

Article

Comparative Assessment of Diesel–Palm-Based Biodiesel and Green Diesel Blends on Engine Performance, Operating Parameters, and Acoustic Emissions in a Compression-Ignition Engine

Nur Cahyo ^{1,2}, Berkah Fajar Tamtomo Kiono ^{1,*}, M. S. K. Tony Suryo Utomo ^{1,*},
Mujammil Asdhiyoga Rahmanta ² and P. Paryanto ^{1,*}

¹ Department of Mechanical Engineering, Diponegoro University, Tembalang, Semarang 50275, Indonesia; nurcahyo3@pln.co.id

² PLN Research Institute, Jl. Durentiga No. 102, Pancoran, Jakarta Selatan 12760, Indonesia; mujammil1@pln.co.id

* Correspondence: berkahfajar@undip.ac.id (B.F.T.K.); tonsuryoutomo@lecturer.undip.ac.id (M.S.K.T.S.U.); paryanto@ft.undip.ac.id (P.P.)

Abstract

A short-term performance test of blended biodiesel (FAME), green diesel (HVO), and diesel was experimentally assessed in a 100 kW Cummins 6BTAA5.9-G12 diesel engine under multiple load conditions. The objective was to determine the technical feasibility, operational trade-offs, and optimal blend formulations for renewable energy deployment in diesel power plants. All tested blends operated stably without engine modification, confirming the “drop-in capability” of FAME–HVO mixtures for existing diesel engines. Specific fuel consumption (SFC) increased notably at high loads, with penalties up to 15.15% for B30D20 and B35D15 relative to neat diesel, although overall efficiency improved with load. Among the ternary fuels, B30D10 and B30D20 provided the most balanced compromise between combustion reactivity and flow properties. Exhaust gas temperatures rose with load for all fuels, with FAME-rich blends exhibiting higher temperatures than neat diesel, while coolant-side analysis showed D100 and D50 as thermally favorable and B50–B100 imposing the highest cooling demand. The results emphasize the need for injection system recalibration on an energy basis for HVO-rich fuels, and for strengthened filtration and maintenance practices for FAME-rich blends to avoid filter clogging and injection instability. Considering performance, operability, and system stability up to 100 kW, B30D10 and B35D15 are identified as optimal compromise blends. The study highlights the necessity of future work on long-term durability, fuel system compatibility, supply chain robustness, and techno-economic viability to safely scale green diesel use in Indonesian stationary power generation.



Academic Editors: Venera Giurcan
and Codina Movileanu

Received: 17 April 2026

Revised: 4 June 2026

Accepted: 11 June 2026

Published: 21 June 2026

Copyright: © 2026 by the authors.
Licensee MDPI, Basel, Switzerland.
This article is an open access article
distributed under the terms and
conditions of the [Creative Commons
Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

Keywords: biodiesel; green diesel; performance; SFC; efficiency; noise level; diesel engine

1. Introduction

Only a relatively small share of Indonesia’s crude palm oil (CPO) output is currently allocated to the mandatory biodiesel program, despite the country’s position as the world’s largest CPO producer and leading biodiesel user [1]. To enhance energy security, reduce dependence on fossil diesel, and stabilize the domestic CPO market, the Government of Indonesia has progressively tightened its blending mandate over the last decade. Following

earlier B10 and B15 steps, the nationwide B20 policy—requiring a 20% volume fraction of FAME in diesel fuel—was made mandatory across all sectors starting in September 2018 [2]. This was rapidly followed by an acceleration of the B30 mandate, under which diesel fuel must contain 30% biodiesel by volume. Since the initial mandate in 2006, blending rates have been incrementally increased, establishing Indonesia as the first nation globally to implement such a high biodiesel blend on a national scale. The purpose of this transition from B20 to B30 is to enhance energy security and support the rural palm oil economy by reducing diesel imports, stabilizing domestic CPO demand, and buffering CPO price [3].

The Indonesian Biofuel Producers Association has ardently endorsed this policy direction, collaborating with governmental bodies to address logistical, technical, and investment impediments that may have hindered implementation [4]. The early realization of B30 has been framed not only as an energy policy, but also as an instrument of industrial and rural development, given its potential to raise the added value of palm oil, provide a buffer against shocks such as EU trade restrictions, and reorient CPO flows from export markets to domestic energy use [1,5]. Economic modeling and policy analyses indicate that higher blending mandates can increase domestic demand for CPO, improve macroeconomic indicators such as GDP and wages, and partially compensate for declining export opportunities, though they may also introduce short-term inflationary pressures and reallocation effects in the agricultural sector [3,5].

In parallel with FAME biodiesel, there is growing interest in green fuels: drop-in hydrocarbons such as green gasoline, green diesel, and biojet produced from palm-based feedstocks via hydrotreating, hydrocracking, fluid catalytic cracking, and related processes [6]. Laboratory and pilot studies demonstrate that CPO, refined bleached deodorized palm oil (RBDPO), and low-value side streams such as palm fatty acid distillate (PFAD) can be coprocessed with conventional refinery streams to yield gasoline, diesel, and kerosene range hydrocarbons with high conversion (often >85%), high cetane numbers for diesel fractions, and low sulfur contents [6,7]. Such drop-in biofuels closely match the molecular structure and performance of fossil fuels, allowing use in existing engines and distribution infrastructure without major modification [7,8]. Coprocessing and dedicated hydroprocessing routes therefore offer promising pathways to expand domestic utilization of palm-based feedstocks into second-generation biofuels that combine operational compatibility with improved emissions profiles and lower life cycle greenhouse gas intensities [6].

Green diesel, often termed hydrotreated vegetable oil (HVO) or renewable diesel, is typically produced via hydrotreating of triglycerides contained in vegetable oils such as CPO under elevated hydrogen pressure and temperature [9]. In this process, oxygen present in triglycerides and free fatty acids is removed mainly through hydrodeoxygenation, decarboxylation, and decarbonylation pathways, yielding long-chain n-paraffins with physicochemical properties closely resembling petroleum-derived diesel [9,10]. The resulting green diesel generally exhibits a high cetane number, low density, very low sulfur and aromatic contents, and excellent combustion and emission characteristics compared to conventional diesel, making it a drop-in fuel for existing diesel engines and infrastructure [11].

The development of green fuels from lipid feedstocks in refineries can follow two main implementation strategies: coprocessing and stand-alone (green refinery) operation. In the coprocessing approach, vegetable oils or other bio-derived oils are blended at limited ratios (typically ≤ 10 –20 wt.%) with petroleum fractions such as VGO, gasoil, or petrodiesel and processed in existing hydroprocessing or FCC units [12]. This strategy leverages existing refinery assets and logistics, enabling near-term greenhouse gas mitigation and partial decarbonization of transportation fuels with comparatively low capital expenditure; however, renewable feed ratios are constrained by unit operability, catalyst stability, and fuel quality specifications [6,13]. By contrast, stand-alone green refineries are specifically

designed to convert renewable lipid or broader biogenic feedstocks directly into a spectrum of drop-in fuels, including green diesel, green gasoline, sustainable aviation fuel, and LPG-range gases, without co-feeding fossil oil [14,15].

The implementation of green fuels offers environmental and economic benefits, yet concurrently presents significant technological and sustainability challenges [16]. Advanced biofuels can significantly diminish life cycle greenhouse gas emissions, enhance local air quality, and facilitate the transition to a low-carbon energy system. In comparison to fossil diesel, HVO can yield 60–95% CO₂ reductions over its life cycle as a paraffinic renewable diesel, contingent upon the feedstock and process configuration [17]. Engine bench and vehicle studies demonstrate significant reductions in soot, CO, HC, and particulate number emissions while maintaining equivalent efficiency, frequently allowing adherence to rigorous post EU6 or Tier 4 standards without compromising performance [18]. In terms of the economy, the growth of green fuels can lower reliance on imported fossil fuels, boost bio-based and agricultural industries, and generate jobs in rural areas [16,19]. Techno-economic analyses of HVO production from low-value residues, such as palm oil sludge, demonstrate favorable returns on investment and brief payback periods when combined with optimized hydrogen management and existing refinery infrastructure. The capacity to utilize inedible and waste lipids as feedstock alleviates some of the food–fuel trade-off while enhancing the value of industrial byproducts [20].

Despite these benefits, numerous significant obstacles impede large-scale implementation of HVO. The production costs of HVO and other advanced green fuels exceed those of conventional diesel, influenced by hydrotreating severity, hydrogen availability, and capital intensity, especially in stand-alone units [17]. Continuous investment in research and development is essential to enhance catalyst efficacy, process intensification, and integration with current refineries to lower unit costs and energy consumption [21]. It is essential to secure a sustainable supply of oils, such as palm oil, without contributing to deforestation, biodiversity depletion, or food security issues, particularly in key producing regions like Indonesia and Malaysia [19,20]. Transitioning to non-food and waste lipid sources—such as waste cooking oil, industrial byproducts, and alternative non-edible oils—constitutes a pivotal strategy for aligning environmental sustainability with the growth of the fuel market [20,22].

Fundamental diesel engine theory and prior experimental findings indicate that fixed losses—such as mechanical friction, air-pumping work, and auxiliary drives—represent a greater portion of the total energy balance at low loads. As the load increases and brake power rises, these relatively constant losses are mitigated, resulting in reduced fuel consumption per unit of useful work [23]. Consequently, operational efficiency improves at medium to high loads, as evidenced by lower specific fuel consumption (SFC) values. Fuel blends with high hydrotreated vegetable oil (HVO) content, such as Dxx, exhibit unique specific fuel consumption (SFC) characteristics due to HVO's high cetane number and paraffinic nature. These properties result in shorter ignition delays, quick heat release, and cleaner combustion [24,25]. Nonetheless, HVO's lower density compared to fossil diesel can reduce the chemical energy supplied under volumetric fuel injection systems, necessitating compensatory adjustments in duration or flow rate [26]. Studies have indicated that HVO and its blends can match or slightly underperform fossil diesel in SFC during moderate loads, primarily attributed to enhanced thermal efficiency and improved combustion completeness.

Characterizing HVO involves assessing various fuel properties through ASTM methods, emphasizing that high cetane numbers, low density, and favorable combustion traits are critical under high-load scenarios. While biodiesel varieties generally show higher SFC than fossil diesel due to lower heating values and altered physical properties, diesel-

dominant blends typically achieve better thermal efficiencies, especially under medium to high loads [25,26].

Operational challenges arise from fuel cleanliness—particularly particulate contamination and residual mono-, di- and triglyceride contents—where particulate contamination can lead to fouling and injection quality deterioration, affecting spray structure and combustion efficiency. High water content increases risks of micro-corrosion and influences spray dynamics, thereby elevating variability under high loads. Contaminants increase pressure drop across filters, compromising effective injection pressure and spray quality, which are vital in managing combustion stability. Meanwhile, cetane enhancers like HVO improve ignition characteristics and overall efficiency in compression-ignition engines, reducing cyclic variations and enhancing thermal efficiency [27].

The balance between low-load and high-load engine operations reveals that higher demand for fuel mass flow translates to increased chemical energy release. Low-load conditions typically exhibit insufficient temperatures for effective aftertreatment. In contrast, high loads lead to increased exhaust temperatures due to larger fuel quantities entering the combustion chamber. Elevated loads may restrict the utilization of high cetane numbers and exert stress on the injection system due to the lower density of HVO [28]. At 15 °C, density and kinematic viscosity at 40 °C are of equal significance. In comparison to fossil diesel and HVO, FAME adheres. Viscosity inhibits breakup, enlarges droplet size, and constricts the spray cone angle, diminishing air–fuel mixing and extending combustion duration [27,29].

Energy loss analyses in modern compression-ignition engines show that friction and auxiliary losses constitute a significant fraction of the fuel energy and that, while their absolute magnitude may change with speed and operating condition, their relative impact diminishes as more of the input energy is converted into useful brake work at higher load [30]. The compression-ignition engines typically improve efficiency with increasing load up to a near-optimal range before plateauing or slightly declining at very high loads [31]. Possessing similar advantages to fossil diesel compared with various biodiesel blends, particularly at higher loads, diesel often delivers the highest thermal efficiency and lowest specific fuel consumption in unmodified engines [24].

The higher shaft power demand must be met by a greater fuel mass flow rate and, consequently, a higher rate of chemical energy release in the cylinder [32]. Low-load conditions in diesel engines are generally characterized by reduced in-cylinder temperatures and modest exhaust temperatures, often below the threshold required for effective aftertreatment activity [33]. In addition, EGT increases with load due to elevated fuel flow into the combustion chamber [34,35], peaking at full-load operation in compression-ignition engines fueled with diesel and various biodiesel blends [32,36]. Previous studies also observed the longer ignition delay, larger premixed heat release, and higher exhaust temperature for low cetane oxygenated blends in CI engines [33,35]. Higher exhaust temperatures for high biodiesel blends due to late burning and poor atomization have been documented for blends in the B50–B80 range [37,38].

Fuel ignitability, heating value, and viscosity markedly affect in-cylinder heat release, cooling losses, and thermal efficiency in diesel and biofuel blends [39,40]. The absence of FAME, sulfur, and aromatics, together with the lack of carbonaceous deposit formation, allows heat to be effectively converted to useful work rather than stored as residual thermal energy in the engine structure [41]. HVO generally yields cleaner combustion, lower soot formation, and improved control over combustion phasing compared with conventional diesel at various coolant temperature states [40].

Combustion noise in diesel engines arises from rapid and irregular in-cylinder pressure fluctuations, which are strongly linked to the local combustion mode and fuel properties.

High pressure rise rates during the premixed combustion phase generate high-frequency pressure oscillations and combustion chamber resonances that transmit to the engine structure as vibro-acoustic noise [42,43]. Fuels with a low cetane number or unfavorable physical properties (e.g., high viscosity, high surface tension) tend to exhibit longer ignition delay and more abrupt heat release, thereby increasing the maximum pressure rise rate and intensifying combustion noise [44]. In addition, non-uniform atomization and heterogeneous air–fuel mixing promote spatially distributed ignition sites and irregular flame propagation, which enhance cycle-to-cycle variability in peak pressure and pressure oscillations [45]. These effects are particularly pronounced under low to medium engine loads, where ignition delay, mixture preparation, and local equivalence ratio stratification are more sensitive to fuel properties and operating conditions [46].

Engine operating instability, such as load fluctuations and hunting, observed for certain fuel formulations, reflects limitations in combustion phasing control and mixture formation, and manifests as distinct acoustic signatures and vibration patterns for different fuels [47,48]. Studies on alternative and blended fuels—including hydrous ethanol–gasoline, diesohols, biodiesel, biomethane, and dimethyl ether—consistently show that changes in cetane number, volatility, viscosity, and oxygen content modify ignition delay, heat release rate, and pressure rise behavior, which in turn reshape the engine’s noise and vibration profile [44,45]. Consequently, a comprehensive assessment of combustion noise cannot be decoupled from thermal and performance parameters such as heat release characteristics, indicated and brake efficiencies, emissions, and vibro-acoustic response. A coupled analysis of in-cylinder pressure traces, combustion phasing, cyclic variation indices, noise spectra, and vibration metrics is essential to elucidate the interaction between fuel characteristics, combustion stability, and diesel engine noise levels, and to identify operating and fuel property windows that minimize combustion-induced acoustic emissions while maintaining acceptable efficiency and emissions.

Ignition-related combustion properties are primarily governed by the cetane number, aromatic content, and chemically bound oxygen in FAME. A higher cetane number shortens ignition delay and moderates the rate of pressure rise, which generally leads to smoother pressure traces and reduced combustion noise; similar noise and pressure rise reductions with high cetane diesel and biofuels have been reported elsewhere [49,50]. Conversely, lower cetane number and elevated aromatic content promote longer ignition delay, higher premixed burn fraction, and sharper pressure gradients, which are typically associated with higher structure-borne and radiated noise levels. The oxygen content in FAME can further modify the burn fraction: it may accelerate oxidation and enhance completeness of combustion, but in the presence of suboptimal atomization, it can prolong an unstable diffusion-controlled phase, thereby increasing cyclic variability and perceived roughness. Injection and spray characteristics are controlled by kinematic viscosity, density, and bulk modulus of the fuel. High viscosity and high density fuels such as FAME tend to produce larger droplets and slower air–fuel mixing, which can extend the combustion duration and increase spatial inhomogeneity, with documented links to higher noise and vibration in biodiesel applications [51,52].

This study addresses a key gap in biofuel research by jointly evaluating Indonesian palm oil-based biodiesel (FAME) and green diesel (HVO) blended with fossil diesel in a single experimental framework and explicitly linking these blends to engine performance, operational parameters, and acoustic noise emissions. Previous studies have either focused on FAME versus HVO in non-palm feedstocks or investigated these fuels separately, with limited integration of performance, full emission spectrum, and noise behavior in one coherent study [24]. Existing work on HVO–FAME–diesel mixtures has shown that HVO generally improves fuel consumption and reduces CO, HC, NO_x, and smoke compared

with diesel, while FAME fractions can increase NO_x and BSFC due to lower heating value and higher oxygen content [53]. However, those studies mostly used rapeseed-based esters, maritime or laboratory conditions, and did not systematically examine noise level as a direct environmental indicator. Noise has been modelled and optimized together with gaseous emissions only for simple “B20 diesel” biodiesel blends (corn, sunflower, and palm) without including second-generation green diesel components or detailed combustion diagnostics [54]. Palm oil methyl ester (POME) has been widely studied for PM–NO_x trade-offs and combustion characteristics [55], and palm-based biodiesel blends have been shown to reduce PM and engine noise versus diesel in stationary engines [54]. Yet no study has comprehensively compared palm FAME and palm-based HVO in mixed blends against neat diesel in a diesel engine, under realistic operating loads, while simultaneously measuring performance (BTE, BSFC), combustion parameters, gaseous and particulate emissions, and sound pressure level and spectral noise distribution.

Thus, the main novelty of this article can be framed as: demonstrating, for the first time, the synergistic and antagonistic effects of cofiring Indonesian palm-derived FAME and Indonesian palm-derived HVO with neat diesel on performance–operating parameter–noise trade-offs, extending earlier HVO–FAME studies that used non-palm feedstocks and omitted acoustics [53]. This study provides a multiobjective assessment (performance and external noise) of palm oil-based biofuel–diesel mixtures, enabling comparison with earlier palm-only biodiesel work that mainly focuses on PM/NO_x and ignores green diesel [56]. Moreover, this study aims to quantify whether optimized palm FAME–HVO–diesel blend ratios can simultaneously maintain or improve brake thermal efficiency and BSFC relative to diesel, as suggested for some HVO–biodiesel–diesel blends [53], or lower engine noise levels relative to neat diesel and single biofuel blends, thus extending prior regression optimization results for palm biodiesel noise [54].

