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Application of Ultra Fine Bubble Addition to Diesel Fuel on The Performance of Agricultural Transport Vehicle Engines

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ABSTRACT - Diesel engines have long been the primary choice across various industrial sectors, including agricultural transport vehicles. However, energy efficiency and fuel consumption remain significant challenges. One approach to address these issues is the application of Ultra Fine Bubble (UFB) technology to diesel fuel, which aims to enhance physical fuel properties and improve combustion efficiency. This study was conducted to evaluate the effect of UFB treatment on B0 CN-51 and B40 fuels in relation to fuel quality and diesel engine performance. The fuel characterization tests showed that the calorific value of B0 CN-51 increased from 43.73 MJ/kg to 45.68 MJ/kg, and B40 from 42.46 MJ/kg to 42.94 MJ/kg. The cetane number also increased, accompanied by a reduction in sulfur content and lubricity. Performance testing using a chassis dynamometer indicated improvements in maximum power and torque. B0 CN-51 UFB produced 95.68 kW of power and 344.18 Nm of torque, while reducing specific fuel consumption (SFC) from 42.25 to 39.82 g/kWh. In addition, fuel consumption in ℓ/100 km decreased significantly, with an average reduction in efficiency of up to 4.85%. For B40, SFC decreased from 44.99 to 43.75 g/kWh, with an average consumption reduction of 1.73%. These results demonstrated that UFB can significantly improve diesel engine performance and fuel efficiency.

Keywords: agricultural transport vehicle, diesel engine, diesel fuel, engine performance, ultra fine bubble.

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INTRODUCTION

Diesel engines have long been the primary choice in various industrial sectors, including agriculture and transportation, due to their high efficiency and durability. Four-wheeled diesel-powered vehicles, such as pick-up trucks and light commercial vehicles, are also widely used to support agricultural and plantation operations, including crop transportation, fertilizer distribution, and agricultural equipment logistics. However, despite their robust performance, diesel engines still face challenges in improving combustion efficiency and reducing fuel consumption, both of which have a direct impact on operational costs and overall productivity (Attalasyah et al., 2024).

The main challenge in optimizing diesel engines lies in incomplete combustion caused by suboptimal fuel air mixing (Maulana et al., 2023; Kristanto & Tirtoatmodjo 2000). Currently, diesel fuels commonly used in Indonesia such as pure diesel (B0), biosolar (B40), and biodiesel (B100) offer varying levels of efficiency. However, under heavy-duty operating conditions, further performance enhancement is still required. In this context, the use of alternative fuels such as B40 (a blend of 40% biodiesel and 60% petroleum diesel) has been implemented as part of the national mandate (Kementerian Energi dan Sumber Daya Mineral 2025). Nevertheless, the characteristics of biodiesel, such as higher viscosity, add complexity to the combustion process. Currently, diesel fuel is sold below its economic price, which places a burden on the state budget (APBN) through increased subsidies and compensation. Consumption has also continued to increase, with the majority of benefits enjoyed by wealthier households. Meanwhile, vehicle emissions generated from subsidized fuels contribute 32–57% of air pollution. Through equitable consumer control, the consumption of subsidized fuels (including diesel) is projected to be reduced by up to 17.8 million kiloliters per year (Kementerian Keuangan 2024). The performance of diesel engines, particularly in terms of power and torque, is strongly influenced by the quality of the fuel used. The power produced by a diesel engine is directly related to its capacity to drive heavier loads, while torque determines a vehicle's ability to accelerate and maintain speed under heavy load conditions (Rusli et al., 2022). Diesel engines generally provide higher torque at lower engine speeds compared to gasoline engines, making them more efficient for commercial vehicles and heavy equipment.

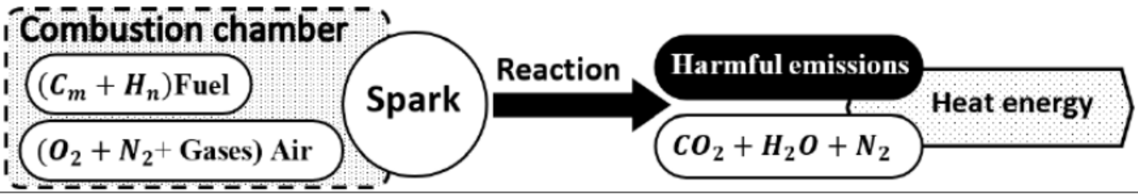
However, this performance is still influenced by incomplete combustion, which can reduce the maximum torque and power output. Alongside the testing of various types of fuels, fuel consumption also serves as an important parameter affecting operational efficiency. The use of fuels with higher viscosity, such as biodiesel, although environmentally friendly, often results in greater fuel consumption. Therefore, optimization is required to achieve a balance between fuel efficiency, engine performance, and emission reduction. In diesel engines, achieving complete combustion is essential, as it leads to reduced emissions and improved fuel efficiency. A schematic representation of the theoretical combustion reaction is presented in Figure 1.

One of the innovations with the potential to improve combustion efficiency is Ultra Fine Bubble (UFB) technology. UFB refers to bubbles with a diameter of less than 1 micrometer, which possess unique properties such as long lifespan, pH -dependent surface charge, and the ability to enhance reaction processes and particle technology applications through improved gas transfer efficiency. These characteristics enable more complete combustion (Yasuda 2024). With enhanced oxidation, significant improvements can be achieved in combustion efficiency, fuel consumption, and exhaust emission reduction. The working principle of the bubbling process in Ultra Fine Bubble (UFB) technology is illustrated in Figure 2. The application of UFB in diesel fuel holds great potential for enhancing vehicle operational efficiency. According to Nakatake et al. (2013), their study demonstrated that technologies such as nano air bubbles have significant potential to improve efficiency and reduce emissions in modern common-rail diesel engines. Under harsh environmental conditions and challenging terrains, improved fuel efficiency can help reduce operational costs and increase productivity. This is further supported by previous studies, which have shown that UFB technology effectively increases power output and reduces fuel consumption in hand tractor diesel engines using fuels such as B0 (pure diesel), B35, and B100 (Herodian 2025). The implementation of this technology is therefore expected to provide an innovative solution for optimizing diesel engine performance, while simultaneously promoting energy efficiency and reducing environmental emissions.

METHODOLOGY

Sample preparation was carried out at the Lube Oil Blending Plant (LOBP), while data collection was conducted at the Product Application Building 1, Oil and Gas Testing Center (BBPMGB LEMIGAS), Jakarta. Data processing and analysis were performed at the Siswadhi Soepardjo Field Laboratory, Department of Mechanical and Biosystem Engineering, Faculty of Agricultural Technology, IPB University, Bogor. The overall research workflow and experimental procedures are illustrated in Figure 3.

