Automotive Experiences

Vol. 6 No. 3 (2023) pp. 687-701

p-ISSN: 2615-6202 e-ISSN: 2615-6636

Research Paper

Effect of Diethyl Ether on Performance and Exhaust Gas Emissions of Heavy-Duty Diesel Engines Fueled with Biodiesel-Diesel Blend (B35)

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https://doi.org/10.31603/ae.10311

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Published by Automotive Laboratory of Universitas Muhammadiyah Magelang collaboration with Association of Indonesian Vocational Educators (AIVE)

Article Info
Submitted: 03/10/2023
Revised: 27/12/2023
Accepted: 28/12/2023
Online first: 29/12/2023

Abstract

To accelerate the energy transition, starting February 1, 2023, the Indonesian government has made it mandatory to use biodiesel (B35). Biodiesel has different characteristics from diesel oil, especially its greater viscosity and density, lower heating value, and high NOx emission. Therefore, this research has been carried out by adding the additive diethyl ether (DEE) to B35 to reduce the viscosity and density, increase the cetane number, and reduce emissions. The effects of diethyl ether on engine performances have been evaluated, including parameters of torque, power, brake thermal efficiency, brake-specific fuel consumption, exhaust emissions, and lubricants. The fuels used are B35 (35% FAME palm oil + 65% diesel oil), and B35 + DEE, with a DEE volume percentage of 3% to 6%. Diesel fuel (B0) was used as a comparison. Tests were carried out in the engine performance test laboratory using the heavy-duty diesel engine Komatsu SAA12V140E-3 at various engine speeds. The test results showed that adding diethyl ether slightly increases the average maximum power, increases brake thermal efficiency, and reduces brake-specific fuel consumption and emissions compared to B35. Very significant effects were seen in NOx and SO_2 exhaust emissions. At maximum load, the mixture with 4% diethyl ether gave the greatest brake thermal efficiency, the lowest brake-specific fuel consumption, and the greatest reduction in NOx and SO_2 emissions, respectively 7.69%, 6.30%, 53.48%, and 40.89% compared to B35, and 2.24%, (-0.90%), 48.88% and 71.17% compared to B0, respectively. Evaluation of lubricating oil during the performance test did not show a significant difference for all types of fuel used.

Keywords: Biodiesel; Diethyl ether; Diesel engine performance; Exhaust emissions; Oil sample

1. Introduction

To realize energy independence and security towards a just and equitable energy transition, the Government of Indonesia continues to be committed to implementing the use of new renewable energy, one of which is through the Mandatory Biodiesel Program, which has been implemented since 2008 [1]. Biodiesel can be used as unmixed fuel (D100) [2] or a mixture of diesel oil with palm-based oil or other plants [3]–[9]. During the last nine years, the use of biodiesel has continued to increase. From 2015, it was 15% (B15), to 20% (B20) in 2016, and in 2020, it was 30% (B30). Starting February 1, 2023, as a commitment to use renewable energy, the Government of Indonesia accelerates the level of biodiesel use to 35% (B35), according to the Ministry of Energy and Mineral Resources Regulation no. 208.K/EK.05/DJE/2022 [10]. The total allocation of B35 in 2023 will be 13.15 million kiloliters for the domestic industry. This policy is also expected to save IDR 161.25 trillion in foreign exchange and increase the added value of the downstream industry to IDR 16.76 trillion. The B35 policy is also expected to reduce greenhouse gas emissions by 34.9 million tons of CO_2 compared to the use of diesel oil and improve environmental quality.

Based on data compiled by the Directorate General of Climate Change Control, Ministry of Environment and Forestry, in 2019, total carbon emissions in Indonesia were at the level of 1,866,552 Gigagrams of carbon dioxide equivalent (CO_2e). The amount of carbon emissions is dominated by the energy sector (34.22%), worth 638,808 Gigagrams of carbon dioxide equivalent (CO_2e) [11]. With the implementation of a carbon tax in Indonesia, it is hoped that it will significantly reduce emissions [12]. Then, data obtained through the Greenhouse Gas Emissions Inventory Report [11], the coal industry sector was included in the category of imposing a carbon tax at the beginning of its implementation. To explain further the sources of carbon emissions from the energy sector, they are shown in **Table 1**.

Global warming is one of the major challenges in this century as well as the greatest threat to natural life, prosperity, and security. It accounts for nearly two-thirds of all greenhouse gas (GHG) emissions in the form of carbon dioxide [13]. Based on Government Regulation Number. 41 of 1999, every industry or company is responsible for managing air waste resulting from the production process [14]. Several parameters or compounds are regulated by Indonesian air quality standards nationally, such as SO_x, CO, and NO_x levels. To obtain an accurate sample, one of the criteria that can be met is by conducting a study on reducing exhaust emissions and taking samples of ambient air tests carried out at the research site.

At the beginning of the application of biodiesel, there were doubts and concerns among businessmen and mining contractors who use heavy equipment that the use of biodiesel could cause interference with the engine, such as a blockage in the fuel filter that causes a decrease in engine power or causes the engine to stop suddenly and cause work accidents [15]. Expenditure on fuel is one of the biggest expenses of the mining business [16], so if the fuel costs are not proportional to the income in the production business, it will cause losses due to decreased engine performance. Based on the characteristics of biodiesel, it has a higher viscosity, density, and acidity compared to diesel fuel, so using it for a long time may have an impact on the lubricating oil due to the effect of friction between parts in the engine [17]. Biodiesel also has poor low-temperature properties and lower volatility compared to diesel fuel, making it difficult to use it in low-temperature environmental conditions. Therefore, the addition of oxygenated additives such as diethyl ether (DEE) is found to be a suitable choice [18]–[21].

Previously, several researchers had conducted research on diethyl ether and several fuel mixtures used for diesel engines so that it could be used as reference material in this study, namely Patil [22], who researched diethyl ether that aimed to increase the cetane number in a mixture of kerosene and diesel. When mixing diesel, the amount of diethyl ether should not exceed 25%.

The limit is 15% for diethyl ether for a mixture of kerosene and diesel. In a diethyl ether-kerosene-diesel mixture, both diethyl ether and kerosene are limited to 15%. The results show that

Table 1. Sources of emissions from fuel combustion [11]

No	Category	Activity
1	Energy Producing Industry	Power plants Oil and Gas Refinery Coal Processing
2	Manufacturing Industry	Iron and Steel Chemistry Pulp, Paper, and Printing Food, Beverage, and Tobacco Processing Non-Metallic Minerals
3	Transportation Industry	Air transport Land transportation Water transportation
4	Other Sectors	Commercial and Office Activities Housing Activities Other Non-Specific Activities

diethyl ether can dissolve in any mixture composition, and the resulting exhaust emissions have decreased even without any engine modifications. There is also research by Gojandra [23] that, based on the results of the research that has been done, shows that the use of diethyl ether in biodiesel fuel (B20) produces better emissions than biodiesel (B20) itself. Where is the value of the difference in smoke thickness or opacity when compared to biodiesel (B20) is between 1.40% and 6.20% for the addition of 1% to 6% diethyl ether in B20. Diethyl ether has a higher cetane and oxygen number, which can enhance the quality of biodiesel and facilitate a reduction in ignition delay, resulting in complete combustion in the combustion chamber and reduced exhaust emissions. Yesilyurta and Aydin [24] also conducted tests on a diesel and B20 combination that included 2.5%, 5%, 7.5%, and 10% DEE. All fuel samples were run in four-stroke, single-cylinder, direct-injected diesel engines under fixed speed circumstances and five different engine loads. According to the testing results, adding 10% DEE to the mixture resulted in a drop in BTE of 17.39% and an increase in BSFC of 29.15% when compared to diesel fuel. Furthermore, compared to diesel fuel, the ternary mix fuel engine demonstrated an average reduction of up to 12.89%, 4.12%, and 8.84% in HC, smoke, and NOX emissions. Although a fall of up to 40.09% is indicated for lower concentrations at full load, CO emissions exhibit a rising tendency when the DEE fraction of diesel fuel is utilized. At large weights, CO2 also decreases. Nonetheless, when the CI engine is operated on all ternary mixes, the combustion behavior somewhat diminishes. Therefore, DEE may be viewed as a positive feature that resolves the primary issues with the usage of biodiesel made from cottonseed oil.

