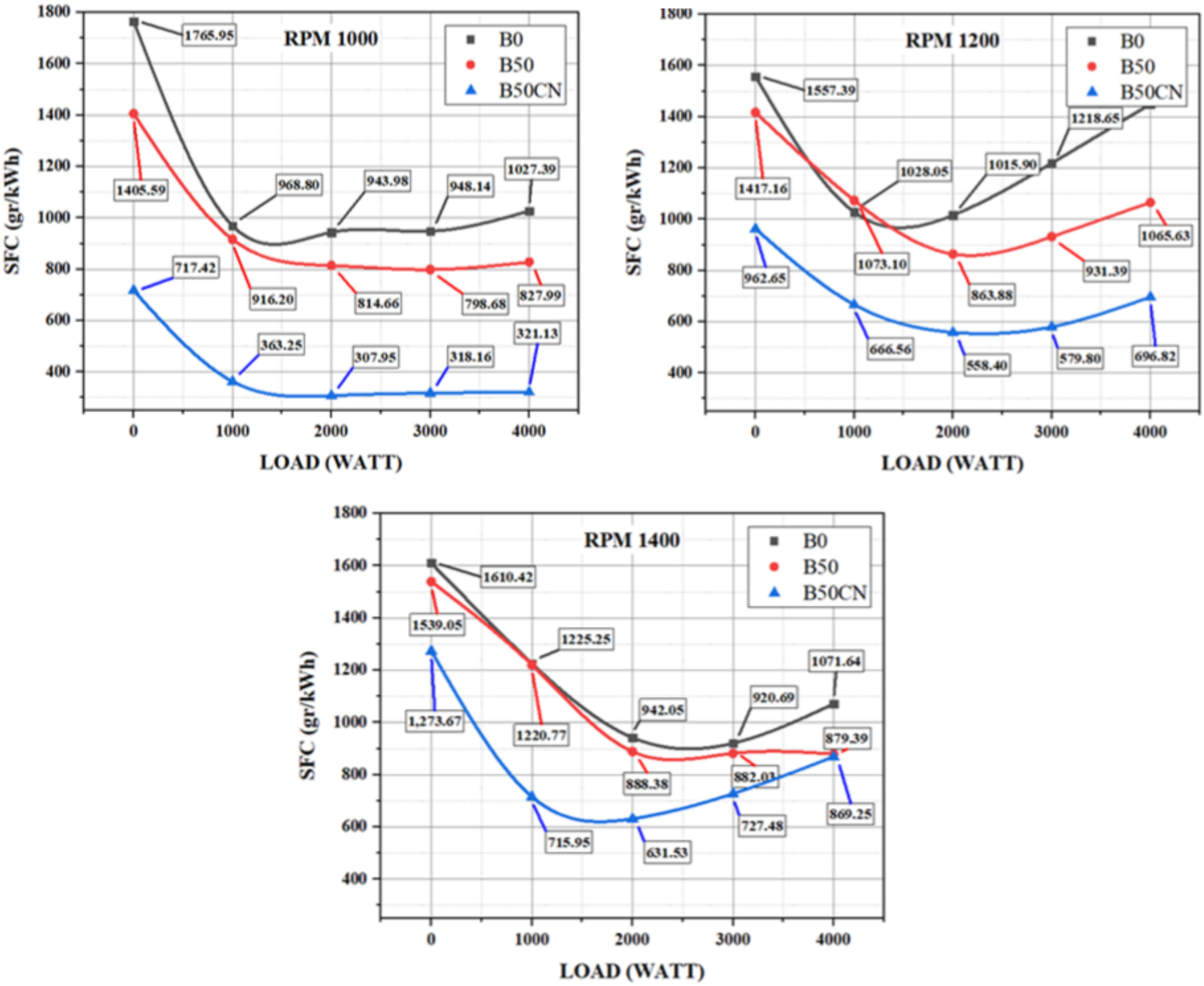

Figure 6. SFC vs. Load Comparison Chart at 1000 RPM, 1200 RPM, and 1400 RPM

The graph in Figure 6 presents a comparison of Specific Fuel Consumption (SFC) against load at a 1000 RPM engine speed variation. The highest SFC value was found with fuel B0 during the no-load test, reaching 1765.953 g/KWh, while the lowest SFC value, 307.94 g/KWh, was observed with fuel B50CN under a 2000 Watt load. The experiment results show that fuel B50CN consistently delivered the best performance across all tests and loads compared to fuels B0 and B50. Fuel consumption is heavily influenced by the SFC value; the lower the SFC, the more efficient the engine becomes, as it generates more power with less fuel.

