Combustion Enhancement of Bergamot Peel Oil–Diesel Blends Using 2-Ethylhexyl Nitrate as a Cetane Improver in a CRDI Diesel Engine

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1. INTRODUCTION

The continued dependence on petroleum-derived diesel in compression ignition (CI) engines presents a persistent challenge for energy security and environmental sustainability. Diesel engines remain the backbone of heavy transport and many industrial applications due to their high thermal efficiency and durability, yet the need to meet stringent emission standards (e.g., BS-VI/Euro-VI) and reduce greenhouse-gas and particulate emissions has intensified the search for renewable fuel alternatives (Kaur et al., 2026). Plant- and fruit-derived oils recovered from waste streams have attracted attention as partial diesel substitutes because their intrinsic oxygenation, volatility, and biodegradability can improve combustion quality and reduce soot and unburned hydrocarbon emissions (Han et al., 2025). Studies across different low-viscosity bio-oils reveal consistent trends: improved atomization and reductions in smoke, CO and HC are often achievable at moderate blend ratios, albeit with trade-offs in ignition quality that must be addressed for safe, wide-scale adoption (Ashok et al., 2018).

Recent experimental work has broadened the set of low-viscosity bio-oils evaluated in diesel engines and shown promising outcomes under optimized injection and blending strategies (Nguyen et al., 2024). For example, eucalyptus oil–diesel blends demonstrated favorable performance and emission trends when injection parameters were adapted, increased the brake thermal efficiency and reduced the smoke by 60% (Chivu et al., 2024). Investigations of orange and other citrus peel oils showed substantial smoke and CO reductions at modest blend fractions when paired with optimized injection pressure and pilot injection strategies (Hoang et al., 2023). Broader reviews and comparative studies of low-viscosity essential oils emphasize that while many such fuels increase brake thermal efficiency from 2% to 4% and lower particulate emissions, the reduction in cetane number and associated ignition delay often exacerbates NOx formation from 5% to 10% and causes combustion phasing shifts that require compensatory control measures (e.g., timing adjustments, EGR, or ignition additives) (Ramalingam et al., 2023). Recent work has also explored alternative waste-to-fuel routes (e.g., citrus peels, turpentine, and certain hydrothermal liquefaction oils), showing that operational gains in some pollutants can be realized but that each feedstock imposes a unique set of physical-chemical trade-offs (Mercado-Cordova, 2025).

Bergamot peel oil (BPO), derived from discarded bergamot rinds, is an underexplored candidate in this family of low-viscosity, oxygenated bio-oils. Characterization studies indicate that BPO contains a substantial fraction of oxygenated monoterpenes—limonene, linalool, and linalyl acetate among the major constituents—resulting in relatively high volatility and a calorific value comparable to or slightly above petroleum diesel (Vikneswaran et al., 2022). These attributes can enhance local oxidation and reduce soot formation in CI combustion. Recent baseline engine investigations (Karthikeyan & Thambidurai, 2025) on BPO–diesel blends (10–50% v/v) reported monotonic increases in brake thermal efficiency and reductions in smoke, CO and HC with rising BPO fraction; however, these studies also documented a significant fall in cetane index and attendant increases in ignition delay, peak heat-release rates and NOx at higher blends. The key practical limitation identified for BPO and many other oxygenated low-viscosity oils is ignition quality. Reduced cetane index causes longer ignition delay, which increases the premixed combustion fraction and produces sharper, later heat release (Vellaiyan & Kandasamy, 2022). While this can sometimes improve indicated thermal efficiency, it often leads to higher instantaneous temperatures and a corresponding rise in thermal NOx, as well as the potential for undesirable pressure-rise rates or combustion instability at heavy loads. These effects are well documented across essential-oil and alcohol-blend studies, which consistently point to ignition control as the critical lever to expand permissible blend ratios without compromising emissions or engine safety (Valera et al., 2026).

A straightforward and widely practiced strategy to correct poor ignition quality is the use of cetane-number improvers. Several experimental studies have evaluated different additives and their influence on auto-ignition, combustion phasing and emissions (Mohammed et al., 2023). Investigations spanning biodiesel, alcohol blends and other low-cetane fuels show that small dosages of commercially available agents can shorten ignition delay, restore combustion phasing, and in some cases moderate NOx by enabling earlier, more controlled heat release—although additive chemistry can also influence radical pools and thereby alter NOx behavior in subtle ways (Chacko et al., 2021). Notably, 2-ethylhexyl nitrate (2-EHN) is one of the most extensively studied and commercially used cetane improvers; experimental evidence demonstrates its effectiveness at dosages below a few percent by volume across diverse fuel matrices, improving cetane index and reducing ignition delay while having only modest effects on density and viscosity (Labeckas & Slavinskas, 2021). Recent controlled studies of 2-EHN with alcohol/diesel and other bio-diesel blends confirm its capability to recover ignition properties and improve engine operability, though effects on NOx may be case dependent and require complementary controls (e.g., EGR or timing adjustments) for net emission benefit (Kuszewski et al., 2024). Considering the breadth of these findings, 2-EHN stands out as a pragmatic choice for BPO blends: it quickly improves auto-ignition characteristics even at low concentrations, is compatible with CRDI systems, and does not materially degrade the favorable atomization and volatility attributes of the base blend. Prior works across both laboratory single-cylinder rigs and multi-cylinder platforms have used 2-EHN successfully with ethanol, alcohols, and certain bio-oils to return combustion phasing to desirable ranges and to prevent excessive premixed peaks that drive pressure-rise concerns (Kumar et al., 2019).

The literature indicates two consistent themes. First, low-viscosity, oxygenated bio-oils (including citrus and pine oils) offer compelling benefits for smoke, CO and HC mitigation and can improve BTE when blends are optimized and injection strategies adjusted. Second, ignition quality is the gating constraint for higher substitution levels; cetane improvers such as 2-EHN have been validated as an effective mitigation strategy in several recent experimental studies across different fuel matrices. However, to date there appears to be no published study that explicitly couples bergamot peel oil–diesel blends (a waste-derived citrus oil with favorable calorific and oxygen content) with a systematic evaluation of 2-EHN dosing to correct cetane index and quantify the resulting impacts on performance, in-cylinder combustion, and regulated emissions. The recent characterization and engine screening reported by the authors (Karthikeyan & Thambidurai, 2025) established BPO30 as the most promising base blend (a compromise between viscosity and cetane), but did not investigate ignition-quality enhancement using cetane improvers. Bridging this gap is important for two reasons: (a) demonstrating that ignition-quality correction can unlock higher practical substitution of a waste citrus oil would strengthen the case for circular, low-carbon fuel pathways; and (b) quantifying how small additive dosages influence the combustion dynamics of a uniquely oxygenated fuel—whose chemistry differs from conventional biodiesel and straight alcohols—helps design targeted injection and after-treatment strategies to manage NOx trade-offs.

This study provides the first systematic experimental evaluation of 2-ethylhexyl nitrate (2-EHN) added to a bergamot peel oil–diesel blend (BPO30) across multiple additive concentrations (0.5%, 1.0% and 1.5% by volume). It integrates fuel-property analysis, in-cylinder pressure and heat-release diagnostics using a CRDI single-cylinder test engine, and full exhaust emission characterization to quantify both performance gains and NOx trade-offs. By building directly on prior BPO characterization and screening, the work isolates the role of ignition-quality correction for this specific, waste-derived citrus oil.

