

Research Paper

Experimental Assessment of Performance, Emissions, and Short-Term Wear of a Heavy-Duty Diesel Engine Fueled with High-Blending FAME and HVO (B40–B70)

Catur Hardiyanto✉, Supriyono, Nur Aklis

Department of Mechanical Engineering, Muhammadiyah University of Surakarta, Surakarta 57162, Central Java, Indonesia

✉ ctr.hardiyanto@gmail.com

🌐 <https://doi.org/10.31603/ae.16033>

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Article Info

Submitted:

21/01/2026

Revised:

29/04/2026

Accepted:

14/05/2026

Online first:

14/05/2026

Abstract

High-blend biodiesel and renewable diesel are increasingly recognized as viable drop-in fuels for heavy-duty diesel engines to meet stringent emission reduction targets. This study experimentally investigates the effects of conventional diesel (B0), diesel-FAME blends (B40F–B70F), and diesel-HVO blends (B40H–B70H) on engine performance, exhaust emissions, and short-term wear characteristics. Tests were conducted on a production heavy-duty Komatsu SAA12V140E-3 engine under controlled operating conditions over a wide range of engine speeds. Engine performance was evaluated in terms of brake torque, brake power, brake thermal efficiency, and brake-specific fuel consumption, while emissions of CO, NO_x, O₂, and CO₂ were measured. The results show that increasing the FAME blending ratio leads to noticeable performance deterioration. At higher blend levels (B60F–B70F), brake power and thermal efficiency decrease by approximately 5–10%, whereas fuel consumption increases by 12–25% relative to B0, primarily due to the lower heating value and higher viscosity of FAME. In contrast, diesel-HVO blends exhibit performance comparable to conventional diesel, with reductions in power and efficiency generally below 5%. All biofuel blends reduce CO emissions by approximately 8–20%; however, FAME blends show a more pronounced increase in NO_x emissions at higher blending ratios, whereas HVO blends provide a more balanced emission profile. Wear metal concentrations in used lubricating oil remain below critical limits for all tested fuels. Overall, the results indicate that HVO offers superior compatibility as a high-blend renewable fuel for heavy-duty diesel engines, achieving favorable performance–emission trade-offs without requiring engine hardware modifications.

Keywords: Biodiesel; Fatty Acid Methyl Ester (FAME); Hydrotreated Vegetable Oil (HVO); Engine performance; Exhaust emissions

1. Introduction

Heavy-duty diesel engines remain the primary power source in the mining, construction, agricultural, and transportation sectors due to their high thermal efficiency, durability, and ability to deliver high torque under demanding operating conditions [1], [2]. However, the extensive use of fossil diesel fuel contributes significantly to greenhouse gas emissions and environmental pollution, particularly CO₂, NO_x, CO, and particulate matter, thereby intensifying

global efforts to develop sustainable alternative fuels for compression-ignition engines [3], [4]. Recent studies have demonstrated that renewable fuels, such as biodiesel and hydrotreated vegetable oil (HVO), can reduce emissions and improve combustion characteristics while maintaining acceptable engine performance under real operating conditions [5], [6].

Fatty Acid Methyl Ester (FAME)-based biodiesel has been widely adopted in diesel

engines due to its renewable origin, oxygenated structure, and ability to reduce particulate emissions and carbon monoxide compared to conventional diesel fuel [7], [8]. Several recent studies have reported that biodiesel blends can enhance combustion efficiency and reduce exhaust emissions; however, higher blending ratios tend to increase brake-specific fuel consumption due to their lower heating value and higher viscosity [9], [10]. The application of high-blend biodiesel (B40–B70) is currently being explored in industrial and heavy-duty diesel engines to reduce fossil fuel dependency while maintaining operational reliability and engine durability [2], [11].

Hydrotreated Vegetable Oil (HVO) has emerged as a promising renewable diesel alternative produced through hydrotreatment processes that remove oxygen and yield paraffinic hydrocarbons with properties similar to petroleum diesel [3], [6]. Previous studies have shown that HVO provides cleaner combustion, lower CO and HC emissions, and improved ignition characteristics due to its high cetane number and low aromatic content, making it suitable for modern diesel engines without major hardware modifications [12], [13]. Furthermore, HVO blends have been reported to reduce emissions while maintaining fuel consumption levels comparable to diesel under various injection and load conditions [10], [14].

Although biodiesel and HVO fuels have been extensively studied, direct comparative experimental investigations between high-blend diesel–FAME and diesel–HVO fuels in heavy-duty diesel engines remain limited. Most existing studies focus on either biodiesel or HVO individually, and comparative analyses under identical operating conditions are still scarce in the literature [6], [9], [12]. Variations in fuel properties, such as viscosity, density, cetane number, and chemical composition, significantly influence spray formation, combustion behavior, engine performance, and emission formation in compression-ignition engines [13], [15]. In addition, lubricating oil analysis is widely used as an indicator of engine wear and fuel compatibility in heavy-duty diesel engines [1], [16]. Therefore, a comprehensive experimental comparison of high-blend renewable fuels in real industrial diesel engines is necessary to evaluate their

performance, emission characteristics, and operational compatibility.

Despite the growing body of research, most previous studies have focused on low-to-medium blending ratios or have examined these fuels independently [10], [12], [17]. Direct experimental comparisons between high-blend diesel–FAME and diesel–HVO fuels under identical operating conditions in production-scale heavy-duty diesel engines remain limited [18], [19]. This study addresses this gap by providing a comprehensive experimental evaluation of high blending ratios (B40–B70), incorporating engine performance, exhaust emissions, and short-term wear characteristics through lubricating oil analysis [9], [16]. The novelty of this work lies in its integrated approach, combining high renewable fuel fractions with real-engine operation and direct fuel-to-fuel comparison, thereby providing new insights into the influence of fuel chemistry on combustion behavior, emission formation, and engine durability.

To address the identified research gap, this study presents a comprehensive experimental investigation of a production-scale heavy-duty diesel engine fueled with high-blend diesel–FAME (B40–B70) and diesel–HVO (HVO40–HVO70) under identical operating conditions. Unlike previous studies that typically examine these fuels separately or at lower blending ratios, this work directly compares their performance at high renewable fractions within the same engine platform. The analysis includes engine torque, brake power, brake thermal efficiency, brake-specific fuel consumption, as well as CO₂, NO_x, and CO emissions. In addition, lubricating oil degradation is evaluated as an indicator of short-term engine wear and fuel compatibility. This integrated assessment provides deeper insights into the interplay between fuel properties, combustion behavior, emission formation, and engine durability in real industrial engine applications.

2. Methods

2.1. Test Fuels

The fuels investigated in this study were classified into three main groups: conventional diesel fuel (B0), diesel–FAME blends (B40–B70), and diesel–HVO blends within the same blending range. Both FAME and HVO fuels were

commercially supplied by the same provider, ensuring consistency in fuel quality and handling conditions.

The FAME fuel represents a conventional biodiesel derived from vegetable oil feedstocks and consists primarily of fatty acid methyl esters containing both saturated and unsaturated carbon chains. In contrast, HVO is a paraffinic renewable diesel produced via hydrotreatment, consisting predominantly of saturated hydrocarbons with negligible oxygen content. Although the detailed feedstock origin (e.g., palm, soybean, or sunflower oil) was not disclosed by the supplier, the physicochemical characteristics of both fuels are consistent with typical commercial FAME and HVO fuels reported in the literature [17], [18].

From a molecular perspective, FAME contains polar ester functional groups ($-\text{COO}-$) together with varying degrees of unsaturation. These characteristics tend to strengthen intermolecular interactions with diesel hydrocarbons, which in turn increases viscosity and limits volatility. In comparison, HVO is composed of non-polar paraffinic hydrocarbons, promoting more effective fuel–air mixing and a shorter ignition delay, ultimately supporting more stable combustion behavior [18].

All fuel samples (B0, B40FAME–B70FAME, and B40HVO–B70HVO) were prepared through a controlled mass-based blending process prior to engine testing, as illustrated in Figure 1. Following preparation, all fuels were characterized according to ASTM and EN standards, including

density, kinematic viscosity, cetane number, lower heating value, and cold-flow properties [20].

The results summarized in Table 1 show systematic variations in fuel properties with increasing blending ratio. For FAME blends, density and viscosity increase while heating value decreases, primarily due to the oxygenated ester structure. In contrast, HVO blends exhibit lower viscosity and higher cetane number. The opposite trends between density and flash point for FAME and HVO are governed by their molecular composition and production pathways. FAME shows concurrent increases due to oxygenated ester interactions and reduced volatility, whereas HVO exhibits decreasing density and increasing flash point due to its paraffinic structure and absence of oxygenated compounds. These contrasting behaviors reflect the fundamental differences between transesterification-derived FAME and hydrotreated paraffinic HVO fuels [11], [21].