The first stage involved instrument preparation and literature review. A comprehensive literature study and discussions were conducted to establish the theoretical framework and research procedure. References included SNI 7554:2010 for standardized fuel consumption testing, ASTM methods for general physico-chemical fuel characterization, and regulations from the Directorate General of Oil and Gas (Dirjen Migas) as benchmarks for fuel quality assessment. Subsequently, instrument trials were conducted in the laboratory, including verification of the



where: C=carbon, H=hydrogen, O=oxygen, N=nitrogen

Figure 1. Chemical reaction of complete combustion (Sharif et al. 2019)

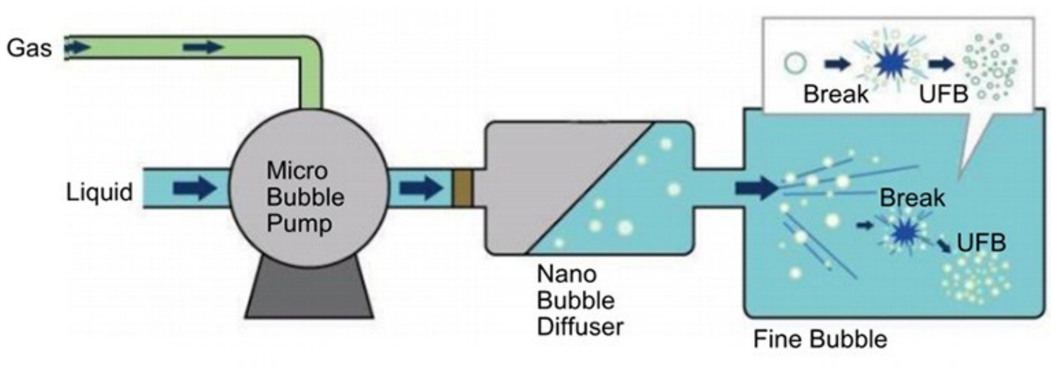


Figure 2. Working principle of ultra fine bubble (UFB) technology (hollyep.com 2021)

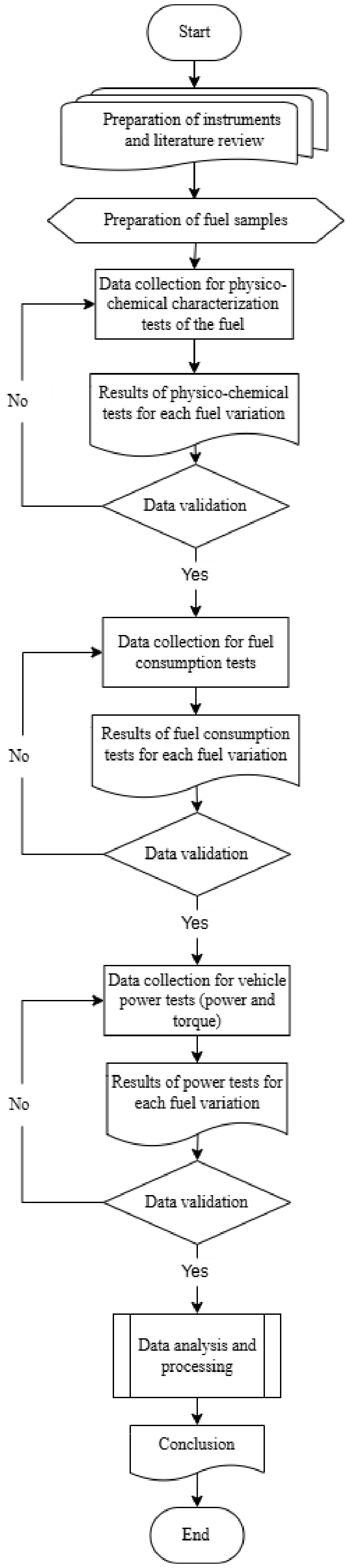


Figure 3. Research procedure flowchart

dynamometer, calibration of measuring devices such as the fuel flow indicator (for fuel consumption measurement), and the stopwatch (for time measurement). The fuels tested in this study were B0 CN-51 and B40 biodiesel. All instrument preparation procedures were carefully executed to ensure data validity, with the testing parameters, equipment, and standards presented in Table 1.

Fuel sample preparation was conducted according to Dirjen Migas Decree No. 384.K/MG.06/DJM/2024 and No. 447.K/MG.06/DJM/2023. The samples of B0 CN-51 and B40 were stored under sterile and controlled environmental conditions. The Ultra Fine Bubble (UFB) treatment was applied using an oxygen concentrator with a flow rate of 1 liter per minute, following Alfath (2023), who reported optimal diesel performance at this injection rate. The bubbling process was carried out for 50 minutes per 20 liters of fuel, producing modified UFB-treated fuel.

Fuel characterization tests were then conducted to evaluate both B0 CN-51 and B40 before and after UFB treatment. The parameters tested included cetane number, density, viscosity, sulfur content, distillation T90, FAME content (for B40), lubricity, calorific value, and cleanliness. ASTM standards and Dirjen Migas regulations were used as the basis for testing. To improve accuracy, sulfur, density, viscosity, calorific value, and cleanliness were tested three times, while other parameters were tested twice. Results outside tolerance limits were retested to ensure reliability.

Fuel consumption testing was conducted using a four-wheel diesel-powered double-cabin vehicle (model year 2019) mounted on a chassis dynamometer, combined with a fuel flow indicator and stopwatch to simulate real driving conditions. Tests were performed at steady speeds of 50, 70, 90, and 120 km/h at gears 2, 3, 4, and 5, in accordance with SNI 7554:2010. Fuel consumption was initially measured in ml/s, then converted to ℓ/h, and finally expressed in ℓ/100 km. Each scenario was repeated five times to ensure accuracy, exceeding the minimum four repetitions required by the standard.

Engine performance testing was also carried out using the four-wheel diesel-powered double-cabin vehicle (model year 2019) on the same chassis dynamometer, integrated with Dynomax software. This allowed the measurement of power (kW) and torque (Nm), along with supporting parameters such as engine speed (rpm), vehicle speed (km/h), ambient temperature (°C), humidity (%), and barometric pressure (m-bar). Tests were conducted for both untreated and UFB-treated fuels, with ten repetitions each to ensure consistency. Data validation was carried out by examining the stability of the power and torque curves. In the event of anomalies, tests were repeated to obtain valid results.

Finally, data analysis and processing were carried out to evaluate the effect of fuel type and UFB treatment on diesel engine performance. The data were first validated using the Z-test to detect and eliminate outliers that could distort accuracy. Once validated, the datasets were grouped based on parameters, converted into standard units, and analyzed using descriptive and comparative methods to obtain average values, peak values, and performance trends. Comparisons between scenarios with and without UFB were then conducted to assess changes in fuel characteristics, consumption efficiency, and performance outcomes. To further strengthen the statistical validity, a T-test was applied to determine whether the observed differences between UFB-treated and untreated fuels were statistically significant ($p < 0.05$). This ensured that the improvements in efficiency and performance could be attributed to the UFB treatment rather than random variations or measurement errors.

Table 1. Fuel characterization tests

Parameter	Instrument	Test Method
Cetane Number	CFR F5	ASTM D613
Density (at 15 ºC)	SVM 3001 Cold Properties	ASTM D4052
Viscosity (at 40 ºC)	SVM 3001 Cold Properties	ASTM D445
Sulfur Content	UV Fluorescent Total Sulfur (tShR)	ASTM D5453
Distillation (T90)	OptiDist: Atmospheric Distillation	ASTM D86
FAME Content	Eralytics: Automatic FAME Analyzer	ASTM D7371
Lubricity	HFRR (High Frequency Reciprocating Rig)	ASTM D6079
Caloric Value	Isoperibol Calorimeter AC500	ASTM D240
Cleanliness	ARGO-HYTOS OPCom Portable Oil Lab	ASTM D7619

RESULT AND DISCUSSION

Results of fuel physico-chemical characterization

Fuel characterization tests were carried out on two types of fuel, namely B0 CN-51 and B40, both in normal conditions and after Ultra Fine Bubble (UFB) injection. The parameters tested included cetane number, density at 15 °C, viscosity at 40 °C, FAME content, sulfur content, calorific value, and cleanliness, each with three repetitions. Meanwhile, distillation and lubricity tests were conducted only once. The results of the B0 CN-51 fuel characterization test are presented in Table 2.