The primary objective of the present investigation is to enhance the combustion characteristics of bergamot peel oil–diesel blends by addressing the ignition-quality limitation associated with the low cetane index of bergamot peel oil. Building upon the earlier identification of BPO30 as the optimum base blend, this study aims to systematically evaluate the effect of adding 2-ethylhexyl nitrate (2-EHN) at varying concentrations (0.5%, 1.0%, and 1.5% by volume) on the physicochemical properties of the fuel, particularly cetane index and ignition-related behavior. Furthermore, the study seeks to quantify the influence of cetane improver addition on engine performance parameters such as brake thermal efficiency and brake specific fuel consumption, as well as on combustion characteristics including ignition delay, start of combustion, in-cylinder pressure development, and heat release rate. In addition, a detailed assessment of exhaust emissions—namely carbon monoxide, unburned hydrocarbons, nitrogen oxides, and smoke opacity—is carried out to understand the trade-offs between improved ignition quality and emission formation mechanisms. Ultimately, the objective is to identify an optimum 2-EHN dosing level for the BPO30 blend that delivers improved combustion stability and efficiency while maintaining emissions within acceptable limits, thereby strengthening the feasibility of bergamot peel oil as a sustainable partial replacement for conventional diesel fuel in compression ignition engines. Figure 1 shows the schematic of this experimental work.

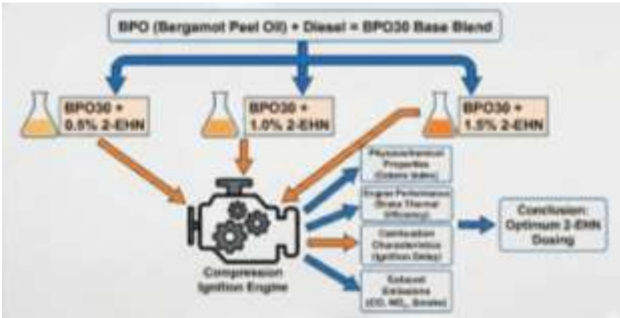

Figure 1. Experimental Framework

2. FUEL PREPARATION AND ADDITIVE BLENDING

Based on the outcomes of the earlier fuel characterization and blend screening studies, a bergamot peel oil–diesel blend containing 30% BPO by volume (BPO30) was selected as the base fuel for the present investigation. This selection was made as BPO30 offered an optimal compromise between favorable physicochemical properties—such as acceptable viscosity, improved calorific value, and enhanced oxygen content—and manageable ignition quality without introducing severe combustion instability. However, despite these advantages, the cetane index of BPO30 remained lower than that of conventional diesel, necessitating further improvement to address ignition delay and combustion phasing issues.

To overcome this limitation, a commercially established cetane improver, 2-ethylhexyl nitrate (2-EHN), was employed as an additive in the present phase of the study. 2-EHN was selected due to its proven effectiveness in enhancing auto-ignition characteristics at low dosing levels and its compatibility with compression ignition engine fuel systems. The additive functions by decomposing rapidly at lower temperatures during the compression stroke, generating reactive radical species that promote early ignition and reduce ignition delay.

Fuel blends were prepared by adding 2-EHN to the BPO30 base blend at three different volumetric concentrations: 0.5%, 1.0%, and 1.5%, designated as BPO30+2EHN 0.5, BPO30+2EHN 1.0, and BPO30+2EHN 1.5, respectively. The required quantity of 2-EHN was measured using a precision burette and added to pre-measured volumes of the BPO30 blend. Mixing was carried out under ambient laboratory conditions using mechanical stirring for a sufficient duration to ensure homogeneity. No surfactants or stabilizing agents were used, as 2-EHN exhibited complete miscibility with the BPO–diesel blend. Following blending, all fuel samples were stored in airtight, opaque containers to prevent exposure to light and moisture prior to testing. Visual inspection was carried out to confirm the absence of phase separation or sedimentation, ensuring blend stability throughout the experimental period. The addition of 2-EHN was not observed to cause any noticeable change in fuel appearance or handling characteristics.

2.1 Fuel Properties

The physicochemical properties of the prepared fuel blends were taken from literature in accordance with relevant ASTM standards are shown in Table 1, with particular emphasis on parameters influencing ignition and combustion behavior, such as density, kinematic viscosity, calorific value, and cetane index. These measurements were intended to confirm that the addition of 2-EHN primarily influenced ignition quality while maintaining the favorable atomization and energy characteristics of the BPO30 base blend. The resulting fuel properties served as the baseline for analyzing the effects of cetane improver addition on engine performance, combustion characteristics, and exhaust emissions discussed in subsequent sections.

Table 1. Fuel Properties

Properties	ASTM	Diesel*	BPO*	BPO30*	2-EHN**	Limit (BS-VI)
Density (kg/m³)	D1298	835.1	864	843.8	963	820–845
Kinematic viscosity (mm²/s) @ 40 °C	D445	2.57	1.62	2.28	1.7	2–4.5
Flash point (°C)	D93	56	51	52	74	Min. 35
Fire point (°C)	D93	62	58	58	80	–
Calorific value (MJ/kg)	D420	42.30	44.05	42.82	27.4	–
Final boiling point (°C)	D86	150–380	162	165	307	–
Cetane Index	D976	49	25	42	>100	Min. 46

*Taken from literature (Karthikeyan & Thambidurai, 2025)

**Taken from literature (Liu et al., 2023)

3. EXPERIMENTAL SETUP

The experimental investigations were carried out using a single-cylinder compression ignition engine equipped with a common rail direct injection (CRDI) fuel delivery system. The CRDI arrangement comprises a fuel conditioning unit, a low-pressure supply pump, a high-pressure pumping module, a shared fuel rail, a pressure control valve, a rail pressure sensor, and an electronically actuated fuel injector fitted with a three-hole nozzle (Delphi TVS make). Fuel injection and control operations were managed through a Bosch electronic control unit (ECU) operating under open-loop mode.

The ECU permitted real-time adjustment of key injection parameters, including main injection timing, injection duration, pilot injection quantity, pilot injection timing, and rail pressure, through a computer-based interface using *Tuner Pro* software. In the present investigation, all injection parameters were maintained constant except for the fuel injection pressure, which was set at 400 bar to ensure adequate atomization of the tested fuel blends. The target rail pressure set by the operator was communicated to the ECU, which continuously regulated the fuel pressure in the common rail using feedback signals from the pressure sensor. Pressurized fuel was delivered from the rail to the injector and subsequently sprayed directly into the combustion chamber.

Engine loading was achieved using an eddy current dynamometer coupled to the crankshaft. Rotational speed was monitored using a magnetic pickup sensor, and the measured signal was cross-verified with crankshaft speed data to ensure rotational consistency. The engine torque output was determined using an S-type load cell integrated with the dynamometer. Calibration of the torque measurement system was performed by applying a known dead weight corresponding to 24 Nm, thereby validating the repeatability and accuracy of the load measurements. A schematic representation of the complete experimental arrangement is presented in **Fig. 2**, while the technical specifications of the test engine are summarized in **Table 2**.

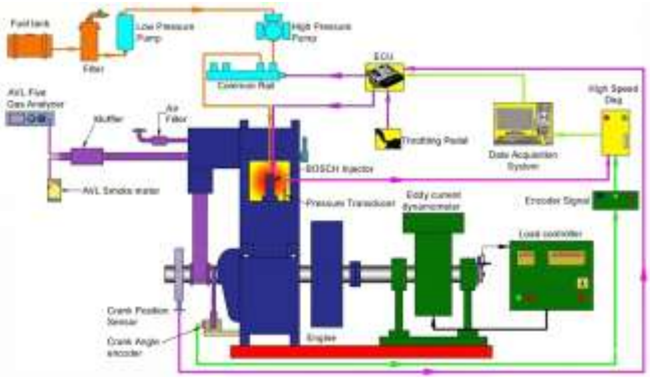

Figure 2. Schematic layout of the Experimental setup

Table 2. Specifications of the CRDI Diesel Engine

Parameter	Specification
Engine type	Single-cylinder, vertical, four-stroke, water-cooled VCR DI diesel engine
Rated power	3.7 kW
Rated speed	1500 rpm
Bore	80 mm
Stroke	110 mm
Compression ratio	17.5:1
Loading system	Eddy current dynamometer

Fuel injection system	Electronically controlled CRDI
Starting method	Manual cranking
Injection timing	23° CA before TDC

To capture combustion characteristics, a crank angle encoder was mounted on the crankshaft to provide precise angular position information. In-cylinder pressure measurements were obtained using a piezoelectric pressure sensor (Kistler make), installed flush with the combustion chamber during cylinder head assembly. Signals from the pressure transducer and crank angle encoder were synchronized and processed through a dedicated data acquisition system, with combustion data recorded and stored using *Engine Express* software for subsequent analysis.