2.2. Test Equipment and Engine Operating Conditions

Engine performance, fuel consumption, exhaust emissions, and lubrication condition were evaluated using a production heavy-duty diesel engine (Komatsu SAA12V140E-3), widely applied in mining and construction operations. This engine was selected due to its capability to represent real-world heavy-duty conditions, characterized by large displacement, a high comp-

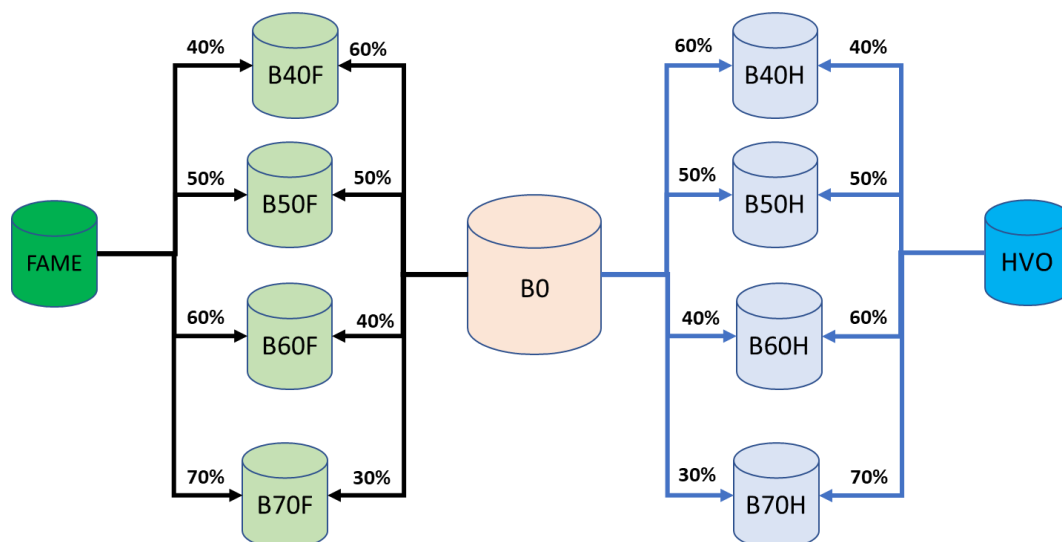


Figure 1. Schematic illustration of the fuel blending scheme used in this study

Table 1. Laboratory-measured physicochemical properties of the investigated fuels

Properties	Units	Method	B0	B40F	B50F	B60F	B70F	B40H	B50H	B60H	B70H
Calorific Value	MJ/kg	ASTM D240	43.18	40.44	39.75	38.96	38.43	41.51	41.22	41.10	40.73
Cetane Number	-	ASTM D613	53.2	54.9	57.1	56.8	56.4	53.4	53.7	53.8	54.8
Cloud Point	°C	ASTM D2500	18	16	17	15	16	16	16	15	16
Cold Filter Phigging Point	°C	ASTM D6371	9	14	11	12	9	13	11	9	11
Density at 15 °C	kg/m ³	ASTM D1298	850.0	858.9	861.3	864.1	866.9	847.7	843.3	836.7	833.7
FAME Content	% vol	ASTM D7371	3.35	37.25	48.63	60.35	69.47	27.6	29.68	30.06	32.99
Flash Point	°C	ASTM D93	82	78	82	89	98	73	81	84	97
Kinematic Viscosity at 40 °C	cSt	ASTM D445	3.702	3.880	3.997	4.020	4.187	3.778	3.738	3.605	3.556
Lubricity (HFRR)	µm	ASTM D6079	276.0	248.5	232.5	235.5	231.0	213.0	228.5	205.0	226.0
Pour Point	°C	ASTM D97	9	3	3	6	6	6	3	6	6
TAN	mg KOH/g	ASTM D974	0.11	0.30	0.31	0.32	0.33	0.21	0.23	0.21	0.24
Water Content	ppm	ASTM D6304	173	318	418	529	704	243	217	249	243

ression ratio, and a high-pressure common-rail fuel injection system. The main technical specifications are summarized in [Table 2](#).

The test engine was coupled with an eddy-current dynamometer to enable precise control of speed and load, with specifications provided in [Table 3](#). A schematic overview of the experimental setup is presented in [Figure 2](#). The test system comprised the engine, dynamometer, fuel and air flow measurement units, a computerized data acquisition system, and exhaust gas analysis equipment.

Operating parameters were controlled through a computer-integrated dynamometer system, ensuring stable and repeatable test conditions. All experiments were conducted up to a maximum engine speed of 2,250 rpm in accordance with the manufacturer's operating limits. Exhaust emissions, including CO, NO_x, O₂, and CO₂, were

measured using a calibrated gas analyzer, as shown in [Table 4](#), as these parameters represent key indicators of combustion quality, oxidation efficiency, and in-cylinder thermochemical processes influenced by fuel properties [\[22\]](#), [\[23\]](#), [\[24\]](#).

To assess potential engine wear, lubricating oil samples were collected after each test cycle using a vacuum extraction method, as illustrated in [Figure 3](#). The samples were subsequently analyzed in an accredited laboratory to determine wear metal concentrations and lubricant degradation. These parameters provide reliable indicators of the engine's tribological condition during operation [\[25\]](#).

To ensure data reliability and repeatability, each fuel condition was tested three times under identical operating conditions, and the reported results represent averaged values. All experiments

Table 2. Specifications of the tested heavy-duty diesel engine

Parameter	Technical Specification
Engine Model	Komatsu SAA12V140E-3, V-configuration
Engine Type	4-stroke, water-cooled diesel engine with 12 cylinders
Rated Power Output	895 kW at 1,900 rpm (approximately 1,200 HP at 1,900 rpm)
Maximum Torque	5,080 Nm at 1,350 rpm (equivalent to about 518 kgm at 1,350 rpm)
Piston Displacement	30.48 liters
Bore X Stroke	140 mm x 165 mm
Rated Operating Speed	1,900 rpm
Engine Oil Capacity	129 liters

Table 3. Technical specifications of the test dynamometer

Parameter	Specification
Brand/Manufacturer	Taylor Dynamometer
Peak Torque Capacity	8,723 Nm
Maximum Power Rating	2,000 HP (=1,491 kW)
Unit Weight	3,195 kg
Rated Operating Speed	4,000 rpm
Rotation Capability	Supports bi-directional rotation

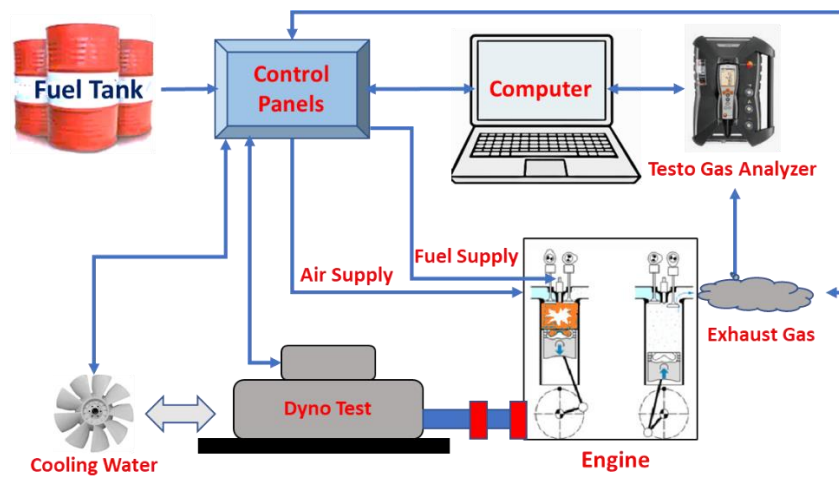


Figure 2. Schematic layout of the engine testing setup

Table 4. Gas analyzer measurement capabilities

Parameter	Measurement Range (ppm)	Accuracy	Resolution (ppm)
CO (H ₂ -compensated)	2,500 – 50,000	±5% of reading (plus pressure related error, -40 to 0 range)	1
CO _{low} (H ₂ -compensated)	500 – 2,500		0.1
NO	1,500 – 20,000		1
NO _{low}	300 – 1,500		0.1
SO ₂	500 – 25,000		1

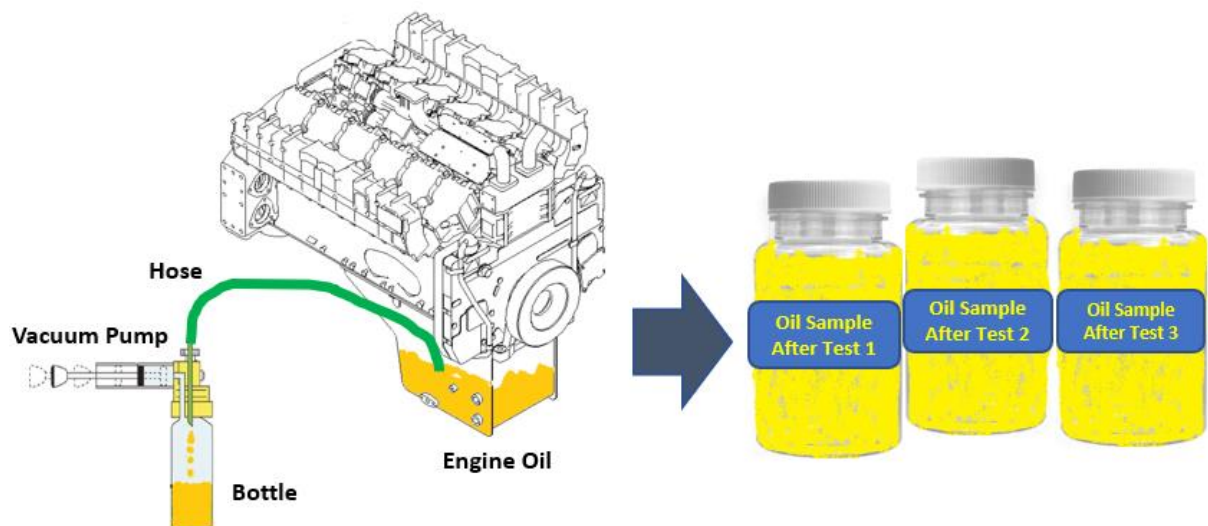


Figure 3. Sampling of lubricating oil

were conducted under controlled ambient conditions to minimize the influence of temperature and humidity on combustion and emission behavior [4], [8].

Engine operating conditions were defined under full-load operation across the investigated speed range, corresponding to 100% load at each test point as controlled by the dynamometer. Testing commenced at 2,250 rpm and was followed by a gradual reduction in speed under a

controlled stepwise loading sequence. Fuel injection was governed by the standard factory electronic control unit (ECU), with injection timing and injection pressure maintained at default manufacturer settings throughout the experiments. No manual adjustments to injection parameters were performed. In addition, exhaust gas recirculation (EGR) was not activated during testing, ensuring that the observed performance and emission characteristics were solely

influenced by fuel properties. All measurements were conducted under steady-state conditions to ensure consistency and reproducibility.

3. Results and Discussion

3.1. Engine Performance

The performance of the heavy-duty diesel engine was evaluated in terms of brake torque, brake power, brake thermal efficiency (BTE), and brake-specific fuel consumption (BSFC), with conventional diesel fuel (B0) used as the baseline reference. These parameters provide a comprehensive representation of engine output characteristics and energy conversion efficiency under varying operating conditions.

Figure 4 presents the relationship between brake torque and engine speed for the baseline fuel, illustrating the repeatability of the experimental measurements. In general, brake torque increases as engine speed decreases from high to medium range, followed by a tendency to stabilize at lower speeds. This behavior is consistent with typical heavy-duty diesel engine operation, where improved volumetric efficiency and more effective combustion phasing at medium engine speeds contribute to higher torque output.