There has not been much research on the use of high concentrations of biodiesel such as B35 in heavy vehicles which are widely used in the mining sector. With a lower calorific value than diesel fuel, the higher the concentration of FAME in biodiesel, the more fuel is wasted for the same load. So comprehensive data is needed on how much influence biodiesel (B35) has on performance, fuel consumption, exhaust emissions, and its effect on diesel engine lubricating oil. Including the use of additives to overcome or reduce the above problems, assist mining business actors, and assist government programs in the use of biofuels.

2. Materials and Methods

2.1. Test Fuels

The biodiesel used in this research is in the form of fatty acid methyl esters (FAME) made from palm oil, which meets quality standard requirements. It has physical and chemical properties similar to diesel oil, as shown in **Table 2**. So it can be used in pure or mixed form in diesel engines without modification or with minor modifications. Biodiesel mixed fuel (B35) was prepared by adding FAME (B100) to biodiesel purchased from the local market in Balikpapan, Indonesia after the latter was tested for FAME content according to ASTM D7371-14 standard. The DEE used with the chemical formula given as $C_4H_{10}O$ is also obtained from the local market in Balikpapan. The fuel used has different contents, namely Diesel Oil (B0), Biodiesel 35 (B35), a mixture of 97% B35 with 3% Diethyl Ether (B35DEE3), a mixture of 96% B35 with 4% Diethyl Ether (B35DEE4), a mixture of 95% B35 with 5% Diethyl Ether (B35DEE5), and a mixture of 94% B35 with 6% Diethyl Ether (B35DEE6). The additive mixture was selected based on a review of the literature by previous researchers, which can be seen in **Figure 1**. Which is the mixing scheme used to make the mixture, and as shown in **Table 3**, from the laboratory results the cetane value increases with the addition of the percentage of diethyl ether while the viscosity and density decrease.

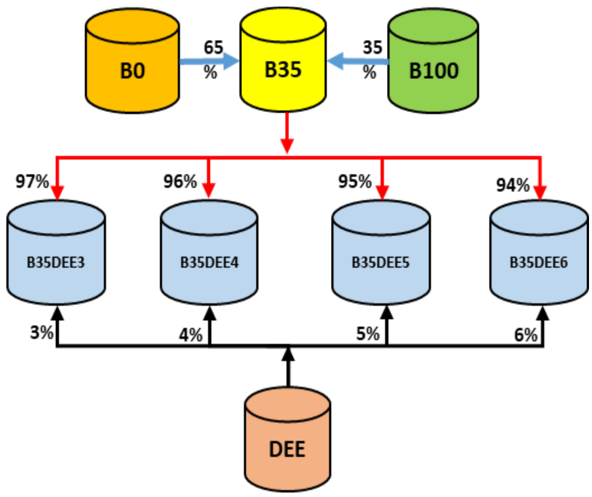

Figure 1. Scheme of mixing test fuel

Table 2. Physicochemical properties of reactants [25]

Properties	Units	Diesel	B100	DEE
Carbon	-	0.87	0.77	0.649
Hydrogen	-	0.126	0.121	0.135
Oxygen	-	0.004	0.109	0.216
Molecular Mass	g/mol	190	296	74
Lower Heating value	MJ/kg	42.5	40.20	33.9
Kinematic Viscosity @ 40 °C	cst	3	4.9	0.23
Density	Kg/m^3	830	870	718
Flash Point	°C	76	130	-45
Cetane Number	-	48	51	>125
C/H ratio	-	6.9	6.4	4.8

Table 3. Physicochemical properties of tested fuels

Fuel properties	Units	B0	B35	B35DEE3	B35DEE4	B35DEE5	B35DEE6
Calorific value	MJ/kg	46.13	45.28	45.05	44.93	44.84	44.75
Cetane number	-	50.2	52.7	54.86	55.58	56.3	57.02
Density at 15 °C	kg/m3	850.00	856.20	853.27	852.30	851.32	850.34
Kinematic viscosity at 40 °C	cSt	3.602	3.680	3.610	3.587	3.564	3.541

2.2. *Engine Setup and Operating Conditions*

Engine performance, fuel consumption, exhaust emissions, and wear and tear on the inner parts have been tested on the heavy-duty diesel engine (Komatsu SAA12V140E-3). The engine test scheme is shown in **Figure 2a**, while the specifications are shown in **Table 4**. The maximum test speed is 2250 rpm, and the engine setup consists of a diesel engine, a dynamometer, a fuel and airflow measurement unit, a data readout connected to a data analyzer, and an exhaust gas analyzer. Engine speed and load are regulated by a computer system connected to the dyno test, with specifications as in **Table 5**. Exhaust gas analysis in the form of CO, NO_x, and SO_2 emissions is measured using an exhaust gas analyzer, whose specifications are given in **Table 6**. Analyze engine wear content by taking oil samples after each engine performance test using a vacuum pump as shown in **Figure 2a** and sending them to the Petrolab laboratory. To obtain valid data, each sample was tested identically three times, and the results were averaged.

3. Results and Discussion

3.1. *Engine Performance*

Brake torque, brake power, brake thermal efficiency, and brake-specific fuel consumption are tested as the performance characteristics of

Table 4. Engine specifications

Model	: KOMATSU SAA12V140E-3 V type
Type	: 4-cycle, water-cooled, in-line 12-cylinder
Rate Output	: 895/1,900 kW/rpm (1,200/1,900 HP/rpm)
Max. torque	: 5,080/1,350 Nm/rpm (518/1,350 kgm/rpm)
Piston displacement	: 30.48 liter
Bore x Stroke	: 140 mm x 165 mm
Rate rpm	: 1,900
Engine oil capacity	: 129 liter

Table 5. Dynamometer specifications

Brand	: Taylor Dynamometer
Max. Torque	: 8,723 Nm
Maximum Power	: 2,000 Hp (1,491 kW)
Weight	: 1,195 kg
Rated Speed	: 4,000 Rpm
Rotation	: bi-directional

Table 6. Emission measurement tool specifications

Measurement	Measurement range (ppm)	Accuracy	Resolution (ppm)
CO (H_2 compensated)	2500 to 50000	±5 % of m.v.	1
CO_{low} (H_2 compensated)	500 to 2500	(additional	0.1
NO	1500 to 20000	error) Pressure	1
NO_{low}	300 to 1500	range -40 to 0	0.1
SO_2	500 to 25000		1