Exhaust emission measurements were conducted using a calibrated five-gas analyzer capable of measuring carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO). Smoke opacity was quantified using a smoke meter, with results expressed in Hartridge Smoke Units (HSU). Prior to experimentation, the gas analyzer was calibrated using certified reference gases to ensure measurement reliability. To assess the credibility of the experimental results, an uncertainty analysis was performed, and the accuracy of each measuring instrument employed in the study is listed in Table 3.

Table 3. Accuracy of Measuring Instruments

Measurement	Accuracy	Instrument
Engine load	±10 N	S-type load cell
Engine speed	±10 rpm	Magnetic pickup sensor
Fuel mass	±1 g	Electronic weighing scale
Time	±0.1 s	Stopwatch
CO	±0.02%	Exhaust gas analyzer
HC	±10 ppm	Exhaust gas analyzer
NO	±10 ppm	Exhaust gas analyzer
Cylinder pressure	±1 bar	Pressure transducer
Crank angle	±1°	Crank angle encoder

4. RESULT AND DISCUSSIONS

This section presents a comprehensive evaluation of the effects of cetane improver addition on the performance, emission, and combustion characteristics of bergamot peel oil–diesel blends operated in a CRDI diesel engine. The analysis focuses on a BPO30 base blend, which was identified in earlier investigations as the most suitable compromise between favorable physicochemical properties and combustion stability, and examines how incremental additions of 2-EHN influence engine behavior under varying load conditions. Comparisons are made between neat diesel, BPO30, and BPO30 blends containing different concentrations of 2-EHN to clearly isolate the role of ignition enhancement. The discussion emphasizes both the beneficial effects and trade-offs associated with cetane improver addition, enabling identification of an optimum additive concentration that delivers improved efficiency and combustion stability without compromising emission performance.

4.1 Performance Characteristics

4.1.1 Brake Thermal Efficiency

The variation of brake thermal efficiency (BTE) with engine load for neat diesel, BPO30, and BPO30 blended with different concentrations of 2-EHN is presented in Fig. 3. For all tested fuels, BTE increases with load, which is a typical characteristic of compression ignition engines and can be attributed to the reduction in relative heat losses and improved utilization of the fuel's chemical energy at higher loads.

At all load conditions, the BPO30 blend exhibits higher BTE than neat diesel. At the lowest load of 0.74 kW, BTE increases from 12.8% for diesel to 13.6% for BPO30, corresponding to an improvement of approximately 6.3%. Similar enhancements are observed across the load range, with BTE rising from 24.8% (diesel) to 25.8% (BPO30) at full load (3.7 kW). This improvement is primarily attributed to the oxygenated nature of bergamot peel oil, which promotes better fuel–air mixing and enhances oxidation of fuel-rich regions during combustion. Additionally, the slightly higher calorific value of BPO compared to diesel contributes to increased energy availability per unit mass of fuel, leading to improved thermal efficiency. However, despite these benefits, the BTE improvement with BPO30 alone remains moderate, particularly at higher loads. This limitation is associated with the relatively lower cetane index of BPO30 compared to diesel, which leads to a longer ignition delay and retarded combustion phasing. As a result, a larger fraction of heat release occurs later in the expansion stroke, reducing the fraction of released energy that can be effectively converted into useful work.

The addition of 2-EHN to the BPO30 blend results in a further enhancement of BTE across all operating conditions, with the magnitude of improvement increasing with additive concentration. At 0.74 kW load, BTE increases from 13.6% for BPO30 to 13.9% for BPO30 + 1.5% 2-EHN, indicating a clear benefit of ignition quality improvement even under low-load conditions. At medium loads (2.22–2.96 kW), the BTE enhancement becomes more pronounced; for instance, at 2.96 kW, BTE rises from 25.6% (BPO30) to 26.1% for BPO30 + 1.5% 2-EHN. At full load, the highest BTE of 26.8% is obtained with BPO30 + 1.5% 2-EHN, representing an improvement of approximately 8.1% compared to neat diesel and about 3.9% compared to BPO30 without additive. The observed improvement in BTE with 2-EHN addition can be attributed to the enhancement of ignition quality and subsequent optimization of combustion phasing. 2-EHN decomposes at relatively low temperatures during the compression stroke, generating reactive radicals that initiate earlier auto-ignition. This reduces ignition delay and limits excessive fuel accumulation before combustion, thereby moderating the premixed combustion fraction. As a result, the peak heat release shifts closer to top dead center, increasing the effective expansion work and improving thermal efficiency. Among the tested additive concentrations, BPO30 + 0.5% 2-EHN shows only marginal improvement over BPO30, particularly at low and medium loads. This suggests that at low dosing levels, the cetane enhancement is insufficient to fully compensate for the ignition delay associated with the BPO fraction. Increasing the additive concentration to 1.0% results in a noticeable rise in BTE across the entire load range, indicating more effective ignition delay reduction and improved combustion timing. The maximum efficiency gains are achieved with 1.5% 2-EHN, where ignition characteristics approach those of neat diesel while retaining the oxygenation and volatility benefits of BPO. It is also noteworthy that the improvement in BTE with increasing 2-EHN concentration becomes more significant at higher loads. At elevated loads, the cylinder temperature and pressure are higher, which amplifies the effectiveness of the cetane improver in accelerating ignition chemistry. Consequently, combustion becomes more stable and better phased, leading to enhanced conversion of chemical energy into brake power.

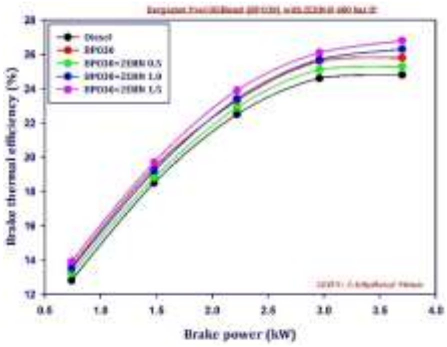

Figure 3 Effect of 2EHN addition on Brake thermal efficiency of BPO30 blend

4.1.2 Brake Specific Fuel Consumption

The variation of brake specific fuel consumption (BSFC) with engine load for neat diesel, BPO30, and BPO30 blended with different concentrations of 2-ethylhexyl nitrate (2-EHN) is illustrated in Fig. 4. For all test fuels, BSFC decreases with increasing load, which is a well-established behavior of compression ignition engines and is primarily due to improved combustion efficiency, reduced relative heat losses, and better utilization of injected fuel energy at higher loads.

Across the entire load range, the BPO30 blend consistently exhibits lower BSFC than neat diesel. At the lowest load of 0.74 kW, BSFC decreases marginally from 0.681 kg kW⁻¹ h⁻¹ for diesel to 0.675 kg kW⁻¹ h⁻¹ for BPO30. The reduction becomes more pronounced at medium and higher loads; for example, at 2.22 kW, BSFC drops from 0.395 to 0.381 kg kW⁻¹ h⁻¹, and at full load (3.7 kW), from 0.392 to 0.372 kg kW⁻¹ h⁻¹. These reductions indicate more efficient fuel utilization with BPO30 compared to diesel. The lower BSFC of BPO30 can be attributed to a combination of its higher calorific value and oxygenated molecular structure. The additional fuel-bound oxygen enhances local oxidation in fuel-rich regions, reducing incomplete combustion losses and increasing the fraction of released energy converted into useful work. Moreover, the lower viscosity of BPO compared to diesel promotes finer spray atomization and faster evaporation, improving air–fuel mixing and combustion efficiency, particularly at medium and high loads.