2. Materials and Methods

The research process began with a planning and data acquisition phase, which established the basis for all subsequent activities. In this stage, two categories of data were collected. Primary data were obtained from the Diesel Engine Operational Data (DOM), including real-time operating parameters of the diesel engine, and from fuel sampling for laboratory characterization. In parallel, secondary data were gathered through a systematic literature review on diesel engine operation with alternative and blended fuels, engine performance, and emission characteristics, in line with recent studies on diesel–alcohol, diesel–biodiesel–ethanol, and other multicomponent blends [57].

Subsequently, a baseline performance test under no-load (idle) conditions was conducted. In this phase, the reference fuel and candidate fuel samples were tested by progressively varying the blend ratio to observe the initial response of the engine under idle operation. Similar staged blending and preliminary screening are common in alternative fuel investigations to ensure stable combustion and safe operation before moving to loaded tests [58]. The results of the idle tests were evaluated in terms of combustion stability, fuel consumption trends, and qualitative exhaust behavior to determine whether each fuel sample was suitable for further testing under load. Samples that met the predefined acceptance criteria were subjected to loaded engine tests. The diesel engine was operated at incrementally increasing load levels (50%, 75%, and 100% load) according to the pre-designed fuel scenarios, following common practice in performance and emission mapping of diesel and dual-fuel genset engines [59]. At each load step, steady-state measurements of torque, power, brake thermal efficiency, specific fuel consumption, and exhaust gas emissions (e.g., CO, HC, NO_x, CO₂, and opacity, where applicable) were recorded. Upon completion of the loaded tests, a post-performance inspection of the engine was carried out.

This examination comprised visual inspection of combustion chamber and injector regions using a borescope, analysis of performance and emission test results, and laboratory tests on retained fuel and lubricating oil samples to identify any abnormal degradation, contamination, or deposit-forming tendencies. All data collected from the testing, inspection, and evaluation stages were processed and statistically analyzed to derive accurate information on the fuel's performance.

2.1. Fuel Test and Analysis Method

This study examined various fuel compositions, including neat fossil diesel (B0), neat biodiesel (B100/FAME), neat hydrotreated vegetable oil (D100/HVO), and binary and ternary blends of these basic components (Bxx, Dxx, and BxxDxx). Table 1 summarizes the comprehensive list of fuel samples and their volumetric blending ratios. Furthermore, the laboratory test results are shown in Table 2.

Table 1. Fuel sample code and formula.

No.	Code	Symbol	Fuel Formulation (% by Volume)
1	PP 01	B0	Fuel consisting of 100% petroleum diesel.
2	PP 02	B30	Blended fuel consisting of 70% diesel and 30% FAME (biodiesel).
3	PP 03	B35	Blended fuel consisting of 65% diesel and 35% FAME (biodiesel).
4	PP 04	B30D5	Blended fuel consisting of 65% diesel, 30% FAME (biodiesel), and 5% HVO.
5	PP 05	D35	Blended fuel consisting of 65% diesel and 35% HVO.
6	PP 06	B40	Blended fuel consisting of 60% diesel and 40% FAME (biodiesel).
7	PP 07	B35D5	Blended fuel consisting of 60% diesel, 35% FAME (biodiesel), and 5% HVO.
8	PP 08	B30D10	Blended fuel consisting of 60% diesel, 30% FAME (biodiesel), and 10% HVO.
9	PP 09	D40	Blended fuel consisting of 60% diesel and 40% HVO.
10	PP 10	B50	Blended fuel consisting of 50% diesel and 50% FAME (biodiesel).
11	PP 11	B35D15	Blended fuel consisting of 50% diesel, 35% FAME (biodiesel), and 15% HVO.
12	PP 12	B30D20	Blended fuel consisting of 50% diesel, 30% FAME (biodiesel), and 20% HVO.
13	PP 13	D50	Blended fuel consisting of 50% diesel and 50% HVO.
14	PP 14	D100	Fuel consisting of 100% HVO.
15	PP 15	B100	Fuel consisting of 100% FAME (biodiesel).

Table 2. Psychochemical properties of fuel samples.

Parameter	PP01	PP02	PP03	PP04	PP05	PP06	PP07	PP08	PP09	PP10	PP11	PP12	PP13	PP14	PP15
Cetane Number	49.7	53.2	54.0	53.1	49.5	54.9	53.7	53.0	49.6	55.4	53.5	53.0	49.8	53.2	60.4
Sulfur; % m/m	0.145	0.104	0.101	0.100	0.091	0.084	0.093	0.067	0.082	0.070	0.083	0.073	0.081	0.016	n/a
Distillation; °C	349.1	354.5	352.0	340.2	345.3	342.4	339.6	337.2	324.2	337.4	352.5	351.1	339.7	306.2	349.3
Flash Point; °C	66	75	76	79	81	78	78	78	81	82	81	83	86	132	106
Carbon Residue; % m/m	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
FAME; % v/v	0.0	30.47	35.02	30.24	0.0	39.29	34.23	29.82	0.0	48.29	32.75	29.24	0.0	0.0	94.97
Ash; % m/m	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.005
Sediment; % m/m	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Particulate; mg/L	1.5	5.5	6.0	7.0	1.0	6.0	11.5	7.5	0.8	13.3	8.5	6.5	0.5	0.0	
Total Acid Number; mg KOH/g	0.21	0.21	0.21	0.21	0.26	0.22	0.23	0.22	0.35	0.23	0.21	0.23	0.27	0.34	0.21
Cloud Point; °C	8	8	8	8	7	7	8	8	6	6	6	6	5	10	10
Density @15 °C; kg/m ³	860.6	864.6	865.29	860.9	834.6	865.9	861.5	856.9	830.9	867.3	854.18	849.6	823.5	786.5	874
Oxidation Stability; Minute	1553	347	302	360	1689	241	295	356	1593	187	284	342	1817	1150	855
Pour Point; °C	3	3	3	3	3	3	3	3	3	3	3	3	6	15	9
Kinematic Viscosity @40 °C; kg/m ³	3.883	4.100	4.102	4.089	3.723	4.136	4.085	3.968	3.693	4.174	3.922	3.883	3.575	3.358	4.432
Water Content; mg/kg	70	41.895	202	192	63	212	198	178	62	256	198	185	57	37	338
Lower Heating Value; MJ	42.8	43.2	43.4	43.4	41.9	41.9	42.0	42.2	41.7	41.8	41.9	41.6	41.3	43.9	39.8

Fuel characterization was carried out by comparing the measured properties of each test fuel with the corresponding regulatory or normative specifications. For fossil diesel and its blends containing FAME, the reference limits were taken from the Indonesian Decree of the Director General of Oil and Gas No. 146.K/10/DJM/2020 [60], which is analogous in scope to international automotive diesel standards such as EN 590 [61] that define requirements for density, cetane number, distillation profile, cold-flow properties, and other key parameters [5].

The quality assessment of neat biodiesel adhered to the Decree of the Director General of Renewable Energy and Energy Conservation No. 189.K/10/DJE/2019 [62], which parallels EN 14214 [63] in establishing limits for ester content, oxidation stability, water and monoglyceride content, viscosity, and cold filter plugging point to guarantee dependable engine performance and storage stability [64]. The assessment of neat HVO adhered to the requirements of SNI 8968:2021 [65] concerning diesel biohydrocarbon fuels, aligning with global practices where paraffinic hydrotreated oils are generally regulated via specific HVO guidelines (e.g., Neste Renewable Diesel specifications) or by exhibiting comprehensive conformity with diesel fuel standards, barring properties intrinsically influenced by the paraffinic composition and reduced density of HVO [41,66].

2.2. Equipment Set-Up and Testing Parameters

The experimental campaign was conducted on a Cummins diesel engine equipped with a fully instrumented fuel, air handling, exhaust, and data acquisition system, as shown in Figure 1. The testing process begins with fuel being transferred from the main raw fuel storage tank (1) to the daily fuel service tank (3) by means of a transfer pump (2). Within the service tank, the fuel mass is measured with high precision using a load cell (4), enabling accurate determination of instantaneous and cumulative fuel consumption. From the service tank, fuel is routed to the engine through a supply line monitored by a supply flow meter (5) and an initial pre-filter (6), while the differential pressure across the filter is tracked by a pressure transmitter (25). A lift pump (7) subsequently elevates the fuel pressure and transmits it to the primary filter and separator assembly (8), prior to the conditioned fuel entering the high-pressure fuel injection pump (9). The injection pump delivers high-pressure fuel to each injector (11), which injects it directly into the combustion chamber (12); the excess unburned fuel is returned through a dedicated line, with its flow rate quantified by a return flow meter (10) to ascertain the engine's net fuel consumption.

The air intake system simultaneously takes new air through the air inlet (17), which is then compressed by a turbocharger (18) and cooled in an intercooler (19) to enhance air density and for more efficient and cleaner combustion. The combustion byproducts are expelled via the exhaust stack (20), where a continuous slipstream of exhaust gas is sampled and analyzed in real time by an exhaust gas analyzer (21) to measure regulated emissions. The exhaust gas temperature along the same pipe is consistently measured using thermocouples (26). The mechanical power produced by the diesel engine (13) is transformed into electrical power by an alternator (15), and the resultant electrical output is managed by a stepwise resistive load bank (16), facilitating gradual and precise load increments from the no-load condition to the nominal 100 kW, in accordance with recognized generator testing protocols for performance, emission, and noise assessment [67,68].

All essential operating characteristics are observed using sensors connected to the engine data panel (14) and supplementary instruments constituting an integrated data acquisition (DAQ) architecture. The sensor signals are processed and directed through a junction box (22) and logic panel (23) to a centralized data acquisition system (24). The DAQ system captures, synchronizes, and analyzes time-resolved datasets to extract detailed performance indicators and diagnostic measures. Each test measures or computes the

following parameters: lubricating oil pressure, fuel pressure, coolant temperature, engine speed (rpm), electrical current, voltage, frequency, active and apparent power, power factor, and operating duration. In addition to quantitative assessments, visual examinations of carbon deposits on the combustion chamber and cylinder head are conducted following operation with various fuels. The detailed test equipment specifications, including the diesel genset, are given in Table 3 and Figure 2.

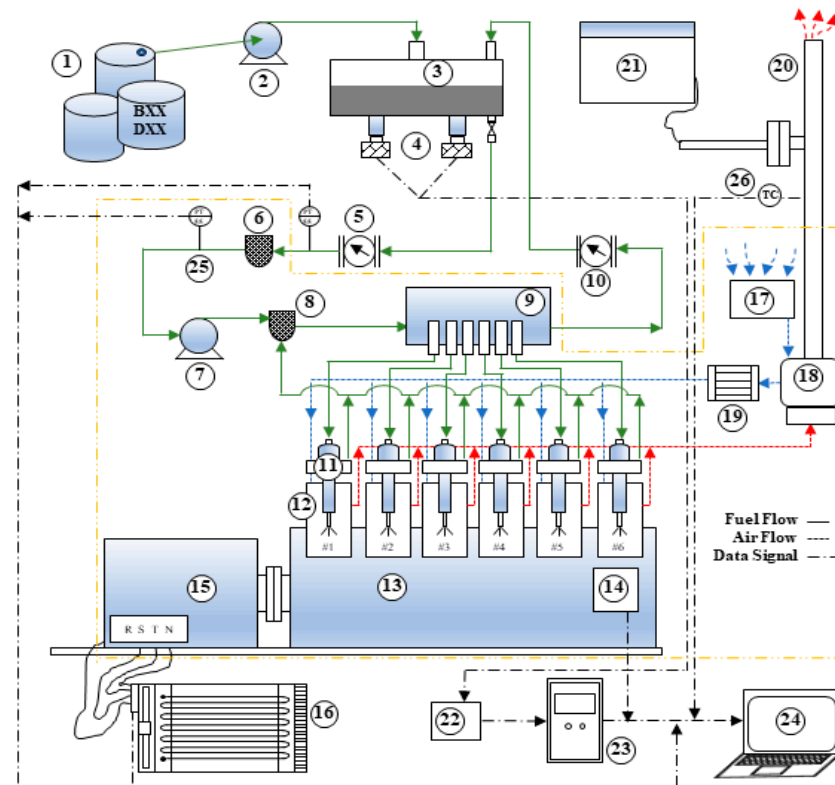


Figure 1. Schematic set-up of test equipment. The green arrow represents the fuel line subsystem. The blue arrow represents the combustion air line subsystem. The red arrow represents the exhaust gas line subsystem resulting from combustion. The dashed black arrows represent the measurement instrumentation process. Component descriptions: 1. Raw Fuel Storage; 2. Fuel Pump; 3. Fuel Service Tank; 4. Load Cell; 5. Supply Flowmeter; 6. Pre-Filter; 7. Lift Pump; 8. Primary Filter and Separator; 9. Fuel Injection Pump; 10. Return Flowmeter; 11. Injector; 12. Combustion Chamber; 13. Diesel Engine; 14. Data Panel; 15. Alternator; 16. Load Bank; 17. Air Inlet; 18. Turbocharger; 19. Intercooler; 20. Exhaust Stack; 21. Exhaust Gas Analyzer; 22. Junction Box; 23. Logic Panel; 24. Data Acquisition; 25. Pressure Transmitter; and 26. Thermocouple.



Figure 2. Diesel generator set Cummins 6BTAA5.9-G12.

Table 3. Test equipment specifications.

No.	Parameter Equipment	Value
1	Diesel Genset Type Combustion system Number and arrangement of cylinders Cylinder bore × piston stroke Total displacement Engine dimensions (without fan) Overall length Overall width Overall height Generator Output Generator control panel and auxiliaries	Diesel Genset Cummins/6BTAA5.9-G12 (Dongfeng Cummins Engine Co., Xiangyang, Hubei, China) Silent Direct Injection 6 cylinders; in-line 102 × 120 mm 5900 cc 3250 mm with enclosure; 2350 mm for the genset only 1200 mm with enclosure; 950 mm for the genset only 1600 mm with enclosure; 1430 mm for the genset only Stamford 150 kVA, 50 Hz, 1500 rpm; power factor 0.8; three-phase AC 200 A panel, DC panel, DES 8610 (Deep Sea) control module, battery, diesel fuel tank, exhaust silencer, and flexible connector
2	Dummy Loadbank Rated voltage/frequency Rated power Load steps up to 200 kW Power factor Display accuracy Communication interface Cooling	TANEKO (PT. Tan Energy Indonesia, Indonesia) 400 VAC 3 phase 4 wire, 50 Hz Resistive load: 200 kW 1 kW, 2 kW, 2 kW, 5 kW, 10 kW, 20 kW, 40 kW, 40 kW, 80 kW (load can be selected from 1 kW to 200 kW) 1 0.5 class Load power supply input—Copper bar (star coupling “Y”) Control power supply input—3-core power plug Forced air cooling, horizontal air inlet and outlet
3	Data Acquisition System	DAQ-000-USB: Compatible with IBM PC Pentium III or above Windows98/NT/XP/Vista/7/8/10; RS 232C serial port (9 pin), USB port; RS 232C serial port (9 pin), USB port; Converter SCM-US48I (PT. Autonics Indonesia, Jakarta, Indonesia)
4	Flow Meter	Oval Corp; Model: LGL49A20 (OVAL Corporation, Tokyo, Japan)
5	Emission Monitoring System	MRU VarioPlus Ind; Model: EN 50379-2 (Messgeräte für Rauchgase und Umweltschutz GmbH, Neckarsulm, Jerman)
6	Sound Level Meter	SEW; Model: 2310SL (Standard Electric Works Co., Ltd., New Taipei City, Taiwan)
7	Machinery Health Analyzer	CSI; Model: B213000 (Emerson Electric Co., Clayton, MI, USA)
8	Pressure Transmitter	Autonic; range 0, 2 bar (PT. Autonics Indonesia, Indonesia)
9	Load Cell	DSD SBD, capacity 250 kg (DSCells., Qingdao, China)
10	Fuel Tank Capacity	200 kg

2.3. Measurement of Noise Levels

Noise level measurements in this study were conducted systematically at six observation points located around the tested generator set, designated as U1 to U6 (see Figure 3). Each measurement point was positioned at a uniform radial distance and azimuthal orientation with respect to the primary noise source to ensure that the acquired data adequately captured the spatial distribution of sound around the machine. The sound pressure levels were recorded using a SEW 2310SL sound level meter, operated in accordance with the

procedures specified in the experimental methodology. Before each measurement campaign, the device was calibrated per the manufacturer's instructions to ensure accurate and repeatable sound pressure readings in A-weighted decibels (dB).

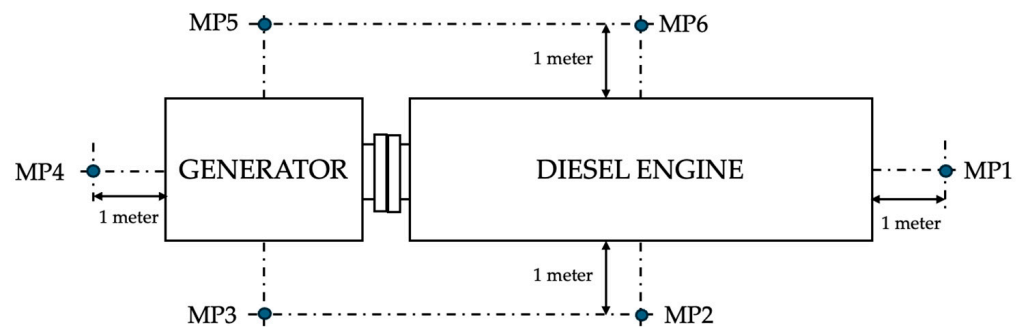


Figure 3. Noise level testing measurement point (MP).

3. Results

3.1. Performance Evaluation

3.1.1. Power Output

Figure 4 demonstrates that when the diesel generator set operates at elevated loads, specifically over around 90 kW, the engine's ability to augment torque to meet additional electrical demand is significantly constrained. This operational mode is marked by a diminished torque reserve, which is defined as the disparity between the maximum torque achievable at a specific speed and the torque necessary to sustain the nominal speed of 1500 rpm in a 50 Hz system. As the load nears the stated capacity, this margin diminishes, resulting in even minor fluctuations in fuel supply, combustion quality, or air handling conditions, potentially causing an immediate decline in engine speed. Under such circumstances, the engine must release a sufficiently large amount of chemical energy per cycle to keep the output power constant. Any transient imbalance between the in-cylinder released energy and the torque demanded by the alternator results in a short-term speed reduction. The mechanical governor reacts by enriching the fuel delivery; however, this response often overshoots, leading to a sudden recovery in speed. The repeated interaction between fuel reduction and enrichment induces oscillations in engine speed, which manifest as power fluctuations for several fuels when the load approaches or exceeds 90 kW.