All experiments were conducted under steady-state conditions and repeated three times at each operating point to ensure data reliability. The variation among repeated measurements remained below 2.5%, indicating a high level of experimental consistency. Error bars presented in all figures correspond to the standard deviation (mean $\pm$ SD, $n = 3$), providing a quantitative representation of experimental uncertainty.

3.1.1. Brake torque and power performance

As shown in Figure 5, Figure 6, and Figure 7 the brake torque and brake power of all tested fuels exhibit a clear dependence on engine speed under full-load operating conditions. In this study, engine speed was gradually reduced from 2,250 rpm while maintaining maximum load at each test point using the dynamometer. Under these conditions, both brake torque and brake power increase as engine speed decreases from the high-speed region to the mid-speed range, before tending to level off at lower speeds.

This trend is characteristic of heavy-duty diesel engines. At medium engine speeds, improved volumetric efficiency, more effective air-fuel mixing, and more favorable combustion phasing lead to higher in-cylinder pressure and, consequently, greater torque output. At higher

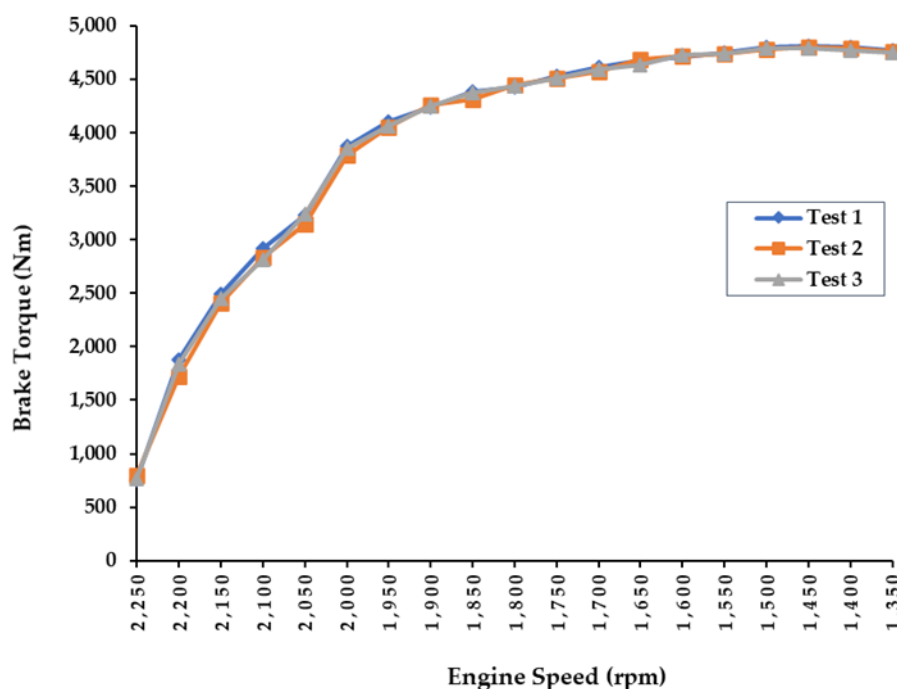


Figure 4. Brake torque repeatability at different engine speeds for B0 fuel

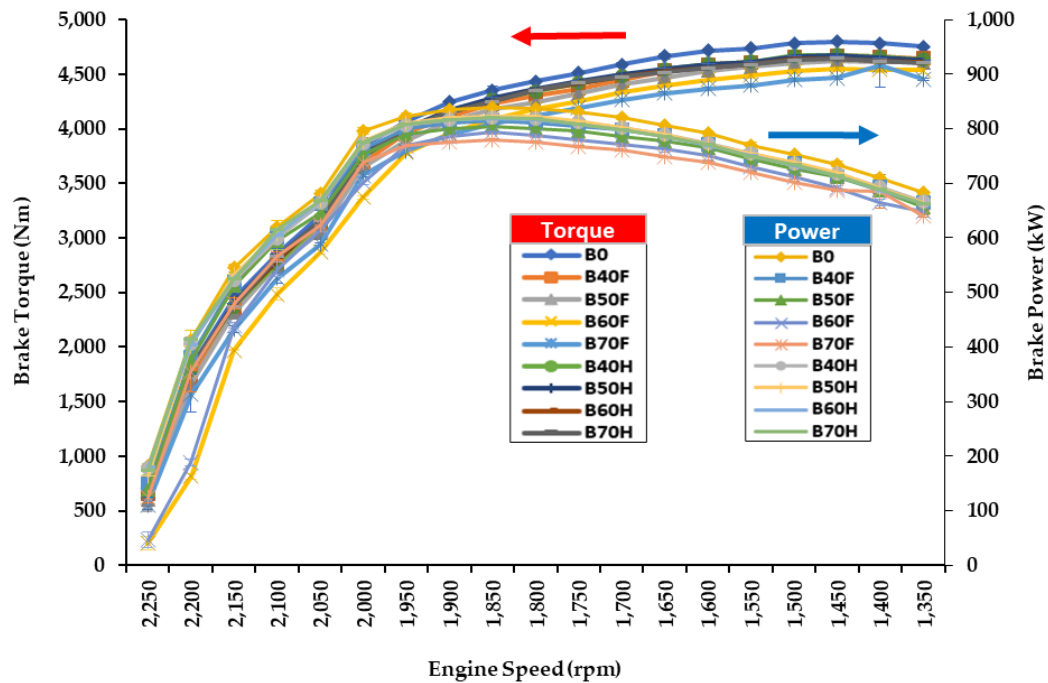


Figure 5. Variation of brake torque and brake power with engine speed for different fuel blends (mean $\pm$ SD, $n=3$)

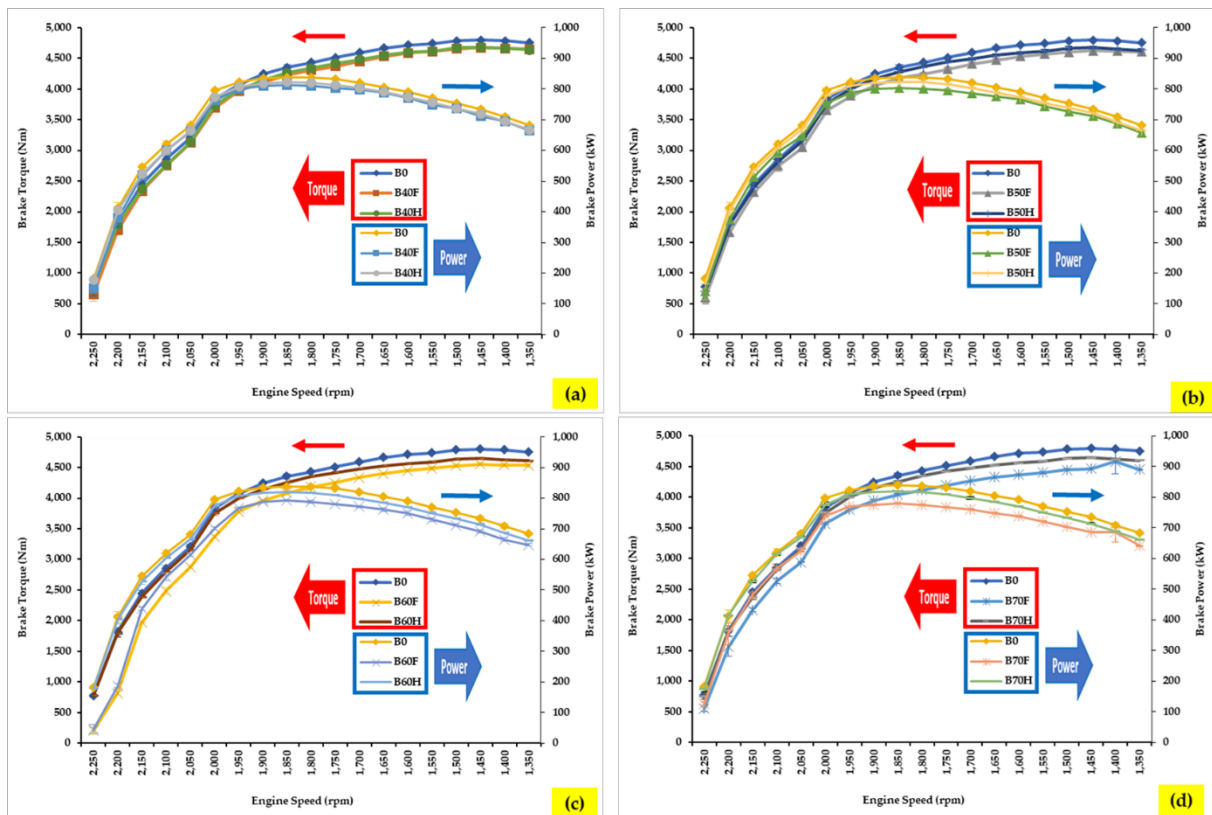


Figure 6. Brake torque and power versus engine speed for different fuel blends: (a) B0-B40F/B40H; (b) B0-B50F/B50H; (c) B0-B60F/B60H; (d) B0-B70F/B70H (mean $\pm$ SD, $n=3$)

engine speeds, limited combustion time and increased mechanical losses restrict pressure development, whereas at lower speeds, further gains in torque are constrained by air supply

limitations and injection control under full-load operation.

Overall, the results confirm that fuel physicochemical properties play a key role in

determining engine performance at high blending ratios, with FAME leading to noticeable performance penalties, while HVO maintains performance characteristics closer to conventional diesel.

3.1.2. Brake thermal efficiency and brake-specific fuel consumption

Brake thermal efficiency (BTE) and brake-specific fuel consumption (BSFC) are key indicators for assessing the energy conversion performance of compression-ignition engines.

BTE represents the fraction of fuel chemical energy effectively converted into useful brake power, whereas BSFC quantifies the amount of fuel required to produce a unit of output power. These parameters are strongly governed by fuel physicochemical properties, including heating value, viscosity, density, and cetane number, which influence spray atomization, ignition delay, and combustion completeness [15], [26].