The results of B0 CN-51 fuel characterization with UFB treatment show positive effects on nearly all parameters. The cetane number increased from 53.3 to 54.1, indicating faster and more stable ignition quality. A higher cetane number contributes to smoother and more efficient combustion, reduces knocking in diesel engines, improves performance, lowers noise, and enhances the combustion process (Gea 2023).

Density slightly increased from 830.3 to 831.4 kg/m³, still within standard limits and not harmful to the injection system. This rise can be attributed to additional oxygen introduced via UFB. Viscosity increased from 3.079 to 3.107 mm²/s, suggesting slightly improved lubrication, which benefits injector and pump durability, although it may potentially increase injector clogging risk.

Sulfur content decreased from 0.001757 to 0.001707% m/m, indicating cleaner combustion with less sulfur residue—crucial for reducing harmful exhaust gas emissions. Distillation temperature (T90) rose slightly from 339.1 to 340.3 °C, still within safe limits, showing stable volatility during heating.

While FAME content remained at zero, lubricity improved significantly from 372.5 to 347 microns. Lower lubricity values indicate better lubrication capacity, reducing wear risk in the fuel system. Conversely, higher lubricity in diesel fuels may accelerate component wear and lower engine performance (Semar, 2007). The most notable improvement was calorific value, which rose from 43.73 MJ/kg to 45.68 MJ/kg (4.46%). This reflects higher energy per kilogram of fuel, directly improving performance and fuel efficiency (Sehatpour et al., 2017).

Finally, cleanliness improved from ISO 19/18/15/14 to 19/18/15/13, meaning UFB-treated fuel contained fewer solid particles. This is especially beneficial for high-pressure injection systems such as common-rail injectors. The results of the B40 fuel characterization test are presented in Table 3

Similarly, UFB treatment on B40 fuel also demonstrated an overall improvement trend. The cetane number increased from 54.7 to 55.5, which accelerates ignition and improves diesel combustion (Gea, 2023). Density remained nearly unchanged (853.3 to 853.4 kg/m³), showing minimal effect of UFB on density. Viscosity slightly decreased from 3.375 to 3.356 mm²/s, potentially enhancing atomization during injection and improving air–fuel mixing quality.

Sulfur content dropped from 0.0511 to 0.0475% m/m, supporting cleaner combustion and reducing SO_2 formation in exhaust gases. Distillation (T90)

Table 2. B0 CN-51 fuel characterization results

No.	Characteristic	Unit	B0 CN-51		
			Normal	With UFB	Standard
1.	Cetane Number	-	53.3	54.1	Min. 51
2.	Density (at 15 °C)	kg/m^3	830.3	831.4	810-850
3.	Viscosity (at 40 °C)	mm^2/s	3.079	3.107	2.0-4.5
4.	Sulfur Content	% m/m	0.001757	0.001707	Maks. 0.005 [1)]
5.	Distillation (T90)	°C	339.1	340.3	Maks. 370
6.	FAME Content	% v/v	0	0	-
7.	Lubricity	micron	372.5	347	Maks. 460
8.	Calorific Value	MJ/kg	43.73	45.68	-
9.	Cleanliness	-	19/18/15/14	19/18/15/13	ISO 4406

(Source: Directorate General of Oil and Gas Decree No.447.K/MG.06/DJM/2023)
(Note 1): The 0.005% m/m limit is equivalent to 50 ppm.

showed no significant change (337.7 to 337.9 °C), indicating stable evaporation properties. FAME content slightly rose from 40.8 to 41.2% v/v, but this fell within the instrument ±2% accuracy margin, hence not significant.

Lubricity improved from 263 to 254 microns, suggesting better lubrication and reduced wear in metal components. Calorific value increased from 42.46 MJ/kg to 42.94 MJ/kg (1.13%), indicating slightly higher energy availability per kilogram of fuel, thus improving efficiency (Sehatpour et al., 2017). Cleanliness also improved from ISO 21/19/14/12 to 20/18/14/11, showing that UFB treatment helps reduce particulate contamination in B40 fuel. This is particularly important since biodiesel is more prone to contamination, and cleaner fuel ensures injector system durability.

Overall, the results show that Ultra Fine Bubble (UFB) treatment improved the quality of both B0 CN-51 and B40 fuels. UFB addition enhances combustion efficiency through improvements in several key parameters. These findings align with Farafisha et al. (2025), who reported significant effects of UFB on cetane number and lubricity of B35 and biodiesel, but no significant changes in density, viscosity, distillation, FAME, and sulfur. Similarly, Asbanu et al. (2025) highlighted UFB as a promising future technology to improve diesel fuel performance in a cleaner and more efficient manner. In their study using pure diesel (B0, CN 51), UFB addition increased cetane number while reducing viscosity, density, flash point, cloud point, and distillation temperature.

In conclusion, UFB technology has a positive impact on fuel properties and performance, both for pure diesel and biodiesel blends. Its effects include enhanced energy efficiency, lower emissions, and improved combustion quality.

Diesel fuel consumption test results

Fuel consumption is one of the key parameters in evaluating the efficiency of diesel engines, particularly in the context of alternative fuels and combustion-supporting technologies. Diesel engines are generally known to have higher thermal efficiency compared to gasoline engines; however, efficiency challenges remain crucial, especially regarding emissions, performance, and operating costs (Koto, 2019). Therefore, various innovations—such as blended fuels and Ultra Fine Bubble (UFB) technology—have been developed to reduce fuel consumption without compromising engine output. Figure 4 presents the graph of fuel consumption at different vehicle speeds in the agricultural transport vehicle.

The graph shows that UFB-treated fuel improves fuel consumption efficiency across all four tested speeds (50, 70, 90, and 120 km/h). Enhanced mixing of air and fuel due to UFB presence results in more complete combustion.

Table 3. B40 fuel characterization results

No.	Characteristic	Unit	B40		
			Normal	With UFB	Standard
1.	Cetane Number	-	54.7	55.5	Min. 51
2.	Density (at 15 °C)	kg/m³	853.3	853.4	815-850
3.	Viscosity (at 40 °C)	mm²/s	3.375	3.356	2.0-5.0
4.	Sulfur Content	% m/m	0.0511	0.0475	Maks. 0.2
5.	Distillation (T90)	°C	337.7	337.9	Maks. 370
6.	FAME Content	% v/v	40.8	41.2	40 [1)]
7.	Lubricity	micron	263	254	Maks. 460
8.	Calorific Value	MJ/kg	42.46	42.94	-
9.	Cleanliness	-	21/19/14/12	20/18/14/11	ISO 4406

(Source: Directorate General of Oil and Gas Decree No.384.K/MG.06/DJM/2024)
(Note 1): In accordance with MEMR Decree No.341.K/EK.01/MEM.E/2024 on Biodiesel Utilization as a 40% blend for diesel oil.