For neat HVO (D100), the high cetane number likely indicates a short ignition delay and cleaner, faster combustion. Nevertheless, HVO exhibits lower density and lower heating value on a volumetric basis (LHV_v) than conventional diesel fuel. Since the injection system of typical diesel engines meters fuel on a volumetric rather than mass basis, an identical injected volume of HVO contains less chemical energy in the combustion chamber compared to mineral diesel. Consequently, the maximum attainable torque is reduced and the torque reserve is rapidly depleted at high load. As the demanded load approaches 100 kW, the governor must increase injection duration or flow rate in an attempt to offset this energy deficit. Beyond a certain point, the injection system reaches its mechanical rack limit, so that the injected fuel quantity cannot be further increased. The actual engine torque then fluctuates, the rotational speed becomes unstable, and the delivered real power declines. This behavior is consistent with the measured fuel properties, which show that HVO has lower LHV and density than fossil diesel, despite its higher cetane number and faster combustion characteristics.

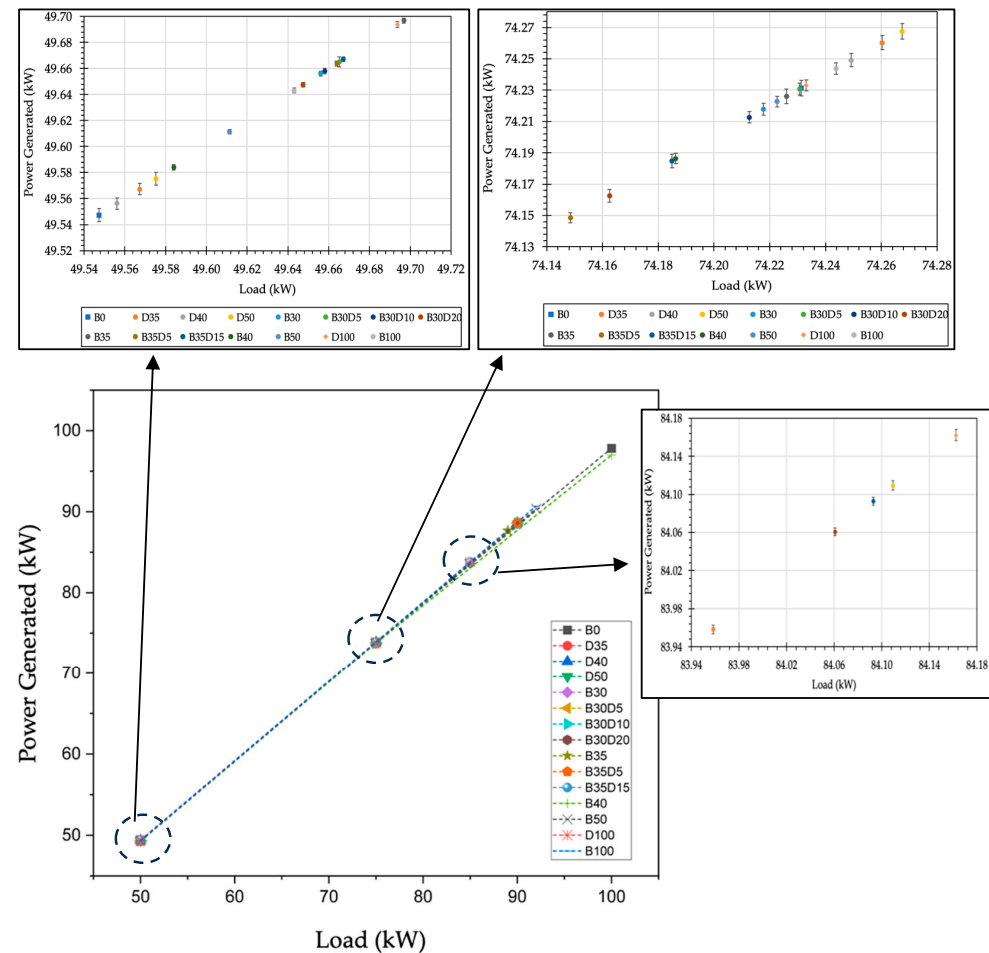


Figure 4. The correlation of the actual power generated to the load variation setting.

In contrast, for neat biodiesel and blends with a high FAME fraction such as B50, the primary limitation at high loads is not the calorific value per unit mass, but the atomization process and mixture formation in the combustion chamber [3,4]. The increased viscosity of FAME reduces atomization, resulting in bigger fuel droplets, slower evaporation, and less uniform air–fuel distribution. These effects favor incomplete combustion, especially at high loads where injection pressure and flow rate rise dramatically. Furthermore, the chemically attached oxygen in FAME promotes local oxidation of a portion of the fuel while decreasing the effective heating value per unit mass and volume, lowering the released energy per cycle, and accelerating torque reserve depletion under high loads. Fuel characterization studies show that FAME has a higher kinematic viscosity at 40 °C, higher density, and higher water and particle content than ordinary diesel. This combination increases the differential pressure (ΔP) across fuel filters, resulting in decreased effective injection pressure. Reduced injection pressure deteriorates the spray pattern, increasing torque instability over 90 kW. Under some conditions, recirculated hot return fuel can cause micro-cavitation or vapor lock in the return line, further destabilizing the fuel supply system.

Ternary blends, such as B30D10 or B35D15, provide the most consistent high-load performance due to their mutually compensating features. The HVO fraction increases the cetane number and accelerates combustion, while the FAME fraction improves fuel system lubricity. At the same time, the presence of traditional diesel keeps viscosity and density at optimal levels, resulting in a reasonably high volumetric heating value. As a result, these mixes can maintain a substantial torque reserve to attain or approach 100 kW without experiencing severe speed fluctuations. The experimental results show that most ternary mixes are stable in the 90–95 kW range, with some capable of maintaining a continuous

100 kW output, underscoring the need for balanced physical and chemical fuel qualities in guaranteeing steady high load operation.

In addition to energy and viscosity, fuel cleanliness reduces stability margins above 90 kW. FAME-rich fuels have high particulate and monoglyceride levels, which raise filter differential pressure and diminish injection pump supply pressure, disrupting spray production at high flow rates. Fuel characterization reveals higher particle counts and monoglyceride levels in FAME formulations compared to mineral diesel, increasing deposit formation and micro-blocking at nozzle tips. These principles explain field-scale speed oscillation and real power fluctuation at high loads. A distillation temperature at 90% recovery and cloud point have little effect under room temperature test conditions, but these thresholds can explain soot generation from heavy FAME fractions when atomization is inadequate. Heavy fractions evaporate slowly and may leave carbonaceous residues on combustion chamber walls and injector tips. Several fuels cannot achieve 100 kW due to a combination of fuel physical and chemical qualities and injection–governor system dynamics. For fuels with low energy per unit volume (HVO) or poor atomization (FAME), higher torque is needed to maintain nominal speed at a given load. Even minor load increments diminish engine speed, trigger excessive governor correction, and cause continuous rotational speed and actual power oscillations after the torque reserve is expended.

3.1.2. Specific Fuel Consumption

Figures 5 and 6 present the specific fuel consumption (SFC) characteristics of the tested fuels as a function of engine load, revealing a pattern that is well-established for compression-ignition engines: SFC decreases as the brake load increases from part-load to near-rated conditions. At 50 kW, SFC values for almost all fuel formulations remain relatively high on the order of 0.248–0.287 kg/kWh. As the load is raised to 75 kW and further towards 90–100 kW, SFC consistently decreases into a narrower band of approximately 0.233–0.270 kg/kWh.

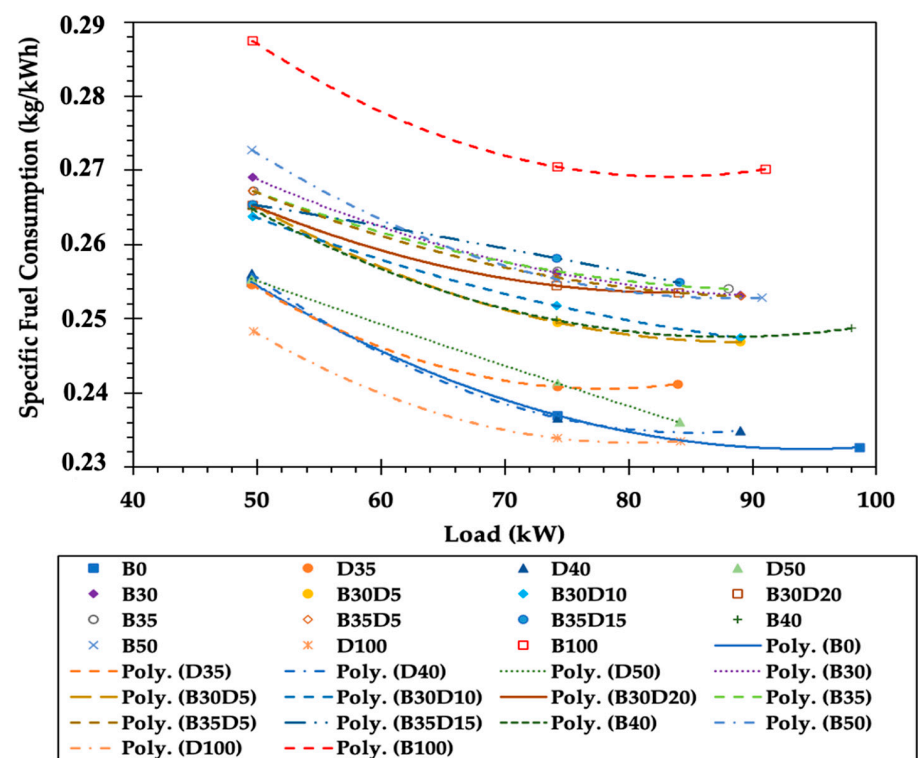


Figure 5. The specific fuel consumption on load variation settings.

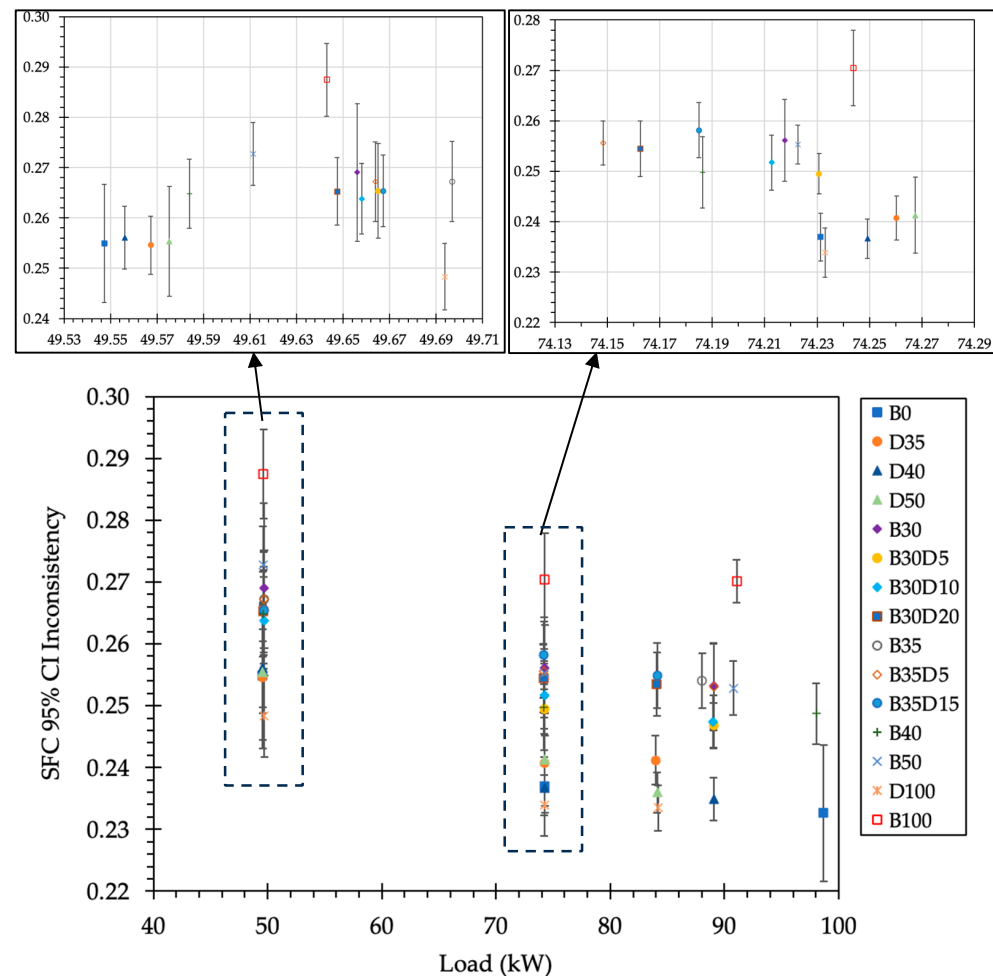


Figure 6. Specific fuel consumption inconsistency Confidence Interval (CI) 95%.

However, this consistent decrease in SFC is not evident across all fuel formulations when the load nears 100 kW. Not all mixes can maintain stable operation at the highest load point. In certain mixtures—especially those constrained by energy content per unit injected volume or by atomization quality at elevated injection rates—the engine demonstrates notable hunting, characterized by substantial variations in engine speed. Under such circumstances, the test operator must realistically reduce the applied load to preserve stable engine operation, and the measurements are practically terminated in the 90–95 kW range. As a result, some SFC data at 100 kW are missing, not due to a lack of data acquisition, but because the engine could not reach a steady-state condition under those operating points. Therefore, the SFC curve in Figure 5 not only illustrates the expected decrease in fuel consumption at high load, but also implicitly reflects the physical limitations and combustion characteristics of each fuel formulation. SFC values are only valid at operating points where the engine runs stably; the absence of some data at maximum load is a logical consequence of the complex interaction among fuel properties, injection system performance, and diesel governor dynamics.

At 50 kW, the neat diesel exhibits an SFC of approximately 0.255 kg/kWh. Increasing the load to 75 kW reduces the SFC to about 0.237 kg/kWh, and at the highest stable load of 100 kW, the SFC further decreases to roughly 0.233 kg/kWh. The technical characteristics of B0 in the present study show a cetane number of about 49.7, kinematic viscosity near 4 mm²/s at 40 °C, and density of roughly 851.8 kg/m³ at 15 °C. Such properties likely suggest fine atomization, stable spray development, and an ignition delay that matches the original injector and combustion chamber design. Comparisons against this neat diesel

enable a clearer assessment of how variations in density, viscosity, cetane number, and oxygen content in alternative fuels modify engine efficiency across different load levels. Figure 5 shows that at medium to near-high loads, HVO-rich fuels tend to achieve low SFC values due to their favorable combustion phasing and high mass-based heating value. In the present results, D100 at 50–75 kW emerges among the fuels with the lowest SFC, decreasing from about 0.248 to 0.234 kg/kWh.

At very high load, several Dxx blends struggle to reach or maintain steady operation at 100 kW. Because of the lower density, the energy per unit of injected volume becomes increasingly insufficient at peak power conditions, forcing the injection system toward longer actuation times and higher pressure demands. As the actuation approaches mechanical or control limits, the torque reserve diminishes, and then the system becomes more sensitive to small fluctuations in delivered fuel energy, which can trigger speed oscillations and hunting. In this regime, the operator must reduce the external load to approximately 90–95 kW to restore a stable operating point. This explains why some Dxx do not exhibit stable SFC measurements at the nominal 100 kW point despite competitive SFC levels at medium load.

At 50–75 kW, most FAME-rich formulations display higher SFC than both neat diesel and HVO blends. For instance, the B100 formulation at 50 kW appears among the fuels with the highest SFC, indicating that more fuel mass per kWh is required due to less favorable spray characteristics and reduced energy content. When the generator load approaches 90–100 kW, several FAME-rich formulations are still able to maintain competitively low SFC; however, their operational stability becomes markedly more sensitive than that of HVO or fossil diesel-like blends. This sensitivity at high load is consistent with the strong coupling between fuel physical quality and mixture formation, increased viscosity, and the presence of higher boiling. Heavy fractions typical of FAME can degrade atomization, prolong combustion duration, and raise SFC, especially when compared with HVO and fossil diesel, which exhibit lower viscosity and shorter combustion duration [25,28].

In practice, ternary blends of FAME, HVO, and fossil diesel often provide the most balanced performance characteristics compared with formulations dominated by a single component. The presence of an HVO fraction, which is paraffinic and essentially free of aromatics, substantially increases the cetane number and shortens ignition delay, thereby stabilizing the onset of combustion and enabling a more regular, controlled heat release profile [26]. Shorter ignition delay and smoother premixed combustion have been repeatedly associated with improved brake thermal efficiency (BTE) and reduced cyclic variability, particularly at medium to high loads [39,56]. At the same time, the FAME fraction does not excessively dominate the blend viscosity, so the resulting kinematic viscosity remains lower than that of neat FAME. This avoids the severe penalty in atomization quality that is typical for high viscosity biofuels, where larger Sauter mean diameters and poorer spray dispersion lead to incomplete combustion and higher SFC. The remaining diesel fraction helps to maintain density and volumetric energy content closer to conventional fuel, counteracting the low-density penalty of neat HVO, which otherwise tends to increase volumetric fuel demand at a given load. As a consequence, the injection system does not need to approach extreme injection durations or rail pressures to sustain peak torque, supporting stable governor control and mitigating phenomena such as torque hunting or sudden torque drops near full load.

HVO-rich blends exhibit reduced BSFC and enhanced BTE at medium loads due to their clean and stable combustion; however, restricted volumetric energy delivery may compromise stability at 100 kW when the governor approaches its limits. Conversely, FAME-rich fuels possess greater density and volumetric energy content, enabling high

power output despite suboptimal atomization and combustion; nonetheless, elevated loads result in increased SFC, similar to high-viscosity, oxygenated biofuels.

3.1.3. Total Efficiency

Figures 7 and 8 show a typical trend in diesel engine system performance, where the overall efficiency increases as the load rises from 50 kW to 75 kW and further to 90–100 kW. At low loads such as 50 kW, a substantial portion of the fuel energy is consumed by fixed losses, including internal mechanical friction, pumping work, and the power demanded by auxiliary components. These losses are only weakly dependent on load and therefore remain nearly constant over the operating range, so that at small loads their share of the total brake power output becomes disproportionately large, resulting in a low overall efficiency. Consequently, as the engine load is increased towards 75 kW and 90–100 kW, the fixed-loss contribution is distributed over a larger useful power output, leading to a pronounced rise in total efficiency.