As shown in Figure 8 and Figure 9, BTE and BSFC exhibit a clear inverse relationship across the investigated engine speed range. BTE increases as

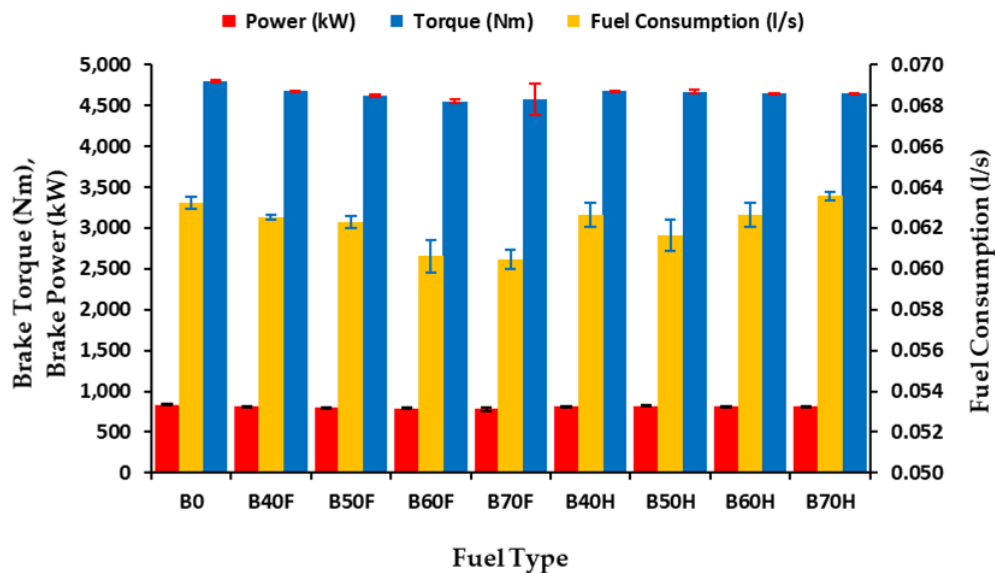


Figure 7. Comparison of peak engine performance parameters for different fuel blends (mean $\pm$ SD, $n = 3$)

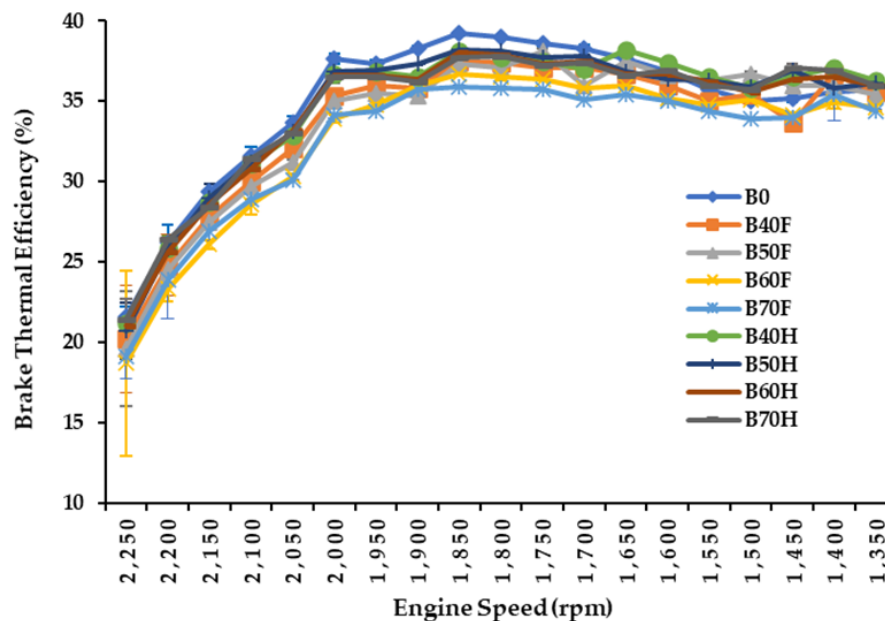


Figure 8. Variation of brake thermal efficiency with engine speed for all tested fuel blends (mean $\pm$ SD, $n = 3$)

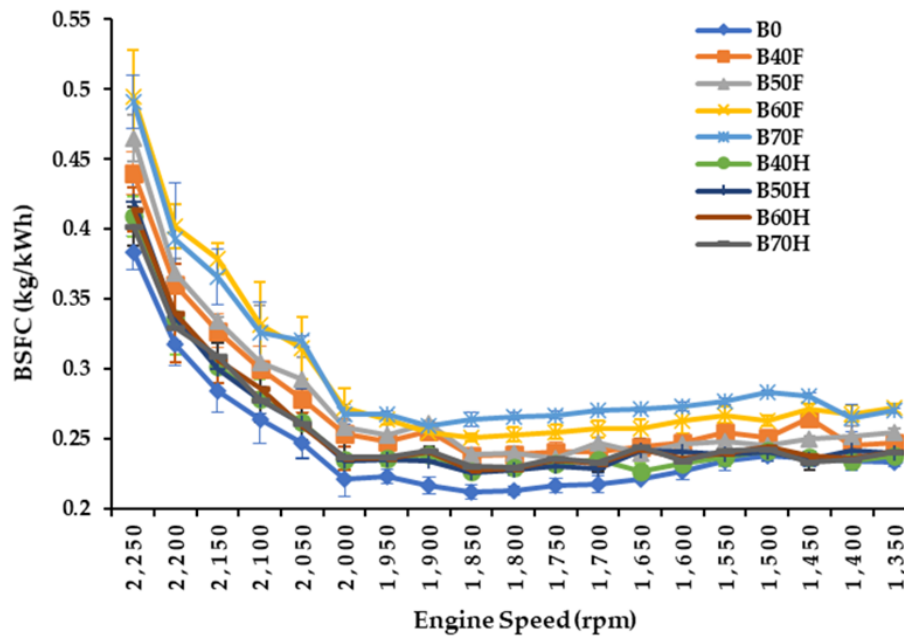


Figure 9. Brake-specific fuel consumption versus engine speed for different fuel blends (mean $\pm$ SD, $n = 3$)

engine speed decreases from high-speed operation to the mid-speed region, reaching a maximum near the peak torque condition, and then slightly declines at lower speeds. In contrast, BSFC decreases toward the mid-speed region and increases again at lower engine speeds. This behavior is primarily attributed to improved volumetric efficiency and more favorable combustion phasing at medium engine speeds, where the heat release process is better aligned with the expansion stroke [17], [27].

The experimental deviations remain relatively small across most operating conditions, indicating

stable and repeatable measurements. Slightly higher variability is observed at the highest engine speed; however, this does not affect the overall trends or the comparative behavior among the tested fuels.

A more distinct comparison among fuels is observed at the maximum torque condition, as presented in Figure 10 and Figure 11. Conventional diesel fuel (B0) achieves the highest BTE of approximately 39.2% and the lowest BSFC of about 0.212 kg/kWh. In contrast, diesel-FAME blends exhibit a progressive deterioration in efficiency, with BTE decreasing from 37.4% (B40F)

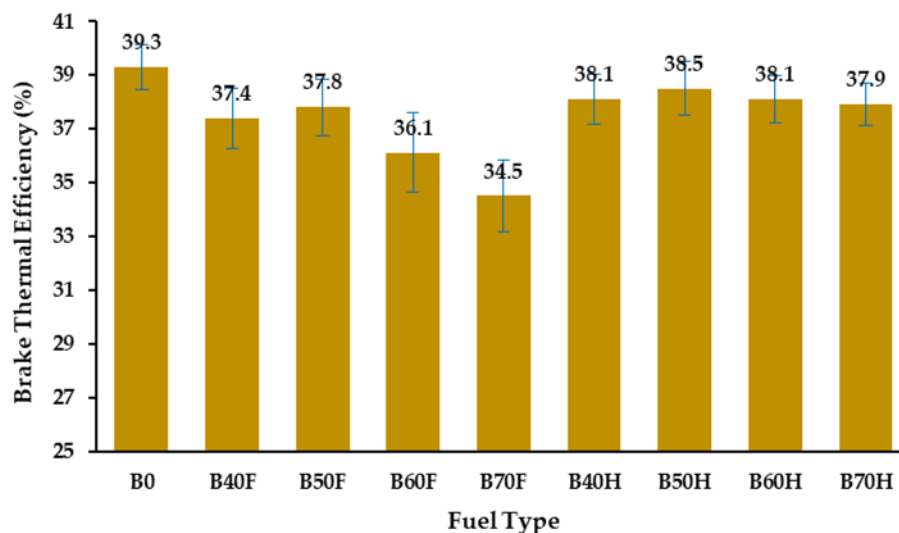


Figure 10. Brake thermal efficiency of the tested fuel blends at maximum brake torque (mean $\pm$ SD, $n = 3$)

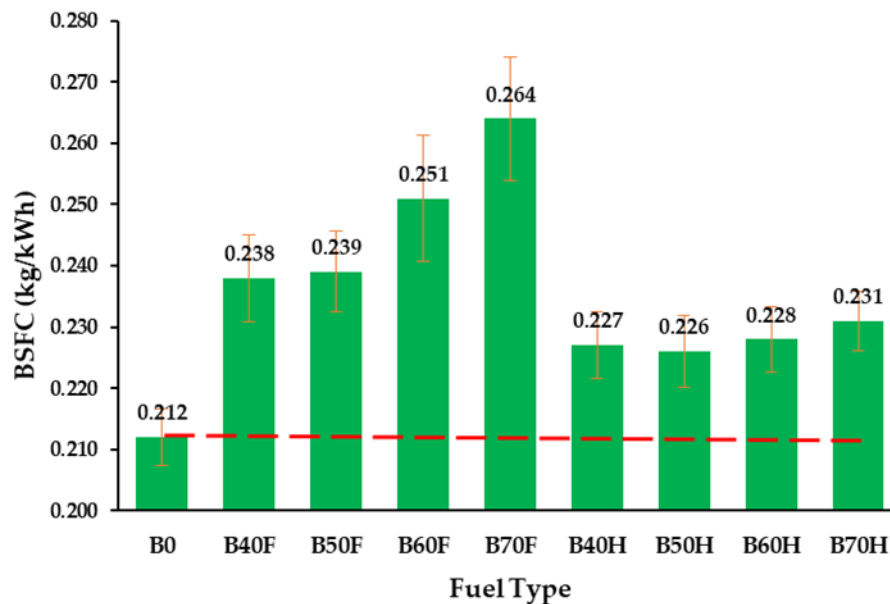


Figure 11. Brake-specific fuel consumption of the tested fuel blends at maximum brake torque condition (mean $\pm$ SD, $n = 3$)

to 34.5% (B70F), accompanied by an increase in BSFC ranging from 0.238 to 0.264 kg/kWh. This behavior is primarily associated with the lower heating value and higher viscosity of FAME, which impair spray atomization, slow evaporation, and lead to less homogeneous air–fuel mixing, ultimately reducing combustion efficiency [8], [10], [28].

