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# Experimental Investigation of 2-Ethylhexyl Nitrate Effects on Engine Performance and Exhaust Emissions in Biodiesel-2-Methylfuran Blend for Diesel Engine

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**Abstract:** Biodiesel and 2-methylfuran (MF) exhibit significant potential as alternative fuels due to advancements in their production techniques. Despite this potential, the low cetane number (CN) of biodiesel–MF (BMF) blends limits their practical use in diesel engines due to poor auto-ignition characteristics and extended ignition delays. This study addresses this issue by investigating the impact of the cetane improver 2-ethylhexyl nitrate (2-EHN) on the performance and emissions of a BMF30 blend. The blend consists of 70% biodiesel and 30% MF, with 2-EHN added at concentrations of 1% and 1.5% to enhance ignition properties. The experiments were conducted on a four-cylinder, four-stroke, direct-injection compression ignition (DICI) engine at a constant speed of 1800 rpm with brake mean effective pressures (BMEP) ranging from 0.13 to 1.13 MPa. The results showed that 2-EHN improved the CN of the BMF30 blend, leading to earlier combustion initiation and longer combustion duration. At low BMEP (0.13 MPa), 2-EHN increased the peak rate of heat release and in-cylinder pressure, whereas at higher BMEP (0.88 MPa), these parameters decreased. The key findings include a reduction in brake-specific fuel consumption (BSFC) by 5.49–7.33% and an increase in brake thermal efficiency (BTE) by 3.30–4.69%. Additionally, NOx emissions decreased by 9.4–17.48%, with the highest reduction observed at 1.5% 2-EHN. CO emissions were reduced by 45.1–85.5% and soot emissions also declined. Hydrocarbon (HC) emissions decreased by 14.56–24.90%. These findings demonstrate that adding 2-EHN to BMF30 blends enhances engine performance, reduces key emissions, and offers a promising alternative fuel for diesel engines.

**Keywords:** 2-ethylhexyl nitrate; 2-methylfuran; biodiesel-MF blend; combustion; emissions

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## 1. Introduction

The urgent need to reduce fossil fuel dependence has accelerated biodiesel development as a renewable alternative, offering significant reductions in HC, CO, and PM emissions compared to conventional diesel [1–6]. It is both eco-friendly and has been reported to offer improved combustion stability and performance consistency under specific

operating conditions, as noted in previous studies [7,8]. Biodiesel has gained widespread recognition as a feasible substitute for conventional diesel, mainly because of its environmental advantages. Compared to petroleum-derived diesel, the combustion of biodiesel markedly reduces emissions of HC, CO, particulate matter (PM), and other harmful air pollutants [9,10]. Moreover, it offers enhanced lubricity, which improves both engine performance and durability. Its renewable availability further enhances its appeal as a sustainable option for reducing fossil fuel reliance [11–13]. Collectively, these advantages make biodiesel a compelling option for mitigating the environmental impact of transportation and other diesel-engine applications. However, its drawbacks—including higher viscosity, lower energy density, and elevated NOx emissions [14–16]—have prompted research into blending strategies. 2-Methylfuran (2-MF) has emerged as a promising additive, improving fuel volatility and oxygen content while reducing soot emissions. However, blending biodiesel with MF also introduces new challenges, particularly concerning ignition delay (ID), combustion stability, and increased NOx emissions, particularly at blend ratios above 20% [17].