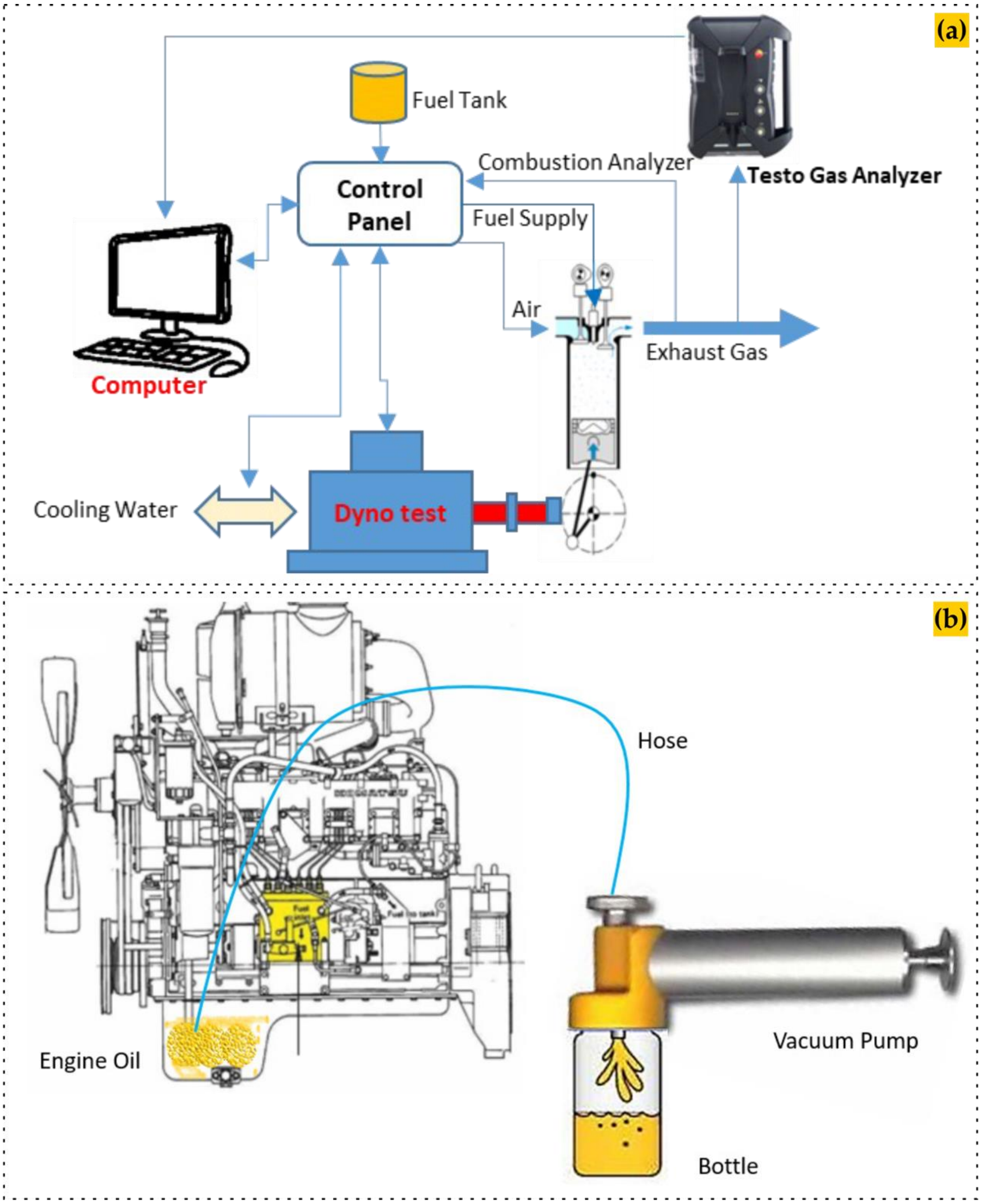

Figure 2. (a) Engine test schematic diagram; (b) oil sampling

a heavy diesel engine. **Figure 3** shows a graph of break torque versus engine speed from the results of three tests during the performance test with B35 fuel. With a maximum difference in data reading of 2.5%, apart from the first data when the engine is not yet stable, the consistency of the test data assures us that the data used in the analysis is valid.

3.1.1. Brake Torque and Brake Power

All blended fuels, both B35 and B35 plus DEE can almost reach the maximum performance of engines with B0 diesel fuel. There was a slight decrease with B35 and a slight improvement with the addition of DEE, as shown in **Figure 4**. The addition of palm oil to diesel fuel reduces engine torque and increases fuel consumption. This is caused by the low calorific value and high viscosity of palm oil, so the fuel atomization process is not good and worsens the combustion process in the cylinder [26]. Meanwhile, the addition of DEE to the B35 fuel mixture was able to improve the negative effect of palm oil on engine torque. DEE has a high cetane number, so reduces ignition delay and the fuel can hold pressure longer before it burns during the compression stroke, resulting in better combustion [27]. In addition, the high oxygen content in DEE can help the combustion process in the cylinder more completely, so that the engine torque increases and emission decreases [28]. The addition of 3% to 6% DEE has a relatively equal effect on torque or power, increasing engine brake torque to around 4,701 Nm or the equivalent of 820 kW in brake power for B35DEE3, until 4,704 Nm or 821 kW for B35DEE6 compared to 4,685 Nm or 814 kW in the B35, but still 2% lower than diesel fuel (B0), which reaches 4,795 Nm or 837 kW, This shows that with an engine setting that uses B0, it turns out that biodiesel mixed with DEE can achieve performance like B0. as shown in **Figure 5**. This is following research conducted by Fatkhurrozak et al. [29].