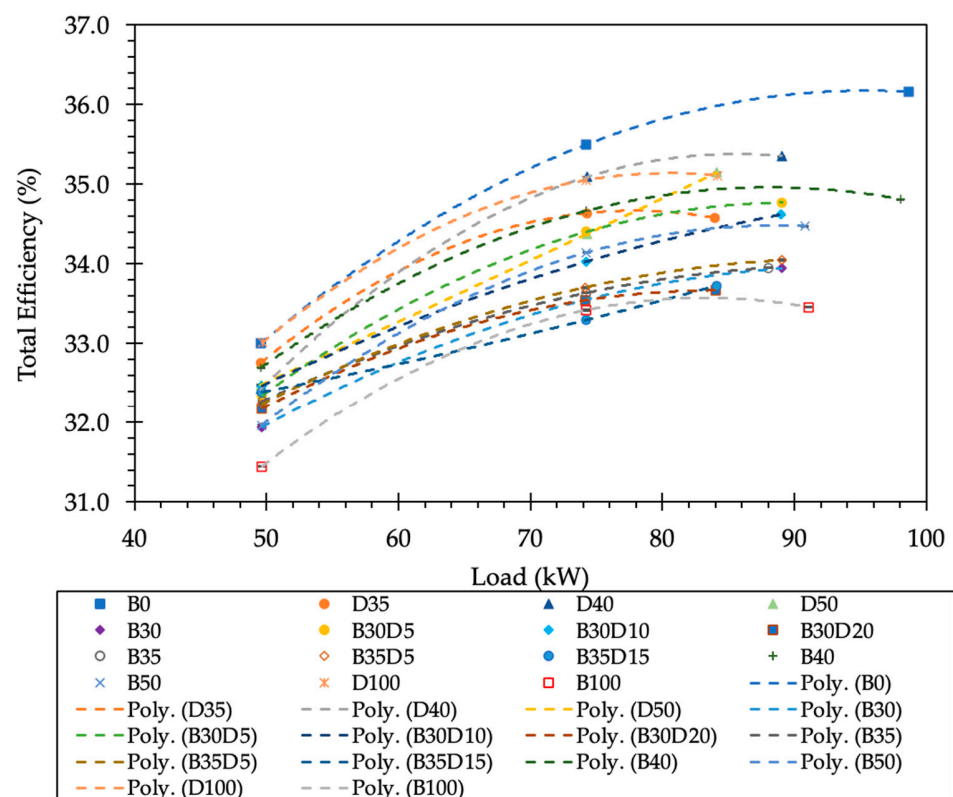


Figure 7. The correlation between total efficiency and load variation settings.

When the brake load is increased to around 75 kW, the quasi-constant mechanical and auxiliary losses are distributed over a higher effective power output. As a result, a larger fraction of the supplied fuel energy is converted into useful brake work, and the overall brake thermal efficiency rises sharply. In the present study, the high-load window of 90–100 kW corresponds to approximately 70–85% of the rated capacity. Within this band, most of the investigated fuel formulations exhibit their best thermodynamic performance, provided that stable operating conditions are maintained and the engine is able to sustain torque without noticeable fluctuations.

Quantitatively, the initial efficiencies at 50 kW lie in the range of 31–33%. Increasing the load to 75 kW yields efficiencies of about 33–35%, while at loads approaching 100 kW, the efficiency further improves to approximately 34–36%. The highest value, around 35.8%, is attained by the neat fossil diesel fuel (B0) at 100 kW. This monotonic rise of efficiency

with load agrees with previous studies, in which brake thermal efficiency increases up to a certain part-load fraction as fixed losses are diluted and combustion phasing becomes more favorable [31,67].

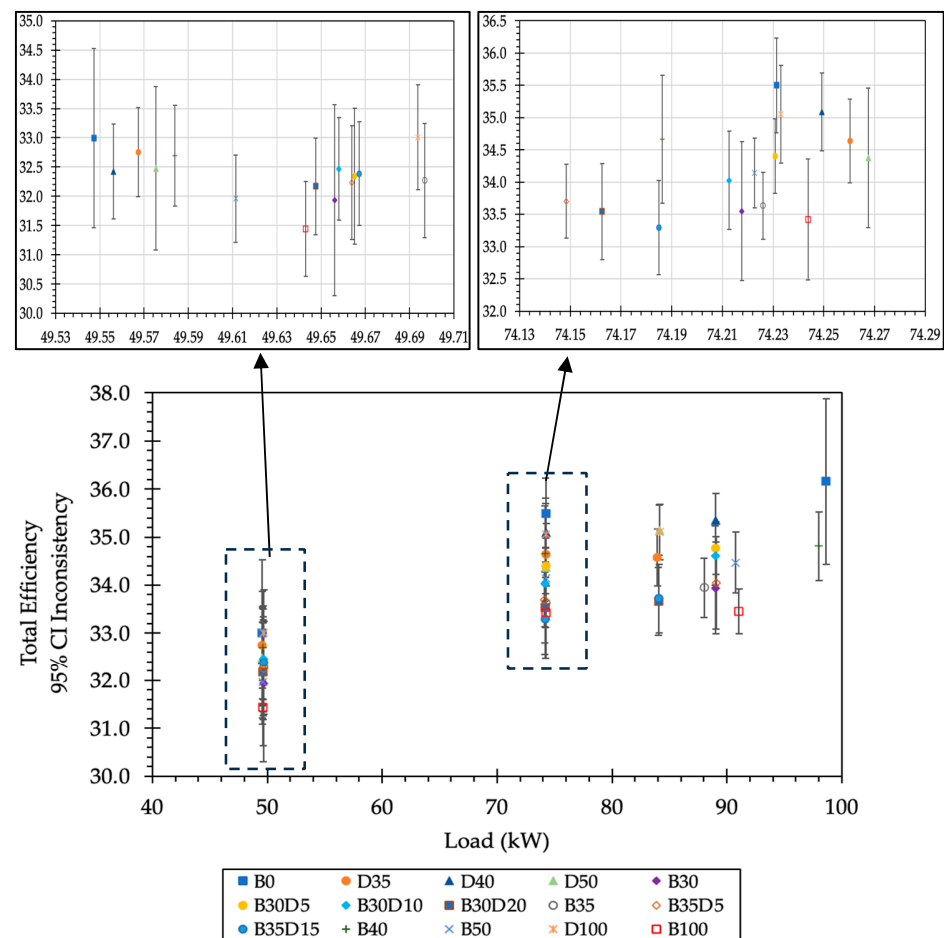


Figure 8. Total efficiency inconsistency Confidence Interval (CI) 95%.

Within the tested load range, B0 consistently emerges as the best-performing fuel. At 50 kW, B0 reaches an efficiency of 32.88%, which increases to 35.23% at 75 kW and peaks at 35.80% at 100 kW. This robust performance can be attributed to the favorable physical and chemical characteristics of conventional diesel, including a cetane number near 50, a kinematic viscosity of about 4 mm²/s, and a density around 850 kg/m³, combined with a volatility profile compliant with ASTM D975 diesel specifications. These properties likely indicated fine atomization, an ignition delay close to the optimal range, and a stable, well-phased heat-release process, which together sustain efficient combustion across all investigated loads. For this reason, B0 is considered the baseline fuel in the present analysis, and all alternative formulations are evaluated in terms of relative improvements or degradations in efficiency with respect to this reference.

Hydrotreated vegetable oil (HVO) is typically characterized by a very high cetane number, often in the 70–90 range, which shortens ignition delay and leads to more controlled and cleaner heat-release, thereby improving indicative efficiency [25,69]. The measured cetane number of HVO-based fuels is more moderate, around 49–55, likely due to blending effects or differences in correction methodology. Nonetheless, the intrinsic tendency of HVO remains evident. The elevated cetane number and paraffinic composition are known to facilitate rapid auto-ignition, smoother pressure rise, and lower soot formation compared to conventional diesel and FAME biodiesel. At medium loads (50–75 kW), blends with

a high HVO fraction demonstrate relatively good efficiency. For example, the neat HVO (D100) exhibits an efficiency increase from 32.71% to 34.82% between 50 and 75 kW, while D50 improves from 32.31% to 34.19%, and D40 from 32.18% to 34.81%. These results align with prior findings that HVO and HVO–diesel blends can achieve brake thermal efficiencies similar to or slightly higher than fossil diesel, particularly under medium-load conditions [67,70]. However, at loads close to 100 kW, only the neat HVO (D100) maintains stable operation, reaching an efficiency of 34.88%. Most HVO-containing blends cannot be extended to the full 100 kW due to torque instability and injection-system limitations at peak load, an issue also hinted at in studies where injection pressure and combustion phasing need to be re-optimized when switching between diesel, HVO, and FAME fuels.

In contrast, FAME-based fuels present a distinct set of trade-offs. FAME typically has a higher density ($\approx 860\text{--}900\text{ kg/m}^3$) and kinematic viscosity ($\approx 4\text{--}6\text{ mm}^2/\text{s}$) than fossil diesel, along with an intrinsic oxygen content of about 10–12 wt.%. The bound oxygen facilitates soot oxidation and can contribute to cleaner combustion, but at the expense of a lower heating value, which tends to increase brake-specific fuel consumption and may reduce efficiency, especially at high load [25,67]. In the present experiments, FAME-containing blends achieve initial efficiencies of about 31–32% at 50 kW, rising to 33–35% at 75 kW, which is similar in magnitude to other fuel groups. Yet near 100 kW, several FAME-rich formulations fail to reach their potential peak performance. The high viscosity and the presence of water, sediments, and glyceride residues increase the pressure drop across the fuel filter and promote deposit formation, which can induce nozzle fouling and disturb the injection pattern. Such effects become more critical at high load, where injection duration is long and the fuel system operates close to its capacity. As a result, the pure FAME fuel (B100) remains stable only up to about 92 kW, where it attains an efficiency of 33.23%, but it cannot be operated reliably at the full 100 kW. This behavior is in line with multiple reports indicating that FAME biodiesel tends to raise kinematic viscosity, exacerbate fouling, and slightly deteriorate thermal efficiency at high load unless the injection system and operating parameters are recalibrated [25,67,71].

Ternary blends comprising diesel, HVO, and FAME exhibit the most balanced performance among the tested fuel groups. For the B30 formulation, efficiency increases from 31.69% at 50 kW to 33.36% at 75 kW. The B30D10 blend shows a more consistent progression, from 32.26% at 50 kW to 33.73% at 75 kW, and reaching 34.45% at loads near 100 kW. Similarly, the B35D15 blend records an efficiency of 32.04% at the initial load, rises to 33.26% at 75 kW, and attains 33.80% at high load. These results suggest that carefully formulated three-component mixtures can exploit the elevated cetane number of HVO to improve ignition quality, while FAME and diesel contributions help maintain density in an optimal range and prevent excessive reductions in lower heating value. At the same time, the overall viscosity of the ternary blends remains lower than that of neat FAME, preserving good atomization and stable spray development.

The net effect of this property balance is a combustion process that remains stable and efficient across the entire tested load spectrum, including the high-load region where some binary blends fail. Comparable findings have been noted in studies on binary and ternary blends of diesel, HVO, and FAME, where mixtures containing both paraffinic and oxygenated components can match or slightly surpass diesel in efficiency while simultaneously reducing particulate emissions, provided that the blend ratio and engine calibration are appropriately selected [24,25,56,67]. In the present work, the three-component blends emerge as the most load-robust option, delivering the most consistent efficiency profile from 50 to 100 kW and thus representing a promising compromise between performance, stability, and renewable content.

3.1.4. Exhaust Gas Temperature

Exhaust gas temperature (EGT) is one of the most informative global indicators of the combustion process in diesel engines. It reflects the balance between the chemical energy released during fuel oxidation and the effectiveness of in-cylinder and exhaust heat transfer processes. As such, EGT is routinely used as a diagnostic parameter to distinguish between thermally efficient, well-phased combustion and conditions associated with over-fueling, incomplete combustion, or abnormal heat loading on engine components [52].

From a thermodynamic standpoint, higher in-cylinder peak temperatures and longer high-temperature residence times generally result in elevated EGT, whereas rapid heat transfer to walls, high excess air operation, or strong dilution tend to reduce the exhaust temperature. In practical diesel operation, EGT therefore emerges as an integrated response to multiple coupled phenomena: fuel–air mixing, ignition delay, heat release phasing, turbulence, and in-cylinder heat transfer.

Figures 9 and 10 present the evolution of exhaust gas temperature (EGT) as a function of brake load for the constant-speed diesel engine investigated. A markedly monotonic and nearly linear increase in EGT is observed with rising load. As the load is increased, a larger fraction of the fuel's chemical energy is converted into thermal energy within the combustion chamber, elevating the temperature of the burned gases and, therefore, the temperature of the exhaust stream.

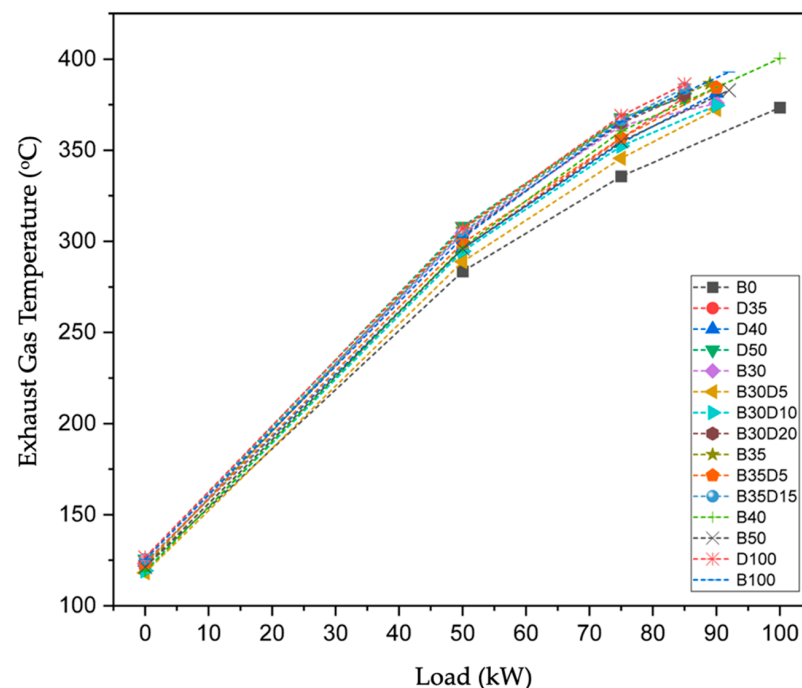


Figure 9. The correlation between exhaust gas temperature and load variation settings.

At no-load operation (0 kW), the EGT remains relatively low, in the range of 121–126 °C, reflecting a light-combustion regime in which only a minimum quantity of fuel is supplied to maintain engine speed. When the brake load is increased to 50 kW, the EGT rises sharply to approximately 285–307 °C. This substantial increase indicates a higher proportion of energy being released and retained in the working gases. Further increasing the load to 75 kW results in EGT values in the range of 345–367 °C. This trend signifies a more intense combustion process with higher peak in-cylinder pressures and temperatures. At this stage, the rate of heat release per unit time rises in proportion to the injected fuel rate, and the exhaust temperature becomes a sensitive indicator of combustion effectiveness and of the fraction of energy not recovered as useful work. At the maximum tested load

of 100 kW, the EGT attains its highest values, between 373 and 400 °C, representing the upper bound of the experimental campaign. Such elevated exhaust temperatures suggest that most of the chemical energy of the fuel is converted into thermal energy to sustain the maximum mechanical output, leaving a smaller margin for further EGT growth without approaching thermal saturation of the system.

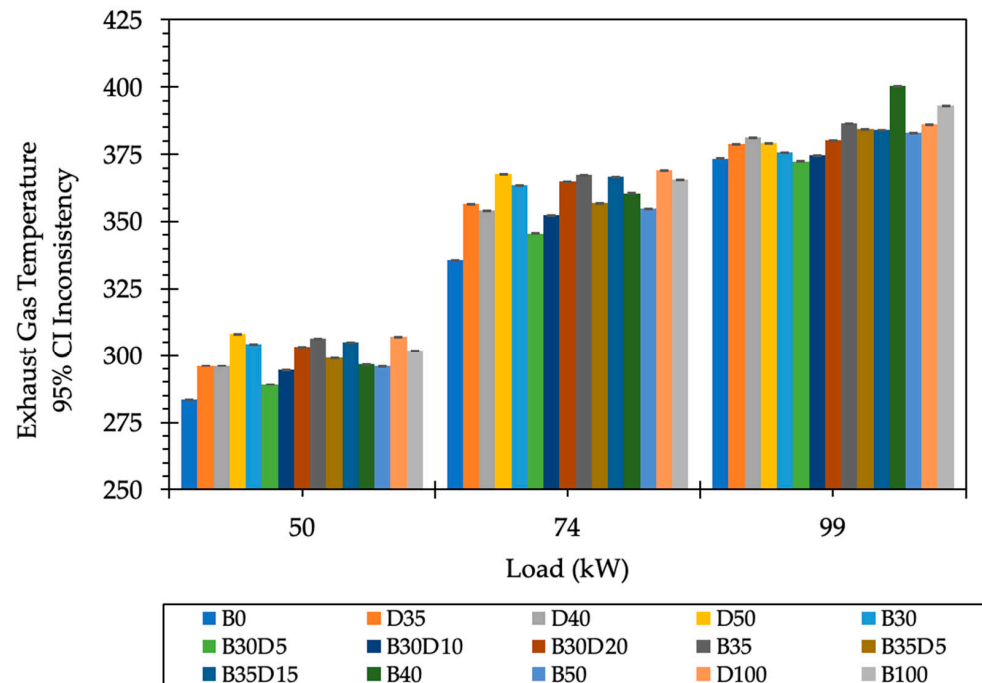


Figure 10. The exhaust gas temperature inconsistency Confidence Interval (CI) 95%.

From a theoretical standpoint, the observed EGT trend is in full agreement with classical diesel engine thermodynamics. In constant-speed operation, an increment in brake load requires a proportional increase in fuel energy input to maintain the same rotational speed while delivering higher torque [34,72]. The enhanced fuel supply leads to greater heat release, higher in-cylinder temperatures, and thus higher exhaust temperatures, typically exhibiting an almost linear dependence on load up to a region where thermal losses and mixture-limiting effects induce a tendency toward saturation. Numerous experimental investigations using both mineral diesel and biodiesel blends corroborate this relationship, consistently reporting EGT growth with load as a direct consequence of increased fuel flow and intensified combustion [32,35,36].