Numerous studies have extensively analyzed the engine performance and exhaust emissions attributes of biodiesel and its different blends, highlighting various benefits and challenges. Chaudhary et al. [18] demonstrated that blending MF with biodiesel enhances combustion efficiency and reduces PM emissions, owing to the higher oxygen content and superior volatility of MF. Similarly, research on biodiesel blends with other oxygenated compounds, such as waste swine oil and waste cooking oil, has demonstrated significant reductions in particulate and soot emissions. However, these blends also tend to raise Nox emissions [19,20]. Xiao, H. et al. [21] examined the effects of injection timing and exhaust gas recirculation (EGR) on the combustion and emissions of biodiesel/2-methylfuran (BMF) blends in a modified 4-cylinder DICI engine. The results showed that advanced injection timing improved combustion efficiency but increased Nox emissions, while higher EGR ratios prolonged ignition delay (ID) and combustion duration (CD), reducing Nox but increasing HC, CO, and aldehyde emissions. BM20 outperformed BM10 in terms BTE but both blends showed combustion deterioration at advanced injection timing. Zheng et al. [22] investigated the impact of different biodiesel blends on combustion and emissions in a single-cylinder diesel engine, specifically examining biodiesel combined with n-butanol (B20), ethanol (E20), and 2,5-dimethylfuran (DMF20).Their findings showed that, although these blends had lower BTE than diesel at lower loads, they outperformed diesel at higher load conditions. However, Nox emissions were higher for biodiesel, B20, and DMF20 compared to diesel, while E20 resulted in lower NOx emissions. In terms of HC and CO emissions, the blends displayed increased concentrations at lower engine loads, conversely, these emissions decreased with increasing load. These findings are consistent with other studies suggesting that biodiesel blends may enhance BTE while frequently leading to elevated NOx emissions, attributed to higher combustion temperatures and increased oxygen content [23]. Studies on biodiesel blends with dimethyl ether (DME) and butanol have shown similar trends, with enhanced combustion efficiency and reduced particulate emissions but increased Nox emissions [24]. Xiao et al. [17] investigated the effects of MF blends with biodiesel in a direct-injection compression ignition engine. The results showed that increasing MF content reduced heat release rate and cylinder pressure at low loads but enhanced them at medium to high loads. Emissions analysis revealed reduced HC and CO, increased NOx, and consistently low soot emissions. Additionally, unregulated emissions of 1,3-butadiene, benzene, and acetaldehyde decreased with higher MF content, particularly at higher loads. Overall, the challenge of increased NOx emissions remains a critical area for further optimization and research [25,26].

Previous investigations have indicated that the low CN of 2-MF contributes to an increase in NOx emissions in diesel engines (DEs), primarily due to higher in-cylinder temperatures. As NOx formation is highly sensitive to elevated temperatures, these conditions facilitate its increased production. To address this issue, significant efforts have been directed towards enhancing the CN of biofuels. One proposed approach to mitigate the negative effects of low CN is the incorporation of cetane enhancers, such as 2-ethylhexyl nitrate (2-EHN). Cetane improvers are known to improve the ignition characteristics of fuels by reducing ID, thereby fostering more efficient combustion processes [27,28]. Studies on the use of cetane improvers in various fuel blends have shown promising results. Kuszewski et al. [29] studied the effect of 2-EHN on the autoignition characteristics of a 1-butanol–diesel blend with 30% ($v/v$) 1-butanol. Their findings demonstrated that increasing 2-EHN concentration significantly shortened ignition and combustion delays, thereby improving the derived CN. This study underscores the potential of 2-EHN to address the autoignition challenges of alcohol-diesel fuel blends for compression ignition engines. Estevez et al. [30] evaluated blends of fossil diesel, sunflower or castor oil, and 2-EHN. They found that 2-EHN reduced the viscosity of straight vegetable oils, enabling their use in conventional diesel engines without compromising fuel properties. The blends exhibited power outputs similar to or greater than fossil diesel with comparable fuel consumption and significantly reduced emissions of CO and soot, although NOx emissions were slightly higher. Salmani et al. [31] conducted a study on the performance and emission characteristics of diesel-ethanol blends enhanced with 2-EHN in a compression ignition engine. Their findings indicated that incorporating 2-EHN significantly enhanced BTE and decreased BSFC. Moreover, the addition of 2-EHN effectively reduced CO and HC emissions. However, a marginal increase in NOx emissions was observed as a trade-off for the improved combustion efficiency. Kuszewski et al. [32] investigated the addition of 2-EHN to a 15% ethanol-diesel blend (EDB) to enhance its ignition properties. The results show that increasing 2-EHN concentration reduces ignition and combustion delays, with higher ambient temperatures further improving ignition performance, indicating 2-EHN's potential in improving EDB's viability for diesel engines. Imdadul, H.K. et al. [33] demonstrated that the addition of 2-EHN enhanced the fuel characteristics and CN of n-butanol-diesel-biodiesel blends, resulting in improved engine performance and reduced NOx and smoke emissions; however, CO and HC emissions were observed to increase. The study concluded that the integration of a cetane improver into oxygenated alcohol-treated biodiesel blends positively influences diesel engine efficiency. Similarly, Li et al. [34] investigated the effects of EHN on the combustion and emissions of methanol in a compression ignition engine. The study used pure methanol and blends with 0.1%, 1%, and 3% 2-EHN, with diesel as a baseline. The results showed that increasing EHN reduced ID and improved BTE at low intake temperatures, although NOx emissions increased with higher 2-EHN concentrations. Methanol with 3% 2-EHN exhibited lower soot emissions and optimal BTE (30.5%) compared to diesel under specific operating conditions.