UFB bubbles carry high levels of dissolved oxygen and are extremely small in size, allowing them to disperse uniformly throughout the fuel volume, leading to complete combustion reactions (Herodian, 2025). This increases fuel–oxygen contact, promotes more homogeneous mixing, and raises the cetane number. Consequently, combustion becomes faster, smoother, and more complete, which directly reduces the amount of fuel required to produce the same power output, thereby improving fuel efficiency.

The general trend of the graph resembles an inverted "U" curve. The selected test speeds follow SNI 7554:2010 on vehicle fuel consumption measurement using a chassis dynamometer, with calculation conversions presented in Appendix 5. At 50 km/h, B0 CN-51 UFB recorded a consumption of 6.81 ℓ/100 km, lower than normal B0 CN-51 at 7.02 ℓ/100 km, yielding an efficiency gain of 2.99%. At 70 km/h, B0 CN-51 UFB consumed 4.66 ℓ/100 km, compared to 4.82 ℓ/100 km for the normal condition, giving an efficiency improvement of 3.18%. The highest efficiency occurred at 90 km/h, where B0 CN-51 UFB required only 3.90 ℓ/100 km, lower than 4.13 ℓ/100 km for normal B0 CN-51, resulting in a 5.57% reduction. The most significant efficiency gain was observed at 120 km/h, where consumption dropped from 4.48 ℓ/100 km (normal) to 4.14 ℓ/100 km (UFB), representing a 7.67% improvement. On average, B0 CN-51 with UFB achieved an overall fuel efficiency improvement of approximately 4.85%. A similar trend was observed for B40, where UFB-treated B40 consistently showed lower consumption compared to untreated B40, although the improvements were less pronounced than in B0 CN-51. At 50 km/h, B40 UFB consumed 7.33 ℓ/100 km compared to 7.37 ℓ/100 km for normal B40, giving an efficiency improvement of 0.52%. At 70 km/h, B40 UFB recorded 4.81 ℓ/100 km, more efficient than normal B40 at 4.86 ℓ/100 km, for a 1.03% improvement. The effect became more evident at 90 km/h, where B40 UFB consumed 4.12 ℓ/100 km, compared to 4.21 ℓ/100 km for untreated B40, resulting in a 2.08% efficiency gain. The highest efficiency was at 120 km/h, where B40 UFB consumed 4.30 ℓ/100 km, compared to 4.45 ℓ/100 km for normal B40, giving a 3.29% saving. On average, UFB-treated B40 achieved a fuel efficiency improvement of about 1.73%. Figure 5 illustrates the comparison between fuel consumption and engine speed.

The upward trend in fuel consumption with engine speed reflects real-world engine operating conditions. Although certain optimal efficiency points exist (typically around 2200 rpm), the overall curve rises because higher speeds increase engine load, reduce thermal efficiency, and increase aerodynamic drag. This suggests that UFB provides the most significant fuel-saving effects in the medium rpm range, where air–fuel mixing is optimal. These findings align with Nakatake et al. (2013), who reported that nanobubbles reduced fuel consumption by up to 6.2% at low load and 3.2% at

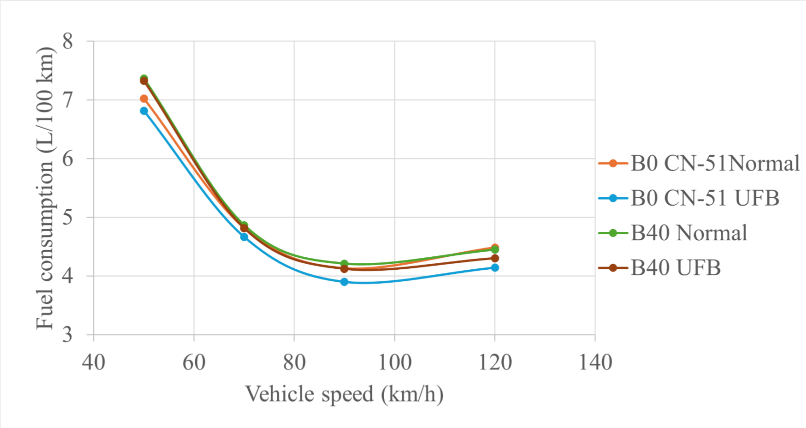


Figure 4. Comparison of fuel consumption at various vehicle speeds

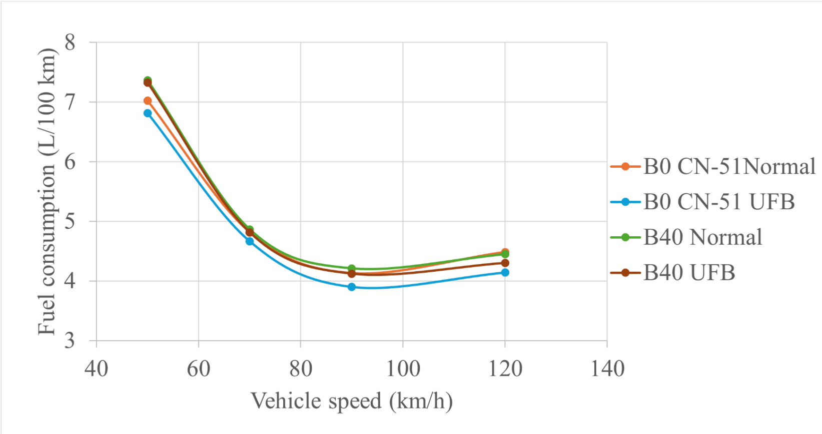


Figure 5. Comparison of fuel consumption at different engine speeds

medium load, owing to enhanced air–fuel mixing and uniform dissolved oxygen distribution. Similarly, Alfath (2023) observed that biodiesel injected with UFB achieved a 13.2% reduction in fuel consumption at peak power. More recently, Herodian (2025) confirmed that UFB technology enhanced diesel engine performance by increasing power output by 7.45% in B35 fuel and reducing specific fuel consumption by 11.2%. Furthermore, UFB improved cetane number and flash point, contributing to more complete combustion, higher fuel efficiency, and lower emissions.

Performance test results of diesel engine fuel

The purpose of the diesel engine performance test was to evaluate the effect of fuel type and treatment on engine performance. Two types of fuel were tested: B0 CN-51 and B40, each under normal conditions and after Ultra Fine Bubble (UFB) treatment. The analyzed parameters included torque, power, and vehicle speed at various engine speeds (rpm). UFB is known to enhance air–fuel mixing quality, leading to improved combustion efficiency. The tests were carried out using a chassis dynamometer, with data recorded in PDF format, converted into Excel, summarized, and presented in performance comparison graphs for each fuel. Figure 6 shows the performance comparison between B0 CN-51 with and without UFB treatment.

With untreated B0 CN-51, engine torque increased significantly, peaking at around 325 Nm at 2200 rpm, before gradually decreasing as rpm rose. Power output increased with rpm, reaching a peak of about 90 kW at 3000 rpm, then declining near 4000 rpm. Vehicle speed exhibited a linear relationship with rpm, reflecting proportional engine response.