Neat diesel (B0) shows a moderate rise in EGT, from about 121 °C at the no-load condition to 373 °C at the full-load condition (100 kW), and remains lower than most biodiesel and HVO blends at medium–high loads (see Figure 7). This behavior is attributable to the high LHV and relatively low kinematic viscosity of fossil diesel, which promote efficient atomization and rapid, complete combustion. Higher LHV and lower density/viscosity favor conversion of fuel energy into brake work, thereby limiting residual heat in the exhaust. Moreover, the lack of inherent oxygen and the relatively high cetane number shorten the ignition delay and yield a more controlled, “cooler” flame, so that the EGT increases smoothly with load [32,73]. Furthermore, oxidative diesel blends (D35, D40, and D50) display slightly higher EGT than B0, especially at part and medium loads. The modest reduction in cetane number has the potential to lengthen ignition delay and increase the premixed combustion fraction, which raises local peak temperatures and, consequently, the measured EGT. Since the kinematic viscosity of these Dxx series fuels remains close to that

of diesel, spray atomization and overall combustion efficiency are preserved, leading to stable combustion and a non-extreme EGT profile.

For low to medium biodiesel blends such as B30 and its derivatives, the increase in EGT with load is more pronounced. Initial temperatures at 0 kW lie around 118–125 °C, rising to 352–364 °C at 75 kW and reaching approximately 380 °C or higher near full load (see Figure 9). Several mechanisms are responsible. First, the inherent oxygen content of FAME (≈ 10 –12 wt.%) accelerates oxidation and increases the heat release rate, which enhances combustion completeness but also elevates in-cylinder and exhaust temperatures [34,36,74]. Second, higher viscosity produces larger fuel droplets and slower evaporation, causing part of the heat release to shift into the late expansion phase (afterburning), thereby increasing EGT, a phenomenon reported widely for high viscosity biodiesels [32,34,36]. Third, higher density admits more fuel mass per cycle for a given injection command, increasing the total energy released and further raising exhaust temperatures [32,75]. Overall, the present results confirm that, within this group, higher biodiesel shares (e.g., D5, D10, and D20 relative to B30-type baselines) are associated with systematically higher EGT. In the higher biodiesel regime (B35, B35D5, and B35D15), EGT rises more steeply: temperatures already reach about 299–306 °C at 50 kW, increase to 356–367 °C at 75 kW, and attain ≈ 384 °C at maximum load, with B35D15 among the hottest cases. The elevated FAME fraction amplifies internal oxygen availability and accelerates combustion, but the reduced oxidative stability of highly unsaturated methyl esters can promote spatially non-uniform combustion at high load, generating strong local temperature gradients and, consequently, a higher average EGT. Blends B40 and B50 approach the behavior of neat biodiesel, with consistently high exhaust temperatures across all loads. The primary causes are the combination of high oxygen content and slightly longer ignition delay, which enlarges the premixed burn fraction and raises the flame temperature, together with the high viscosity that impairs evaporation and intensifies afterburning during expansion [32,76].

Neat biodiesel (B100) delivers the highest EGT at nearly all load points, with measured values of 125.6 °C at 0 kW, 302 °C at 50 kW, 365.7 °C at 75 kW, and about 392 °C at 90–100 kW (see Figure 9). Several factors concur: (i) the lowest LHV among all tested fuels requires a greater fuel mass to achieve the same brake power, increasing the total heat released to the exhaust; (ii) the highest oxygen content (≈ 11 –12%) intensifies oxidation and produces a hotter flame; and (iii) elevated viscosity hampers atomization, prolongs combustion into the expansion stroke, and increases EGT through afterburning [32,37,38,76]. Although the typically higher cetane number of biodiesel shortens the ignition delay, a substantial fraction of the heat is released in an initial rapid burn followed by extended diffusion combustion of larger droplets, which sustains high temperatures late in the cycle [37,77].

The D100-type fuel, characterized by high cetane diesel with low viscosity, shows exhaust gas temperature (EGT) values that are higher than those of conventional B0 diesel but lower than those of high biodiesel blends. Its excellent atomization and mixing contribute to efficient and uniform spatial combustion. The high cetane number results in a short ignition delay, which helps limit excessively high local peak temperatures. Additionally, the high lower heating value (LHV) indicates a significant energy content per unit mass. A considerable portion of this energy is transformed into useful work rather than being wasted as exhaust heat. Consequently, D100 occupies an intermediate thermal position: it is hotter than standard diesel due to its higher paraffinic content yet cooler than high fatty acid methyl ester (FAME) blends because of more stable flame development [37,38,78]. Overall, the observed EGT hierarchy—B0 < oxidative diesel blends < low–medium biodiesel blends < high biodiesel blends < B100—is in good qualitative agreement with previous biodiesel engine studies, which consistently report that higher biodiesel content, higher viscosity/density, and higher oxygen content favor more complete but thermally “hotter”

combustion with elevated exhaust temperatures. The fuel characteristics' effects on exhaust gas temperature (EGT) are illustrated in Table 4.

Table 4. Fuel characteristics' effects on exhaust gas temperature (EGT).

Fuel Group	Fuel Code	Main Characteristics	Influence on EGT	EGT Level (Relative)	Key Remarks
Neat Diesel	B0	High Cetane Number, high LHV, no bound oxygen, low viscosity	Stable combustion, "cooler flame"	Lowest	Efficient; low heat loss
Paraffinic Diesel	D100	Very high Cetane Number, excellent atomization, high LHV	Very stable combustion, moderate peak temperature	Low–medium	Hotter than B0, cooler than biodiesel
Oxidative Diesel	D35, D40, D50	Lower CN, viscosity similar to B0	Slightly longer ignition delay → slightly increased EGT	Lower–medium	Combustion remains stable
Low–Medium Biodiesel	B30, B30D5, B30D10, B30D20	Low–medium FAME content, 10–12% bound oxygen, increased viscosity	Higher heat release, reduced atomization	Medium	EGT increases proportionally with FAME fraction
Medium Biodiesel	B35, B35D5, B35D15	Higher FAME content, reduced oxidative stability	Hotter and less uniform combustion	Medium–high	Afterburning becomes significant
High Biodiesel	B40, B50	High FAME content, high viscosity, low LHV	Fast and extended combustion → strong afterburning	High	Almost comparable to B100
Neat Biodiesel	B100	100% FAME, highest bound oxygen, highest viscosity, lowest LHV	Hottest combustion, long flame duration	Highest	Greatest thermal risk; highest EGT

3.1.5. Cooling Temperature

Coolant temperature is a key indicator of the thermal balance between the heat released in the combustion chamber and the capacity of the cooling circuit to remove this heat. It provides an indirect measure of combustion efficiency, lubricant viscosity, and the overall stability of diesel engine operation, aspects that are widely recognized as central to engine thermal management and emissions control [40,79,80]. Figures 11 and 12 show that, for all tested fuel formulations, the coolant temperature exhibits a monotonic increase with engine load. Under no-load conditions (0 kW), the coolant temperature lies between 66 and 81 °C, depending on the fuel type.

When the load is increased to 50 kW, almost all fuel formulations converge to a coolant temperature of approximately 82 °C. At this operating point, the cooling system reaches a quasi-steady thermal equilibrium, where the heat generated by combustion is balanced by the heat rejected through the coolant to the radiator. Such a balance is crucial for maintaining stable combustion phasing, limiting friction losses, and supporting efficient aftertreatment performance, as emphasized in earlier coolant temperature studies on automotive and heavy-duty diesel engines [40,81].

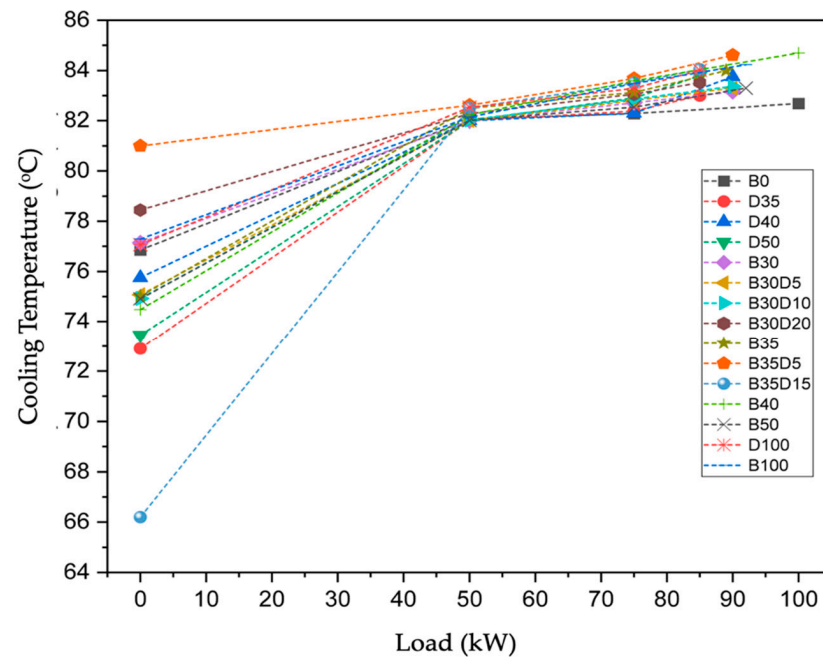


Figure 11. The correlation between cooling temperature and load variation settings.

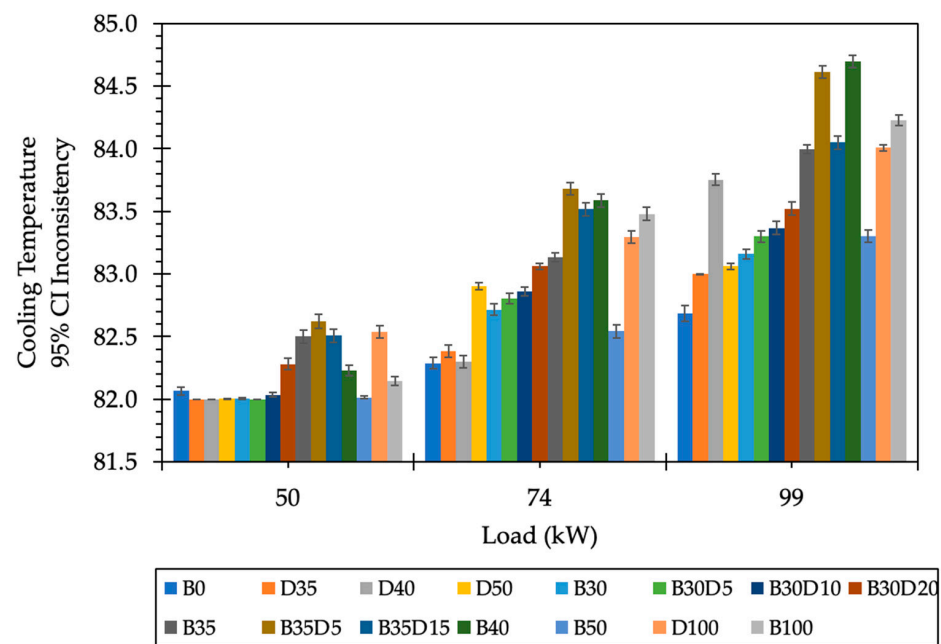


Figure 12. The cooling temperature inconsistency Confidence Interval (CI) 95%.

For loads of 75 kW and above, the coolant temperature remains nearly constant in the range of 82–84 °C, indicating that the cooling system operates close to its optimum in maintaining the engine below the critical temperature threshold. For medium-duty diesel engines, safe operating limits are typically reported around 85–90 °C [40,79,82], so the measured values confirm that the engine remains within a thermally safe region, with negligible risk of overheating.

The observed trend is in line with the characteristics of the four-stroke Cummins 6BTAA5.9 G12 diesel engine employed in this study. In such engines, an increase in load directly raises the fuel flow rate to the combustion chamber, thereby increasing the heat release. The cooling system then acts to reestablish thermal balance by removing the excess heat from the cylinder block and head and rejecting it to the ambient air via the radiator.

Consequently, even though the brake power rises substantially at higher loads, the coolant temperature remains effectively controlled. This behavior highlights the thermal efficiency of the engine and the effectiveness of the cooling system in maintaining an almost load-independent operating temperature band, in agreement with recent findings that intelligent or load-sensitive cooling strategies can reduce heat losses while keeping the engine within safe thermal limits [81,83].

The coolant temperature measurements revealed distinct thermal behavior among the fifteen fuel formulations evaluated. In all cases, coolant temperature increased with engine load; however, the magnitude and stability of this rise were strongly governed by the physicochemical properties of each fuel, particularly cetane number, viscosity, density, oxygen content, and LHV. The following paragraphs provide a comparative narrative across fuel groups based on the test results and reference fuel properties.

Neat diesel (B0) exhibited the most stable thermal profile among all tested fuels. The coolant temperature at idle was approximately 77 °C and increased smoothly to about 82 °C at 50–100 kW (see Figure 8). This high thermal stability can be attributed to its relatively high cetane number (~50) and high LHV (~42–43 MJ/kg), which promote rapid and efficient combustion, short combustion duration, and a uniform heat release profile [39,41]. As a result, a larger fraction of the released energy is converted to mechanical work, while the fraction transferred to the cooling system remains relatively low. Moreover, the low sulfur and particulate content contribute to clean heat transfer surfaces, limiting deposit formation on cylinder walls and preserving heat transfer efficiency.

The B30 and B35 blends showed slightly higher idle coolant temperatures (77–78 °C) compared with neat diesel. This increase is associated with the internally bound oxygen in FAME (about 10–12 wt.%), which tends to accelerate early combustion phases and raise local in-cylinder temperatures. Nevertheless, at medium to high loads (50–100 kW), the coolant temperature for both blends remained in a narrow band of 82–83 °C, indicating that the oxygenation effect does not lead to uncontrolled thermal rise at higher loads. Their densities (~864–865 kg/m³) and viscosities (~4.1 mm²/s) are slightly higher than those of diesel, causing marginally poorer atomization and somewhat longer burn duration [37,84]. This leads to modestly higher heat rejection without significantly disturbing the overall thermal balance of the cooling system. Overall, B30 and B35 present acceptable thermal performance, albeit slightly hotter operation than neat diesel.

The group of FAME–HVO blends (B30D5, B30D10, B30D20, B35D5, and B35D15) displayed the best thermal stability among all biodiesel-based formulations. At idle, the coolant temperature ranged between 75 and 81 °C, depending on HVO content, and remained within 82–84 °C at 50–100 kW, with B30D20 and B35D15 at the upper end (≈83–84 °C). The addition of HVO lowers fuel viscosity and density and thereby enhances atomization and air–fuel mixing, while its high cetane number accelerates ignition and shortens combustion duration. Consequently, a larger share of the combustion energy is converted to indicated work and less is rejected as heat to the coolant, an effect also observed for other high-cetane paraffinic fuels that reduce cooling losses at high load. With negligible sulfur, no aromatics, and high oxidation stability, HVO significantly improves the thermal behavior of FAME-based blends, helping to maintain stable coolant temperatures and supporting longer component life. These characteristics make FAME–HVO blends a well-balanced compromise between combustion efficiency, thermal stability, and engine durability.

The D35, D40, and D50 series (medium to high HVO blends) showed the lowest idle coolant temperatures, in the range of 73–76 °C, and the slowest rise with increasing load, highlighting the strong thermal-stabilizing capability of HVO. Owing to its low density (≈780–800 kg/m³) and low viscosity (~3–3.7 mm²/s), HVO provides excellent

spray atomization and homogeneous mixing, which in turn promote efficient combustion and reduced heat rejection to the cooling circuit [41,85]. With an LHV around 43 MJ/kg, comparable to or slightly higher than fossil diesel, the thermal energy released is effectively utilized for gas expansion rather than being dissipated as residual heat. The essentially sulfur-free and aromatics-free composition of HVO also minimizes deposit formation and maintains high heat-transfer effectiveness at the cylinder wall. Among this group, D50 emerges as one of the most efficient fuels in terms of engine heat management, as its coolant temperature only reaches about 82–83 °C at maximum load without any sharp increase.

Blends with high biodiesel content, such as B40 and B50, exhibited relatively high idle temperatures (74–75 °C) and a rapid rise up to about 84 °C at full load. This behavior is driven by the high FAME fraction (≈ 39 –48%), which increases kinematic viscosity (~ 4.13 – 4.17 mm²/s) and density (866–867 kg/m³) and lowers LHV to around 41.8 MJ/kg. These properties require higher fuel consumption at a given load and tend to prolong combustion, both of which increase the total heat to be removed by the cooling system [37,84]. Elevated water content (≈ 212 –256 mg/kg) further degrades atomization and extends combustion duration, increasing wall heat flux and coolant temperature. Consequently, B40 and B50 impose a higher thermal load on the cooling system than other blends, implying that engines fueled with such high-FAME blends may demand more robust cooling capacity to avoid overheating at full load.

Neat HVO (D100) produced the most stable coolant temperature profile among all tested fuels. At idle, the coolant temperature was around 77 °C and rose gradually to 83–84 °C at maximum load. This stability stems from the superior physical properties of HVO: very high cetane number (70–90), low density (~ 786 kg/m³), and low viscosity. These properties collectively facilitate very rapid and clean combustion [41,85]. As a result, D100 can be considered the fuel with the highest thermal efficiency and most favorable coolant-temperature behavior in the present comparison.

Neat biodiesel (B100) showed the highest coolant temperatures of all fuels. At idle, the coolant temperature reached about 77 °C and increased to approximately 84 °C at full load, similar to B50 but with a more pronounced thermal burden on the cooling system. This outcome is directly related to the very high FAME content ($\sim 95\%$), the presence of mono- and diglycerides, and the resulting elevated viscosity (~ 4.43 mm²/s) and water content (~ 338 mg/kg) [86]. These features degrade spray quality and atomization, lengthen combustion, and increase the residual heat that must be transported away by the coolant. Furthermore, the relatively low LHV (≈ 37 –39 MJ/kg) leads to higher fuel consumption per unit power output, further raising total heat release. Parameters such as higher total acid number and poor cold-flow behavior (e.g., high CFPP) indicate a tendency toward oxidative instability and deposit formation at elevated temperatures, which can impair heat transfer and accelerate lubricant degradation. Prolonged operation with B100 therefore risks higher coolant and oil temperatures, potential loss of lubrication pressure, and faster wear of engine components.

Overall, neat HVO (D100) and blends with moderate HVO fractions (D50, B30D20, and B35D15) demonstrated the most favorable thermal stability, owing to their high cetane numbers, low viscosities and densities, and high oxidation stability, which collectively support fast, clean, and efficient combustion. In contrast, biodiesel-rich fuels with high FAME content (B40, B50, and B100) tended to significantly increase coolant temperature due to their higher viscosity, lower LHV, and longer combustion duration, in agreement with previous work showing higher exhaust and wall temperatures for high-biodiesel blends relative to diesel. These findings reinforce that incorporating HVO into biodiesel blends is an effective strategy to improve thermal characteristics and reduce cooling system heat load, thereby enabling more efficient and stable diesel engine operation under high-

load conditions. The comparative thermal stability characteristics of the different fuels are summarized in Table 5.

Table 5. Fuel characteristics' effects on coolant temperature.