3.1.3. Combustion characteristics interpretation

Although direct measurements of in-cylinder pressure and heat release rate (HRR) were not performed, the combustion behavior of the tested fuels can be reliably inferred from key performance indicators, including brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and exhaust gas temperature. These parameters are closely associated with ignition characteristics, fuel–air mixing quality, and the overall heat release process in compression-ignition engines [15], [26].

The lower BTE and higher BSFC observed for diesel–FAME blends indicate a reduction in combustion efficiency. This behavior is primarily attributed to the higher viscosity and lower heating value of FAME, which negatively affect spray atomization and evaporation processes. As a result, fuel–air mixing becomes less homogeneous, leading to slower combustion rates and a less efficient heat release process [10], [28]. In addition, the presence of oxygenated molecular

structures in FAME may promote localized oxidation; however, this effect is insufficient to compensate for the limitations in spray and evaporation characteristics at higher blending ratios.

In contrast, diesel–HVO blends exhibit combustion characteristics that are much closer to those of conventional diesel fuel. The paraffinic molecular structure and higher cetane number of HVO contribute to shorter ignition delay and more controlled combustion phasing. These properties promote a more uniform heat release process and improved combustion stability, resulting in higher thermal efficiency and lower fuel consumption compared to FAME blends [14], [18].

The observed exhaust gas temperature trends further support this interpretation. Higher exhaust temperatures in FAME blends suggest prolonged combustion duration and increased heat losses, likely due to delayed and less efficient combustion. Conversely, relatively lower exhaust temperatures for HVO blends indicate more effective energy conversion and a more favorable alignment between heat release and the expansion stroke [12].

These differences become more pronounced under high-load conditions, where fuel injection rates increase and the sensitivity to spray formation and ignition behavior becomes more critical. Under such conditions, FAME blends

tend to exhibit less optimal combustion phasing, while HVO blends maintain combustion characteristics closer to those of diesel fuel.

Overall, the results demonstrate that fuel physicochemical properties play a dominant role in governing ignition delay, spray development, and heat release behavior, which in turn determine combustion efficiency and engine performance in heavy-duty diesel engines. This interpretation also provides a fundamental basis for understanding the emission trends discussed in the subsequent section.

3.2. Exhaust Emission Test Results

Exhaust emission measurements were conducted to evaluate the environmental impact of heavy-duty diesel engine operation fueled with conventional diesel (B0), diesel-FAME blends (B40F–B70F), and diesel-HVO blends (B40H–B70H). The primary emission species analyzed included carbon monoxide (CO), nitrogen oxides

(NO_x), oxygen (O₂), and carbon dioxide (CO₂), as these parameters collectively reflect combustion efficiency, oxidation behavior, and emission formation pathways [27]. A comparative overview of exhaust gas concentrations for all tested fuels is presented in Figure 12, where CO–NO_x and O₂–CO₂ results are shown separately.

All measurements were performed under steady-state conditions at full load (100%), with each data point obtained from three repeated experiments. The associated error bars represent the standard deviation (mean ± SD, $n = 3$), providing a quantitative measure of experimental uncertainty. In general, the variation among repeated measurements remained within an acceptable range, although slightly larger deviations were observed at high engine speed conditions (2,250 rpm). This behavior is attributed to increased cycle-to-cycle combustion variability and reduced combustion duration at high speeds, which can affect emission stability.

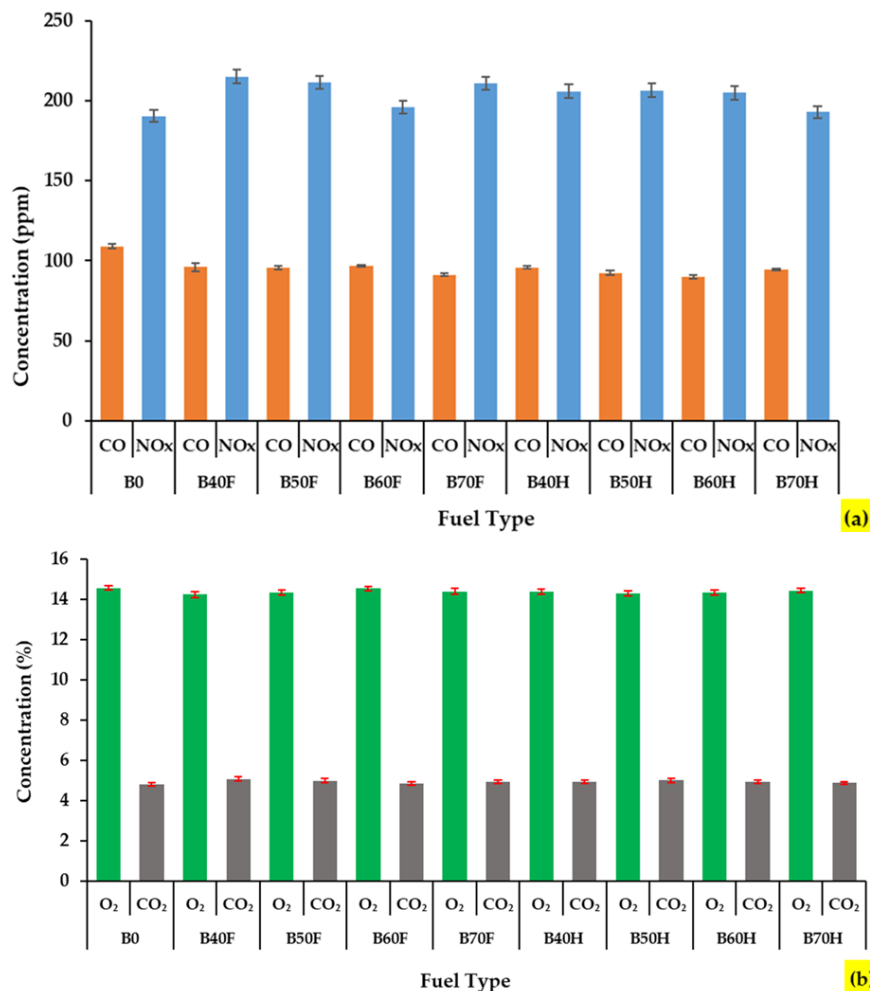


Figure 12. Exhaust gas concentrations of CO, NO_x, O₂, and CO₂ for different fuel blends: (a) CO–NO_x and (b) O₂–CO₂ (mean ± SD, $n = 3$)

In general, diesel–FAME blends exhibit a clear tendency toward lower CO emissions compared to B0, accompanied by a progressive increase in NO_x emissions as the FAME blending ratio increases. This trade-off behavior is primarily attributed to the oxygenated molecular structure of FAME, which enhances carbon oxidation while simultaneously promoting higher local combustion temperatures, thereby intensifying thermal NO_x formation. In contrast, diesel–HVO blends demonstrate a more balanced emission profile, characterized by reduced CO emissions and a comparatively moderate increase in NO_x levels [21]. This behavior is closely related to the paraffinic composition and high cetane number of HVO, which promote shorter ignition delay and more controlled heat release, thereby limiting excessive peak temperatures during combustion.

The O₂ and CO₂ emission results indicate that all tests were conducted under relatively lean combustion conditions, consistent with full-load diesel engine operation without exhaust gas recirculation (EGR). Under these conditions, the observed variations in emission behavior are primarily governed by fuel physicochemical properties and combustion kinetics rather than by significant changes in the global air–fuel ratio. Therefore, the differences in emission characteristics among the tested fuels can be directly associated with variations in molecular structure, oxygen content, and ignition quality.

These overall trends provide a consistent basis for a more detailed discussion of individual emission components, including CO, NO_x, O₂, and CO₂, in the following subsections.

3.2.1. Carbon monoxide (CO) emissions

Carbon monoxide (CO) is a key indicator of incomplete combustion in compression-ignition engines, formed when carbon oxidation is limited by locally insufficient oxygen availability, low combustion temperature, or inadequate reaction time. Under full-load operation, variations in engine speed significantly influence CO formation through their effects on fuel injection rate, mixture distribution, and combustion stability.

As shown in **Figure 13**, all tested fuels exhibit an overall increase in CO emissions as engine speed decreases from 2,250 rpm to approximately 1,350 rpm. At high engine speed (2,250 rpm), CO emissions remain relatively low for all fuels, with B0 producing approximately 18 ppm. Diesel–FAME blends demonstrate a more pronounced reduction in CO emissions, particularly at higher blending ratios, with B70F reaching approximately 11 ppm, corresponding to a reduction is primarily attributed to the presence of reduction of nearly 39% relative to B0. This chemically bound oxygen in FAME, which enhances oxidation reactions during the diffusion combustion phase and suppresses CO formation, even under high-load conditions [29].