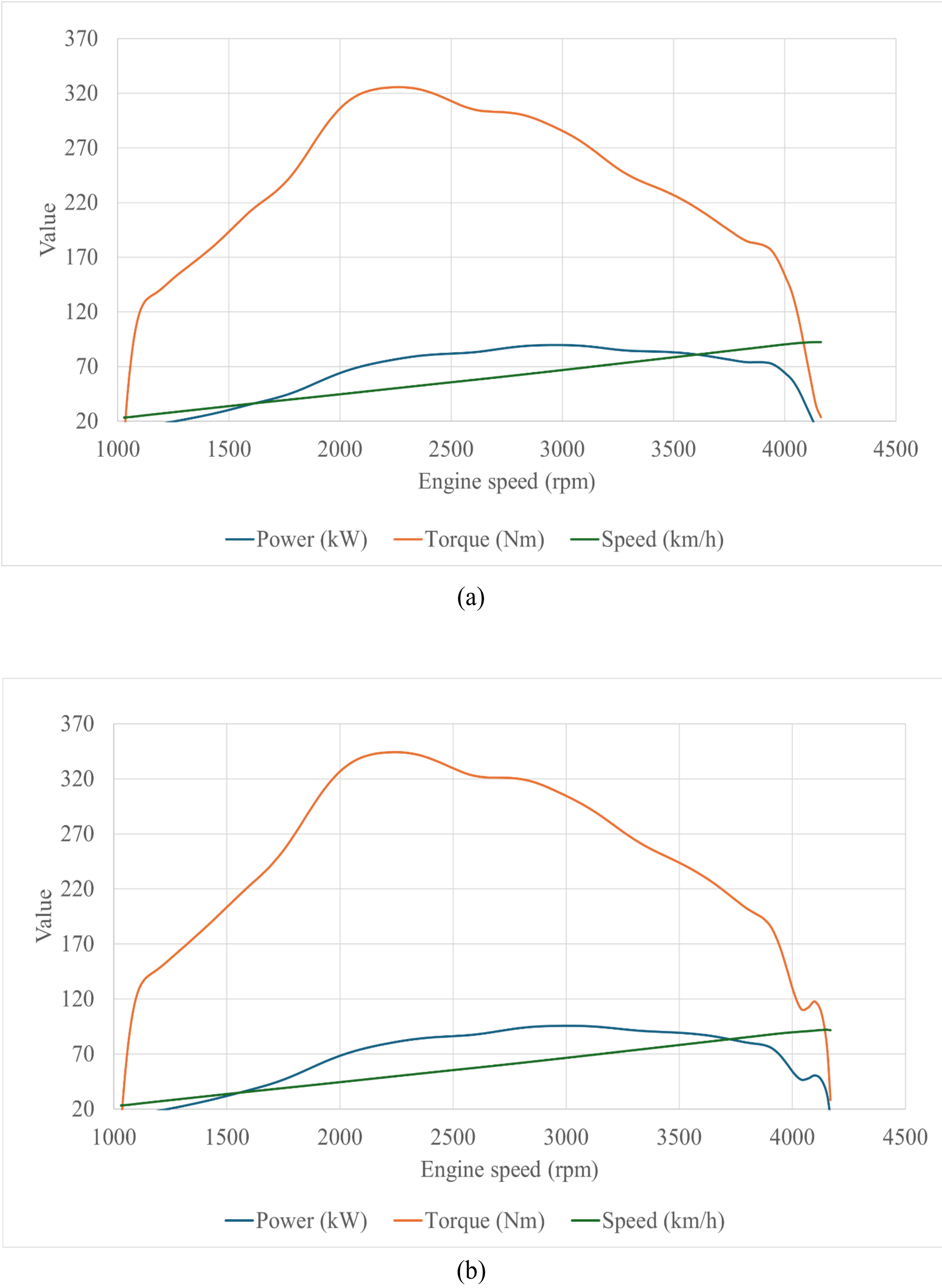


Figure 6. Performance comparison of B0 CN-51 before and after UFB treatment
(a). B0 CN-51 Normal, (b). B0 CN-51 UFB

When using B0 CN-51 with UFB treatment, overall performance improved. The maximum torque was slightly higher, reaching approximately 344 Nm and remaining more stable around 2200 rpm before decreasing. Peak power output rose to about 95 kW, indicating more efficient combustion. Vehicle speed continued to increase linearly with engine rpm. Overall, UFB provided a clear positive effect on B0 CN-51-fueled engine performance.

For untreated B40, torque reached about 320 Nm at 2200 rpm before gradually declining beyond the optimal point. Power increased with rpm, peaking at around 88 kW at 3000 rpm before falling. As with B0 CN-51, vehicle speed increased linearly with rpm, reflecting effective energy conversion, though still below B0 CN-51 performance.

Applying UFB to B40 resulted in noticeable performance improvement, as shown in Figure 7 below. Maximum torque slightly increased to around 326 Nm at 2200 rpm and remained more stable at mid-range rpm. Maximum power also rose to about 90–91 kW, suggesting more efficient fuel combustion. This improvement in torque and power is linked to more complete combustion, producing higher and more stable cylinder pressure. UFB enhanced ignition delay reduction (due to increased cetane number) and optimized chemical energy release into mechanical energy. Improved calorific value, lubricity, and oxygen mixing produced stronger combustion, higher mean effective pressure, and reduced energy loss from uneven burning.

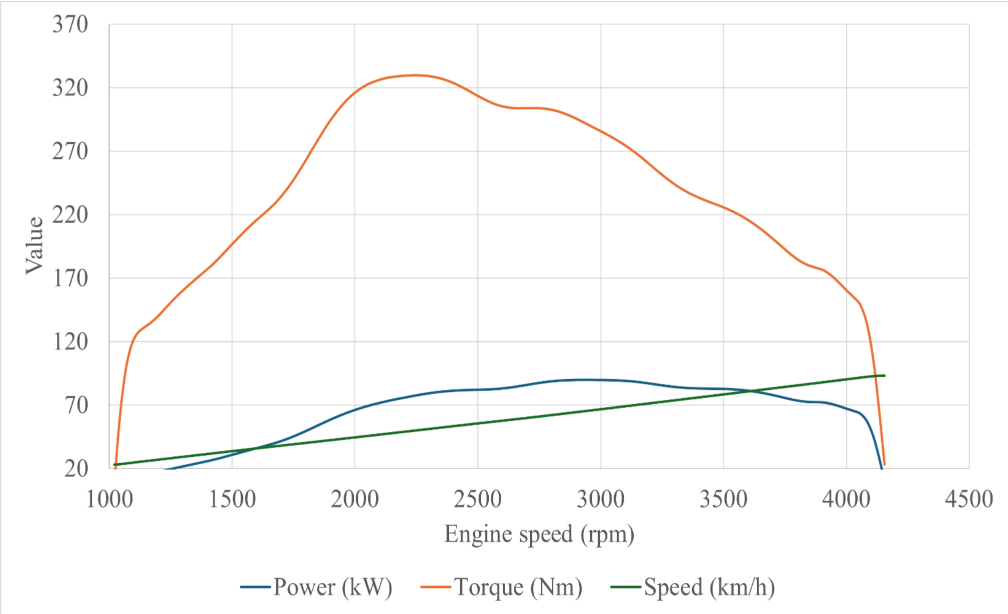
As a result, torque at mid-range rpm (optimal combustion point) and peak power at high rpm both increased. These results confirm that UFB treatment is effective in improving diesel engine performance with both pure diesel fuel (B0) and biodiesel blends (B40).