Findings have highlighted that the addition of 2-EHN to fuels with lower CN significantly enhances their CN and contributes to a reduction in NOx emissions. However, despite these advancements, there remains a notable gap in the existing body of research regarding the effects of 2-EHN on biodiesel/2-methylfuran (BMF30) blend, particularly concerning combustion characteristics, engine performance metrics, and emission profiles in diesel engines. Therefore, this investigation focuses on understanding how 1% and 1.5% concentrations of 2-EHN affect in BMF30 blend critical performance parameters such as BTE, BSFC, and emissions, including NOx and soot emission, thereby offering valuable insights into the potential of use these blends as a sustainable and high-performance fuel alternative.

## 2. Experimental

### *2.1. Engine Configuration and Instrumentation*

The experiments used a modified four-cylinder, four-stroke diesel engine with direct fuel injection, as illustrated in Figure 1. Table 1 contains comprehensive engine specifications. An eddy current dynamometer-controlled output torque to maintain a steady speed of 1800 rpm. An Electronic Control Unit (ECU) was used to regulate important parameters like fuel mass and injection timing. The ECU set the injection timing at 7.5 crank angle degrees before the top dead center. The Kistler 6025C sensor was used to measure the in-cylinder pressure, and a CB-466 combustion analyzer was used to examine the data. At a resolution of 0.25 crank angle degrees, pressure readings were gathered over 100 cycles. While coolant and oil temperatures were maintained at 85 ± 2 °C and 87 ± 1 °C, respectively, intake air temperature was maintained at 25 ± 1 °C. Using an AVL gas analyzer, exhaust emissions were measured, and an NH-T6 opacimeter was used to track smoke. We gathered exhaust gas samples for quantitative evaluation. Moreover, the diesel engine must operate more than 15 min after changing to a new fuel, which ensures the reliability of the test data. Table 2 displays the measured data uncertainty.

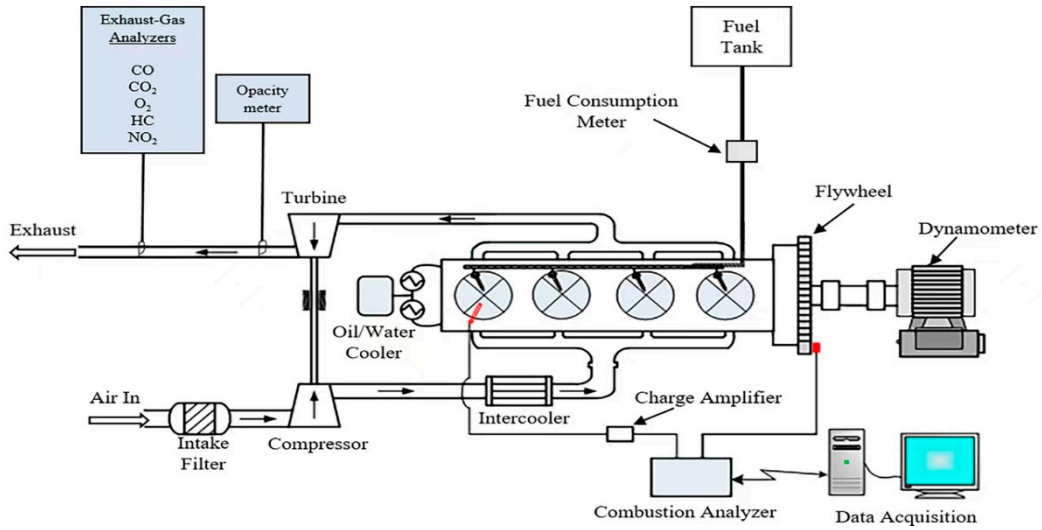



**Figure 1.** Schematic of engine and instrumentation configuration [35].

**Table 1.** Specification of test diesel engine.

| Items | Specifications |
|---|---|
| Engine Type | In-line 4-cylinder DICI |
| Bore × Stroke | 96 mm × 103 mm |
| Compression ratio | 17.5:1 |
| Displacement | 2982 mL |
| Rated power | 85 kW |
| Rated speed | 3200 rpm |
| Injection hole numbers | 7 |
| Type of cooling | Water-cooled |
| Injection hole diameter | 0.137 mm |
| Method of starting | Electric start |