At an engine speed of 1200 RPM, the highest SFC was recorded with fuel B0 during the no-load test, reaching 1557.386 g/KWh, while the lowest SFC, 558.40 g/KWh, was observed with fuel B50CN under a 2000 Watt load. The results showed that fuel B50CN consistently outperformed fuels B0 and B50 under all conditions. A lower SFC indicates higher engine efficiency, as the engine produces more power using less fuel. For the 1400 RPM variation, the graph shows that the highest SFC was observed with fuel B0 during the no-load test, reaching 1610.423 g/KWh, while the lowest SFC, 631.533 g/KWh, was found with fuel B50CN under a 2000 Watt load.

3. Thermal efficiency vs load

The examination of thermal efficiency in relation to load offers essential insights into engine performance and energy use. Thermal efficiency measurements were conducted at different loads with engine speeds of 1000 RPM, 1200 RPM, and 1400 RPM. The data reveal varying trends, with thermal efficiency changing according to the load (up to a maximum of 4000 watts). This analysis provides key information for improving engine performance and boosting energy efficiency, supporting the research goal of assessing the impact of B50 fuel with a cetane number improver in diesel engines across various operating conditions.

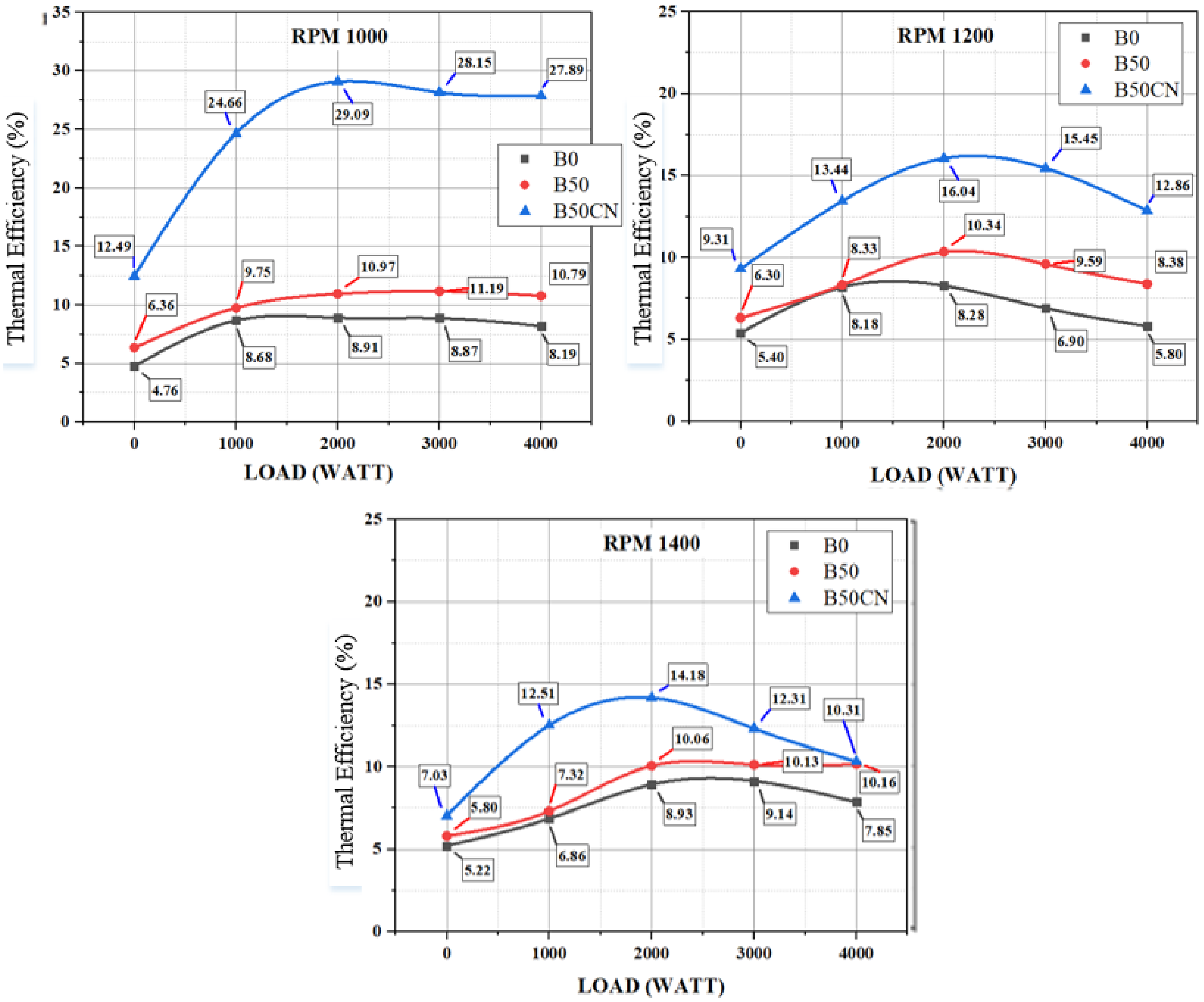

Figure 7. Thermal Efficiency vs. Load Comparison Chart at 1000 RPM, 1200 RPM, and 1400 RPM