Fuel Type	Fuel Code	Coolant Temp (°C)		Thermal Stability	Key Remarks
		Idle	Max Load		
Neat diesel	B0	~77	82	Very stable	High cetane number, high lower heating value (LHV), efficient combustion
Low–medium biodiesel	B30, B35	77–78	82–83	Stable	High oxygen content → higher initial temperature but remains controlled
FAME–HVO blend	B30D5, B30D10, B30D20, B35D5, B35D15	75–81	82–84	Highly stable (best among the biodiesel group)	HVO improves atomization and accelerates combustion
Diesel–HVO blend	D35, D40, D50	73–76	82–83	Very high stability	Low viscosity, very clean combustion
High biodiesel content	B40, B50	74–75	84	Less stable	High viscosity, low LHV → higher thermal load
Neat HVO	D100	~77	83–84	Most stable	Very high cetane number, practically no carbon residue
Neat FAME biodiesel	B100	~77	84	Highest coolant temperature	High water content, poor atomization, and long combustion duration

3.1.6. Environmental Noise Level Assessment

The six noise measurement panels exhibit a consistent trend for all fuel formulations, namely a monotonic increase in overall sound pressure level with increasing generator-set load, as shown in Figures 13 and 14. This behavior is fully consistent with fundamental acoustic principles for stationary diesel engines, where higher torque and mechanical power output are accompanied by proportional growth of the dominant noise components, including exhaust noise, induction/turbo noise, and mechanical noise emanating from the valvetrain, gear train, and alternator [86]. As the load increases from idle to medium and high levels, the exhaust gas energy and in-cylinder peak pressure rise accordingly, leading to several-decibel increases in the equivalent continuous sound level (LAeq) relative to no-load operation. The near-linear increase observed for most fuel blends indicates that the engine system and its acoustic paths respond in a nominal manner to rising brake power.

A closer inspection reveals small local “bumps” in the 50–70 kW range, notably at positions MP2 and MP3. These features can be interpreted as the result of transitions in the governor control system, such as changes in gain or speed control response during rapid load increments, which temporarily modify torque oscillations and associated acoustic emission. In addition, such localized increases may be linked to shifts in the ratio of premixed to diffusive combustion, where a more dominant premixed phase at mid-load enhances pressure rise fluctuations and combustion noise intensity [87,88]. In some operating points, the onset of a turbocharger spool in this load window can further augment induction noise due to high velocity airflow in the intake system [89].

A comparison of the different microphone locations shows that MP2 and MP6 consistently record higher sound levels, especially above 60 kW, suggesting that these points are located closer to the exhaust outlet or the cooling fan discharge, which are known to be primary noise sources in diesel generator sets. Conversely, positions MP3–MP5 tend

to exhibit slightly lower levels across most loads. Because all microphones were installed at a uniform distance of approximately 1 m from the genset, as specified in the noise measurement methodology, the observed differences cannot be ascribed to distance or procedural effects. Instead, they reflect the directional dominance of specific noise sources and the local pattern of sound reflections around the enclosure. The tested unit is a “silent type” genset equipped with acoustic panels on all cabin sides; hence, the orientation of the cooling air discharge and the exhaust outlet plays a decisive role in shaping the measured noise distribution.

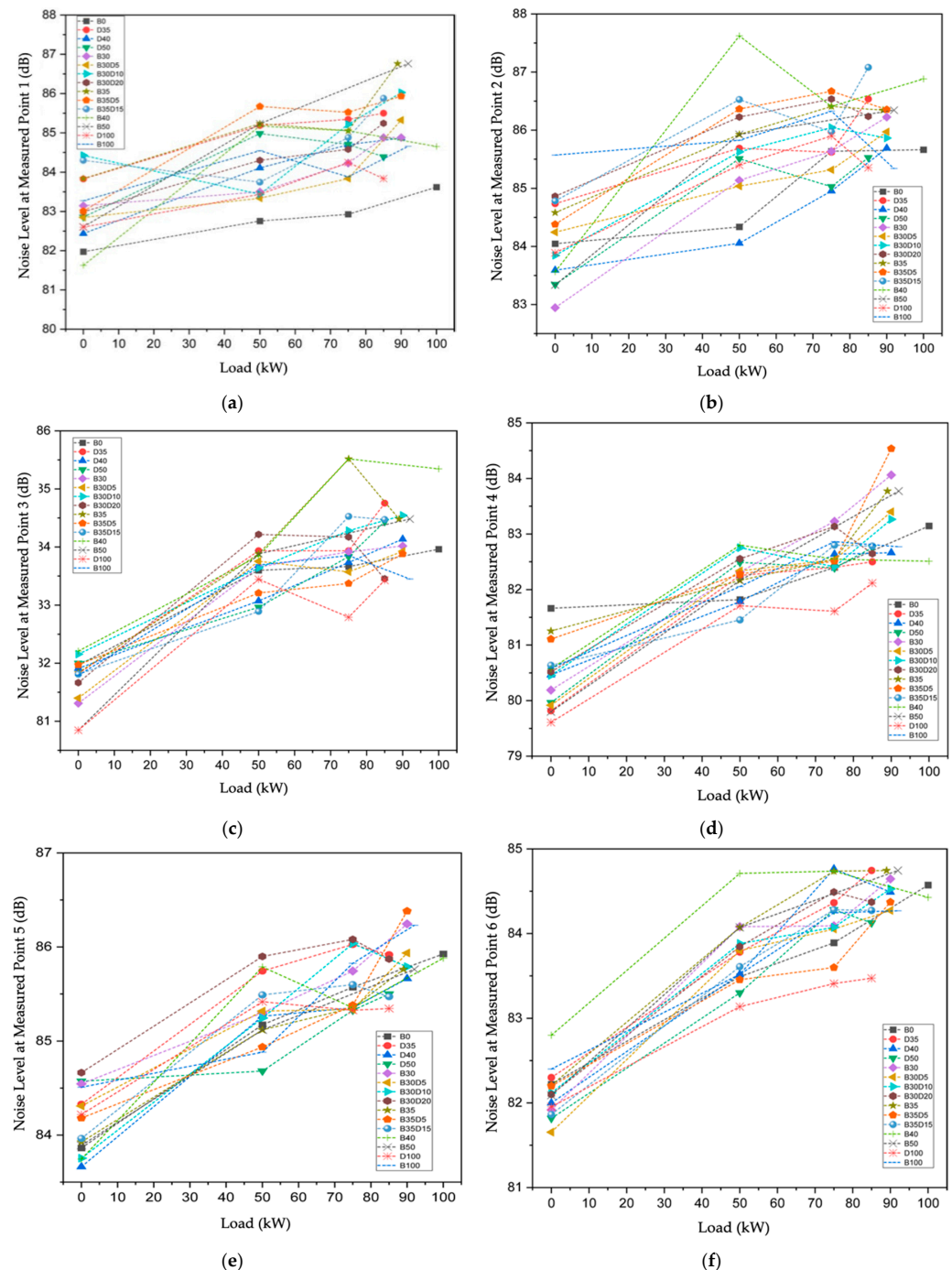


Figure 13. Noise level measurement results under varying load conditions: (a) Measured Point 1, (b) Measured Point 2, (c) Measured Point 3, (d) Measured Point 4, (e) Measured Point 5, and (f) Measured Point 6.

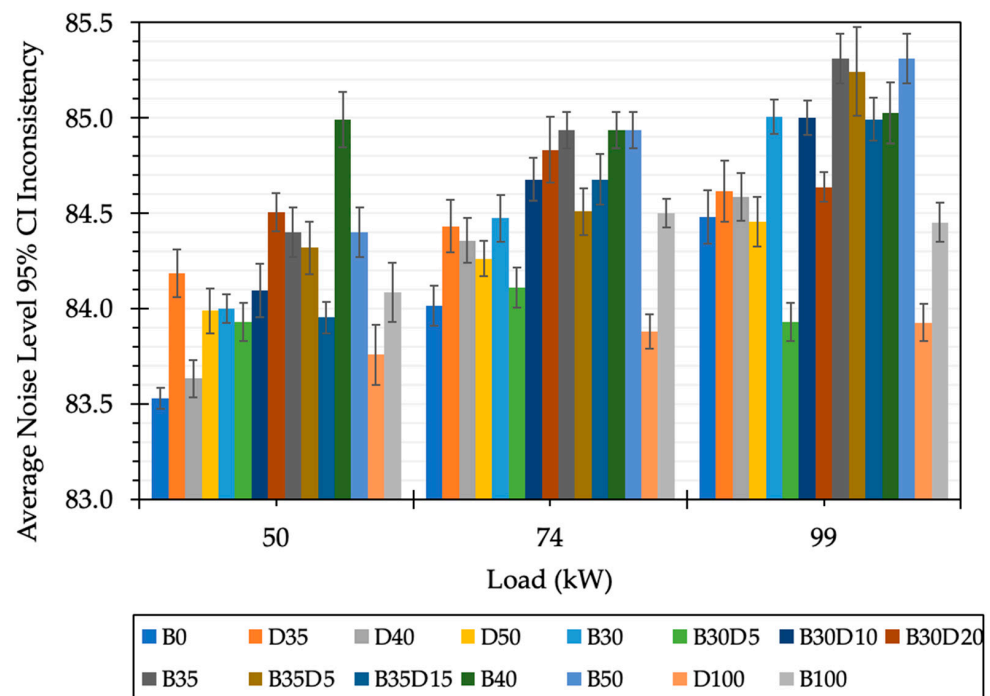


Figure 14. Average noise level measurement results inconsistency Confidence Interval (CI) 95%.

Overall, the variations between panels and measurement locations can be interpreted as a manifestation of the spatial distribution of dominant noise sources and the interaction among mechanical resonances, exhaust gas pulsations, and acoustic reflections from the lined enclosure. These results reinforce the notion that diesel engine noise assessment cannot be attributed solely to fuel formulation, but must also account for mechanical design, acoustic pathways, and the layout of the cooling and exhaust systems.

To elucidate the differences in combustion noise between the investigated fuel formulations, the analysis is grounded in the physical and chemical properties of the fuels as specified in the fuel property documentation. This interpretative framework focuses on four groups of parameters known to control diesel combustion behavior and noise generation: (i) ignition-related combustion properties, (ii) injection and spray characteristics, (iii) lower heating value, and (iv) fuel cleanliness and lubricity. Together, these aspects provide a comprehensive basis for explaining the observed noise trends across neat diesel, FAME-containing blends, and HVO-based fuels.

To obtain a comprehensive understanding of the noise behavior of each fuel, the fifteen formulations investigated in this study were classified into four main families according to their chemical composition. Each family exhibits a distinct acoustic signature, governed by differences in cetane number, viscosity, density, lower heating value, and bound oxygen content in the fuel molecules. The noise assessment combines data acquired at six measurement locations around the engine exhaust system (MP1–MP6) with the fuels' physicochemical properties determined in a certified laboratory.

Conventional neat diesel (B0) serves as the acoustic baseline for all comparisons. With a cetane number of about 49.7 and a moderate aromatic content, B0 exhibits a smooth, monotonic increase in overall noise level with rising engine load. Its sound pressure levels are neither the highest nor the lowest across the test matrix. Combustion noise for B0 is generally higher than for neat hydrotreated vegetable oil (D100) because of its lower cetane number, which likely indicates a longer ignition delay. However, it tends to be slightly lower than that of biodiesel fuels with high FAME content, particularly under partial load conditions where the sensitivity to ignition delay and pressure rise rate is most pronounced.

At part load, fuels with higher viscosity and bulk modulus, such as FAME-rich blends, tend to advance the effective injection timing, accelerating the premixed combustion phase and increasing the pressure rise rate, thereby enhancing combustion-induced noise, a trend also observed for various biodiesel formulations [52,90]. Within this context, B0 can be regarded as occupying a mid-acoustic position between the low-noise HVO family and the more “harsh-sounding” high-FAME biodiesels. Its stable physical properties, low sulfur content, and relatively clean combustion make B0 a robust reference for quantifying the acoustic impact of fuel modifications.

Fuels with a high FAME fraction (B30, B35, B40, B50, and B100) show a characteristic acoustic behavior driven by their higher viscosity and density relative to B0 and by the presence of chemically bound oxygen. Neat biodiesel (B100) represents the extreme case within this group and introduces two major effects on engine noise. First, the higher bulk modulus of FAME-rich fuels leads to an advance in the effective start of injection, sharpening the premixed burn and increasing the in-cylinder pressure rise rate at medium loads, which is consistent with observations that biodiesel can modify ignition delay and maximum cylinder pressure evolution [49,54]. This typically results in a measurable increase in A-weighted sound pressure levels by several decibels compared with pure diesel in the 40–70 kW load range, a behavior compatible with prior findings that higher biodiesel fractions can intensify certain energetic frequency bands in the combustion cycle. Second, at high load, the intrinsic oxygen content of FAME promotes more complete diffusion combustion and soot reduction; however, the higher injected mass required to compensate for its lower heating value prevents any substantial decrease in overall noise relative to B0, as also noted in studies where biodiesel blends reduce particulate emissions but maintain comparable or slightly altered noise characteristics [91,92].

Noise maps obtained from MP5 and MP6 reveal that the curves associated with B50 and B100 do not define the lowest envelope in the 60–90 kW range; instead, they remain in a mid-to-upper noise band. This is coherent with theoretical and experimental work showing that increased viscosity and elevated injection rates can augment mechanical excitation and exhaust gas turbulence, thereby increasing the total noise level, particularly around the exhaust manifold and turbocharger outlet regions [24,93]. In contrast, intermediate FAME blends such as B30, B35, and B40 generally exhibit medium noise levels—higher than HVO-rich blends but lower than neat biodiesel—while maintaining a gradual increase in noise as the FAME fraction rises, especially under partial load. The overall noise increment, however, remains limited to only a few decibels, suggesting that the differences are primarily governed by combustion chemistry (ignition delay, heat release shaping) rather than by gross mechanical disturbances. This trend is consistent with several experimental campaigns on biodiesel-fueled turbocharged diesel engines, where biodiesel blends tend to slightly alter the acoustic spectrum without drastically changing the overall sound pressure level [49,90].

The HVO blends (D35, D40, D50, and D100) are characterized by high cetane numbers and almost zero aromatic content, which likely indicates a drastically shortened ignition delay and reduces the fraction of premixed combustion. From an acoustic standpoint, this results in a reduced initial pressure rise rate and consistently lower combustion noise than both conventional diesel and FAME biodiesel. The noise curves for D50 and D100 are systematically located at the lower bound of the SPL envelope in the 50–80 kW load range, reflecting the smoother heat release associated with high-cetane, paraffinic fuels. With densities in the range of 786–834 kg/m³ and kinematic viscosities of approximately 3.4–3.7 mm²/s, HVO formulations ensure fine atomization without introducing additional injection noise, while their clean, soot-free combustion supports cycle-to-cycle pressure stability and attenuates acoustic fluctuations. At very high loads, approaching the engine’s

actual maximum power, differences among fuels diminish because exhaust and mechanical noise—linked to turbocharger, alternator, and valvetrain dynamics—dominate the overall sound field. In this regime, the separation among noise curves is reduced to roughly 0.5–1.5 dB based on visual estimation, though D100 still delivers the most favorable acoustic performance, with the smoothest perceived sound quality across all measurement points, which is consistent with previous findings of slightly lower noise and vibration levels for HVO compared with diesel [94].

Three-component blends (B30D5, B35D5, B30D10, B35D15, and B30D20) combine the combustion stability of fossil diesel, the high efficiency and clean-burning nature of HVO, and the oxygenation effect of FAME. Acoustically, this group occupies an intermediate-to-low noise position relative to the previous two families. Even modest HVO fractions (e.g., B30D5, B35D5) are sufficient to produce a noticeable reduction in combustion noise at medium loads (50–70 kW) compared with FAME-only blends, due to the increased cetane number and more controlled ignition behavior. As the HVO share increases in B30D10, B35D15, and B30D20, their noise curves increasingly resemble those of the D-series, particularly at locations MP4 and MP6, which are more sensitive to exhaust and turbocharger radiation. In operational terms, these ternary blends provide an attractive acoustic compromise, delivering reduced noise without substantial penalties in fuel consumption or emissions. Furthermore, the ternary mixtures exhibit improved resistance to governor hunting at high loads compared with pure FAME-rich fuels, owing to their more predictable thermal behavior and easier controllability by the injection system.

Overall, the findings demonstrate that fuel composition exerts a significant influence on the acoustic behavior of compression-ignition engines. HVO-rich blends offer the lowest noise levels and the most stable combustion, whereas high-FAME biodiesels tend to increase noise due to higher viscosity, advanced effective injection timing, and longer combustion duration. Three-component blends (FAME + HVO + diesel) emerge as a promising compromise, balancing efficiency, operational stability, and acoustic comfort.

4. Discussion

HVO blend fuels exhibit high cetane numbers comparable to or higher than conventional diesel, leading to reduced ignition delay and a suppressed premixed heat-release spike, which is consistent with previous findings on HVO and other high CN paraffinic fuels. This combustion phasing generally lowers combustion noise and improves efficiency at medium loads, but the reduced LHV per unit volume of HVO, due to its relatively low density, constrains peak power at high load despite excellent ignition characteristics. By contrast, FAME blends such as B40–B100 show higher kinematic viscosity and density than fossil diesel, in line with typical biodiesel behavior. Elevated viscosity degrades spray quality, causing coarser atomization, less homogeneous air–fuel mixing, and a higher tendency to nozzle tip deposits, effects widely reported for high-FAME blends.

Across the tested blends, the apparent power tracks the dummy load almost linearly up to roughly 75–90 kW, with deviations of only 1–2%, which is within normal engine–generator tolerances. Above ~90 kW, however, systematic differences emerge: HVO-rich fuels become limited by volumetric energy content, while FAME-rich fuels are penalized by viscosity and contamination-related filter loading, which reduces effective injection pressure and degrades spray formation.

Specific fuel consumption trends reflect these intertwined property effects. Most blends exhibit their highest SFC at 50 kW, while many three-component mixtures and neat HVO achieve relatively low SFC in the 50–75 kW partial load range. Between 75 and 90 kW, several blends form a low SFC “efficiency plateau,” beyond which stability rather than SFC becomes the primary constraint. Near 100 kW load, some HVO-rich and fossil

diesel fuels deliver very low SFC but suffer from intermittent instability, whereas several FAME-rich fuels can reach 100 kW only with higher SFC due to lower LHV and poorer atomization. Blends with balanced composition, notably B30D10 and B35D15, emerge as optimal compromise fuels: they combine sufficient cetane reactivity and favorable distillation behavior from HVO with moderated viscosity and adequate volumetric heating value from diesel and FAME, allowing stable operation at 100 kW with low SFC and without torque fluctuations.