The incorporation of 2-EHN into the BPO30 blend leads to a further reduction in BSFC, with the magnitude of improvement increasing with additive concentration. At 0.74 kW, BSFC decreases from 0.675 kg kW⁻¹ h⁻¹ for BPO30 to 0.661 kg kW⁻¹ h⁻¹ for BPO30 + 1.5% 2-EHN, representing a reduction of approximately 3.9% relative to diesel. At medium load (2.22 kW), BSFC reduces progressively from 0.381 kg kW⁻¹ h⁻¹ (BPO30) to 0.362 kg kW⁻¹ h⁻¹ with 1.5% 2-EHN, while at full load the minimum BSFC of 0.332 kg kW⁻¹ h⁻¹ is recorded for the highest additive concentration, corresponding to a reduction of about 15.3% compared to diesel. These improvements can be directly linked to the enhancement of ignition quality provided by 2-EHN. By shortening ignition delay, the additive reduces excessive premixed fuel accumulation prior to combustion and shifts the main heat release closer to top dead center. This results in a more favorable pressure–volume work interaction during the expansion stroke, allowing a larger portion of the fuel's chemical energy to be converted into brake power, thereby lowering the mass of fuel required per unit output.

At a lower additive dosage of 0.5%, the reduction in BSFC is relatively small and, in some cases (particularly at low load), BSFC values approach or slightly exceed those of BPO30. This suggests that at low concentrations, the cetane enhancement is insufficient to fully offset ignition delay effects under low-temperature conditions. Increasing the 2-EHN concentration to 1.0% produces a noticeable decrease in BSFC across all loads, indicating more effective ignition control and improved combustion efficiency. The most significant reductions are achieved with 1.5% 2-EHN, where the combined benefits of improved ignition quality and the inherent oxygenation of BPO result in optimal fuel utilization. The effect of 2-EHN becomes increasingly prominent at higher loads. Elevated in-cylinder temperatures at these conditions accelerate the decomposition of the cetane improver, intensifying its impact on ignition chemistry. Consequently, combustion becomes more stable and better phased, minimizing energy losses associated with late combustion and incomplete oxidation, and leading to substantially lower BSFC.

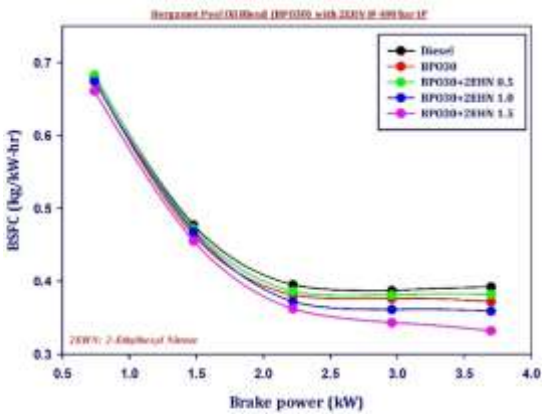

Figure 4 Effect of 2EHN addition on BSFC of BPO30 blend

4.2 Emission Characteristics

4.2.1 CO emission (CO) Emissions

The variation of carbon monoxide (CO) emissions with engine load for neat diesel, BPO30, and BPO30 blended with different concentrations of 2-ethylhexyl nitrate (2-EHN) is presented in Fig. 5. For all fuels, CO emissions increase with engine load, which is characteristic of CI engines and is primarily associated with richer local equivalence ratios, reduced oxygen availability in diffusion-controlled combustion regions, and shorter residence time for complete oxidation at high loads.

At all operating conditions, BPO30 exhibits lower CO emissions than neat diesel. At the lowest load of 0.74 kW, CO decreases from 0.09 g/kWh for diesel to 0.08 g/kWh for BPO30. The reduction becomes more pronounced as the load increases; at 2.96 kW, CO drops from 0.21 g/kWh (diesel) to 0.17 g/kWh (BPO30), and at full load (3.7 kW), from 0.54 to 0.44 g/kWh, corresponding to an approximate reduction of 18.5%. This reduction can be attributed mainly to the oxygenated nature of bergamot peel oil. The presence of fuel-bound oxygen improves local oxidation conditions within fuel-rich zones, facilitating the conversion of CO to CO_2 during the later stages of combustion. Additionally, the lower viscosity of BPO compared to diesel enhances spray atomization and evaporation, leading to improved air–fuel mixing and reduced formation of locally rich pockets where CO typically originates.

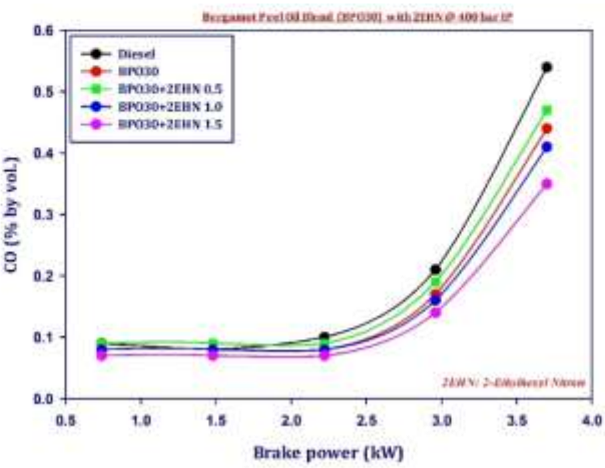

Figure 5 Effects of 2EHN addition on CO emission of BPO30 blend

The introduction of 2-EHN into the BPO30 blend leads to a further decrease in CO emissions, particularly at medium and high loads. At full load, CO emission decreases progressively from 0.44 g/kWh for BPO30 to 0.35 g/kWh for BPO30 + 1.5% 2-EHN, representing a reduction of approximately 35% relative to neat diesel and about 20% relative to BPO30 without additive. A similar trend is observed at 2.96 kW, where CO decreases from 0.17 g/kWh (BPO30) to 0.14 g/kWh with 1.5% 2-EHN. The reduction in CO emissions with 2-EHN addition is primarily linked to improved ignition quality and combustion completeness. By reducing ignition delay, 2-EHN limits excessive fuel accumulation prior to ignition and promotes a more controlled and timelier onset of combustion. This results in higher local temperatures early in the combustion process, which enhances the oxidation kinetics of CO-to-CO_2. Moreover, improved combustion phasing increases the availability of hydroxyl (OH) radicals, which play a critical role in the oxidation of CO during the expansion stroke.

At a low additive dosage of 0.5%, the effect on CO emissions is relatively limited, and in some cases, CO levels approach those of BPO30 or even diesel, particularly at lower loads. This suggests that at low concentrations, the cetane improvement is insufficient to significantly alter combustion chemistry under low-temperature conditions. As the additive concentration increases to 1.0% and 1.5%, the improvement in ignition quality becomes more pronounced, resulting in a systematic reduction in CO emissions across all load conditions. The beneficial effect of higher 2-EHN concentration is more evident at elevated loads. Under these conditions, the baseline CO emissions for diesel increase sharply due to diffusion-controlled combustion and oxygen deficiency. The combined effects of fuel-bound oxygen from BPO and improved ignition and oxidation kinetics from 2-EHN significantly mitigate CO formation, leading to the lowest emissions for the BPO30 + 1.5% 2-EHN blend.

4.2.2 Unburned Hydrocarbon (HC) Emissions

The variation of unburned hydrocarbon (HC) emissions with engine load for neat diesel, BPO30, and BPO30 blended with different concentrations of 2-ethylhexyl nitrate (2-EHN) is illustrated in Fig. 6. For all fuels, HC emissions increase with engine load, which is typical of compression ignition engines and is mainly associated with increased fuel quantity, locally rich combustion zones, wall wetting, and reduced residence time for complete oxidation at higher loads.