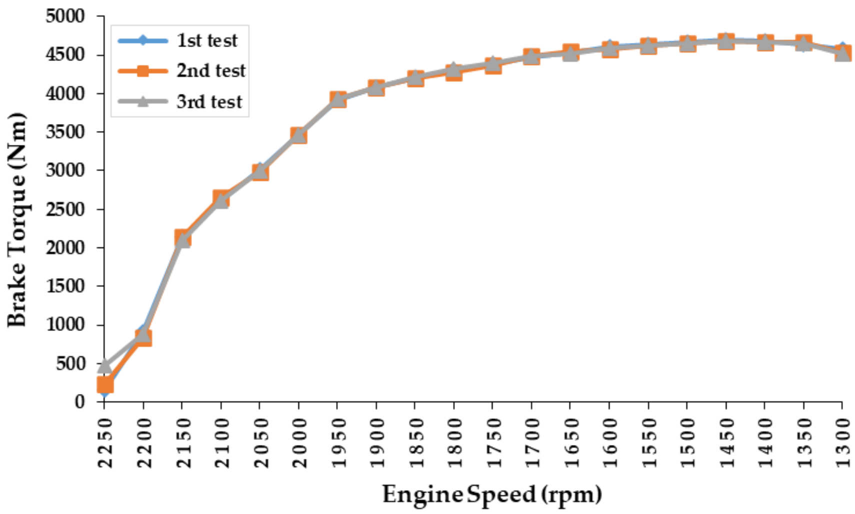

Figure 3. Brake torque repeatability vs engine speed graph for B35 fuel

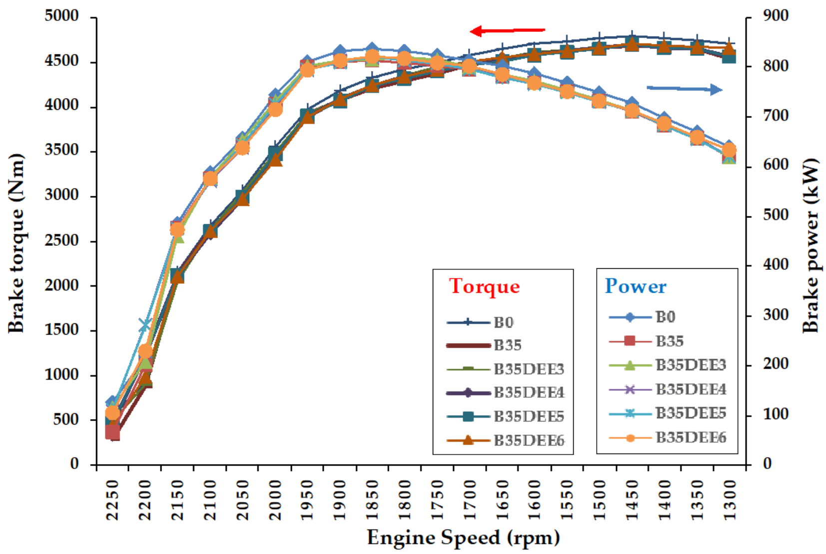

Figure 4. Brake torque and brake power vs engine speed

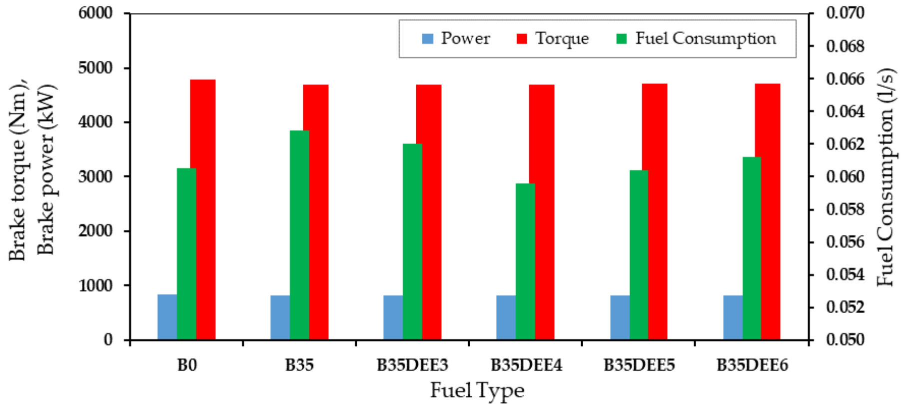

Figure 5. Maximum diesel engine performance

3.1.2. Brake Thermal Efficiency and Brake Specific Fuel Consumption

The brake thermal efficiency is a non-dimension parameter that shows the ratio of the brake power output of the engine to the heat energy supplied, while the brake-specific fuel consumption can be described as the quantity of fuel per unit of the generated engine brake power. Changes in the physical properties of B35 fuel compared to B0 include increased viscosity, resulting in increased fogging, so that it takes longer for the fuel to evaporate in the combustion chamber and more fuel is needed to increase its torque and power. Mixing B35 with DEE lowers the viscosity and density so that the flow of fuel entering the combustion chamber becomes more spread out and evenly distributed. This makes combustion more complete, and less fuel is needed to produce the same torque and power as B0, increasing brake thermal efficiency and decreasing brake-specific fuel consumption.

Brake thermal efficiency and brake-specific fuel consumption (BSFC) with respect to the engine speed for all of the fuel tested are shown in **Figure 6** and **Figure 7** respectively. Brake thermal efficiency and brake-specific fuel consumption indicate the engine's performance to convert consumed energy into net work output. Continuous engineering of diesel engines generally seeks to improve brake efficiency and brake-specific fuel consumption. These parameters show that the breaking thermal efficiency and brake specific fuel consumption of DEE-biodiesel blends are highly dependent on the amount of DEE in the fuel.

A more detailed and interesting picture can be seen in the conditions of maximum load (maximum torque), as shown in **Figure 8** for brake thermal efficiency and **Figure 9** for BSFC respectively. From the two figures, it can be seen that the use of B35 will reduce brake thermal efficiency and increase specific fuel consumption compared to B0. This is very normal and is closely related to the physical properties and calorific value of the fuel used, where the calorific value of B35 is lower than that of B0 so that to produce the same torque or power, more fuel input is required. This result was also compatible with the study conducted by Qi et al. [30] , where there was a slight increase in BSFC and a decrease in BTE for biodiesel and its blends compared to diesel fuel. The addition of DEE, which means improving the density and viscosity of B35 (**Table 1**), will improve the combustion process, increase thermal efficiency, and reduce BSFC to a certain percentage of DEE, in this case, a mixture of B35 with 4% DEE. The addition of more than 4% DEE will significantly reduce the heating value reduce the thermal efficiency and increase the BSFC. The current experimental study aligns with Sivalakshmi and Balusamy's findings [31] indicating that the brake thermal efficiency of biodiesel comprising 5% DEE and 95% neem oil surpassed that of pure biodiesel. This superiority is attributed to the incorporation of DEE in biodiesel, which decreases sample viscosity, thereby enhancing fuel spray formation and atomization qualities. Conversely, Yesilyurt and Aydin [24] presented contradictory findings, suggesting that introducing DEE into the B20 fuel mix as an oxygenated additive adversely affected the brake thermal efficiency and specific fuel consumption in a small stationary diesel engine when used in a ternary fuel blend with biodiesel and diesel.