**Table 2.** Presents the precision of the measurements and the uncertainty of the calculated values for the various examined parameters.

| Measurement | In-Cylinder Pressure | Brake Torque | BSFC | BTE | HC | CO | $NO_X$ |
|---|---|---|---|---|---|---|---|
| Uncertainty (%) | ±0.1 | ±1.5 | ±1 | ±1.14 | ±5.5 | ±4 | ±5.7 |

The uncertainties for the engine performance parameters were determined using the propagation of errors methodology. The following equation shows parameter-specific uncertainty calculation, for example

(a) Brake Thermal Efficiency (BTE):

$$U_{BTE} = BTE \times [(U_{m\cdot f})^2 + (U_T)^2 + (U_N)^2]^{0.5};$$

(b) Ignition Delay:

$$U_{ID} = [U^2_{SOI} + U^2_{SOC}]^{0.5}.$$

*2.2. Tested Fuel and Experimental Conditions*

In the conducted study, a fuel blend was created by combining 2-methylfuran and biodiesel. The mixture, denoted as BMF30, consisted of 30% 2-methylfuran and 70% biodiesel. Following this, the additive 2-EHN was introduced into the BMF30 blend at varying concentrations 1% and 1.5%. These modified blends were labeled as BMF30E1 and BMF30E1.5, respectively. The biodiesel used in the experiment was supplied by the China Petroleum and Chemical Corporation (Beijing, China). At the same time, the 2-methylfuran (99% purity) was supplied by TZHL Biological Technology Co. Ltd. The 2-EHN additive was provided by Tianjin Kermel Chemical Reagent Co., Ltd., Tianjin, China. Tables 3 and 4 outline the physicochemical properties of these four fuel compositions, ensuring transparency and adherence to originality standards.

**Table 3.** Properties of diesel, biodiesel, MF and 2-EHN [36–40].

| Parameters | Diesel | Biodiesel | 2-MF | 2-EHN |
|---|---|---|---|---|
| Chemical formula | $C_{12}$–$C_{25}$ | $CH_3(CH_2)_{18}COOCH_3$ | $(C_5H_6O)$ | $C_8H_{17}NO_3$ |
| Research Octane number | 20–30 | – | 103 | - |
| Cetane number | 52.1 | 46 | 9 | ≥76 |
| Oxygen content (% mass) | 0 | 10.8 | 19.51 | 27.43 |
| Stoichiometric air/fuel ratio | 14.3 | 12.54 | 10.05 | - |
| Density at 20 °C ($kg/m^3$) | 827 | 871 | 913.2 | 963 |
| kinematic viscosity at 40 °C ($mm^2/s$) | 2.47 | 4.24 | 0.48 | 2.21 |
| Water solubility at 20 °C (wt%) | N | N | N | - |
| Evaporation heat at 25 °C (kJ/kg) | 270–301 | 252–258 | 358 | 353.6 |
| Lower heating value (MJ/kg) | 42.5 | 38.5 | 31.2 | 15.7 |
| Boiling point (°C) | 180–370 | – | 64.7 | 307 |
| Flash point (°C) | 96 | 181 | −22 | 76 |

N: Negligible.

**Table 4.** The characteristics of the mixed fuel with 2-EHN.

| Blend Fuel | 2-EHN (%) | Cetane Nunber | Viscosity at 40 °C ($mm^2/s$) | Density at 20 °C ($kg/m^3$) |
|---|---|---|---|---|
| BMF30 | 0 | 34.9 | 3.11 | 883.66 |
| BMF30E1 | 1 | 35.19 | 3.092 | 884.59 |
| BMF30E1.5 | 1.5 | 35.34 | 3.082 | 884.54 |

### *2.3. Experimental Conditions*

All experiments were conducted at a constant speed of 1800 rpm, with engine loads from 10% to 90% in 20% increments, corresponding to BMEP values of 0.13 to 1.13 MPa. The engine was warmed to a steady state, maintaining coolant at 85 °C and lubricating oil at 87 °C. Key data, including control parameters, in-cylinder pressure, and emissions, were recorded for analysis. To clear residual fuel, the engine was run for fifteen minutes after switching fuels. Each measurement set was repeated twenty times for accuracy.