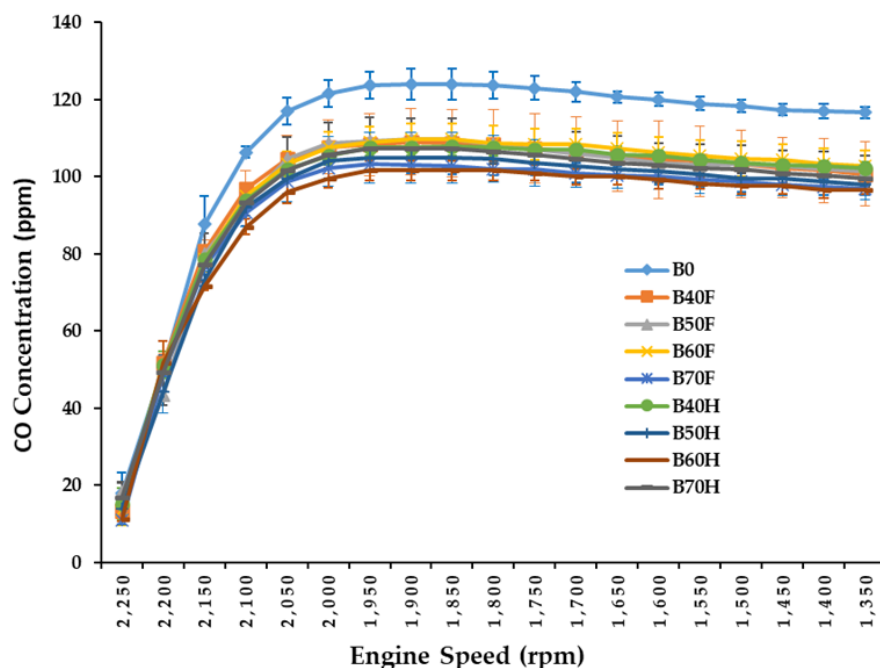


Figure 13. Carbon monoxide (CO) emissions versus engine speed for different fuel blends (mean $\pm$ SD, $n = 3$)

As engine speed decreases toward the maximum power region (approximately 1,850–1,900 rpm), CO emissions increase substantially for all fuels. This trend is associated with higher fuel injection rates and the formation of locally rich combustion zones, which limit oxygen availability and slow down carbon oxidation. Under these conditions, CO emissions for B0 reach peak values of approximately 124 ppm, whereas FAME blends remain within the range of 102–110 ppm, representing a reduction of approximately 11–18% compared to the reference fuel. Although the higher viscosity of FAME may adversely affect spray atomization, the oxygenated nature of the fuel remains the dominant factor, promoting more complete combustion under high-load operation [10].

Diesel–HVO blends exhibit a more stable CO emission profile across the entire engine speed range. At mid-speed conditions, CO emissions for B50H–B60H fall within approximately 100–105 ppm, which is lower than those of B0 and comparable to FAME blends. This behavior is associated with the high cetane number and paraffinic structure of HVO, which promote shorter ignition delay and a more homogeneous combustion process, thereby limiting CO formation despite the absence of chemically bound oxygen [18].

The experimental uncertainty associated with CO measurements remains generally low across most operating conditions, as indicated by the relatively small error bars. Slightly larger deviations are observed at higher engine speeds, which can be attributed to increased cycle-to-cycle variability and reduced combustion duration under these conditions.

Overall, the results confirm that partial substitution of conventional diesel fuel with renewable fuels consistently reduces CO emissions across the full operating range of a heavy-duty diesel engine. While FAME provides a stronger reduction effect due to its intrinsic oxygen content, HVO offers a more stable and controlled reduction without compromising combustion stability. These findings highlight the effectiveness of both fuel types in mitigating incomplete combustion emissions under high-load engine operation.

3.2.2. Nitrogen oxide (NO_x) emissions

Nitrogen oxides (NO_x) are among the most critical regulated emissions in heavy-duty diesel engines and are predominantly formed via the thermal NO_x mechanism. This mechanism is strongly governed by peak in-cylinder temperature, oxygen availability, and the residence time of combustion gases within high-temperature zones. Under steady-state full-load (100%) operation without exhaust gas recirculation (EGR), both engine speed and fuel physicochemical properties play a decisive role in determining NO_x formation characteristics.

As shown in [Figure 14](#), all tested fuels exhibit an overall increase in NO_x emissions as engine speed decreases from 2,250 rpm to approximately 1,350 rpm. At high engine speed (2,250 rpm), NO_x emissions remain relatively low due to the shorter residence time of combustion gases, with B0 recording approximately 56 ppm. Under these conditions, diesel–FAME and diesel–HVO blends show a relatively wide variation in NO_x levels, ranging from 42.77 ppm for B60F to 84.83 ppm for B60H. This variation reflects the sensitivity of early-stage NO_x formation to ignition characteristics and initial combustion temperature, both of which are influenced by fuel composition [30].

As engine speed decreases toward the medium-speed region associated with maximum power output (approximately 1,850–1,800 rpm), NO_x emissions increase significantly for all fuels due to higher injected fuel mass and elevated combustion temperatures. Under these conditions, NO_x emissions for B0 reach approximately 203–205 ppm. Diesel–FAME blends consistently exhibit higher NO_x levels, particularly at higher blending ratios, with B70F reaching approximately 226–228 ppm. This increase is primarily attributed to the oxygenated molecular structure of FAME, which enhances oxidation reactions and promotes higher local flame temperatures, thereby intensifying thermal NO_x formation. In addition, the relatively longer combustion duration associated with FAME can increase the residence time of gases in high-temperature regions, further promoting NO_x formation [31].

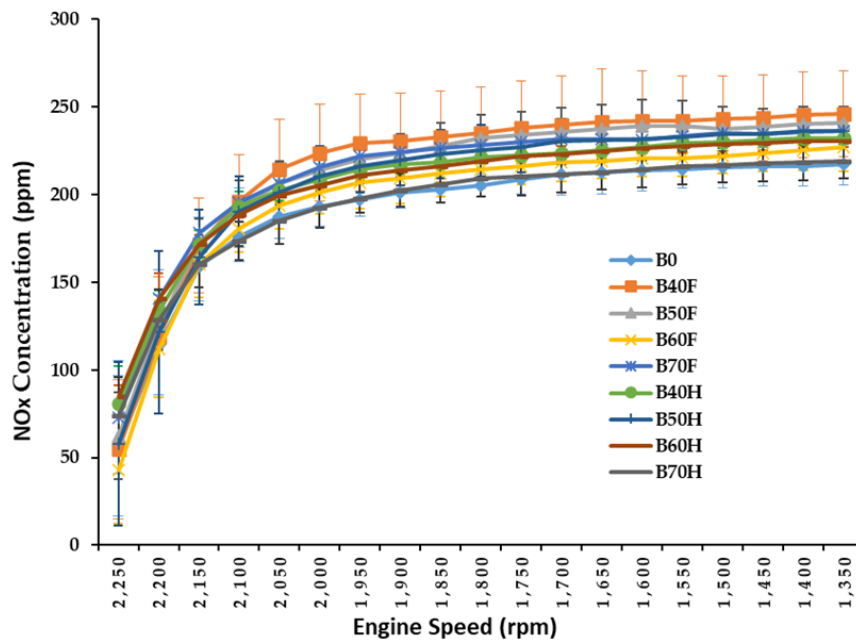


Figure 14. Variation of nitrogen oxide (NOx) emissions with engine speed for different fuel blends (mean $\pm$ SD, $n = 3$)

In contrast, diesel–HVO blends demonstrate a comparatively moderate NOx emission behavior relative to FAME blends at equivalent blending ratios. At approximately 1,800 rpm, NOx emissions for B50H and B60H fall within the range of 219–225 ppm, generally lower than those observed for corresponding FAME blends. This behavior is closely associated with the high cetane number and paraffinic molecular structure of HVO, which promote shorter ignition delay and a more rapid and controlled combustion process. As a result, the residence time of combustion gases at peak temperature is reduced, limiting excessive thermal NOx formation. Furthermore, the absence of chemically bound oxygen in HVO prevents additional temperature rise compared to oxygenated fuels [4], [32].

The variability of NOx measurements, as indicated by the error bars (mean $\pm$ SD, $n = 3$), remains within an acceptable range across all operating conditions. Slightly larger deviations are observed at higher engine speeds, which can be attributed to increased cycle-to-cycle combustion fluctuations and shorter combustion duration. At medium and lower engine speeds, the reduced variation reflects more stable combustion behavior and improved measurement repeatability.

Overall, the results confirm the existence of a clear trade-off between CO and NOx emissions

when oxygenated fuels such as FAME are employed. While FAME effectively reduces CO emissions, it tends to increase NOx formation at higher blending ratios. In contrast, HVO provides a more balanced emission profile, maintaining relatively controlled NOx levels while preserving favorable combustion characteristics. These findings highlight the importance of fuel selection and combustion control strategies in optimizing emission performance for heavy-duty diesel engines operating with high renewable fuel fractions.

3.2.3. Oxygen (O₂) emissions

The concentration of oxygen (O₂) in the exhaust gas is a key parameter for assessing combustion completeness in diesel engines, particularly when alternative fuels are employed [17], [33], as it directly reflects oxygen consumption during the combustion process under varying engine operating conditions. Therefore, analysis of O₂ emissions provides important insight into fuel reactivity, air–fuel mixing quality, and overall combustion efficiency in heavy-duty diesel engines.

O₂ concentration decreases as engine speed is reduced from 2,250 rpm to approximately 1,700 rpm and then remains relatively stable at lower engine speeds, as shown in Figure 15. At high engine speed (2,250 rpm), B0 exhibits the highest O₂ concentration, reaching approximately 17.18%,

while all blended fuels show comparatively lower values. This trend indicates that the use of renewable fuel blends enhances oxygen consumption during combustion, particularly under light-load conditions.

Diesel–FAME blends consistently result in lower O₂ concentrations than B0 across the entire engine speed range. This behavior is attributed to the presence of chemically bound oxygen within the FAME molecular structure, which acts as an internal oxidizer and promotes more complete combustion, thereby reducing residual oxygen in the exhaust gas [10], [13], [28], [34].

In contrast, diesel–HVO blends exhibit O₂ concentration trends that are slightly lower than those of B0 but generally higher than those observed for FAME blends. The high cetane number and pure paraffinic structure of HVO facilitate faster ignition and more stable combustion without contributing chemically bound oxygen, as in the case of FAME. Consequently, oxygen consumption increases moderately, resulting in exhaust O₂ concentrations that fall between those of B0 and FAME blends [12], [18], [35].

At medium to low engine speeds ($\leq 1,800$ rpm), the differences in O₂ concentration among the tested fuels become relatively small, indicating that combustion behavior is increasingly

governed by engine operating conditions rather than fuel composition.