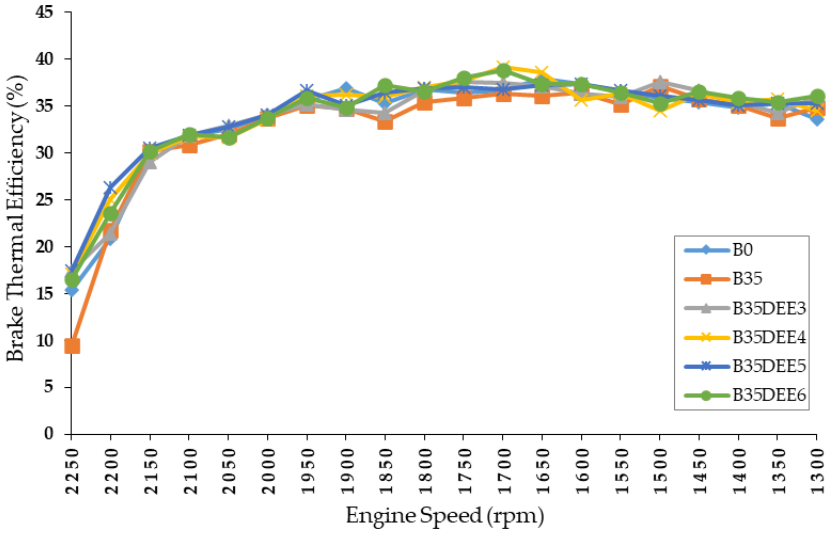

Figure 6. Brake thermal efficiency vs engine speed

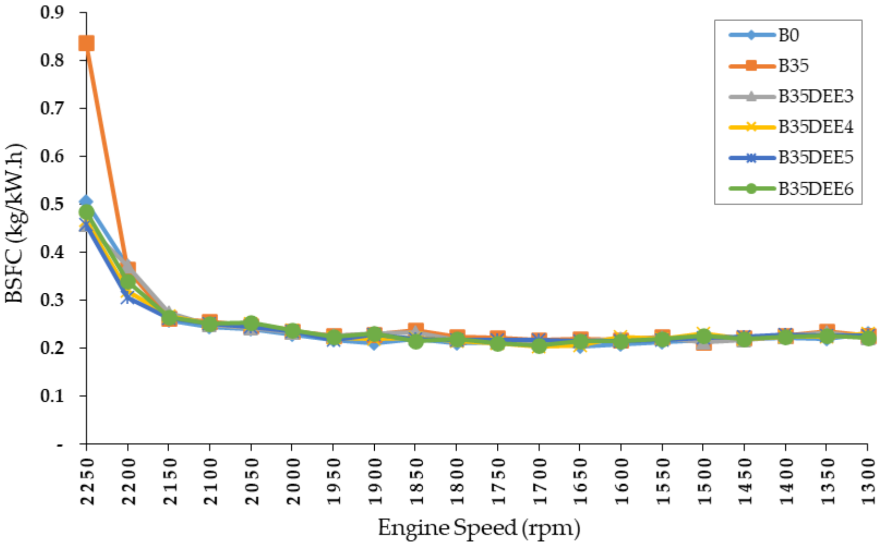

Figure 7. Brake-specific fuel consumption vs engine speed

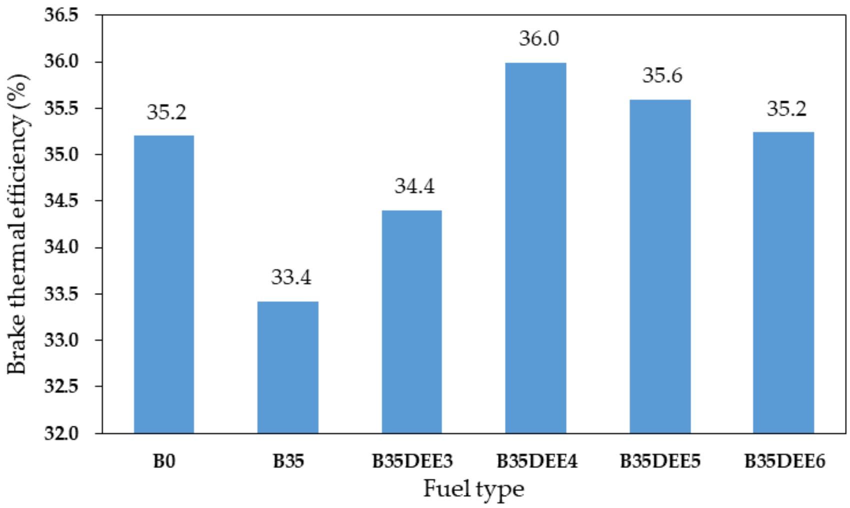

Figure 8. Brake thermal efficiency at maximum brake torque

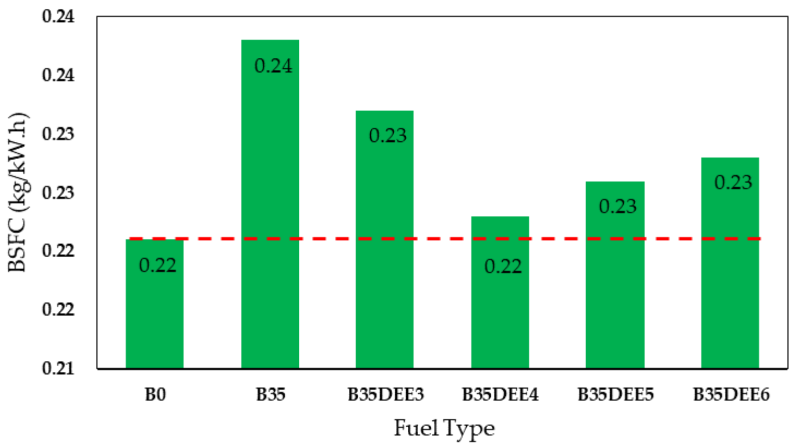

Figure 9. Brake-specific fuel consumption at maximum brake torque

3.2. *Exhaust Emission Test Results*

Testing of exhaust emissions aims to see the impact of air pollution caused by exhaust gases from engine combustion. In this study, the exhaust emissions of heavy-duty diesel engines resulting from the use of B35 mixed with diethyl ether, following the Regulation of the State Minister for the Environment Number 08 of 2023 [32], were still within the allowable threshold value (**Figure 10**).

3.2.1. *Carbon Monoxide (CO) Emissions*

Carbon monoxide (CO) emissions are an indicator of incomplete combustion, produced whenever fuel is burned in an internal combustion engine under conditions of insufficient air and low temperature [33]. **Figure 11** shows changes in CO emissions with engine load on all fuel samples tested with engine speed given the load.

Changes in CO emissions at engine speed given the load for all tested fuel samples It can be seen that CO emissions have increased due to increased engine load (engine speed decreased due to load). The B35 palm oil fuel mixture produces CO emissions 7.8% lower than diesel fuel oil at maximum engine power, which is 1,850 rpm. Primarily, this occurs because biodiesel fuel possesses a higher oxygen content, leading to a more thorough combustion process within the engine cylinder. This outcome is frequently observed in compression ignition engines using biodiesel [24]. Nevertheless, the incorporation of DEE as an oxygenated fuel supplement in the B35 fuel blend did not produce the anticipated substantial decrease in CO emissions, except for lower concentrations. CO emissions on B35DEE3, B35DEE4, and B20DEE5 were found to be 8.25%, 4.40%, and 0.80% lower than diesel fuel and, respectively, 4.1%, 6.2%, and 0.80% lower. 1.7% of the B35 mixture at maximum engine power, which is 1,850 rpm. Meanwhile, CO emissions in B20DEE6 at maximum power reach 6.63%, higher than diesel oil. It's important to highlight that a minimal content of DEE tends to decrease CO emissions across all engine load conditions. This phenomenon may be caused by the combined impact of the inherent oxygen content and higher cetane number within the tested fuel blends. The blend of DEE and palm oil biodiesel contributes to a more efficient combustion process, resulting in reduced CO emissions. Conversely, adding the DEE concentration within a ternary fuel mixture promotes increased CO emissions in the exhaust. Moreover, the increase in this ratio is directly influenced by the presence of DEE in the fuel blend. Despite the initial assumption that incorporating DEE into diesel fuel blends could lower CO emissions, this experimental study yielded partially contrary outcomes, similar to the findings in Yesilyurt and Aydin's research [24].

3.2.2. *Nitrogen Oxide (NOx) Emissions*

The value is shown in the graph of nitrogen oxide exhaust emissions in **Figure 12**. Explains that an increase in engine loading and a decrease in engine rotational speed cause the nitrogen oxide content produced to also increase. This is based on the theory that NO_x emissions are produced due to high combustion temperatures, so increasing engine power will increase the temperature in the