## 3. Results and Discussion

### *3.1. Effect of 2-EHN Additive on Burning Characteristics*

Figure 2a,b demonstrates the impact of adding 2-EHN, a known CN improver, both the cylinder pressure and rate of heat release (RHR) of the BMF30 fuel blend under load conditions of 10% and 70%, respectively. As observed in previous studies, most of the fuels showed a rise in maximum combustion chamber pressure with increasing engine load [41]. Initially, the maximum HRR rose with higher loads but then exhibited a decline. Additionally, for most fuels, the HRR reached its peak near Top Dead Centre (TDC) as load increased. At a BME of 0.13 MPa, the cylinder pressure characteristics for both the blended fuels and pure biodiesel showed similar trends, except for the BMF30 blend. The reduced CN of the BMF30 blend delayed the initiation of combustion, leading to an increased amount of premixed fuel available during the premixed combustion phase. Consequently, this increased the peak cylinder pressure and RHR values. Moreover, the incorporation of 2-EHN, which has a lower viscosity, into the BMF30 blend enhanced the fuel atomization and facilitated the formation of combustible mixtures during the premixed combustion phase, thereby accelerating the ignition onset [35]. Interestingly, the initiation of combustion for BMF30E1 and BMF30E1.5 occurred earlier than that of BMF30 and biodiesel. This phenomenon is mainly attributed to the inclusion of the cetane improver (2-EHN) in the blend, which enhances ignition properties and alters the combustion dynamics. The elevated CN promotes faster and more uniform ignition, thereby expediting the combustion process. Furthermore, the chemical characteristics of 2-EHN and its interaction with fuel components, particularly 2-MF, significantly contribute to the observed earlier combustion behavior.

At a pressure of 0.88 MPa, the combustion chamber pressure and RHR reached their maximum values, with combustion occurring later in the BMF30 blend. The lower CN of the BMF30 blend was a significant factor influencing the peak combustion chamber pressure, whereas the elevated oxygen concentration in the mixture enhanced the combustion process, leading to a rise in the maximum RHR. However, the incorporation of 2-EHN into the BMF30 blend led to an earlier ignition initiation, subsequently reducing both the peak combustion chamber pressure and the RHR, especially at the elevated concentration of 1.5% 2-EHN. Additionally, the ignition for the BMF30E1 and BMF30E1.5 blends occurred earlier than that of the unmodified BMF30 blend, a phenomenon attributed to the characteristics of 2-EHN. As the concentration of the cetane improver increased in the BMF30E1 and even more so in the BMF30E1.5, ignition efficiency improved, resulting in an earlier initiation of combustion. Furthermore, 2-EHN, acting as a cetane enhancer, significantly increased

the CN of the BMF30 blend, thereby decreasing the ID period and expediting the overall burning process.