Comparison of peak power for each fuel

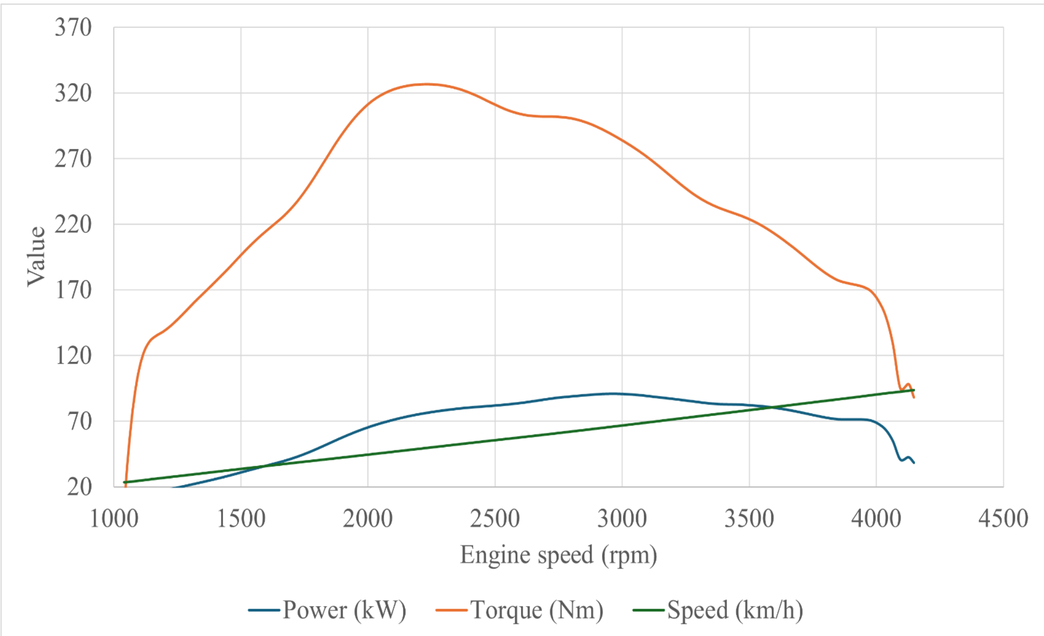
Peak power represents the highest power output that the engine can generate during the testing process. This value indicates the maximum capacity of the engine to convert the chemical energy of the fuel into mechanical energy under the most optimal operating conditions (Nasution et al. 2025). Peak power testing was carried out at varying engine speeds (rpm) to capture the engine's response from ignition to higher operating speeds. In this study, peak power serves as a key reference to assessing the impact of fuel treatments, particularly the addition of Ultra Fine Bubble (UFB), on improving diesel engine performance. UFB is known to enhance the homogeneity of air–fuel mixing and accelerate ignition delay through increased dissolved oxygen content. As a result, combustion efficiency is improved, directly contributing to higher power output. Furthermore, peak power is closely related to fuel characteristics such as cetane number and calorific value. Fuels with higher cetane numbers tend to combust faster and more stably, producing greater power output. Likewise, fuels with higher calorific values contain more energy per unit mass. In this study, peak power changes were carefully observed for two types of fuel (B0 CN-51 and B40), both in untreated conditions and after UFB treatment. The comparison of maximum power values for each fuel treatment is shown in Figure 8 below.

Based on the test results presented in the graphs, B0 CN-51 with Ultra Fine Bubble (UFB) treatment showed an increase in peak power compared to untreated B0 CN-51. B0 CN-51 UFB recorded a peak power of 128.31 HP (95.68 kW) at 3025 rpm, while untreated B0 CN-51 reached only 120.32 HP (89.72 kW) at 2989 rpm. This represents an increase of about 8 HP or 6.6%. This improvement indicates that UFB treatment on B0 CN-51 enhances combustion efficiency and overall engine performance.

Meanwhile, for B40 fuel, the difference between untreated and UFB-treated conditions was not as significant as for B0 CN-51. B40 with UFB treatment achieved a peak power of 121.78 HP (90.81 kW) at 2980 rpm, only slightly higher than untreated B40, which recorded 120.54 HP (89.89 kW) at 2946 rpm. The difference was only about 1.24 HP or around 1%, suggesting that the effect of UFB on increasing peak power in B40 is relatively minor. This may be attributed to the characteristics of the biofuel component B40, which responds differently to UFB treatment compared to pure diesel fuels like B0 CN-51.

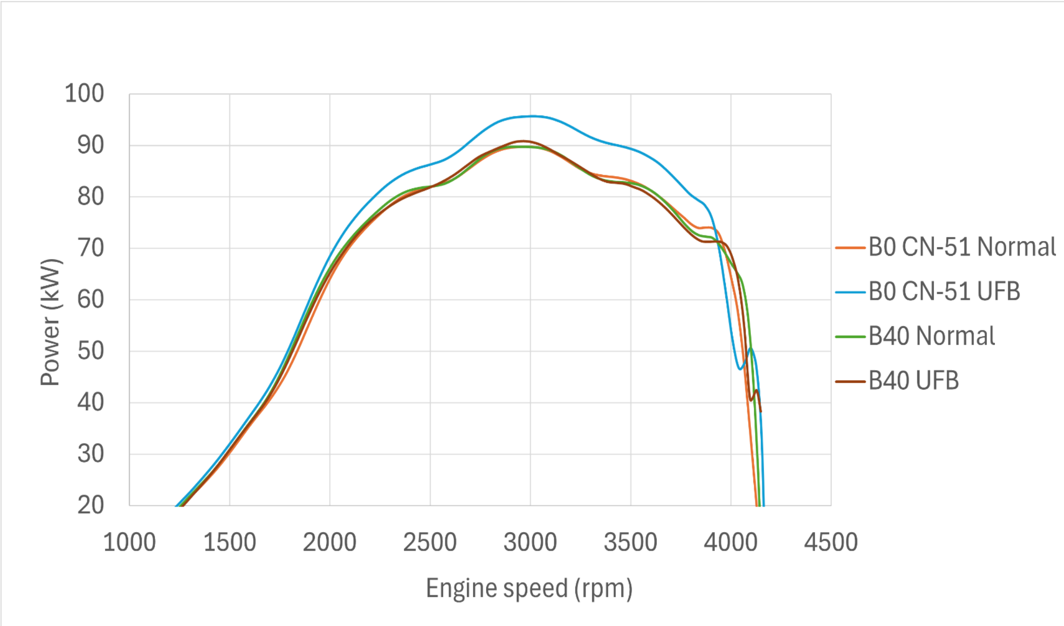


(a)



(b)

Figure 7. Performance comparison of B40 fuel before and after UFB treatment (a). B40 Normal, (b). B40 UFB