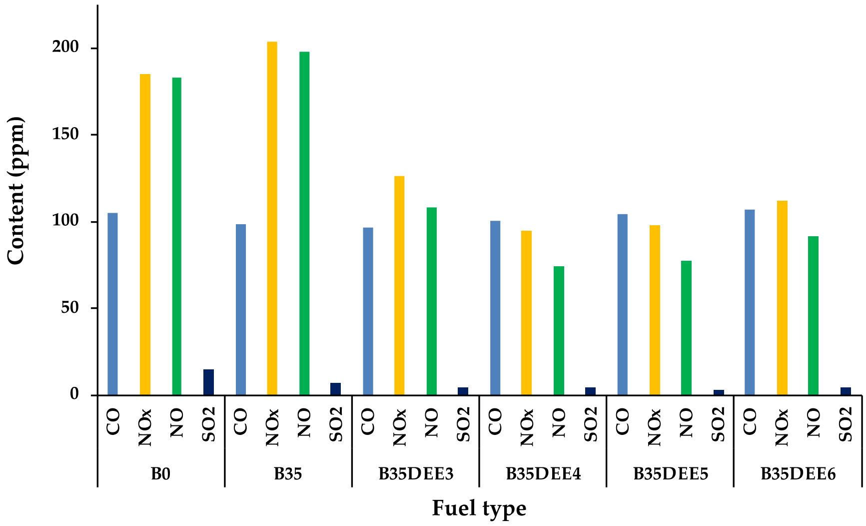

Figure 10. Emission test results

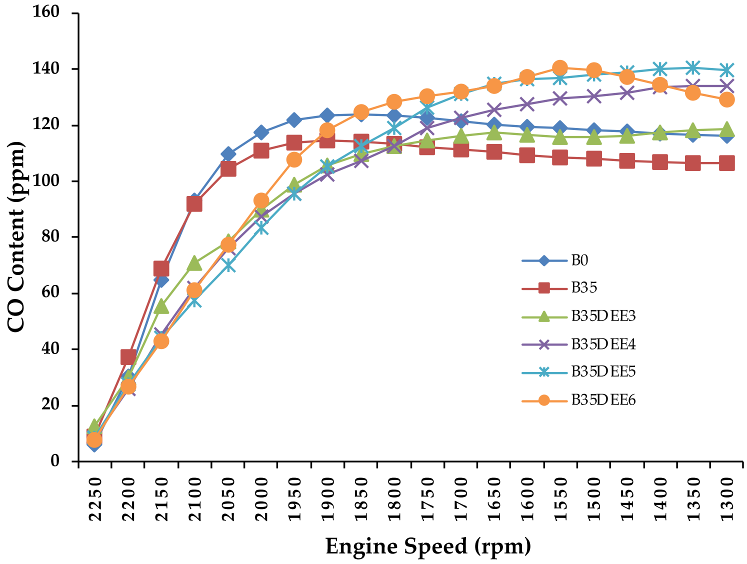

Figure 11. Variation of carbon monoxide emissions with engine speed

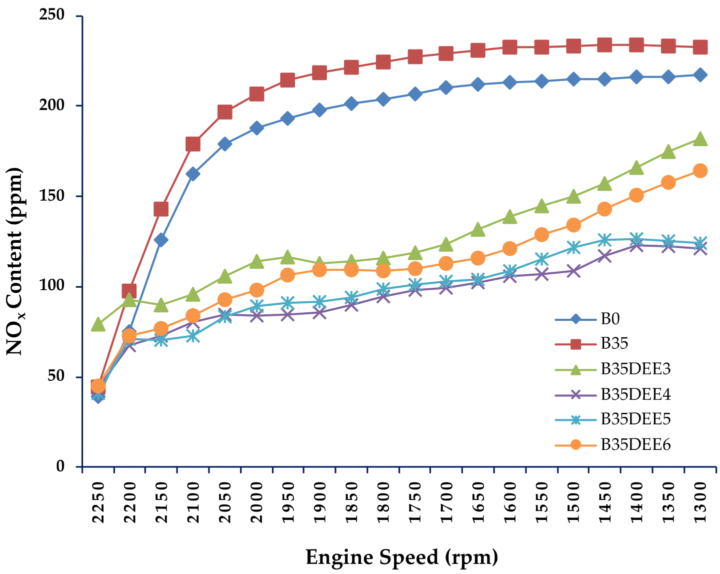

Figure 12. Variation of nitrogen oxide emissions with engine speed

combustion chamber. The value of the nitrogen oxide content of B35 biodiesel fuel is higher when compared to diesel fuel [34]. By the theory that the use of biodiesel cannot reduce the resulting NO_x emissions because the oxygen content contained in biodiesel can cause excess air in the combustion chamber during the combustion process [35]. Nitrate elements contained in vegetable oils in the B35 biodiesel fuel mixture are also a factor in increasing the nitrogen oxide content during combustion [36].

At lower engine loads, molecular nitrogen remains consistently present, undergoing monatomic decomposition at extremely high temperatures. These specific nitrogen molecules are highly reactive and strive to attain equilibrium, thus reacting with the surrounding oxygen to form nitrogen oxides. It's established that the quantity of oxygen molecules in the fuel and the temperature within the engine cylinder play crucial roles in influencing nitrogen oxides' formation in the combustion chamber. Increased oxygen content and higher temperatures primarily lead to elevated concentrations of NOx emissions.

Figure 12 illustrates the fluctuations in nitrogen oxide emissions across different engine loads for the tested fuel samples. The graph indicates a gradual rise in NOx emission levels corresponding to increased engine load, primarily attributed to the heightened temperature in the lower combustion chamber—a factor known to generate NOx emissions within the engine cylinders. Specifically, when the engines used the B35 fuel blend, nitrogen oxides increased by approximately 8.99% compared to unaltered diesel fuel. Despite the similar cetane levels between B35 blended fuel and diesel oil, the former contains molecular oxygen as part of its chemical structure, enhancing combustion efficiency within the cylinder and consequently elevating NOx emissions. There's an evident necessity to significantly curtail nitrogen oxides through the utilization of DEE-enhanced B35. It is anticipated that the higher oxygen content in DEE, coupled with its notably high cetane number, could mitigate NOX emission formation during the combustion process, aligning with earlier research by Reddy et al [33].

The addition of DEE in the fuel mixture raises the cetane number, influencing the diesel aromatics crucial for diesel combustion. Additionally, DEE possesses a high latent heat of vaporization, which generates excess heat, slowing down the combustion process and consequently reducing NOX emissions within the combustion chamber. Patil and Thipse [22] highlighted a significant decrease in NOX emissions from DEE diesel blends compared to conventional diesel oils, with a notable increase in the reduction ratio as the proportion of DEE in the blend rose. Correspondingly, Jayaraman et al. [37] demonstrated that incorporating DEE led to decreased NOx emissions in the exhaust gas.

3.2.3. *Sulfur Oxide (SO_2) Emissions*

The use of biodiesel as a mixture of engine fuels will reduce the incidence of SO_2 emissions because biodiesel derived from plant oils is almost free of sulfur content, so the addition of biodiesel to the fuel will reduce the sulfur content in the fuel itself. As a result, the value of SO_2 emissions from the combustion of engine fuel will also be reduced [38]. The graph shows that the maximum SO_2 emission value for diesel oil is 19.33 ppm, while for B35, the concentration of SO_2 is 9.78 ppm, see **Figure 13**. In general, the use of B35 as a fuel is still feasible and safe because the SO_2 emission value of the diesel-biodiesel mixture is still below the maximum permissible SO_2 emission standard of 50 ppm [39].

3.3. *Sample Oil Test Results*

In testing the content of the used oil after testing each fuel, the sample oil is taken after the oil is used as a lubricant for an average of 2 hours every 3 times the fuel is tested. The sample oil is taken with a special oil sampling tool so that it is not exposed to contamination from outside, and the sample is sent to Petrolab. The results of used oil testing can be seen in **Figure 14**. From the lab results, no significant wear was found, and it was still within the permissible wear standards. According to previous researchers, it took more than 500 hours to get wear trends [40].

4. Conclusion

The results of testing the effect of diethyl ether in B35 on the performance and exhaust emissions of heavy-duty diesel engines (Komatsu SAA12V140E-3) found that in general the addition of DEE to B35 will improve engine performance