The study demonstrates that cetane number, viscosity, density, LHV, and cleanliness jointly control both power stability and SFC, especially near rated load. At constant injection calibration, very high CN does not guarantee maximum power if the volumetric energy content is insufficient, while high LHV per volume is ineffective if the viscosity and contamination compromise injection and mixing. For applications routinely operating at 75–90 kW, many blends offer comparable SFC, allowing selection based on emissions or cost criteria. For sustained 100 kW operation, however, blends with balanced properties—represented here by B30D10 and B35D15—are recommended. The results also imply that further improvements can be achieved by energy-based injection calibration for HVO-rich fuels at ≥ 95 kW, and by enhanced filtration and cleanliness control for FAME blend formulations. These strategies could extend the operating envelope of renewable diesel blends, enabling stable high-load performance without sacrificing efficiency or engine durability.

When fuels are compared on an average basis, a robust acoustic hierarchy emerges. HVO-based formulations (Dxx series) consistently yield the lowest noise, followed by neat diesel and then ternary blends with moderate FAME–HVO fractions, while FAME-rich fuels (B30–B100), particularly B50 and B100, generate the highest combustion noise. This pattern aligns with previous findings that indicate fuels with higher cetane numbers lead to a shorter ignition delay, a smoother pressure rise rate, and a reduction in combustion noise. In contrast, low cetane or highly viscous oxygenated fuels tend to increase the maximum pressure rise and result in rougher combustion.

The analysis highlights that key fuel properties—cetane number, viscosity, density, cold flow behavior, and FAME content—jointly control ignition delay, rate of pressure rise, and mixture formation, which in turn govern both combustion noise and thermal loading. A simplified relationship is confirmed: higher cetane number and lower viscosity correlate with lower SPL, while highly viscous, dense FAME fuels advance effective injection and intensify pressure fluctuations, elevating noise. Practically, the most effective nonmechanical noise control strategy is to increase the HVO fraction, for example, using D40–D100 or carefully formulated ternary blends such as B30D10 or B35D15; these options lower SPL while preserving or improving efficiency, in which HVO or optimized oxygenated blends reduced both combustion noise and pollutant emissions. In contrast, FAME-rich blends tend to exhibit hunting and combustion instability at high load, reinforcing the need to limit FAME content or adjust calibration when targeting high acoustic comfort. Overall, the results support HVO and well-balanced FAME–HVO mixtures (e.g., B30D20, D50) as environmentally favorable fuels that can simultaneously deliver competitive thermal efficiency, manageable cooling temperatures, acceptable lubricant life, and improved acoustic comfort in diesel engines.

5. Conclusions

In this study, the short-term impact of using blended FAME biodiesel and HVO green diesel in a 100 kW Cummins 6BTAA5.9-G12 diesel engine was systematically evaluated under various load conditions. The experimental results confirm that all tested blends can be operated without any hardware modification, demonstrating the technical feasibility of FAME–HVO biofuel implementation in existing generator sets. Nevertheless, clear

trade-offs between fuel consumption, thermal behavior, and acoustic performance were identified as a function of blend composition and engine load.

The use of biofuel blends significantly affected the SFC, particularly at high loads, where the SFC for B30D20 and B35D15 increased by up to 15.15% compared with conventional diesel. Despite this penalty, engine efficiency generally improved with increasing load, and the ternary blends B30D10 and B30D20 emerged as the most balanced formulations, offering a favorable compromise between combustion reactivity and flow properties. Exhaust gas temperature rose with load for all fuels, with FAME-rich blends exhibiting higher exhaust temperatures than neat diesel due to their higher viscosity and oxygen content. Regarding coolant-side thermal management, D100 and D50 provided the most favorable cooling performance, whereas B50 and B100 produced the highest temperature levels, indicating a higher thermal burden on the cooling system.

Acoustic measurements revealed that overall noise levels increased with load, as expected for stationary diesel engines, but HVO-based blends (D35–D100) consistently delivered the lowest noise levels. This improvement is attributed to the high cetane number of HVO, which likely indicates it shortens the ignition delay and mitigates the premixed combustion spike. From an operational standpoint, the results indicate that injection system calibration is critical, especially for HVO-rich fuels. Recalibrating the injection control on an energy-based rather than a volume-based basis is recommended to compensate for the lower density and lower volumetric heating value of HVO compared with conventional diesel. This strategy is essential to maintain stable torque and power output above 95 kW without rotation speed fluctuations.

For FAME blends, the findings highlight the importance of enhanced filtration and maintenance practices. The higher content of fine particles and residues associated with FAME can increase filter pressure drop and promote clogging, particularly during high-load operation. Consequently, routine monitoring of differential pressure, filter cleanliness, and glyceride content is strongly advised to preserve injection stability and engine reliability. Considering both performance and operability up to 100 kW without major engine modification, B30D10 and B35D15 are recommended as optimal compromise blends, offering a robust balance between combustion reactivity, flow characteristics, and system stability.

Beyond the short-term engine performance and acoustic behavior, this work underscores the need for comprehensive follow-up studies addressing long-term durability, fuel system compatibility, feedstock availability, and the techno-economic viability of green diesel deployment in power generation. Risk assessment related to large-scale implementation, including supply chain resilience and maintenance implications, should also be considered. Overall, the present findings provide valuable technical evidence to support Indonesia's national policy on accelerating the penetration of renewable energy, particularly through the wider utilization of biofuels in stationary diesel power plants, while maintaining acceptable performance, reliability, and acoustic comfort.

Author Contributions: Conceptualization, N.C. and B.F.T.K.; methodology, N.C. and B.F.T.K.; validation, B.F.T.K., M.S.K.T.S.U. and P.P.; formal analysis, M.A.R.; investigation, N.C. and P.P.; resources, N.C., M.A.R. and B.F.T.K.; data curation, N.C.; writing—original draft preparation, N.C.; writing—review and editing, B.F.T.K., M.S.K.T.S.U. and P.P.; visualization, N.C.; supervision, B.F.T.K. and M.S.K.T.S.U.; project administration, N.C.; funding acquisition, N.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by PT PLN (Persero) and PT Pertamina (Persero) (Grant No. 0086.Pj/HKM.02.01/E30000000).

Data Availability Statement: The data supporting the findings of this study will be made available by the authors upon reasonable request.

Acknowledgments: We express our gratitude to PT PLN (Persero) for supporting this study to its completion. During the preparation of this work, the author(s) used generative AI and AI-assisted technologies in order to review and edit the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Conflicts of Interest: Authors Nur Cahyo and Mujammil Asdhiyoga Rahmanta were employed by the PLN Research Institute. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BSFC	Brake-specific fuel consumption
BTE	Break thermal efficiency
CO	Carbon monoxide
CPO	Crude palm oil
DAQ	Integrated data acquisition
DOM	Data operation and maintenance
DPF	Diesel particulate filter
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
EU	Europe union
FAME	Fatty acid methyl ester
FCC	Fluid catalytic cracking
GDP	Gross domestic product
HC	Hydrocarbon
HVO	Hydrotreated vegetable oil
LHV	Lower heating value
LHV _v	Lower heating value on a volumetric basis
LPG	Liquefied petroleum gas
PFAD	Palm fatty acid distillate
PM	Particulate matter
POME	Palm oil methyl ester
RBDPO	Refined bleached deodorized palm oil
SFC	Specific fuel consumption
SPL	Sound pressure level
VGO	Vacuum gas oil

References

1. Wirawan, S.S.; Solikhah, M.D.; Setiaprja, H.; Sugiyono, A. Biodiesel implementation in Indonesia: Experiences and future perspectives. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113911. [[CrossRef](#)]
2. Sahara; Dermawan, A.; Amaliah, S.; Irawan, T.; Dilla, S. Economic impacts of biodiesel policy in Indonesia: A computable general equilibrium approach. *J. Econ. Struct.* **2022**, *11*, 22. [[CrossRef](#)] [[PubMed](#)]
3. Mayandi, Z.; Suharjito. Palm oil-based biodiesel industry sustainability model using dynamic systems to balance food, energy, and export allocations. *Smart Agric. Technol.* **2024**, *7*, 100421. [[CrossRef](#)]
4. Djatmika, P.; Listiningrum, P.; Sumarno, T.B.; Mahira, D.F.; Sianipar, C.P.M. Just Transition in Biofuel Development towards Low-Carbon Economy: Multi-Actor Perspectives on Policies and Practices in Indonesia. *Energies* **2024**, *17*, 141. [[CrossRef](#)]
5. Mokhtar, M.; Sukmono, A.; Setiaprja, H.; Ma'ruf, M.; Yubaidah, S.; Haryono, I.; Rochmanto, B.; Soewono, R.T.; Sukra, K.F.A.; Thahar, A.; et al. Towards nationwide implementation of 40% biodiesel blend fuel in Indonesia: A comprehensive road test and laboratory evaluation. *Biofuel Res. J.* **2023**, *10*, 1876. [[CrossRef](#)]
6. Ekananda, R.; Rokhmaturrokhman, R.; Parinduri, W.Y.; Al Fatony, Z. Green-Fuel Production Through Co-Processing Biomass Derived Oil with Standard Gasoil Feedstock. *ALCHEMY J. Penelit. Kim.* **2025**, *21*, 130–137. [[CrossRef](#)]

7. Kamaruzaman, M.F.; Taufiq-Yap, Y.H.; Derawi, D. Green diesel production from palm fatty acid distillate over SBA-15-supported nickel, cobalt, and nickel/cobalt catalysts. *Biomass Bioenergy* **2020**, *134*, 105476. [\[CrossRef\]](#)
8. Srihanun, N.; Dujanutat, P.; Muanruksa, P.; Kaewkannetra, P. Biofuels of Green Diesel–Kerosene–Gasoline Production from Palm Oil: Effect of Palladium Cooperated with Second Metal on Hydrocracking Reaction. *Catalysts* **2020**, *10*, 241. [\[CrossRef\]](#)
9. Di, G.; Nolfi, V.; Gallucci, K.; Rossi, L.; Pereira, E.; Knopp, D. Green Diesel Production by Catalytic Hydrodeoxygenation of Vegetables Oils. *Int. J. Environ. Res. Public Health* **2021**, *18*, 13041. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Sosnina, D.; Altynov, A.; Kirgina, M.; Bogdanov, I. Production of Motor Fuel Components by Processing Vegetable Oils Using a CoMo/Al₂O₃ Hydrotreating Catalyst and a ZSM-5 Zeolite Catalyst. *Resources* **2024**, *13*, 96. [\[CrossRef\]](#)
11. Sonthalia, A.; Kumar, N. Hydroprocessed vegetable oil as a fuel for transportation sector: A review. *J. Energy Inst.* **2019**, *92*, 1–17. [\[CrossRef\]](#)
12. Bhatt, A.H.; Zhang, Y.; Heath, G. Bio-oil co-processing can substantially contribute to renewable fuel production potential and meet air quality standards. *Appl. Energy* **2020**, *268*, 114937. [\[CrossRef\]](#)
13. Yáñez, É.; Meerman, H.; Ramírez, A.; Castillo, É.; Faaij, A. Assessing bio-oil co-processing routes as CO₂ mitigation strategies in oil refineries. *Biofuels Bioprod. Biorefining* **2021**, *15*, 305–333. [\[CrossRef\]](#)
14. Rathore, V.; Newalkar, B.L.; Badoni, R.P. Processing of vegetable oil for biofuel production through conventional and non-conventional routes. *Energy Sustain. Dev.* **2016**, *31*, 24–49. [\[CrossRef\]](#)
15. Su, J.; van Dyk, S.; Saddler, J. Repurposing oil refineries to ‘stand-alone units’ that refine lipids/oleochemicals to produce low-carbon intensive, drop-in biofuels. *J. Clean. Prod.* **2022**, *376*, 134335. [\[CrossRef\]](#)
16. Oloyede, C.T.; Itabiyi, O.E.; Popoola, O.A.; Jekayinfa, S.O.; Olaniyan, M.A.; Adebayo, A.O.; Ogunkunle, O.; Zamri, M.F.M.A.; Fattah, I.M.R. Navigating prospects and challenges for green fuels for achieving economical, environmental and ecological resilience: A scientific review. *Biofuels* **2024**, *15*, 929–941. [\[CrossRef\]](#)
17. Gomes, D.M.; Neto, R.C.; Baptista, P.; Ramos, C.P.; Correia, C.B.; Rocha, R. A review of advanced techniques in hydrotreated vegetable oils production and life cycle analysis. *Biomass Bioenergy* **2025**, *194*, 107689. [\[CrossRef\]](#)
18. Millo, F.; Jafari, M.J.; Piano, A.; Postriotti, L.; Brizi, G.; Vassallo, A.; Pesce, F.; Fittavolini, C. A fundamental study of injection and combustion characteristics of neat Hydrotreated Vegetable Oil (HVO) as a fuel for light-duty diesel engines. *Fuel* **2025**, *379*, 132951. [\[CrossRef\]](#)
19. Dey, S.; Reang, N.M.; Das, P.K.; Deb, M. A comprehensive study on prospects of economy, environment, and efficiency of palm oil biodiesel as a renewable fuel. *J. Clean. Prod.* **2021**, *286*, 124981. [\[CrossRef\]](#)
20. Purnama, I.; Mutamima, A.; Aziz, M.; Wijaya, K.; Maulida, I.D.; Junaidi, J.; Sari, K.; Effendi, I.; Dini, I.R. Environmental Impacts and the Food vs. Fuel Debate: A Critical Review of Palm Oil as Biodiesel. *GCB Bioenergy* **2025**, *17*, e70043. [\[CrossRef\]](#)
21. No, S.Y. Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines—A review. *Fuel* **2014**, *115*, 88–96. [\[CrossRef\]](#)
22. Zeman, P.; Hönig, V.; Kotek, M.; Táboršký, J.; Obergruber, M.; Mařík, J.; Hartová, V.; Pechout, M. Hydrotreated Vegetable Oil as a Fuel from Waste Materials. *Catalysts* **2019**, *9*, 337. [\[CrossRef\]](#)
23. Aldarwish, Z.; Aghkhani, M.H.; Sadrnia, H.; Zareei, J. Investigation of the optimal timing and amount of fuel injection on the efficiency and emissions of a diesel engine through experimentation and numerical analysis. *Heliyon* **2024**, *10*, e38790. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Bao, J.; Hu, S.; Fei, J.; Žaglinskis, J.; Rimkus, A. Research on the Performance Parameters of a Compression-Ignition Engine Fueled by Blends of Diesel Fuel, Rapeseed Methyl Ester and Hydrotreated Vegetable Oil. *Sustainability* **2023**, *15*, 14690. [\[CrossRef\]](#)
25. Hunicz, J.; Krzaczek, P.; Geça, M.; Rybak, A.; Mikulski, M. Comparative study of combustion and emissions of diesel engine fuelled with FAME and HVO. *Combust. Engines* **2021**, *184*, 72–78. [\[CrossRef\]](#)
26. Smigins, R.; Sondors, K.; Pirs, V.; Dukulis, I.; Birzietis, G. Studies of Engine Performance and Emissions at Full-Load Mode Using HVO, Diesel Fuel, and HVO5. *Energies* **2023**, *16*, 4785. [\[CrossRef\]](#)
27. Sun, W.; Zhu, G.; Zhang, H.; Li, D.; Jiang, M.; Yu, C.; Wang, X.; Zhang, X.; Wang, Z. Optical diagnostic study of the effects of fuel properties on engine spray, mixing and combustion processes. *J. Energy Inst.* **2025**, *119*, 101994. [\[CrossRef\]](#)
28. Shepel, O.; Matijošius, J.; Rimkus, A.; Orynycz, O.; Tucki, K.; Świć, A. Combustion, Ecological, and Energetic Indicators for Mixtures of Hydrotreated Vegetable Oil (HVO) with Duck Fat Applied as Fuel in a Compression Ignition Engine. *Energies* **2022**, *15*, 7892. [\[CrossRef\]](#)
29. Haq, M.U.; Jafry, A.T.; Ahmad, S.; Cheema, T.A.; Ansari, M.Q.; Abbas, N. Recent Advances in Fuel Additives and Their Spray Characteristics for Diesel-Based Blends. *Energies* **2022**, *15*, 7281. [\[CrossRef\]](#)
30. Wang, Z.; Shuai, S.; Li, Z.; Yu, W. A Review of Energy Loss Reduction Technologies for Internal Combustion Engines to Improve Brake Thermal Efficiency. *Energies* **2021**, *14*, 6656. [\[CrossRef\]](#)
31. Patel, V.; Buch, V. Energy-Exergy Analysis of CI Engine Fueled with Moringa Oleifera Biodiesel at Different Loading Conditions. *J. Adv. Res. Fluid Mech. Therm. Sci. J. Homepage* **2024**, *122*, 223–243. [\[CrossRef\]](#)