Across the entire operating range, the BPO30 blend exhibits lower HC emissions than neat diesel. At the lowest load of 0.74 kW, HC emissions decrease marginally from 34 ppm for diesel to 33 ppm for BPO30. The reduction becomes more evident as the load increases; at 2.22 kW, HC decreases from 41 ppm (diesel) to 39 ppm (BPO30), and at full load (3.7 kW), from 62 ppm to 58 ppm, corresponding to an approximate reduction of 6.5%. The reduction in HC emissions with BPO30 can be attributed primarily to the oxygenated nature of bergamot peel oil, which enhances oxidation of hydrocarbon fragments that would otherwise escape as unburned species. The presence of fuel-bound oxygen supports more complete combustion, particularly in diffusion-controlled regions where oxygen deficiency is common. Additionally, the lower viscosity of BPO improves spray atomization and evaporation, reducing wall impingement and quenching effects that contribute to HC formation.

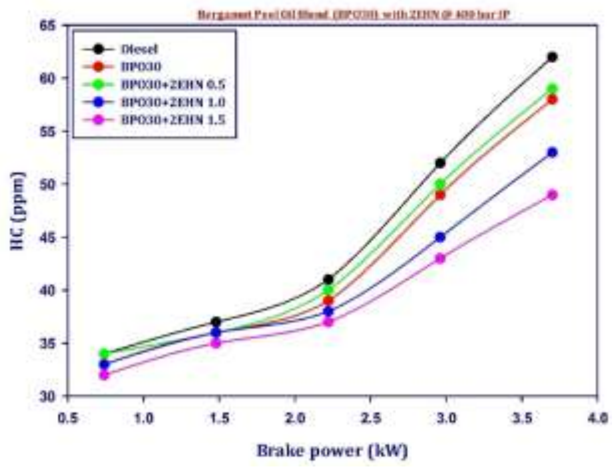

Figure 6. Effect of 2EHN addition on HC emission of BPO30 blend

The incorporation of 2-EHN into the BPO30 blend leads to a further and more systematic reduction in HC emissions, especially at medium and high loads. At full load, HC emissions decrease progressively from 58 ppm for BPO30 to 49 ppm for BPO30 + 1.5% 2-EHN, representing a reduction of approximately 21% compared to neat diesel and about 15.5% relative to BPO30 without additive. A similar trend is observed at 2.96 kW, where HC emissions drop from 49 ppm (BPO30) to 43 ppm with the highest additive concentration. The observed reduction in HC emissions with increasing 2-EHN concentration is primarily associated with improved ignition characteristics and combustion completeness. By shortening ignition delay, 2-EHN promotes earlier onset of combustion and reduces the amount of fuel residing near the cylinder walls during the ignition delay period. This limits wall quenching and crevice-related HC formation. Furthermore, improved combustion phasing results in higher in-cylinder temperatures during the early combustion stages, which enhances the oxidation of intermediate hydrocarbon species before exhaust valve opening.

At a low additive concentration of 0.5%, the effect on HC emissions is minimal, particularly at lower loads where the in-cylinder temperature is insufficient for significant additive activation. In some cases, HC emissions for BPO30 + 0.5% 2-EHN are comparable to or slightly higher than those of BPO30, indicating that a threshold additive concentration is required to produce a measurable improvement in ignition quality. Increasing the additive concentration to 1.0% yields a noticeable reduction in HC emissions across all operating conditions, while the maximum reduction is achieved with 1.5% 2-EHN. The effectiveness of higher additive concentrations becomes more pronounced at elevated loads. At these conditions, higher temperatures and pressures accelerate the decomposition of 2-EHN and amplify its influence on ignition chemistry. This leads to more stable combustion and enhanced oxidation of fuel fragments, resulting in significantly lower HC emissions.

4.2.3 Nitric Oxide (NO) Emission

The variation of nitric oxide (NO) emissions with engine load for neat diesel, BPO30, and BPO30 blended with different concentrations of 2-ethylhexyl nitrate (2-EHN) is shown in Fig. 7. For all test fuels, NO emissions increase with engine load, which is characteristic of compression ignition engines and is primarily governed by in-cylinder temperature, oxygen availability, and the residence time of high-temperature gases.

At all operating conditions, BPO30 exhibits higher NO emissions than neat diesel. At the lowest load of 0.74 kW, NO increases from 147 ppm for diesel to 208 ppm for BPO30, corresponding to an increase of approximately 41%. Similar trends persist across the load range; at 2.96 kW, NO rises from 692 ppm (diesel) to 724 ppm (BPO30), and at full load (3.7 kW), from 682 ppm to 730 ppm. The elevated NO levels observed with BPO30 can be attributed to its oxygenated molecular structure and enhanced combustion intensity. The presence of fuel-bound oxygen promotes more complete oxidation and elevates local flame temperatures, thereby accelerating thermal NO formation through the extended Zeldovich mechanism. In addition, the longer ignition delay associated with the lower cetane index of BPO30 increases the premixed combustion fraction, leading to a rapid release of energy and higher peak temperatures, which further favors NO formation.

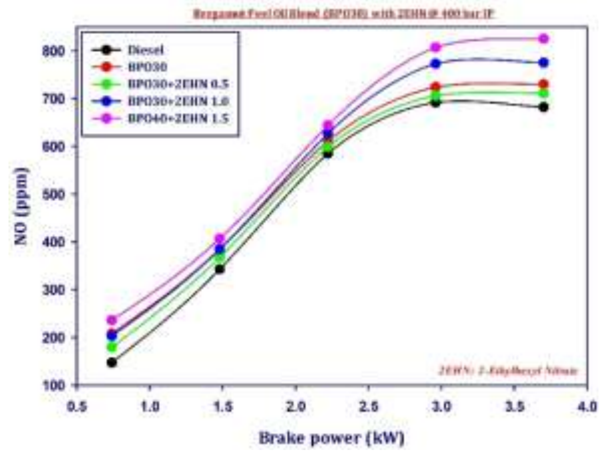

Figure 7. Effect of 2EHN addition on NO emission of BPO30 blend

The introduction of 2-EHN produces a notable and systematic influence on NO emissions. At a low additive concentration of 0.5%, NO emissions are reduced relative to BPO30 across all loads. For example, at 0.74 kW, NO decreases from 208 ppm (BPO30) to 180 ppm with 0.5% 2-EHN, representing a reduction of approximately 13.5%. Similar reductions are observed at medium loads; at 2.96 kW, NO decreases from 724 ppm to 706 ppm with 0.5% additive. This reduction can be attributed to partial mitigation of ignition delay at low additive dosage, which moderates the premixed combustion fraction and reduces peak in-cylinder temperatures. Improved combustion phasing shifts a portion of heat release closer to top dead center but limits excessively sharp heat-release rates, resulting in lower peak temperatures and reduced thermal NO formation. As the 2-EHN concentration increases to 1.0% and 1.5%, NO emissions rise progressively and exceed those of both diesel and BPO30 at all load conditions. At full load, NO increases from 730 ppm (BPO30) to 775 ppm and 825 ppm for 1.0% and 1.5% 2-EHN, respectively. A similar monotonic increase is observed at 2.96 kW, where NO reaches 807 ppm for the highest additive concentration. The increase in NO at higher 2-EHN dosages is primarily associated with more pronounced ignition advancement and intensified combustion. At elevated additive concentrations, ignition delay is significantly reduced, causing a larger portion of heat release to occur earlier in the cycle under high-pressure and high-temperature conditions. This advancement of combustion phasing increases peak in-cylinder temperatures and extends the residence time of gases at NO-forming temperatures, thereby accelerating thermal NO formation. Additionally, the oxygenated nature of BPO combined with improved combustion completeness further enhances the availability of oxygen radicals (O and OH), which actively participate in NO formation pathways.