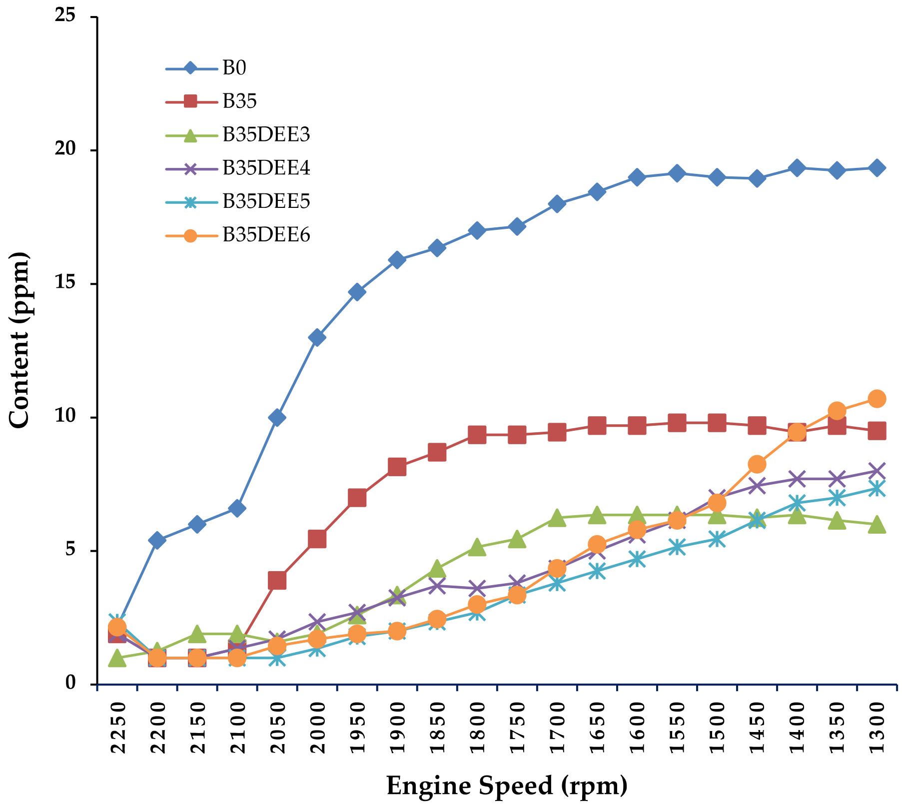

Figure 13. Variation of sulfur oxide emissions with engine speed

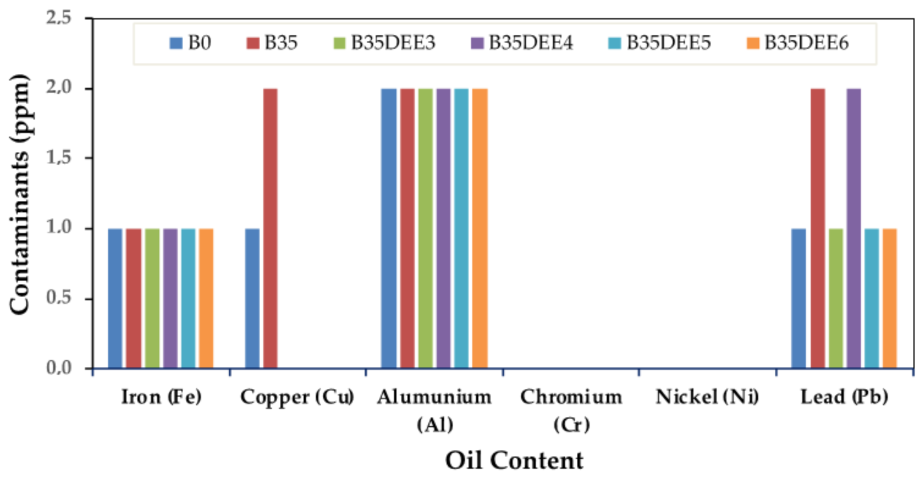

Figure 14. Particle wear results in oil samples

and reduce exhaust emissions. At maximum load, B35DEE4 experienced an increase in brake thermal efficiency of 7.69% compared to B35 and 2.24% compared to B0, reducing brake-specific fuel consumption by 6.30% compared to B35 and only increasing by 0.90% compared to B0. The addition of diethyl ether to B35 reduces the average CO emissions in B35DEE3 by 1.82% compared to B35, while compared to B0 it is 8.25%. The average NOx emissions of B35DEE4 are 53.48% smaller than B35 and 48.88% smaller than B0. Meanwhile, the average SO_2 emissions in B35DEE4 are 40.89% smaller than B35 and 71.17% smaller than B0. The emissions produced from the diethyl mixture are classified as environmentally friendly and are within the permitted limits according to the Minister of the Environment Regulation Number 08 of 2023. They are still within normal conditions and are permitted. To evaluate lubricating oil, it takes quite a long time to detect any changes, so that during the performance test it does not show significant differences for all types of fuel used.

Acknowledgements

The author would like to express his highest gratitude and appreciation to Mr. Joko Santoso and PT Pamapersada, who have allowed the use of the testing facility, and the COMEX Balikpapan laboratory members who have carried out the test.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Funding

No funding information from the authors.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

References

[1] Ministry of Energy and Mineral Resources, "Press Release Number 712.Pers/04/SJI/2019: First Time in the World, Indonesia to Implement 30% Biodiesel (B30)," 2019.

[2] I. C. Setiawan and M. Setiyo, "Renewable and Sustainable Green Diesel (D100) for Achieving Net Zero Emission in Indonesia Transportation Sector," *Automotive Experiences*, vol. 5, no. 1, pp. 1–2, 2022, doi: 10.31603/ae.6895.

[3] D. H. Park, F. I. Nana, and H. M. Cho, "A review of the emission, performance, combustion, and optimization parameters in the production of biodiesel from waste cooking oil," *Automotive Experiences*, vol. 5, no. 3, pp. 371–388, 2022, doi: 10.31603/ae.7005.

[4] S. Syarifudin, F. Fatkhurrozak, F. L. Sanjaya, E. Yohana, S. Syaiful, and A. Wibowo, "The effect of ethanol on brake torque, brake specific fuel consumption, smoke opacity, and exhaust gas temperature of diesel engine 4JB1 fueled by diesel-jatropha oil," *Automotive Experiences*, vol. 5, no. 2, pp. 230–237, 2022, doi: 10.31603/ae.6447.

[5] A. C. Arifin, A. Aminudin, and R. M. Putra, "Diesel-Biodiesel Blend on Engine Performance: An Experimental Study," *Automotive Experiences*, vol. 2, no. 3, pp. 91–96, 2019, doi: 10.31603/ae.v2i3.2995.

[6] S. Supriyadi, P. Purwanto, D. D. Anggoro, and H. Hermawan, "The Effects of Sodium Hydroxide (NaOH) Concentration and Reaction Temperature on The Properties of Biodiesel from Philippine Tung (Reutealis Trisperma) Seeds," *Automotive Experiences*, vol. 5, no. 1, pp. 57–67, 2022, doi: 10.31603/ae.5986.

[7] S. Pambudi, N. Ilminnafik, S. Junus, and M. N. Kustanto, "Experimental Study on the Effect of Nano Additives γAl2O3 and Equivalence Ratio to Bunsen Flame Characteristic of Biodiesel from Nyamplung (Calophyllum Inophyllum)," *Automotive Experiences*, vol. 4, no. 2, pp. 51–61, 2021, doi: 10.31603/ae.4569.

[8] A. Sule, Z. A. Latiff, M. A. Abbas, I. Veza, and A. C. Opia, "Recent Advances in Diesel-Biodiesel Blended with Nano-Additive as Fuel in Diesel Engines: A Detailed Review," *Automotive Experiences*, vol. 5, no. 2, pp. 182–216, 2022, doi: 10.31603/ae.6352.

[9] A. Kolakoti, M. Setiyo, and B. Waluyo, "Biodiesel Production from Waste Cooking Oil: Characterization, Modeling and Optimization," *Mechanical Engineering for Society and Industry*, vol. 1, no. 1, pp. 22–30, 2021, doi: 10.31603/mesi.5320.

[10] Decree of the Minister of Energy and Mineral Resources of the Republic of Indonesia, *Amendments to the Decree of the Minister of Energy and Resources Number 205.K/EK.05/DJE/2022 concerning the Determination of Oil Fuel Business Entities and Biodiesel Type Vegetable Fuel Business Entities and the Allocation of Volumes of Biodiesel Type Veg*. 2022.

[11] Ministry of Environment and Forestry, "Greenhouse gas (GHG) inventory report, and monitoring, verification reporting (MPV)," Jakarta, 2021.

[12] S. Selvi, N. Rahmi, and I. Rachmatulloh, "Urgensi Penerapan Pajak Karbon Di Indonesia," *Jurnal Reformasi Administrasi: Jurnal Ilmiah untuk Mewujudkan Masyarakat*

Madani, vol. 7, no. 1, pp. 29–34, 2020, doi: 10.31334/reformasi.v7i1.845.

[13] A. I. Saputra, "Pajak karbon sebagai sumber penerimaan negara dan sistem pemungutannya," *Jurnal Anggaran Dan Keuangan Negara Indonesia (AKURASI)*, vol. 3, no. 1, pp. 56–71, 2021, doi: 10.33827/akurasi2021.vol3.iss1.art96.

[14] Government of Indonesia, *PP No. 41 of 1999 about Air Pollution Control*. 1999.

[15] S. Primadhyta, "Concerns of Truck and Transport Entrepreneurs regarding the Implementation of B20," *CNN Indonesia*, 2018. .

[16] E. Harsiga and E. I. Novianto, "Analisis Konsumsi Bahan Bakar Alat Angkut Articulated Dump Truck CAT D400E ditinjau dari Pengaruh Perawatan, Umur Alat Angkut pada Pengangkutan Overburden di PT Baturona Adimulya, Musi Banyuasin, Sumatera Selatan," *Jurnal Teknik Patra Akademika*, vol. 8, no. 2, pp. 10–18, 2017.