32. Mohammed, A.S.; Ancha, V.R.; Atnaw, S.M.; Desta, M.; Bhandari, R. Analysis of Cylinder Pressure and Heat Release Rate Variation in Diesel Engine Fueled with Croton Macrostachyus (CMS) Seed Oil Biodiesel as an Alternative Fuel. *Energies* **2025**, *18*, 1449. [\[CrossRef\]](#)
33. Lodi, F.; Zare, A.; Arora, P.; Stevanovic, S.; Jafari, M.; Ristovski, Z.; Brown, R.J.; Bodisco, T. Combustion Analysis of a Diesel Engine during Warm up at Different Coolant and Lubricating Oil Temperatures. *Energies* **2020**, *13*, 3931. [\[CrossRef\]](#)
34. Vargas, F.; Pérez, A.; Delgado, R.; Hernández, E.; Suástegui, J.A. Performance Analysis of a Compression Ignition Engine Using Mixture Biodiesel Palm and Diesel. *Sustainability* **2019**, *11*, 4918. [\[CrossRef\]](#)
35. Inaba, K.; Ojima, Y.; Masuko, Y.; Kobashi, Y.; Shibata, G.; Ogawa, H. Thermal efficiency improvement with super-charging and cooled exhaust gas recirculation in semi-premixed diesel combustion with a twin peak shaped heat release. *Int. J. Engine Res.* **2019**, *20*, 80–91. [\[CrossRef\]](#)
36. N, K.K.; Deep, B.N.A.; Jayanna, V.B.; Sumalatha, C.P.; Khan, A.; Kamangar, S.; Islam, S.; Razak, A.; Jelila, Y.D. Influence of ceramic thermal barrier coating on diesel engine performance using scum oil biodiesel at different compression ratios. *Sci. Rep.* **2025**, *15*, 31094. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Afzal, A.; Soudagar, M.E.M.; Belhocine, A.; Kareemullah, M.; Hossain, N.; Alshahrani, S.; Saleel C., A.; Subbiah, R.; Qureshi, F.; Mujtaba, M.A. Thermal Performance of Compression Ignition Engine Using High Content Biodiesels: A Comparative Study with Diesel Fuel. *Sustainability* **2021**, *13*, 7688. [\[CrossRef\]](#)
38. Vicidomini, M.; Figaj, R.; Cappiello, F.; Zheng, F.; Cho, H.M. The Effect of Different Mixing Proportions and Different Operating Conditions of Biodiesel Blended Fuel on Emissions and Performance of Compression Ignition Engines. *Energies* **2024**, *17*, 344. [\[CrossRef\]](#)
39. Yuan, H.; Tsukuda, T.; Yang, Y.; Shibata, G.; Kobashi, Y.; Ogawa, H. Effects of Chemical Compositions and Cetane Number of Fischer–Tropsch Fuels on Diesel Engine Performance. *Energies* **2022**, *15*, 4047. [\[CrossRef\]](#)
40. Mancarella, A.; Marelllo, O. Effect of Coolant Temperature on Performance and Emissions of a Compression Ignition Engine Running on Conventional Diesel and Hydrotreated Vegetable Oil (HVO). *Energies* **2023**, *16*, 144. [\[CrossRef\]](#)
41. Simacek, P.; Soucek, I.; Pospisil, M.; Vrtiska, D.; Kittel, H. Impact of hydrotreated vegetable oil and biodiesel on properties in blends with mineral diesel fuel. *Therm. Sci.* **2019**, *23*, 1769–1777. [\[CrossRef\]](#)
42. Broatch, A.; Novella, R.; García-Tiscar, J.; Gomez-Soriano, J.; Pal, P. Analysis of combustion acoustic phenomena in compression-ignition engines using large eddy simulation. *Phys. Fluids* **2020**, *32*, 085101. [\[CrossRef\]](#)
43. Broatch, A.; Margot, X.; Novella, R.; Gomez-Soriano, J. Combustion noise analysis of partially premixed combustion concept using gasoline fuel in a 2-stroke engine. *Energy* **2016**, *107*, 612–624. [\[CrossRef\]](#)
44. Waligórski, M.; Bajerlein, M.; Karpiuk, W.; Smolec, R.; Pelczyński, J. The Application of Vibroacoustic Mean and Peak-to-Peak Estimates to Assess the Rapidly Changing Thermodynamic Process of Converting Energy Obtained from Various Fuel Compositions Using a CI Engine. *Energies* **2025**, *18*, 1091. [\[CrossRef\]](#)
45. Chen, Z.; Deng, J.; Zhen, H.; Wang, C.; Wang, L. Experimental Investigation of Hydrous Ethanol Gasoline on Engine Noise, Cyclic Variations and Combustion Characteristics. *Energies* **2022**, *15*, 1760. [\[CrossRef\]](#)
46. Yıldırım, H.; Özsezen, A.N.; Çınar, A.; Kaya, T.; Karabay, S. Effects of Rail Pressure on the Combustion and Vibro-Acoustic Characteristics of a Diesel Engine Running on Biodiesel. *Arab. J. Sci. Eng.* **2025**, *51*, 3255–3270. [\[CrossRef\]](#)
47. Abdul Hameed, N.; Kurien, C.; Kaipakam Jaychandra, R.; Mittal, M. Effect of biomethane substitution on combustion noise and performance of a dual fuel common rail direct injection diesel engine. *Environ. Prog. Sustain. Energy* **2022**, *41*, e13915. [\[CrossRef\]](#)
48. Wrobel, R.; Sierzputowski, G.; Sroka, Z.; Dimitrov, R. Comparison of Diesel Engine Vibroacoustic Properties Powered by Bio and Standard Fuel. *Energies* **2021**, *14*, 1478. [\[CrossRef\]](#)
49. Siavash, N.K.; Najafi, G.; Hassan-Beygi, S.R.; Ahmadian, H.; Ghobadian, B.; Yusaf, T.; Mazlan, M. Time–Frequency Analysis of Diesel Engine Noise Using Biodiesel Fuel Blends. *Sustainability* **2021**, *13*, 3489. [\[CrossRef\]](#)
50. Saikia, N.; Sakunthalai, R.A.; Chakradhar, M.; Masilamani, S.; Maheshwari, M.; Saxena, D. Effects of high cetane diesel on combustion, performance, and emissions of heavy-duty diesel engine. *Environ. Sci. Pollut. Res.* **2022**, *30*, 61246–61256. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Ince, M.; Çelebi, S.; Demir, U.; Haşimoğlu, C. Evaluating Engine Performance, Emissions, Noise, and Vibration: A Comparative Study of Diesel and Biodiesel Fuel Mixture. *Int. J. Automot. Sci. Technol.* **2024**, *8*, 288–302. [\[CrossRef\]](#)
52. Sarıdemir, S.; Polat, F. Experimental Analysis of The Impacts of Biodiesel-Diesel Fuel Mixtures on Engine Vibration, Noise and Combustion. *Duzce Univ. J. Sci. Technol.* **2023**, *11*, 2352–2364. [\[CrossRef\]](#)
53. Sonthalia, A.; Kumar, N. Performance Improvement and Emission Reduction Potential of Blends of Hydrotreated Used Cooking Oil, Biodiesel and Diesel in a Compression Ignition Engine. *Energies* **2023**, *16*, 7431. [\[CrossRef\]](#)
54. Alahmer, A.; Alahmer, H.; Handam, A.; Rezk, H. Environmental Assessment of a Diesel Engine Fueled with Various Biodiesel Blends: Polynomial Regression and Grey Wolf Optimization. *Sustainability* **2022**, *14*, 1367. [\[CrossRef\]](#)
55. Yusop, A.F.; Mamat, R.; Yusaf, T.; Najafi, G.; Yasin, M.H.M.; Khathri, A.M. Analysis of Particulate Matter (PM) Emissions in Diesel Engines Using Palm Oil Biodiesel Blended with Diesel Fuel. *Energies* **2018**, *11*, 1039. [\[CrossRef\]](#)

56. Rayapureddy, S.M.; Matijošius, J.; Rimkus, A.; Caban, J.; Słowik, T. Comparative Study of Combustion, Performance and Emission Characteristics of Hydrotreated Vegetable Oil–Biobutanol Fuel Blends and Diesel Fuel on a CI Engine. *Sustainability* **2022**, *14*, 7324. [CrossRef]
57. Fayyaz, H.H.; Mujtaba, M.; Jahangir, S.; Imran, S.; Malik, M.A.I.; Fayaz, H.; Saleel, C.A.; Hassan, U.; Quershi, S.; Farooq, H. A comprehensive study on the performance and emission analysis in diesel engine via optimization of novel ternary fuel blends: Diesel, manganese, and diethyl ether. *Heliyon* **2023**, *9*, e21133. [CrossRef] [PubMed]
58. Freitas, E.S.D.C.; Guarieiro, L.L.N.; da Silva, M.V.I.; Amparo, K.K.d.S.; Machado, B.A.S.; Guerreiro, E.T.d.A.; de Jesus, J.F.C.; Torres, E.A. Emission and Performance Evaluation of a Diesel Engine Using Addition of Ethanol to Diesel/Biodiesel Fuel Blend. *Energies* **2022**, *15*, 2988. [CrossRef]
59. Agarwal, A.K.; Kumar, V.; Jena, A.; Kalwar, A. Fuel injection strategy optimisation and experimental performance and emissions evaluation of diesel displacement by port fuel injected methanol in a retrofitted mid-size genset engine prototype. *Energy* **2022**, *248*, 123593. [CrossRef]
60. 146.K/10/DJM/2020; Decree of the Director General of Oil and Gas, Ministry of Energy and Mineral Resources of the Republic of Indonesia No. 146.K/10/DJM/2020—Standards and Quality (Specifications) of Diesel Fuel Marketed Domestically. Ministry of Energy and Mineral Resources of the Republic of Indonesia: Central Jakarta, Indonesia, 2020. Available online: <https://migas.esdm.go.id/cms/uploads/regulasi/regulasi-kkkl/2020/146.K-10-DJM-2020.pdf> (accessed on 1 June 2026).
61. DIN EN 590; Automotive Fuels—Diesel—Requirements and Test Methods. European Committee for Standardization: Brussels, Belgium, 2022. Available online: <https://www.en-standard.eu/din-en-590-automotive-fuels-diesel-requirements-and-test-methods/> (accessed on 1 June 2026).
62. No. 189K/2019; Decree of Director General EBTKE 189-2019 Regarding Specifications of B100. Director General of New, Renewable Energy and Energy Conservation (EBTKE): Jakarta, Indonesia, 2019. Available online: <https://www.scribd.com/document/641328631/Keputusan-Direktur-Jenderal-EBTKE-189-2019> (accessed on 1 June 2026).
63. DIN EN 14214; Liquid Petroleum Products—Fatty Acid Methyl Esters (FAME) for Use in Diesel Engines and Heating Applications—Requirements and Test Methods. European Committee for Standardization: Brussels, Belgium, 2019. Available online: <https://www.en-standard.eu/din-en-14214-liquid-petroleum-products-fatty-acid-methyl-esters-fame-for-use-in-diesel-engines-and-heating-applications-requirements-and-test-methods-includes-amendment-2019/> (accessed on 1 June 2026).
64. Hidayat, J.A.; Sugiarto, B.; Anggarani, R.; Aisyah, L.; Fathurrahman, N.A.; Yogi, P.; Riza, F.M.; Hasfi, N.M. Evaluation of Quality of Biodiesel and Diesel Fuel with High Ratio Blends. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1187*, 012018. [CrossRef]
65. SNI 8968:2021; Bio-Based Diesel Fuel (Biohydrocarbon Diesel). National Standardization Agency of Indonesia (BSN): Jakarta, Indonesia, 2021.
66. Rodríguez-Fernández, J.; Hernández, J.J.; Calle-Asensio, A.; Ramos, Á.; Barba, J. Selection of Blends of Diesel Fuel and Advanced Biofuels Based on Their Physical and Thermochemical Properties. *Energies* **2019**, *12*, 2034. [CrossRef]
67. Shepel, O.; Matijošius, J.; Rimkus, A.; Duda, K.; Mikulski, M. Research of Parameters of a Compression Ignition Engine Using Various Fuel Mixtures of Hydrotreated Vegetable Oil (HVO) and Fatty Acid Esters (FAE). *Energies* **2021**, *14*, 3077. [CrossRef]
68. Ghorbanzadeh, M.; Issa, M.; Ilinca, A. Experimental Underperformance Detection of a Fixed-Speed Diesel–Electric Generator Based on Exhaust Gas Emissions. *Energies* **2023**, *16*, 3537. [CrossRef]
69. Rimkus, A.; Žaglinskis, J.; Stravinskas, S.; Rapalis, P.; Matijošius, J.; Bereczky, Á. Research on the Combustion, Energy and Emission Parameters of Various Concentration Blends of Hydrotreated Vegetable Oil Biofuel and Diesel Fuel in a Compression-Ignition Engine. *Energies* **2019**, *12*, 2978. [CrossRef]
70. Hasan, H.A.; Al-Sumaidae, S.A.K.M.; Abdul-Munaim, A.M. Diesel Engine Efficiency under Varying Loads and Engine Oil Contaminated with Safe levels of Glycol. *Basrah J. Agric. Sci.* **2025**, *38*, 20–29. [CrossRef]
71. Uyumaz, A. Experimental evaluation of linseed oil biodiesel/diesel fuel blends on combustion, performance and emission characteristics in a DI diesel engine. *Fuel* **2020**, *267*, 117150. [CrossRef]
72. Aydın, M.; Uslu, S.; Bahattin Çelik, M. Performance and emission prediction of a compression ignition engine fueled with biodiesel-diesel blends: A combined application of ANN and RSM based optimization. *Fuel* **2020**, *269*, 117472. [CrossRef]
73. Guan, W.; Zhao, H.; Ban, Z.; Lin, T. Exploring alternative combustion control strategies for low-load exhaust gas temperature management of a heavy-duty diesel engine. *Int. J. Engine Res.* **2019**, *20*, 381–392. [CrossRef]
74. Uyumaz, A.; Aydoğan, B.; Yılmaz, E.; Solmaz, H.; Aksoy, F.; Mutlu, I.; İpci, D.; Calam, A. Experimental investigation on the combustion, performance and exhaust emission characteristics of poppy oil biodiesel-diesel dual fuel combustion in a CI engine. *Fuel* **2020**, *280*, 118588. [CrossRef]
75. Basaran, H.U.; Ozsoysal, O.A. Effects of application of variable valve timing on the exhaust gas temperature improvement in a low-loaded diesel engine. *Appl. Therm. Eng.* **2017**, *122*, 758–767. [CrossRef]
76. Hoang, A.T.; Nayak, S.K.; Vujanović, M.; Guerrero-Pérez, M.O.; Rodríguez-Castellón, E.; López-Escalante, M.C.; Ahmed, S.F.; Hadiyanto, H.; Luu, V.C.; Nguyen, V.N.; et al. Towards Sustainable Development Goals: Application of Hydrogen-Enriched Mahua Biodiesel/Diesel Blend to Dual-Fuel Diesel Engine. *Glob. Chall.* **2025**, *9*, e00260. [CrossRef] [PubMed]

77. El-Shafay, A.S.; Alqsair, U.F.; Abdel Razeq, S.M.; Gad, M.S. Artificial neural network prediction of performance and emissions of a diesel engine fueled with palm biodiesel. *Sci. Rep.* **2022**, *12*, 9286. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Nguyen, V.H.; Duong, M.Q.; Nguyen, K.T.; Pham, T.V.; Pham, P.X. An Extensive Analysis of Biodiesel Blend Combustion Characteristics under a Wide-Range of Thermal Conditions of a Cooperative Fuel Research Engine. *Sustainability* **2020**, *12*, 7666. [\[CrossRef\]](#)
79. Hossain, A.K.; Sharma, V.; Ahmad, G.; Awotwe, T. Energy outputs and emissions of biodiesels as a function of coolant temperature and composition. *Renew. Energy* **2023**, *215*, 119008. [\[CrossRef\]](#)
80. Dahham, R.Y.; Wei, H.; Pan, J. Improving Thermal Efficiency of Internal Combustion Engines: Recent Progress and Remaining Challenges. *Energies* **2022**, *15*, 6222. [\[CrossRef\]](#)
81. Zhang, J.; Xu, Z.; Lin, J.; Lin, Z.; Wang, J.; Xu, T. Thermal Characteristics Investigation of the Internal Combustion Engine Cooling-Combustion System Using Thermal Boundary Dynamic Coupling Method and Experimental Verification. *Energies* **2018**, *11*, 2127. [\[CrossRef\]](#)
82. Ma, Q.; Zhang, Q.; Chen, Z.; Liang, J. The energy analysis and performance of heavy-duty diesel engine with n-butanol addition and different coolant temperature. *Fuel* **2022**, *316*, 123323. [\[CrossRef\]](#)
83. Naderi, A.; Qasemian, A.; Shojaeefard, M.H.; Samiezadeh, S.; Younesi, M.; Sohani, A.; Hoseinzadeh, S. A smart load-speed sensitive cooling map to have a high- performance thermal management system in an internal combustion engine. *Energy* **2021**, *229*, 120667. [\[CrossRef\]](#)
84. McCormick, R.L.; Fioroni, G.M.; Naser, N.; Luecke, J. Properties That Potentially Limit High-Level Blends of Biomass-Based Diesel Fuel. *Energy Fuels* **2024**, *38*, 8829–8841. [\[CrossRef\]](#) [\[PubMed\]](#)
85. Valeika, G.; Matijošius, J.; Górski, K.; Rimkus, A.; Smigins, R. A Study of Energy and Environmental Parameters of a Diesel Engine Running on Hydrogenated Vegetable Oil (HVO) with Addition of Biobutanol and Castor Oil. *Energies* **2021**, *14*, 3939. [\[CrossRef\]](#)
86. Zikri, J.M.; Mohd Sani, M.S.; Adam, A.A. Effects of load on noise emission level generated by diesel engine including biodiesel application. In Proceedings of the Second International Conference on Precision Engineering and Mechanical Manufacturing (PEMM 2024), Incheon, Republic of Korea, 1–3 August 2024; Volume 13285, pp. 136–142. [\[CrossRef\]](#)
87. Ahmadian, H.; Najafi, G.; Ghobadian, B.; Hassan-Beygi, S.R.; Hoseini, S.S. Evaluation of the combustion-induced noise and vibration using coherence and wavelet coherence estimates in a diesel engine. *Int. J. Engine Res.* **2021**, *22*, 827–846. [\[CrossRef\]](#)
88. Shibata, G.; Yamamoto, K.; Saito, M.; Inoue, Y.; Amanuma, Y.; Kobashi, Y. Optimization of combustion noise and thermal efficiency in diesel engines over a wide speed and load operational range. *Int. J. Engine Res.* **2020**, *21*, 698–712. [\[CrossRef\]](#)
89. Huang, R.; Ni, J.; Wang, Q.; Shi, X.; Yin, Q. Experimental and Mechanism Study of Aerodynamic Noise Emission Characteristics from a Turbocharger Compressor of Heavy-Duty Diesel Engine Based on Full Operating Range. *Sustainability* **2023**, *15*, 11300. [\[CrossRef\]](#)
90. Ağbulut, Ü.; Karagöz, M.; Sarıdemir, S.; Öztürk, A. Impact of various metal-oxide based nanoparticles and biodiesel blends on the combustion, performance, emission, vibration and noise characteristics of a CI engine. *Fuel* **2020**, *270*, 117521. [\[CrossRef\]](#)
91. Khaskheli, A.A.; Arain, H.J.; Memon, I.A.; Rajput, U.A.; Ahsan, M.J. Emission and Noise Characteristics of a Diesel Engine Fuelled with Diesel-Chicken Oil Biodiesel Blends. *Technol. Appl. Sci. Res.* **2020**, *10*, 5387–5391. [\[CrossRef\]](#)
92. Senthil Kumar, A.; Karthikeyan, L.; Alharbi, S.A.; Salmen, S.H. Assessment of the Engine Vibration and Noise Characteristics of an Unmodified Direct Injection Engine Powered With Non-Feedstock Citrullus lanatus Seed Oil. *J. Energy Resour. Technol. Trans. ASME* **2023**, *145*, 012304. [\[CrossRef\]](#)
93. Listiyono, L.; Khambali, K. Analysis of the effect of diesel-essential oil fuel mixture on the performance, noise, vibration of diesel engines. *East.-Eur. J. Enterpr. Technol.* **2022**, *4*, 16–21. [\[CrossRef\]](#)
94. Claudio, C.; d'Ambrosio, S.; Alessandro, M.; Omar, M.; Nicolò, S. Emissions, Performance and Vibro-Acoustic Analysis of a Compression-Ignition Engine Running on Hydrotreated Vegetable Oil (HVO). In Proceedings of the ASME 2024 ICE Forward Conference, San Antonio, TX, USA, 20–23 October 2024. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.