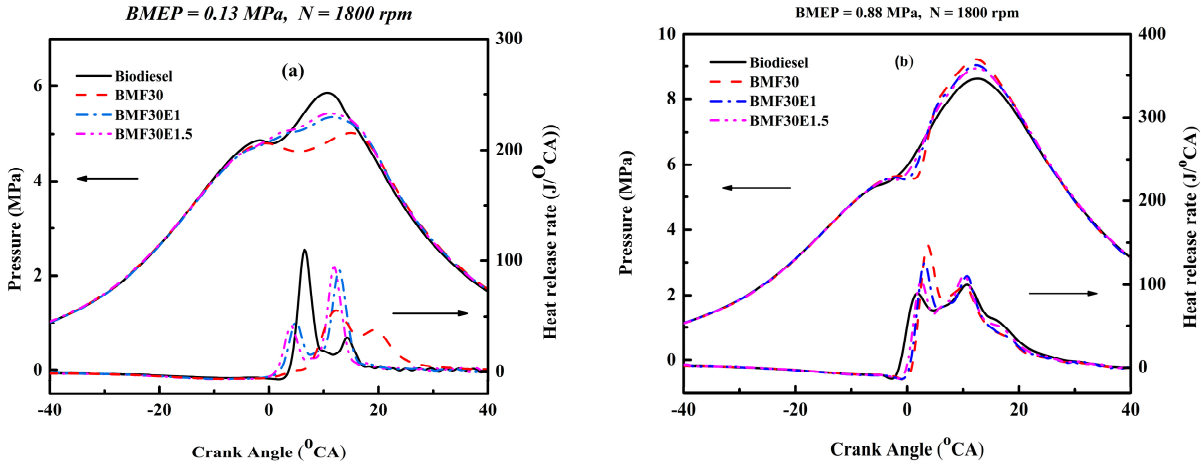



**Figure 2.** In-cylinder pressure and rates of heat release at (**a**) 0.13 MPa BMEP and (**b**) 0.88 MPa BMEP.

Figure 3a,b show how 2-EHN, which improves the cetane number (CN), affects the ID and CD of the BMF30 fuel blend at 10% and 70% engine loads. Scientifically defined, the ID is the time, usually measured in crank angle degrees, between the start of the injection (SOI) of fuel into the combustion chamber and the start of combustion (SOC). The analysis of the HRR during the burning process yields this metric. The analysis of Figure 3a reveals that as engine load increases, ID decreases, primarily due to higher equivalence ratios, which raise in-cylinder temperature, enhance fuel atomization, and create a more uniform fuel-air mixture, facilitating ignition and reducing ID.

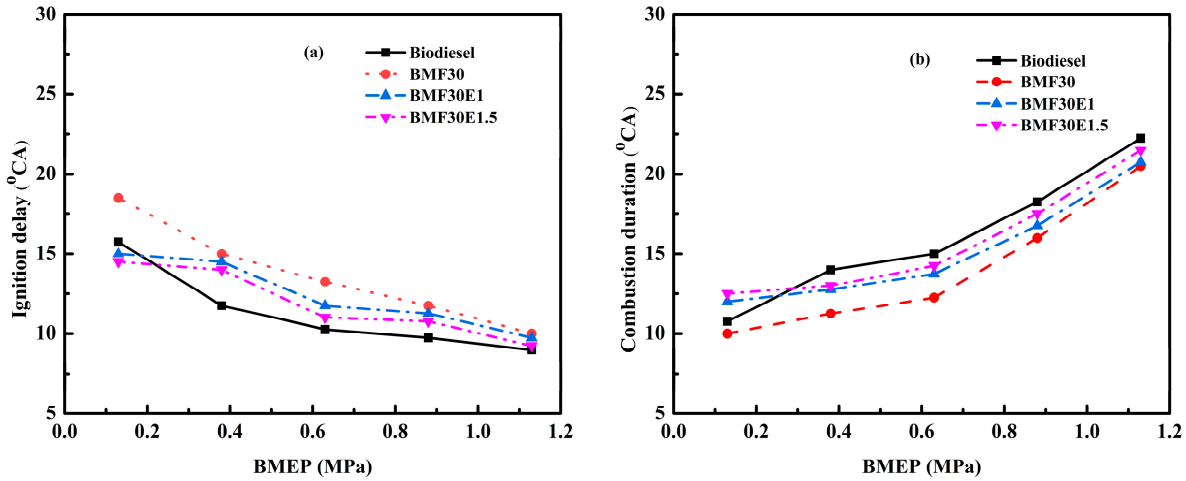



**Figure 3.** Effect of 2-EHN on (**a**) ignition delay (ID) and (**b**) combustion duration (CD) for BMF30 blend at different BMEP levels.

In contrast, the BMF30 blend exhibits a longer ID compared to other fuels tested, which can be attributed to its distinct fuel properties. Two primary factors contribute to this extended delay. First, the relatively lower combustion chamber temperatures associated with the higher latent heat of vaporization of 2-MF, which reduces the rate of fuel evaporation. Second, the lower CN and higher auto-ignition temperature of the 2-MF fuel further prolong ignition [35,42]. However, the incorporation of 2-EHN into the BMF30 blend resulted in a decrease in ID across all engine load conditions. Specifically, the BMF30E1 and BMF30E1.5 blends exhibit shorter IDs compared to the base BMF30

blend. This improvement is likely due to the lower viscosity of 2-EHN, which enhances the atomization of the fuel blends. Better atomization leads to a more efficient fuel-air mixing during the premixed phase, facilitating quicker ignition and reducing the ID. The findings suggest that the addition of 2-EHN to the BMF30 blend enhances the fuel's ignition properties, promoting better combustion efficiency, particularly under varying engine loads.