[17] J. Sentanuhady *et al.*, "Analysis of the Effect of Biodiesel B20 and B100 on the Degradation of Viscosity and Total Base Number of Lubricating Oil in Diesel Engines with Long-Term Operation Using ASTM D2896 and ASTM D445-06 Methods," *TEKNIK*, vol. 41, no. 3, pp. 269–274, 2020, doi: 10.14710/teknik.v41i3.32515.

[18] V. K. Kaimal and P. Vijayabalan, "An investigation on the effects of using DEE additive in a DI diesel engine fuelled with waste plastic oil," *Fuel*, vol. 180, pp. 90–96, 2016, doi: 10.1016/j.fuel.2016.04.030.

[19] H. Venu and V. Madhavan, "Influence of diethyl ether (DEE) addition in ethanol-biodiesel-diesel (EBD) and methanol-biodiesel-diesel (MBD) blends in a diesel engine," *Fuel*, vol. 189, pp. 377–390, 2017, doi: 10.1016/j.fuel.2016.10.101.

[20] H. Sun, W. Zhang, and Y. Wang, "Experimental study on improving cold start performance of diesel engines at extremely low ambient temperatures with diethyl ether," *Energy*, vol. 283, p. 129122, 2023, doi: 10.1016/j.energy.2023.129122.

[21] R. M. EL-Zohairy, A. S. Attia, A. S. Huzayyin, and A. I. EL-Seesy, "Improving the biodiesel combustion and emission characteristics in the lean pre-vaporized premixed system using diethyl ether as a fuel additive," *Fuel*, vol. 356, p. 129614, 2024, doi: 10.1016/j.fuel.2023.129614.

[22] K. R. Patil and S. S. Thipse, "Experimental investigation of CI engine combustion, performance and emissions in DEE–kerosene–diesel blends of high DEE concentration," *Energy Conversion and Management*, vol. 89, pp. 396–408, 2015, doi: 10.1016/j.enconman.2014.10.022.

[23] F. P. L. Gojandra and D. W. Karmiadji, "Analysis Of The Use Of Diethyl Ether Additives In Biodiesel (B20) On Diesel Engine Exhaust Gas Emissions," *Dinamika: Jurnal Ilmiah Teknik Mesin*, vol. 13, no. 1, 2021, doi: 10.33772/djitm.v13i1.18432.

[24] M. K. Yesilyurt and M. Aydin, "Experimental investigation on the performance, combustion and exhaust emission characteristics of a compression-ignition engine fueled with cottonseed oil biodiesel/diethyl ether/diesel fuel blends," *Energy Conversion and Management*, vol. 205, p. 112355, 2020, doi: 10.1016/j.enconman.2019.112355.

[25] V. S. Kharkwal, S. Kesharvani, S. Verma, G. Dwivedi, and S. Jain, "Numerical investigation of engine characteristics of a diesel engine fuelled with ethanol and diethyl ether supplemented diesel-WCO biodiesel blend," 2023, doi: 10.1016/j.matpr.2023.02.106.

[26] S. Dharma *et al.*, "Experimental study and prediction of the performance and exhaust emissions of mixed Jatropha curcas-Ceiba pentandra biodiesel blends in diesel engine using artificial neural networks," *Journal of cleaner production*, vol. 164, pp. 618–633, 2017, doi: 10.1016/j.jclepro.2017.06.065.

[27] A. Ibrahim, "An experimental study on using diethyl ether in a diesel engine operated with diesel-biodiesel fuel blend," *Engineering science and technology, an international journal*, vol. 21, no. 5, pp. 1024–1033, 2018, doi: 10.1016/j.jestch.2018.07.004.

[28] S. Srihari, S. Thirumalini, and K. Prashanth, "An experimental study on the performance and emission characteristics of PCCI-DI engine fuelled with diethyl ether-biodiesel-

diesel blends," *Renewable Energy*, vol. 107, pp. 440–447, 2017, doi: 10.1016/j.renene.2017.01.015.

[29] F. Fatkhurrozak, "Pengaruh Diethyl Ether pada Mesin Diesel Berbahan Bakar Diesel dan Jatropa dengan sistem EGR terhadap Torsi Dan Daya Mesin," *Nozzle: Journal Mechanical Engineering*, vol. 7, no. 2, pp. 7–12, 2018, doi: 10.30591/nozzle.v7i2.2183.

[30] D. H. Qi, H. Chen, L. M. Geng, and Y. Z. H. Bian, "Experimental studies on the combustion characteristics and performance of a direct injection engine fueled with biodiesel/diesel blends," *Energy Conversion and Management*, vol. 51, no. 12, pp. 2985–2992, 2010, doi: 10.1016/j.enconman.2010.06.042.

[31] S. Sivalakshmi and T. Balusamy, "Effect of biodiesel and its blends with diethyl ether on the combustion, performance and emissions from a diesel engine," *Fuel*, vol. 106, pp. 106–110, 2013, doi: 10.1016/j.fuel.2012.12.033.

[32] Government of Indonesia, *Minister of Environment and Forestry Regulation Number 08 of 2023: Application of Motor Vehicle Emission Quality Standards Category M, Category N, Category O, and Category L*. 2023.

[33] K. S. Reddy, Y. V. H. Rao, and V. D. Raju, "Influence of diethyl ether on the diesel engine diverse characteristics fuelled with waste plastic biodiesel," *Materials Today: Proceedings*, vol. 61, pp. 1168–1175, 2022, doi: 10.1016/j.matpr.2022.01.446.

[34] E. Haryono and R. D. E. Witjonarko, "Analisa Unjuk Kerja Mesin Diesel Kapal Dua Langkah (Two Stroke Marine Diesel Engine) Berbahan Bakar Campuran Minyak Solar (Hsd) Dan Biodiesel Minyak Jelantah Pada Beban Simulator Full Load," *Invotek Polbeng*, vol. 7, no. 2, pp. 179–187, 2017, doi: 10.35314/ip.v7i2.220.

[35] E. Saputro, "Study Pustaka Penurunan Parameter Nox Dan Co Pada Emisi Gas Buang B30," *Jurnal Atmosphere*, vol. 2, no. 1, pp. 31–35, 2021, doi: 10.36040/atmosphere.v2i1.3530.

[36] I. G. E. Lesmana, R. C. Hartantrie, and E. Sunjaya, "Analisis Perbandingan Emisi Gas Buang Bahan Bakar Biodiesel B30 Dan Solar Dexlite Pada Mesin Diesel R175A," *Almikanika*, vol. 4, no. 1, pp. 22–27, 2022, doi: 10.32832/almikanika.v4i1.7170.

[37] J. Jayaraman *et al.*, "Production of biodiesel from waste cooking oil utilizing zinc oxide nanoparticles combined with tungsto phosphoric acid as a catalyst and its performance on a CI engine," *Fuel*, vol. 329, p. 125411, 2022, doi: 10.1016/j.fuel.2022.125411.

[38] S. Irfan and H. Purnomo, "Studi Komparasi Emisi Gas Buang Mesin Diesel Menggunakan Bahan Bakar Solar Dan Minyak Kelapa (Virgin Coconut Oil)," *Jurnal 7 Samudra*, vol. 3, no. 1, pp. 18–25, 2018, doi: 10.54992/7samudra.v3i1.26.

[39] Minister of Environment and Forestry of the Republic of Indonesia, *Quality Standards for Exhaust Gas Emissions for New Type Motor Vehicles Category M, Category N and Category O*. 2017.

[40] N. D. Rizaldy and S. Johanes, "Analisa perubahan sifat pelumas terhadap keausan dan performa engine SAA12v140E-3 Komatsu HD785-7," *Jurnal Material Teknologi Proses*, vol. 2, no. 1, pp. 6–12, 2021, doi: 10.22146/jmtp.66065.