The error bars (mean $\pm$ SD, $n = 3$) are relatively larger at high engine speeds (2,250–2,150 rpm), which can be attributed to increased cycle-to-cycle variability and reduced combustion stability under light-load conditions [27]. As engine speed decreases and engine load increases, the variability becomes significantly smaller, indicating improved combustion stability and higher repeatability of the experimental data. Despite this increased scatter at high speeds, the overall trends remain consistent and do not affect the validity of the observed differences among fuel blends.

Taken together, these findings indicate that both FAME and HVO blends enhance combustion effectiveness, as reflected by reduced exhaust O₂ concentrations compared to conventional diesel fuel, without indicating incomplete combustion.

3.2.4. Carbon dioxide (CO₂) emissions

Carbon dioxide (CO₂) emissions are widely recognized as a key indicator of carbon oxidation completeness in diesel engine combustion, as CO₂ represents the final product of fully oxidized carbon species [3], [36]. As illustrated in Figure 16, the variation of CO₂ concentration with engine

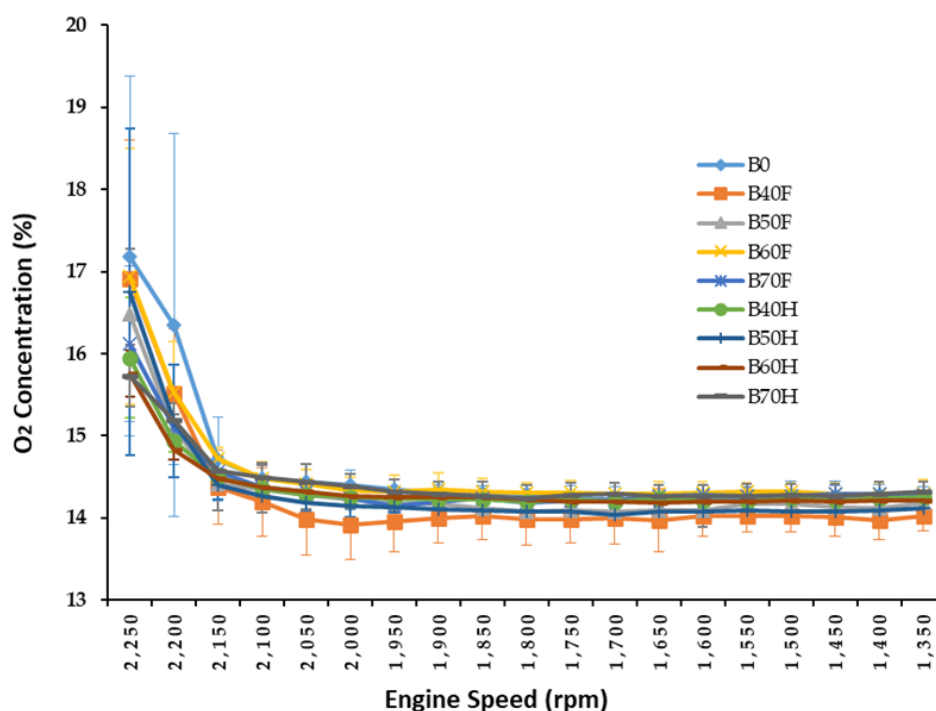


Figure 15. O₂ concentration at different engine speeds for various fuel blends (mean $\pm$ SD, $n = 3$)

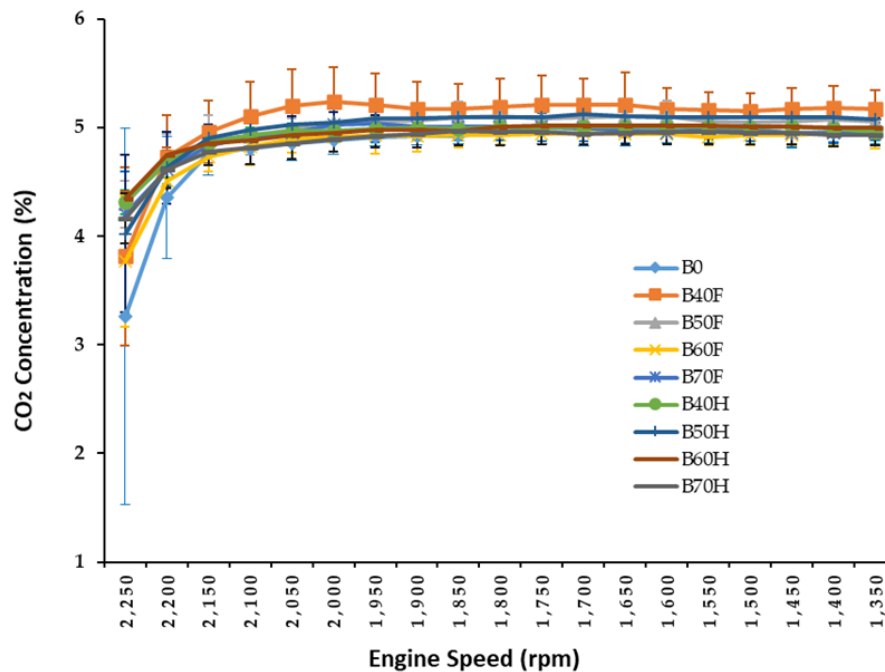


Figure 16. Carbon dioxide (CO₂) concentration versus engine speed for different fuel blends (mean $\pm$ SD, n = 3)

speed is presented for B0, diesel–FAME blends (B40F–B70F), and diesel–HVO blends (B40H–B70H).

In general, CO₂ concentration increases as engine speed decreases from 2,250 rpm to approximately 1,900 rpm, followed by a tendency to stabilize at lower engine speeds. This trend is primarily associated with increasing engine load, which enhances fuel–air interaction and promotes more complete carbon oxidation during combustion [19].

Diesel–FAME blends consistently exhibit higher CO₂ concentrations than B0 across the entire engine speed range. At 2,250 rpm, B0 produces approximately 3.26% CO₂, whereas FAME blends reach values of up to approximately 4.20%. This behavior is attributed to the presence of chemically bound oxygen within the FAME molecular structure, which facilitates oxidation reactions and promotes the conversion of intermediate carbon species into CO₂. These findings are consistent with previous studies reporting enhanced oxidation efficiency in oxygenated fuels [3].

Similarly, diesel–HVO blends also demonstrate elevated CO₂ concentrations compared to B0, with values reaching approximately 4.34% at high engine speed. Although HVO does not contain chemically bound oxygen, its paraffinic molecular structure and high cetane number promote shorter ignition

delay and more controlled combustion, thereby improving oxidation efficiency. As a result, CO₂ formation is enhanced despite the absence of intrinsic oxygen within the fuel [4].

At medium to low engine speeds ($\leq 1,700$ rpm), the differences in CO₂ concentration among the tested fuels become relatively small, indicating that engine operating conditions play a more dominant role than fuel composition under these conditions. Furthermore, the associated error bars indicate slightly higher variability at high engine speed (2,250 rpm), which can be attributed to cycle-to-cycle combustion fluctuations and reduced residence time for complete oxidation. However, the overall variation remains within an acceptable experimental range (SD < 2.5%), confirming good repeatability and reliability of the measurements.

Overall, the higher CO₂ emissions observed for both FAME and HVO blends, together with the simultaneous reduction in CO emissions and stable O₂ trends, indicate improved carbon oxidation during combustion. These results suggest that renewable fuel blends can enhance combustion completeness without compromising engine stability across the tested operating range.

3.2.5. Emission index analysis

The emission index (EI) provides a more representative assessment of pollutant formation by normalizing exhaust emissions with respect to

engine power output, thereby minimizing the influence of operating conditions on absolute emission values [18], [37]. This approach allows a more meaningful comparison of emission performance across different fuel blends under varying engine loads.

As illustrated in Figure 17, the NO_x emission index exhibits a strong dependence on both engine speed and fuel composition. At the highest engine speed (2,250 rpm), elevated EI values are observed for all fuels, particularly for high FAME blends such as B60F, which reaches approximately 137.73 g/kWh. This behavior is primarily attributed to relatively low effective power output under high-speed conditions, which amplifies the normalized emission values. As engine speed decreases toward the mid-speed region (approximately 1,900–1,700 rpm), the NO_x emission index for all fuels converges to a narrower range of approximately 9–13 g/kWh, indicating improved combustion efficiency and more effective energy conversion.

A clear increasing trend in NO_x emission index is observed with increasing FAME blending ratio. This phenomenon is associated with the oxygenated molecular structure of FAME, which enhances local combustion temperatures and promotes thermal NO_x formation [18], [37]. In contrast, diesel-HVO blends exhibit NO_x emission index values closer to those of conventional diesel, typically within a deviation of less than 10%. This behavior reflects a more controlled combustion process resulting from the

paraffinic structure and higher cetane number of HVO, which reduce the residence time of high-temperature combustion zones [38].

Figure 18 presents the variation of the CO emission index across the tested operating conditions. In general, both FAME and HVO blends exhibit comparable or lower CO emission index values relative to B0. This trend indicates improved oxidation efficiency during combustion, particularly for FAME blends, where the presence of chemically bound oxygen promotes more complete carbon oxidation. Meanwhile, HVO achieves similar CO reduction through improved ignition characteristics and more stable combustion behavior, despite the absence of intrinsic oxygen [18].

The experimental uncertainty, represented by error bars (mean $\pm$ SD, $n = 3$), remains relatively small in the mid-speed operating region but becomes more pronounced at high engine speed (2,250 rpm). This increased deviation is attributed to lower engine load stability and higher sensitivity of emission measurements under low effective torque conditions. Nevertheless, the overall variation remains within an acceptable range (<2.5%), confirming good repeatability and reliability of the experimental data.