4.2.4 Smoke Emission

The variation of smoke opacity with engine load for neat diesel, BPO30, and BPO30 blended with different concentrations of 2-ethylhexyl nitrate (2-EHN) is presented in Fig. 8. For all tested fuels, smoke opacity increases with load, which is a typical characteristic of compression ignition engines due to higher fuel injection quantities, increased equivalence ratios, and the dominance of diffusion-controlled combustion at elevated loads.

At all operating conditions, the BPO30 blend produces lower smoke opacity than neat diesel. At the lowest load of 0.74 kW, smoke decreases from 14.3 HSU for diesel to 12.9 HSU for BPO30, corresponding to a reduction of approximately 9.8%. The reduction becomes more pronounced as load increases; at 2.96 kW, smoke decreases from 41.3 HSU (diesel) to 39.1 HSU (BPO30), and at full load (3.7 kW), from 43.7 to 39.7 HSU, representing a reduction of nearly 9.2%. The lower smoke emission observed with BPO30 is primarily attributed to the oxygenated nature of bergamot peel oil. The presence of chemically bound oxygen promotes oxidation of soot precursors formed in locally fuel-rich regions, thereby suppressing soot nucleation and growth. In addition, the lower viscosity of BPO improves spray atomization and fuel–air mixing, which reduces the formation of rich zones where soot formation is favored.

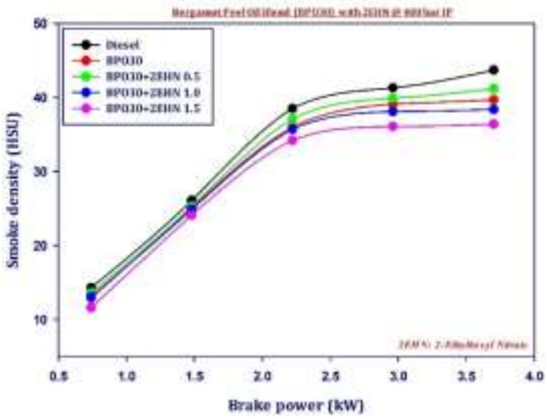

Figure 8 Effect of 2EHN addition on Smoke emission of BPO30 blend

The addition of 2-EHN to the BPO30 blend further reduces smoke opacity, particularly at medium and high load conditions. At full load, smoke opacity decreases progressively from 39.7 HSU for BPO30 to 36.4 HSU for BPO30 + 1.5% 2-EHN, corresponding to an approximate reduction of 16.7% relative to neat diesel and about 8.3% compared to BPO30 without additive. Similar reductions are observed at 2.96 kW, where smoke decreases from 39.1 HSU to 36.1 HSU with the highest additive concentration. The reduction in smoke emissions with 2-EHN addition can be attributed to improved ignition quality and enhanced combustion completeness. By reducing ignition delay, 2-EHN limits excessive fuel accumulation prior to combustion and promotes a more uniform and timely burn. This results in higher local temperatures during the early combustion phase, which favor oxidation of soot nuclei before they can agglomerate into larger particulate structures. Furthermore, improved combustion phasing reduces late-cycle diffusion combustion, a major contributor to soot formation in CI engines. At a low additive concentration of 0.5%, smoke opacity is marginally higher than that of BPO30 at certain load points, particularly at higher loads. This indicates that partial ignition improvement at low additive dosage may not be sufficient to significantly alter soot formation mechanisms and, in some cases, may slightly intensify diffusion combustion. As the additive concentration increases to 1.0% and 1.5%, a consistent reduction in smoke opacity is observed across the entire load range. The effectiveness of higher 2-EHN concentrations becomes more pronounced at elevated loads, where baseline smoke emissions are highest. At these conditions, the combined effects of fuel-bound oxygen from BPO and improved ignition characteristics from 2-EHN significantly enhance soot oxidation, leading to substantial smoke reduction. The lowest smoke opacity is consistently achieved with the BPO30 + 1.5% 2-EHN blend.

4.3 Combustion Characteristics

4.3.1 Pressure vs Crank angle

Figure 9 shows the variation of in-cylinder pressure with crank angle for neat diesel, BPO30, and BPO30 blends containing different concentrations of 2-ethylhexyl nitrate (2-EHN) at an injection pressure of 400 bar. All fuels exhibit the typical compression ignition pressure trace, characterized by a gradual pressure rise during compression, a sharp increase near top dead center (TDC) due to combustion, and a gradual decay during the expansion stroke. Although BPO30 exhibits a peak cylinder pressure comparable to or slightly higher than that of diesel, the crank angle corresponding to peak pressure is retarded by approximately 2° CA relative to diesel. This delayed occurrence of peak pressure is primarily attributed to the lower cetane index of bergamot peel oil, which prolongs ignition delay. The extended ignition delay allows more fuel to accumulate in the combustion chamber before ignition, shifting the main heat release to a later crank angle. This delayed combustion phasing results in a sharper premixed combustion event occurring further into the expansion stroke. While the oxygenated nature of BPO promotes higher energy release and supports reasonable peak pressure levels, the retarded combustion timing reduces the effectiveness of pressure–volume work conversion, explaining why BPO30 does not achieve the same combustion phasing efficiency as diesel despite its higher calorific value.

The addition of 2-EHN significantly influences both the magnitude of peak cylinder pressure and, more importantly, the crank angle at which peak pressure occurs. At a lower additive concentration of 0.5%, the peak pressure and its crank angle location remain nearly identical to that of sole BPO30, indicating that the cetane enhancement at this dosage is insufficient to produce a noticeable advancement in combustion phasing. However, as the additive concentration increases to 1.0% and 1.5%, a clear advancement of peak pressure location is observed. The peak pressure shifts by approximately 1° CA and 2° CA, respectively, relative to BPO30. This advancement indicates a substantial reduction in ignition delay, causing the main heat release to occur closer to TDC under higher pressure and temperature conditions. Among all tested fuels, the BPO30 + 1.5% 2-EHN blend exhibits the highest peak cylinder pressure of approximately 71.6 bar, with the crank angle of peak pressure coinciding with that of neat diesel. This behavior confirms that the addition of an adequate concentration of cetane improver can effectively restore diesel-like combustion phasing for bergamot peel oil–based blends while simultaneously enhancing combustion intensity. The advancement of peak pressure toward TDC with higher 2-EHN concentrations improves the pressure–volume work interaction during the early expansion stroke, directly contributing to the observed increase in brake thermal efficiency and reduction in brake specific fuel consumption. At the same time, the elevated peak pressure and advanced combustion phasing lead to higher in-cylinder temperatures, which explains the increase in nitric oxide (NO) emissions observed for higher additive dosages.

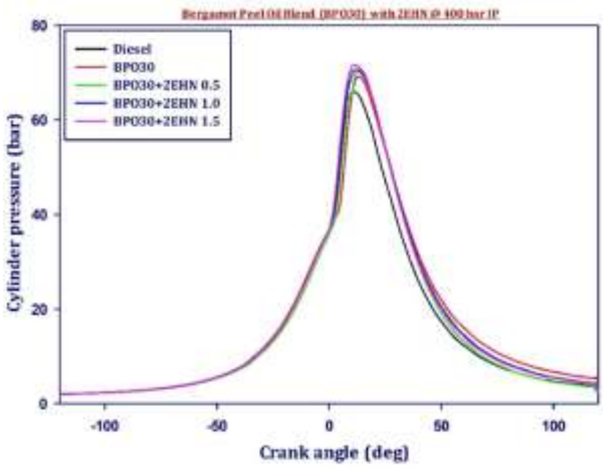

Figure 9 Effect of 2EHN addition on in-cylinder with respect to crank angle

4.3.2 Heat Release Rate

Figure 10 presents the variation of heat release rate with crank angle for neat diesel, BPO30, and BPO30 blends containing different concentrations of 2-ethylhexyl nitrate (2-EHN) at an injection pressure of 400 bar. All fuels exhibit a typical dual-stage heat release profile, consisting of a dominant premixed combustion peak near TDC followed by a diffusion-controlled combustion phase extending into the expansion stroke. Compared to neat diesel, BPO30 exhibits a higher premixed heat release peak, but the peak occurs at a retarded crank angle. This behavior is a direct consequence of the lower cetane index of bergamot peel oil, which prolongs ignition delay and allows a larger fraction of fuel to accumulate prior to ignition. As a result, when ignition occurs, a larger amount of fuel burns rapidly in the premixed mode, producing a higher HRR peak but shifted further into the expansion stroke. Although the oxygenated nature of BPO enhances combustion intensity, the delayed premixed combustion peak reduces the effectiveness of energy conversion during the early expansion stroke. This delayed heat release explains the slight compromise in combustion phasing relative to diesel and supports the observed increase in nitric oxide (NO) emissions due to locally elevated temperatures associated with an intensified premixed burn.