Figure 7 presents the thermal efficiency values for each fuel variation. The highest efficiency was observed with the B50CN fuel at a load of 2000 watts, achieving an efficiency of 29.08%. Conversely, the lowest thermal efficiency was recorded with B0 fuel during the no-load test, with an efficiency of 4.76%. For B30 fuel, the best result was attained at a load of 3000 watts, with an efficiency of 11.18%. These outcomes are influenced by several factors, including the power generated, fuel rate, and calorific value of the fuel. Therefore, higher power, calorific value, and fuel rate (mf) lead to higher thermal efficiency. Conversely, lower power, calorific value, fuel rate, and load result in lower thermal efficiency, increasing combustion. These results indicate that the addition of a CN improver to the fuel has a significant impact on the rate of increase in thermal efficiency in the engines.

4. Emission

Emissions are a key criterion in determining whether a fuel is suitable for use [27]. After conducting fuel property tests and engine performance evaluations, emissions serve as the final assessment to confirm the fuel's viability. Moreover, there are still numerous complaints from users regarding the use of biodiesel.

The fuel quality standards, both for oil and gas, have been regulated by the Ministry of Environment Regulation No. 11 of 2021, stipulating that the levels of carbon monoxide (CO) and nitrogen oxides (NOx) must not exceed the established limits. The emission standards for engine exhaust gases can be found in Table 2.

TABLE 2.
EMISSION STANDARDS FOR INTERNAL COMBUSTION ENGINES OR GENERATORS [28]

No	Fuel	Parameter	Maximum Level
1	Fuel Oil	Carbon Monoxide (CO)	3400
		Nitrogen Oxide (Nox)	170
2	Gas	Carbon Monoxide (CO)	300
		Nitrogen Oxide (Nox)	450