Overall, the emission index analysis highlights a clear trade-off between NO_x and CO emissions. Increasing FAME content leads to higher NO_x emissions but lower CO levels, whereas HVO provides a more balanced emission profile, maintaining NO_x levels closer to diesel while still

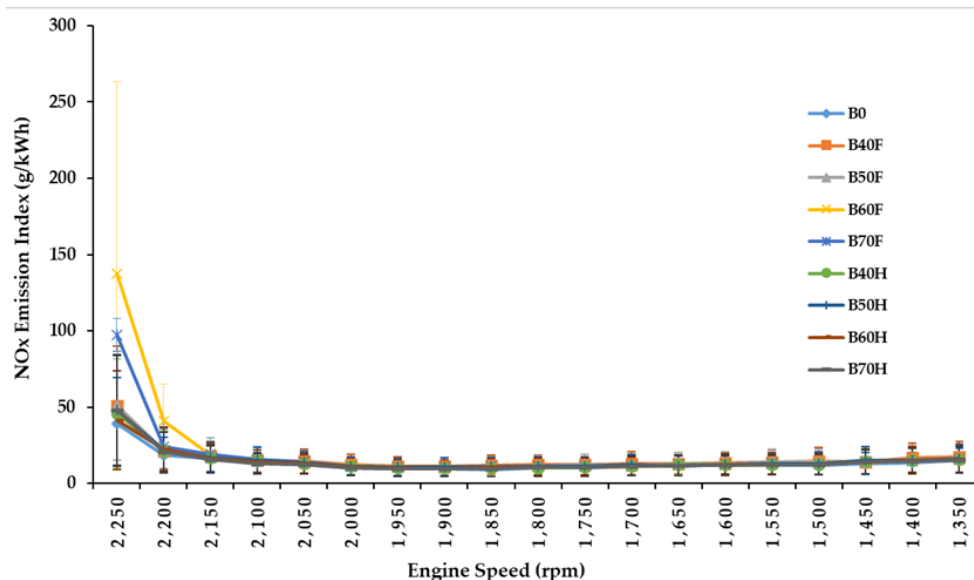


Figure 17. NO_x emission index versus engine speed for different fuel blends (mean $\pm$ SD, $n = 3$)

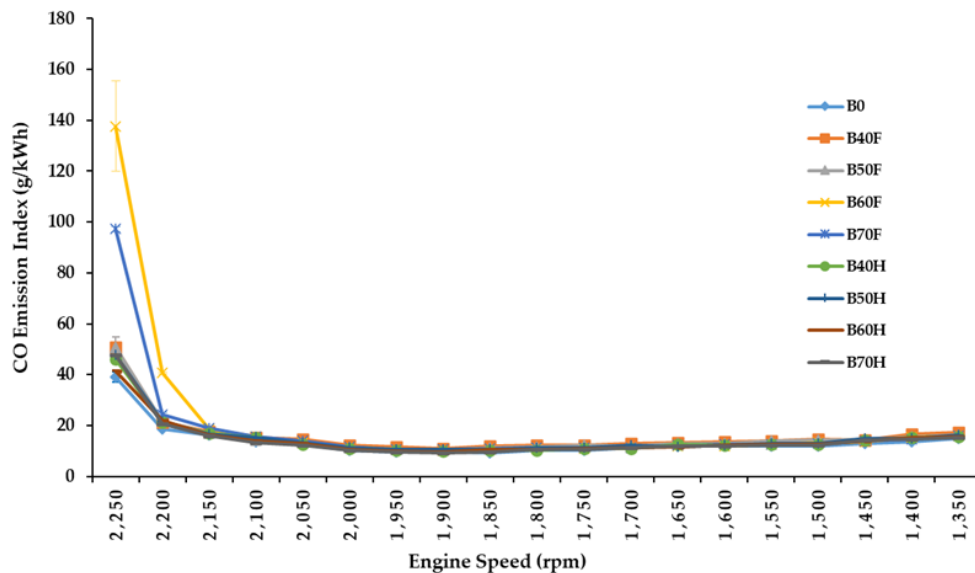


Figure 18. CO emission index versus engine speed for different fuel blends (mean $\pm$ SD, $n = 3$)

reducing CO emissions. These findings further support the potential of HVO as a drop-in renewable fuel for heavy-duty diesel engines with minimal impact on emission performance.

3.3. Sample Oil Test Results

To evaluate the influence of different fuel formulations on engine wear characteristics, used lubricating oil analyses were performed after each fuel test to quantify the accumulation of wear metals as indicators of engine tribological conditions [4], [39]. The lubricating oil was operated for an average duration of approximately 2 h for each test and repeated three times for every fuel variation, following short term durability evaluation procedures commonly adopted in alternative fuel studies [4], [16]. Oil samples were collected using a dedicated sampling device to minimize external contamination and subsequently analyzed in an accredited laboratory in accordance with standard diesel engine used-oil analysis protocols [31]. Figure 19 presents the concentrations of the primary wear metals—aluminum (Al), copper (Cu), iron (Fe), lead (Pb), and nickel (Ni)—for all tested fuels, including conventional diesel (B0), diesel–FAME blends (B40F–B70F), and diesel–HVO blends (B40H–B70H).

Overall, the concentrations of all measured wear metals remain well below established attention and critical threshold limits. Iron (Fe), which is commonly associated with wear of cylinder liners and crankshaft components,

remains nearly constant at approximately 1 ppm across all fuel types, indicating the absence of significant abrasive wear during the test period [40].

The aluminum (Al) concentration is consistently maintained at approximately 2 ppm for all fuel variations, suggesting that wear of aluminum-based components, such as pistons and certain bearing materials, remains within normal operating conditions. Copper (Cu) and lead (Pb), which are typically associated with bearing wear, exhibit minor variations, particularly for FAME blends such as B50F. However, all measured values remain substantially below commonly accepted attention limits (25 ppm for Cu and 40 ppm for Pb), indicating no evidence of abnormal bearing degradation [39].

Nickel (Ni) concentrations are negligible or below detection limits in nearly all samples, indicating that no measurable degradation of high-temperature alloy components occurred during the tests. The overall similarity in wear metal concentrations among B0, FAME blends, and HVO blends suggests that fuel composition has a limited influence on short-term wear behavior under the present operating conditions.

The experimental uncertainty, represented by error bars (mean $\pm$ SD, $n = 3$), is consistently low for all measured elements, indicating high repeatability and stable operating conditions during the oil analysis. While the small error bars confirm the robustness of the experimental data,

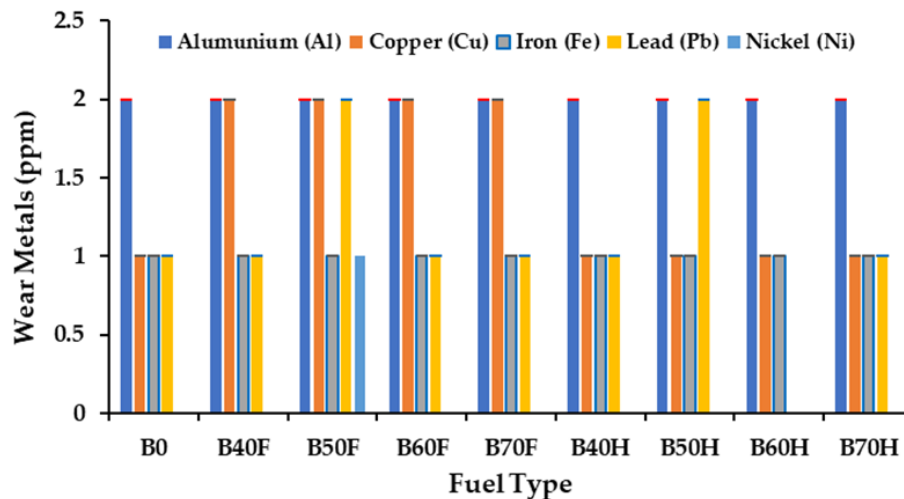


Figure 19. Wear metal concentrations in used engine oil for different fuel blends (mean $\pm$ SD, $n = 3$)

the absence of significant wear is primarily evidenced by the consistently low metal concentrations relative to established threshold limits.

It is important to note that measurable differences in engine wear typically become evident only after extended operation, often exceeding 500 h of service time. Therefore, the present results confirm that none of the tested fuels induce significant wear under short-term operating conditions, supporting the mechanical compatibility of both FAME and HVO blends with heavy-duty diesel engines [34], [41].

4. Conclusion

This study presents a comprehensive experimental evaluation of conventional diesel fuel (B0), diesel-FAME blends (B40F–B70F), and diesel-HVO blends (B40H–B70H) in a heavy-duty diesel engine under identical operating conditions. The results demonstrate that both fuel type and blending ratio significantly influence engine performance, emission characteristics, and short-term durability.

An increase in FAME blending ratio leads to a systematic deterioration in engine performance, as indicated by reductions in brake torque, brake power, and brake thermal efficiency, accompanied by an increase in brake-specific fuel consumption. At higher blending levels (B60F–B70F), performance penalties reach approximately 5–10%, primarily due to the lower heating value and higher viscosity of FAME, which adversely affect fuel atomization and combustion efficiency. In contrast, diesel-HVO

blends exhibit substantially lower performance degradation (<5%) and maintain efficiency levels close to those of conventional diesel, indicating superior compatibility with existing engine systems.

From an emissions perspective, all biofuel blends reduce CO emissions by approximately 8–20%, indicating improved combustion completeness. However, FAME blends are associated with a more pronounced increase in NO_x emissions at higher blending ratios, whereas HVO blends exhibit a more balanced emission profile with comparatively moderate NO_x increments. The observed trends in O₂ and CO₂ emissions further confirm enhanced carbon oxidation efficiency for both fuels, although the underlying mechanisms differ due to variations in molecular structure and oxygen content.

In terms of engine durability, used lubricating oil analysis indicates that all tested fuels maintain wear metal concentrations well below critical threshold limits, suggesting no significant short-term impact on engine wear. These findings support the mechanical compatibility of both FAME and HVO blends under the tested operating conditions.

Overall, HVO demonstrates the most favorable balance between performance retention, emission control, and mechanical reliability among the tested renewable fuels, making it a promising drop-in alternative for high-blend applications in heavy-duty diesel engines without requiring hardware modifications.

Future work will extend this study by incorporating long-term durability evaluation,

advanced lubricant degradation analysis, component-level inspection, and detailed combustion diagnostics, including in-cylinder pressure measurement, heat release rate (HRR) analysis, and ignition delay estimation, to provide a more comprehensive understanding of engine behavior under prolonged operation with high-blend renewable fuels.

Acknowledgements

The authors acknowledge the contribution of the industrial partner for granting access to the engine testing facilities and providing technical assistance. Appreciation is also extended to the laboratory team in Balikpapan for their support throughout the experimental activities.

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.

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