Figure 3b presented a comparison of combustion duration (CD) across different engine loads for four fuel types. CD is calculated as the crank angle interval between the start of combustion (SOC) and the end of combustion (EOC), identified by the cumulative heat release curve. At a BMEP of 0.13 MPa, an increase in CD was noted as the engine load increased, particularly with the inclusion of 2-EHN in the BMF30 blend. As shown in Figure 2a, biodiesel at the same BMEP exhibited a higher proportion of premixed combustion, which reduced the duration of diffusive combustion. Consequently, pure biodiesel displayed the shortest ID but the longest CD when compared to the BMF30 blend. The BMF30E1 and BMF30E1.5 blends exhibit shorter ID compared to the base BMF30 blend. This improvement is likely due to the lower viscosity of 2-EHN, which enhances the atomization of the fuel blends. Improved atomization allows for better fuel-air mixing during the premixed combustion phase, leading to quicker ignition and reduced ID. However, the increased CN associated with the addition of 2-EHN may also lead to a slower combustion rate, contributing to a longer overall CD.

### *3.2. Influence of 2-EHN Addition on the BSFC and BTE*

The effect of incorporating 1% and 1.5% 2-EHN into the BMF30 blend on brake-specific fuel consumption (BSFC) and brake thermal efficiency (BTE) is presented in Figure 4a,b. As shown in Figure 4a, an increase in engine load leads to a rise in combustion chamber temperature, which improves the fuel combustion process, subsequently causing a gradual reduction in BSFC for all tested fuel [43]. Among the fuels evaluated, the BMF30 blend exhibits the highest BSFC, while biodiesel demonstrates the lowest BSFC. This discrepancy can be attributed to the relatively lower calorific value of the BMF30 blend compared to the higher calorific value of biodiesel. The analysis in Figure 4a indicates that the BMF30E1 and BMF30E1.5 blends achieved reductions in BSFC by 5.34–7.25%, respectively. This decrease in BSFC is primarily due to the improved ignition quality of the fuel, which facilitates a more efficient combustion process. The enhanced combustion characteristics optimize fuel injection timing and combustion synchronization, thereby reducing the amount of fuel required to produce a given power output. The observed reductions in BSFC for the BMF30E1 and BMF30E1.5 blends, compared to the base BMF30 blend, highlight the positive effects of 2-EHN in improving overall engine performance. These findings suggest that the addition of cetane improvers, such as 2-EHN, can enhance the combustion process due to its high volatility, which potentially improves the dispersion rate of fuel vapor within the combustion chamber. This, in turn, aids in the preparation of the fuel–air mixture prior to ignition [39]. Furthermore, the incorporation of 2-EHN into the BMF30 blend results in a reduction in ID due to the increased cetane number (CN), leading to lower BSFC.

Figure 4b shows how 2-EHN, a cetane number (CN) enhancer, affects the brake thermal efficiency (BTE) of the BMF30 fuel under engine loads ranging from 10% to 90%. BTE is a function of brake-specific fuel consumption (BSFC) and the lower heating value of the fuel. A progressively increasing BTE was observed for all tested fuels as engine load increased. This enhancement is attributed to elevated combustion temperatures, which facilitate faster fuel evaporation and improve combustion efficiency [38]. Compared to pure biodiesel, the BMF30 blend demonstrated a more favorable combustion profile, characterized by a shorter CD attributed to improved conditions approximating constant-volume combustion, thereby contributing to higher BTE. The elevated oxygen content in BMF30 further supports

more rapid and thorough combustion, reinforcing the improvement in thermal efficiency. The addition of 2-EHN at concentrations of 1% and 1.5% (by volume) into the BMF30 blend resulted in average BTE gains of 3.30% and 4.69%, respectively. This improvement is largely associated with the enhanced calorific value of additive-enriched blends—36.46 MJ/kg for BMF30E1 and 36.54 MJ/kg for BMF30E1.5, compared to 36.31 MJ/kg for the unmodified BMF30. The increased energy content promotes more effective energy conversion during combustion, thereby reducing BSFC.