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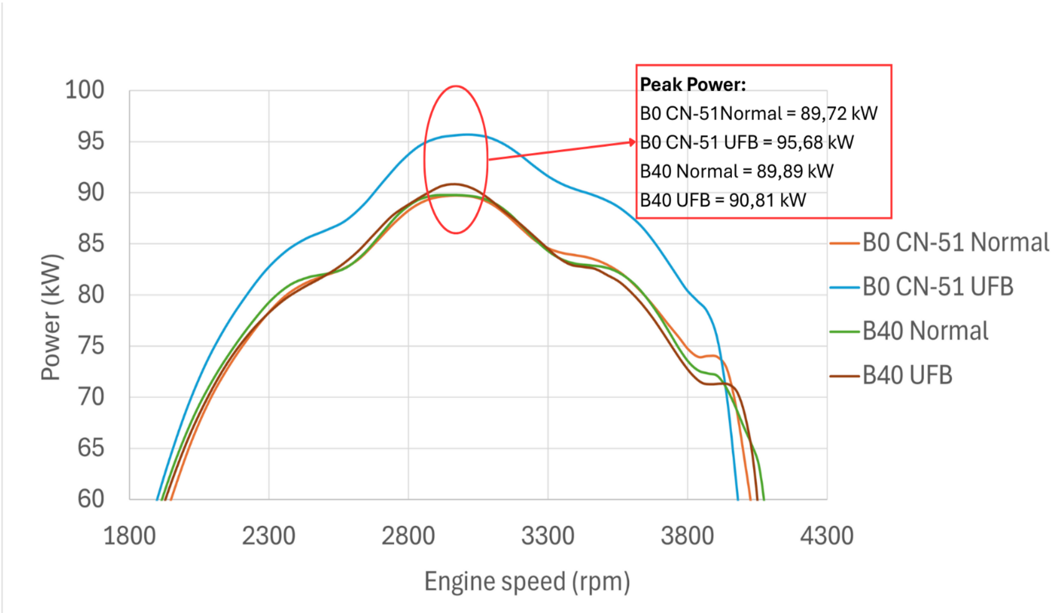
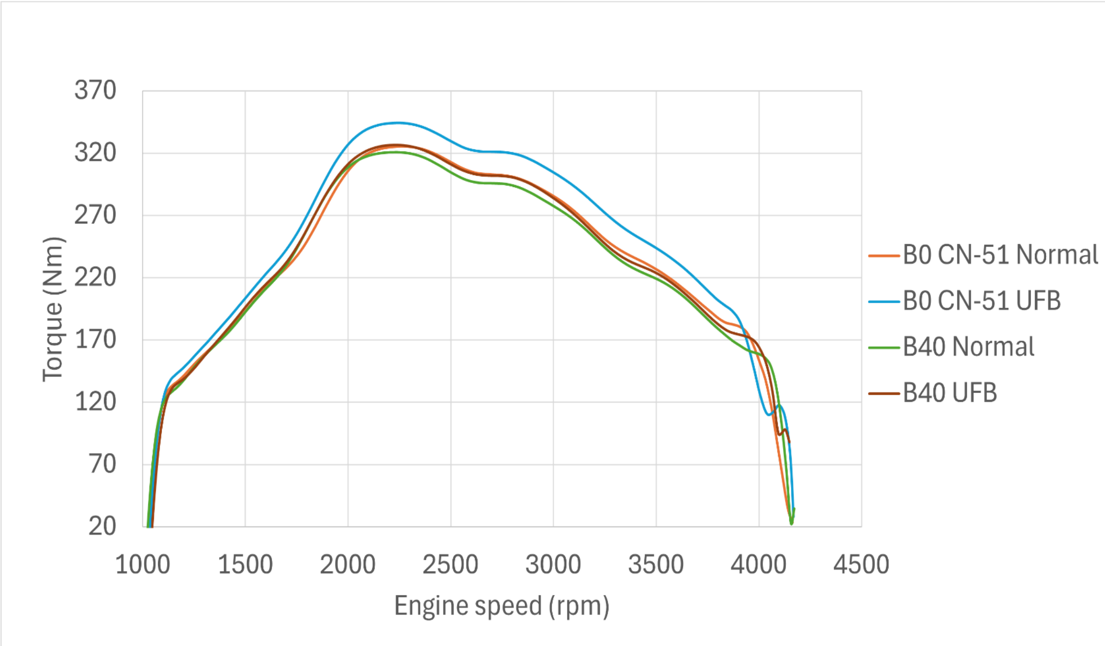
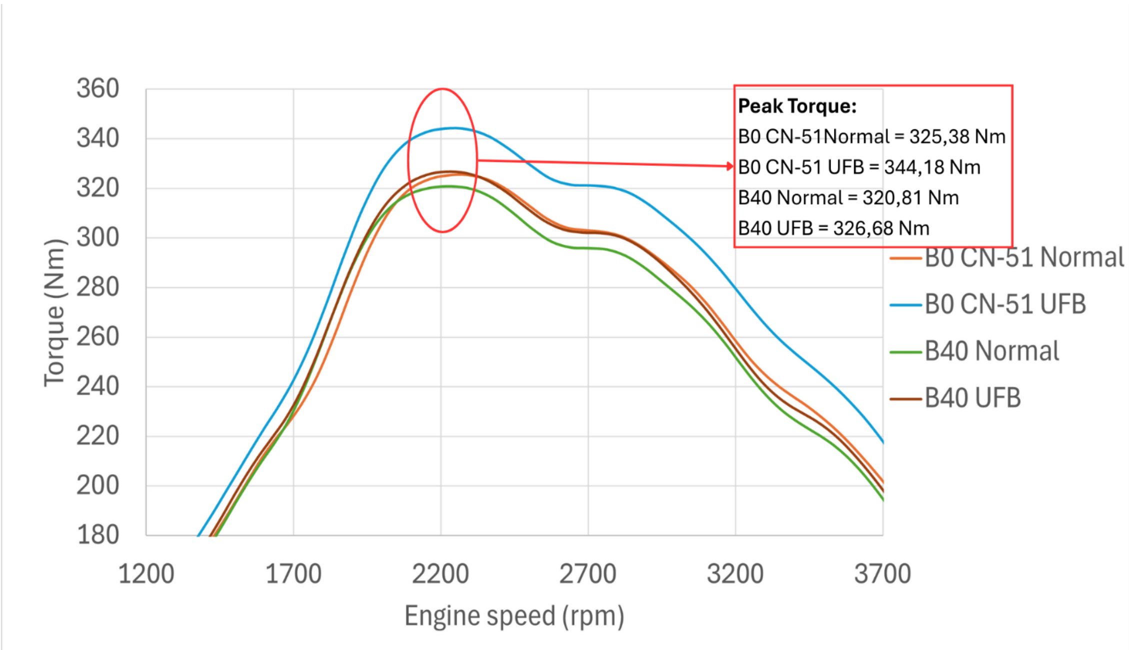


(b)

Figure 8. Comparison of power versus rpm for each fuel treatment (a). Overall, (b). Zoomed in



(a)



(b)

Figure 9. Comparison of torque versus rpm for each fuel treatment (a) overall, (b) zoomed in

Overall, it can be concluded that UFB treatment improves peak power in diesel fuels. This finding is consistent with Herodian (2025), who reported that UFB addition to diesel fuel increased power output, for example by 7.45% in B35.

Comparison of peak torque for each fuel

Maximum torque is the highest value that the engine can achieve during its working cycle. Torque is the rotational force generated by the engine crankshaft, playing an essential role in determining a vehicle's acceleration capability and the maximum load it can handle (Rusli et al. 2022). In performance testing, maximum torque, together with peak power and specific fuel consumption (SFC), is highly valuable for evaluating the strength and combustion efficiency of a fuel under peak load conditions. A comparison of maximum torque is illustrated in Figure 9 below.