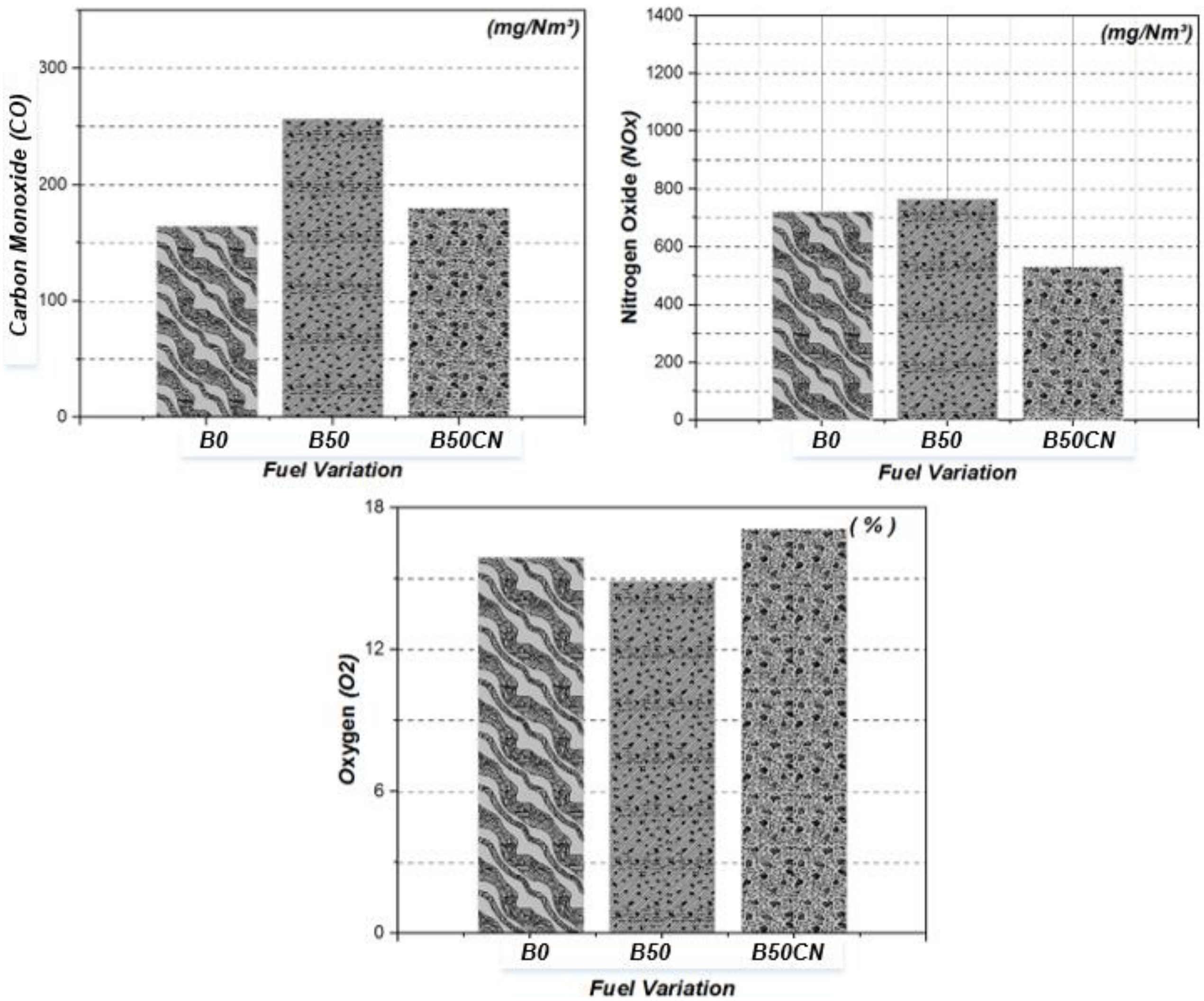

Figure 8. Graph of Emission Test Results for Fuel: Carbon Monoxide (CO), Nitrogen Oxide (Nox), And Oxygen (O2)

From the graph in Figure 8, the levels of CO, NOx, and oxygen content from the three fuel sample variations can be observed. For carbon monoxide (CO), the highest value was recorded in the B50CN sample at 280 mg/Nm³, while the B50 and B0 samples had values of 254 mg/Nm³ and 194 mg/Nm³, respectively. This indicates that none of the three samples meet the established standard of 170 mg/Nm³, as all CO values exceeded the standard limit of 170 mg/Nm³. Regarding nitrogen oxides (NOx), the highest value was recorded in the B0 sample at 852 mg/Nm³, with B50 and B50CN showing values of 755 mg/Nm³ and 825 mg/Nm³, respectively. For NOx, all three samples remain within the standard limit of 3400 mg/Nm³. In terms of oxygen content, B50 showed the highest percentage at 17.04%, compared to the other samples. These experimental results suggest that the addition of a cetane number improver has a measurable impact by increasing CO levels, reducing NOx emissions, and lowering oxygen content

IV. Conclusion

This study demonstrated that the biodiesel samples B0, B50, and B50CN met the required standards for viscosity, density, calorific value, and sulfur content. B50CN, enhanced with a Cetane Number Improver, showed the highest torque and lowest specific fuel consumption (SFC), with both B50CN and B50 exhibiting superior thermal efficiency compared to B0. However, all samples exceeded the safe CO emission limit of 170 mg/Nm³, although NOx emissions remained within the acceptable range of 3400 mg/Nm³. B50 also had the highest oxygen content at 17.04%. These findings suggest that while the addition of a cetane number improver enhances engine performance and reduces NOx emissions, it also contributes to higher CO levels. The study aligns with the objective of improving biodiesel's performance and emissions through additives and suggests practical implications for using up to 50% biodiesel with a cetane number improver in diesel engines to enhance efficiency and reduce waste. The research was limited by the focus on a narrow set of biodiesel blends and engine conditions, highlighting the need for future studies to optimize CO emissions and explore broader applications across different engine types. In conclusion, while improvements are needed to meet emission standards, this study confirms the potential of biodiesel from waste cooking oil, enhanced with cetane number improvers, as a more sustainable and efficient alternative for diesel engines.

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