The addition of 2-EHN markedly influences both the magnitude and timing of the premixed heat release peak. At a lower additive concentration of 0.5%, the HRR profile closely resembles that of sole BPO30, with negligible advancement in the premixed combustion peak. This indicates that the cetane enhancement at this concentration is insufficient to significantly reduce ignition delay or alter combustion phasing. In contrast, increasing the 2-EHN concentration to 1.0% and 1.5% results in a clear advancement of the premixed heat release peak toward TDC, confirming a substantial reduction in ignition delay. This advancement leads to earlier energy release under higher in-cylinder pressure and temperature conditions, which explains the corresponding advancement in peak cylinder pressure observed in the pressure–crank angle analysis. Among all test fuels, the BPO30 + 1.5% 2-EHN blend exhibits the highest premixed HRR peak, occurring at a crank angle nearly coinciding with that of neat diesel. This behavior demonstrates that an adequate concentration of cetane improver can effectively restore diesel-like ignition characteristics while simultaneously enhancing combustion intensity.

Following the premixed combustion phase, the diffusion-controlled heat release for BPO30 and 2-EHN-treated blends is more pronounced than that of diesel. However, with increasing 2-EHN concentration, the magnitude and duration of late-cycle heat release are reduced. This indicates improved combustion completeness and reduced fuel burning during the expansion stroke. The suppression of late-cycle heat release with higher additive concentrations explains the observed reductions in CO, HC, and smoke emissions. Improved ignition quality minimizes fuel-rich regions and promotes more uniform combustion, thereby reducing incomplete oxidation products. The advancement of the premixed heat release peak toward TDC with higher 2-EHN concentrations improves the pressure–volume work interaction during the early expansion stroke, directly contributing to the increased brake thermal efficiency and reduced brake specific fuel consumption. However, the intensified and advanced premixed combustion also elevates peak combustion temperatures, which explains the increase in NO emissions observed for higher additive dosages.

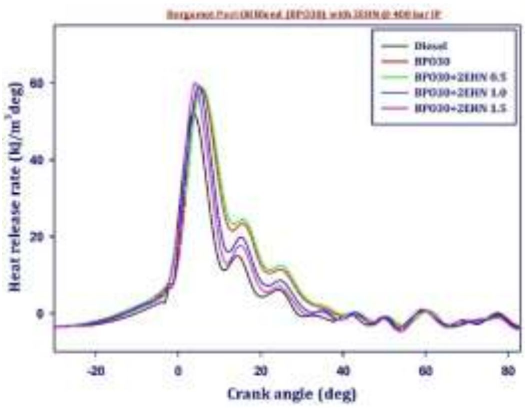

Figure 10 Effect of 2EHN addition on heat release rate with respect to crank angle

4.4 Limitations of the Study

The present investigation was conducted on a single-cylinder CRDI diesel engine operating at a constant speed, which provides detailed insight into combustion and emission behavior but may not fully represent the response of multi-cylinder engines under transient operating conditions. In addition, the study focused on a fixed base blend (BPO30) identified from prior screening, and the effects of cetane improver addition were evaluated only within a limited concentration range. Other blend ratios, alternative ignition-enhancing additives, or combinations of additives were not explored, which may offer additional opportunities for optimization.

Furthermore, the experimental assessment was limited to performance and regulated exhaust emissions without incorporating in-cylinder combustion visualization or optical diagnostics. While ignition delay and combustion behavior were inferred from performance and emission trends, direct visualization of spray and flame development was not performed. The study also did not include exhaust after-treatment systems or long-term durability testing of engine components and fuel injection hardware, which are critical for assessing real-world applicability. These limitations provide scope for future investigations involving advanced combustion diagnostics, after-treatment integration, and endurance testing to fully validate the practical feasibility of bergamot peel oil–diesel blends with cetane improver additives.

5. CONCLUSION

The present study experimentally investigated the influence of cetane improver addition on the performance and emission characteristics of a bergamot peel oil–diesel blend operated in a CRDI diesel engine. Based on earlier fuel characterization and blend optimization, a 30% bergamot peel oil blend (BPO30) was selected as the base fuel, and 2-ethylhexyl nitrate (2-EHN) was added at concentrations of 0.5%, 1.0%, and 1.5% by volume to compensate for the low cetane index of the biofuel.

- BPO30 exhibited higher brake thermal efficiency and lower brake specific fuel consumption across all load conditions, primarily due to its oxygenated composition, improved atomization characteristics, and slightly higher calorific value. The addition of 2-ethylhexyl nitrate (2-EHN) successfully compensated for the low cetane index of BPO30 by improving ignition quality and combustion phasing.

- Brake thermal efficiency increased and brake specific fuel consumption decreased progressively with increasing 2-EHN concentration, with the highest improvement observed for the BPO30 + 1.5% 2-EHN blend, particularly at medium and high loads.

- Carbon monoxide, unburned hydrocarbon, and smoke emissions were significantly reduced with BPO30 compared to diesel, confirming enhanced oxidation and reduced incomplete combustion due to fuel-bound oxygen. The incorporation of 2-EHN further reduced CO, HC, and smoke emissions, with the lowest values consistently recorded for the BPO30 + 1.5% 2-EHN blend.

- Nitric oxide (NO) emissions increased for BPO30 relative to diesel as a result of higher combustion temperatures and enhanced oxidation intensity. A low concentration of 2-EHN (0.5%) marginally reduced NO emissions compared to BPO30 by moderating premixed combustion, whereas higher additive concentrations (1.0% and 1.5%) increased NO emissions due to advanced combustion phasing and elevated peak temperatures.

- In-cylinder pressure analysis revealed that sole BPO30 exhibits a delayed crank angle of peak pressure relative to diesel due to its lower cetane index, whereas the addition of 2-ethylhexyl nitrate progressively advanced combustion phasing. The BPO30 + 1.5% 2-EHN blend achieved the highest peak cylinder pressure (≈71.6 bar) with the crank angle of peak pressure coinciding with that of diesel, confirming effective restoration of diesel-like ignition behavior.

- Heat release rate analysis demonstrated that BPO30 produces an intensified but retarded premixed combustion peak owing to prolonged ignition delay, while higher concentrations of 2-EHN significantly advanced the premixed heat release toward TDC and suppressed late-cycle combustion. This optimized heat release phasing for BPO30 + 1.5% 2-EHN explains the observed improvements in thermal efficiency and reductions in incomplete combustion emissions, albeit with a trade-off in nitric oxide formation.

Overall, BPO30 with 2-EHN addition represents a viable and efficient fuel strategy for CI engines, with higher additive concentrations favoring performance and particulate emission reduction, and lower concentrations offering a better compromise when NO emissions are a concern. The results confirm that cetane improver addition is a key enabling approach for extending the practical applicability of bergamot peel oil as a sustainable partial replacement for conventional diesel fuel.