Based on the test results and the graphs, B0 CN-51 with UFB treatment produced a maximum torque of 344.18 Nm at 2216 rpm, while untreated B0 CN-51 only reached 325.38 Nm at 2291 rpm. This indicates that the application of Ultra Fine Bubble (UFB) technology increased peak torque by about 5.8%, with the maximum torque also achieved at a lower rpm. In other words, UFB-treated fuel enabled the engine to deliver greater rotational force at lighter engine loads.

For B40 fuel, the maximum torque achieved with UFB treatment was 326.68 Nm at 2218 rpm, slightly higher than that of untreated B40, which reached 320.81 Nm at 2252 rpm. This increase of about 1.8% shows that although the effect of UFB on B40 is not as significant as on B0 CN-51, performance improvement still occurred. Like B0 CN-51, B40 with UFB also reached maximum torque at lower rpm compared to its untreated version, reflecting more efficient combustion potential.

These findings are consistent with Alfath (2023), who reported that UFB addition to a two-wheel tractor using B30 biodiesel resulted in a maximum torque of 1176 Nm, higher than the untreated fuel, which only reached 1019.2 Nm. This demonstrates that diesel engine torque output can be improved with UFB-treated fuel compared to untreated fuel. Moreover, it confirms that UFB not only reduces fuel consumption and increases power but also significantly enhances diesel engine torque performance.

Comparison of specific fuel consumption (SFC) values for each fuel

Specific fuel consumption (SFC) is a key parameter in engine performance evaluation, representing the amount of fuel required to generate one kilowatt of power for one hour. The unit used is grams per kilowatt-hour (g/kWh). A lower SFC value indicates higher engine efficiency in utilizing fuel to produce power (Monasari et al. 2021). A comparison of SFC values for each fuel type is illustrated in Figure 10 below.

Based on the diagram, B0 CN-51 with UFB treatment showed a significant reduction in SFC. Untreated B0 CN-51 recorded an SFC of 42.25 g/

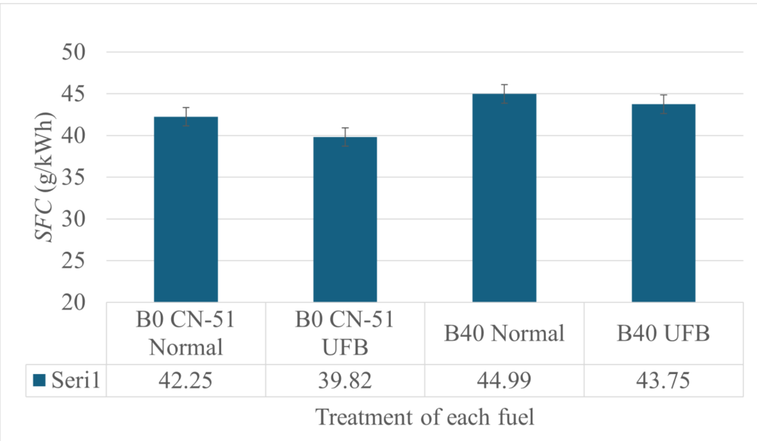


Figure 10. Comparison of specific fuel consumption values for each fuel treatment

kWh, while B0 CN-51 with UFB achieved only 39.82 g/kWh, representing an efficiency improvement of 5.76%. Furthermore, B0 CN-51 with UFB produced higher power output with lower fuel consumption, confirming that improved atomization and combustion were achieved through UFB technology.

For B40 fuel, UFB treatment also improved efficiency, though to a lesser extent than B0 CN-51. The SFC value decreased from 44.99 g/kWh (B40 Normal) to 43.75 g/kWh, reflecting an efficiency gain of about 2.75%. This reduction still demonstrates that UFB technology is effective for biodiesel blends like B40, even though combustion challenges are inherent to biodiesel, limiting efficiency improvements.

Overall, Ultra Fine Bubble (UFB) technology has been proven to enhance combustion efficiency, reduce specific fuel consumption, and improve diesel engine power output. These findings are consistent with Herodian (2025), who reported that UFB addition to biodiesel fuel reduced Specific Fuel Consumption (SFC) by up to 5.2%.

CONCLUSION

The addition of Ultra Fine Bubble (UFB) to B0 CN-51 and B40 fuels resulted in significant changes in the physico-chemical characteristics of the fuels. The calorific value of B0 CN-51 increased from 43.47 to 45.68 MJ/kg (up 4.46%), while B40 rose from 42.46 to 42.94 MJ/kg (up 1.13%). The cetane number increased by 1.5% for B0 CN-51 (from 53.3 to 54.1) and by 1.46% for B40 (from 54.7 to 55.5). In addition, reductions in lubricity and improvements in fuel cleanliness were observed, indicating enhanced combustion quality. Based on these findings, the physico-chemical characteristics of UFB-treated fuels met the quality standards set by the Directorate General of Oil and Gas through Decree No. 447 of 2023 for B0 CN-51 and No. 384 of 2024 for B40.

In engine performance testing, B0 CN-51 with UFB achieved a maximum power of 95.68 kW, representing a 6.63% increase compared to untreated B0 CN-51 (89.72 kW). Maximum torque also increased from 325.38 Nm to 344.18 Nm, or by 5.78%. Specific Fuel Consumption (SFC) decreased from 42.25 g/kWh to 39.82 g/kWh, indicating a 5.76% improvement in efficiency. For B40, maximum power increased by 1.02% (from 89.89 to 90.81 kW), torque rose by 1.83%, and SFC decreased from 44.99 g/kWh to 43.75 g/kWh, corresponding to a 2.75% efficiency gain.

In the fuel consumption test (ℓ/100 km), the highest efficiency improvement was observed in B0 CN-51 with UFB, showing an average consumption reduction of 4.85%, while B40 achieved only a 1.73% reduction.

Overall, UFB has been proven to enhance the physico-chemical quality of fuels, improve engine performance, and reduce fuel consumption. However, the improvements were more significant in B0 CN-51 compared to B40, suggesting that UFB technology is more effective for pure diesel (B0) than for biodiesel blends (B40).

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GLOSSARY OF TERMS

Symbol	Definition	Unit
UFB	Ultra Fine Bubble	
SFC	Spesific Fuel Consumption	
CN	Cetane Number	

MJ/kg	Megajoule per kilogram
Nm	Newton meter
B0	Pure Diesel Fuel (0% Biodiesel)
B35	Diesel Blend with 35% Biodiesel
B40	Diesel Blend with 40% Biodiesel
B100	Pure Biodiesel (100%)
kW	Kilowatt
g/kWh	gram per kilowatt-hour
ℓ/100km	Liter per 100 kilometers
APBN	Anggaran Pendapatan dan Belanja Negara (State Budget of Indonesia)
pH	Potential of Hydrogen
SNI	Standar Nasional Indonesia (Indonesian National Standards)
ASTM	American Standard Testing and Material
T90	Temperature at 90% Recovery
km/h	Kilometer per hour
rpm	Revolutions per minute
°C	Degree Celsius
m-bar	Millibar
FAME	Fatty Acid Methyl Ester
kg/m^3	Kilogram per cubic meter
micron	micrometer
mm^2/s	Square millimeters per second
% m/m	Percent mass by mass
% v/v	Percent volume by volume
ISO	International Organization for Standardization
ppm	Parts per million
HP	Horsepower

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