FUTURE SCOPE

Future investigations can focus on optimizing in-cylinder combustion control strategies for bergamot peel oil–diesel blends with cetane improver by systematically varying fuel injection parameters. In particular, advancing and retarding the main injection timing (21°, 23°, and 25° CA bTDC) can be explored to identify the optimal combustion phasing that maximizes brake thermal efficiency while limiting pressure rise rate and nitric oxide formation. In addition, the role of pilot injection can be examined by varying pilot fuel quantity (5%, 10%, and 15% of the total injected fuel) to regulate ignition delay and premixed combustion intensity. A combined assessment of injection timing and pilot injection fraction would enable fine control over heat release characteristics, improve combustion stability, and mitigate NO emissions, especially at higher cetane improver concentrations where advanced ignition tends to elevate peak temperatures.

To further address emission control, future work can incorporate exhaust after-treatment systems, particularly selective catalytic reduction (SCR) using ammonia as a reducing agent, to effectively reduce NO emissions under a wide range of operating conditions. The interaction between oxygenated bergamot peel oil blends, ignition-enhancing additives, and ammonia–SCR performance can be evaluated to assess overall system-level emission compliance with BS-VI and Euro-VI standards. Additionally, long-term durability studies of fuel injection components and catalyst materials can be undertaken to ensure reliable engine operation and sustained emission reduction. Such integrated combustion optimization and after-treatment strategies would strengthen the practical applicability of bergamot peel oil–based fuels in modern compression ignition engines.

REFERENCE

Ashok, B., Nanthagopal, K., Chaturvedi, B., Sharma, S., & Thundil Karuppa Raj, R. (2018). A comparative assessment on Common Rail Direct Injection (CRDI) engine characteristics using low viscous biofuel blends. *Applied Thermal Engineering*, *145*, 494–506. https://doi.org/10.1016/J.APPLTHERMALENG.2018.09.069

Chacko, N., Johnson, C., Varadarajan, P., Sai Srinivas, S., & Jeyaseelan, T. (2021). A comparative evaluation of cetane enhancing techniques for improving the smoke, NOx and BSFC trade-off in an automotive diesel engine. *Fuel*, *289*, 119918. https://doi.org/10.1016/J.FUEL.2020.119918

Chivu, R. M., Martins, J., Popescu, F., Gonçalves, M., Uzuneanu, K., Frătița, M., & Brito, F. P. (2024). Assessment of Engine Performance and Emissions with Eucalyptus Oil and Diesel Blends. *Energies 2024, Vol. 17, 17*(14). https://doi.org/10.3390/EN17143528

Han, X., Li, T., Liu, G., & Vellaiyan, S. (2025). Comparative evaluation and economic analysis of metal- and carbon-based nanoadditives in low-viscous waste-derived biofuel blends for diesel engines. *Case Studies in Thermal Engineering*, *69*, 106057. https://doi.org/10.1016/J.CSITE.2025.106057

Hoang, A. T., Balasubramanian, D., Venugopal, I. P., Rajendran, V., Nguyen, D. T., Lawrence, K. R., Nguyen, X. P., & Kalam, M. A. (2023). A feasible and promising approach for diesel engine fuelled with a blend of biodiesel and low-viscosity Cinnamon oil: A comprehensive analysis of performance, combustion, and exergy. *Journal of Cleaner Production*, *401*, 136682. https://doi.org/10.1016/J.JCLEPRO.2023.136682

Karthikeyan, K., & Thambidurai, M. (2025). FUEL CHARACTERIZATION AND COMPATIBILITY ASSESSMENT OF BERGAMOT PEEL OIL–DIESEL BLENDS FOR CI ENGINE APPLICATIONS. *JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES*, *20*(12). https://doi.org/10.26782/JMCMS.2025.12.00007

Kaur, L., Singh, J., Ashok, A., Pali, H. S., & Kumar, S. (2026). Assessment of performance, combustion, and emission characteristics of a diesel engine fueled with novel emulsions of cattle dung bio-oil in diesel stabilized by biodiesel. *Next Energy*, *10*, 100492. https://doi.org/10.1016/J.NXENER.2025.100492

Kumar, H., Sarma, A. K., & Kumar, P. (2019). A novel approach to study the effect of cetane improver on performance, combustion and emission characteristics of a CI engine fuelled with E20 (diesel – bioethanol) blend. *Sustainable Chemistry and Pharmacy*, *14*, 100185. https://doi.org/10.1016/J.SCP.2019.100185

Kuszewski, H., Jaworski, A., Kuszewski, H., & Jaworski, A. (2024). Investigating the Effect of 2-Ethylhexyl Nitrate Cetane Improver (2-EHN) on the Autoignition Characteristics of a 1-Butanol–Diesel Blend. *Energies 2024, Vol. 17, 17*(16). https://doi.org/10.3390/EN17164085

Labeckas, G., & Slavinskas, S. (2021). Comparative evaluation of the combustion process and emissions of a diesel engine operating on the cetane improver 2-Ethylhexyl nitrate doped rapeseed oil and aviation JP-8 fuel. *Energy Conversion and Management: X*, *11*, 100106. https://doi.org/10.1016/J.ECMX.2021.100106

Liu, H., Zhang, X., Zhang, Z., Wu, Y., Wang, C., Chang, W., Zheng, Z., & Yao, M. (2023). Effects of 2-ethylhexyl nitrate (EHN) on combustion and emissions on a compression ignition engine fueling high-pressure direct-injection pure methanol fuel. *Fuel*, *341*, 127684. https://doi.org/10.1016/J.FUEL.2023.127684

Mercado-Cordova, J. (2025). Biofuel technologies and global decarbonization by 2050: The role of technological learning, spillovers effects and feedstock constraints. *Energy Strategy Reviews*, *62*, 101932. https://doi.org/10.1016/J.ESR.2025.101932

Mohammed, A. S., Atnaw, S. M., Ramaya, A. V., & Alemayehu, G. (2023). A comprehensive review on the effect of ethers, antioxidants, and cetane improver additives on biodiesel-diesel blend in CI engine performance and emission characteristics. *Journal of the Energy Institute*, *108*, 101227. https://doi.org/10.1016/J.JOEI.2023.101227

Nguyen, V. N., Balasubramanian, D., Rajarajan, A., Venugopal, I. P., Dineshkumar, C., Ravikumar, R., Nguyen Le, D. T., Cao, D. N., Femilda Josephin, J. S., Chinnathambi, A., Pugazhendhi, A., & Varuvel, E. G. (2024). Engine behavior analysis on a conventional diesel engine combustion mode powered by low viscous cedarwood oil/waste cooking oil biodiesel/diesel fuel mixture – An experimental study. *Process Safety and Environmental Protection*, *184*, 560–578. https://doi.org/10.1016/J.PSEP.2024.02.002

Ramalingam, K., Vellaiyan, S., Venkatesan, E. P., Khan, S. A., Mahmoud, Z., & Saleel, C. A. (2023). Challenges and Opportunities of Low Viscous Biofuel─A Prospective Review. *ACS Omega*, *8*(19), 16545–16560. https://doi.org/10.1021/ACSOMEGA.3C00387

Valera, H., Mehra, S., Singh, R. K., Čedík, J., Pexa, M., & Agarwal, A. K. (2026). Alcohol-diesel blends fueled off-road compression ignition engine development: part 2 − Influence of ethanol-diesel blends on engine performance, combustion, and emissions. *Fuel*, *412*, 137577. https://doi.org/10.1016/J.FUEL.2025.137577

Vellaiyan, S., & Kandasamy, M. (2022). Dataset for the combined effect of cetane improver and water emulsion on energy, environmental and economic values of a diesel engine fueled with lemon peel oil. *Data in Brief*, *43*, 108467. https://doi.org/10.1016/J.DIB.2022.108467

Vikneswaran, M., Saravanan, C. G., Manickam, M., Sasikala, J., Femilda Josephin, J. S., Pugazhendhi, A., & Varuvel, E. G. (2022). A study on the feasibility of bergamot peel oil-gasoline blends for spark-ignition engines. *Journal of Cleaner Production*, 130515. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.130515