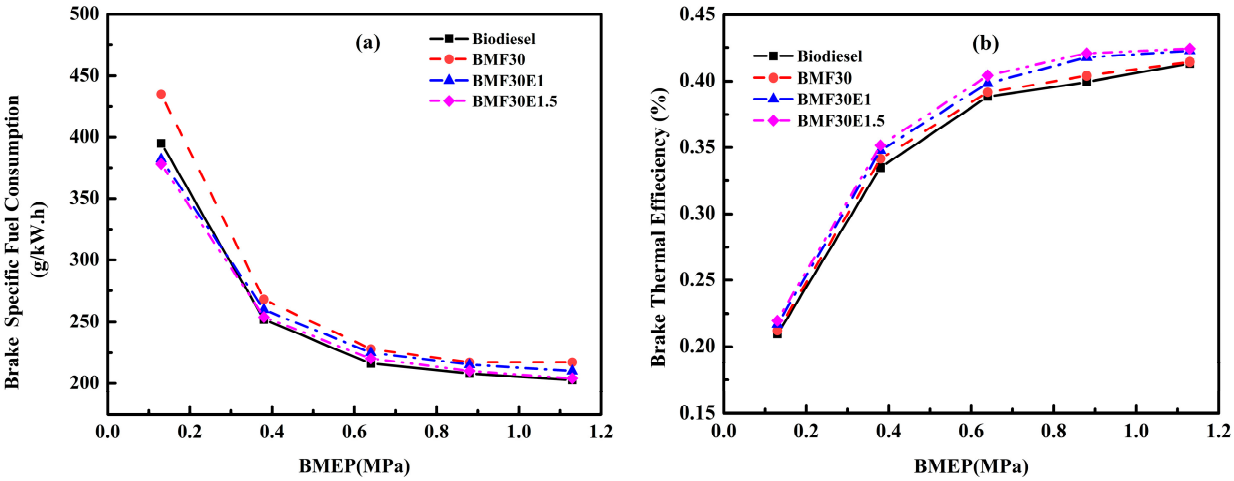



**Figure 4.** Variations in (**a**) BSFC and (**b**) BTE at different engine loads for the tested fuels.

Moreover, the increase in thermal efficiency with 2-EHN addition is also due to improved combustion phasing, where reduced ignition delay (ID) shifts the start of combustion closer to top dead center (TDC). Despite the typical increase in diffusion combustion with reduced ID, the oxygenated nature of the biodiesel–2-methylfuran blend, along with improved atomization and vaporization from 2-EHN, promotes more complete and uniform combustion. This reduces the formation of unburned species, minimizes heat loss, and enhances overall combustion efficiency [40,44].

### *3.3. Impacts of 2-EHN Additive on the Emissions Characteristics*

Figure 5 presents the influence of varying concentrations of 2-EHN on nitrogen oxide (NOx) emissions for the BMF30 fuel blend across different engine load conditions. A marked increase in NOx emissions is observed at higher engine loads, which can be attributed to elevated combustion temperatures within the cylinder, resulting from the increased oxygen content in the fuel blend. The formation of NOx in biodiesel combustion is influenced by multiple factors, including oxygen availability, combustion temperature, and the duration of exposure to high-temperature zones within the engine cycle [45,46]. In comparison to pure biodiesel, the BMF30 blend exhibits higher NOx emissions than pure biodiesel at 0.38–1.13 MPa BMEP due to 2-methylfuran's combustion properties. Its high oxygen content (19.5%) and lower cetane number (~9 vs. biodiesel's ~46) promote complete combustion with longer IDs, increasing peak temperatures and thermal NOx formation. While biodiesel's higher viscosity and cetane rating moderate combustion, BMF30's oxygen enrichment and premixed burning phase intensify temperature-driven NOx production, particularly at mid-high loads. This reflects the typical trade-off where oxygenated fuels reduce HC/CO but increase NOx emissions [47]. The addition 1% and 1.5% concentrations of 2-EHN to the BMF30 blend reduces NOx emissions by 9.4–17.48%, respectively, under all test conditions, through several key mechanisms tied to its chemical properties and combustion effects. As 2-EHN decomposes, it releases radicals ($NO_2$ and OH) that accelerate ignition, shortening ID and reducing the premixed combustion phase—

the primary source of high temperatures that drive thermal NOx formation. While 2-EHN contains nitrogen, its radical donation mechanism promotes more complete combustion of nitrogen intermediates rather than their conversion to NOx. The additive's effectiveness peaks at 0.5–1.5% concentration, where it optimally moderates combustion temperatures without compromising the fuel's oxygen benefits. This allows BMF30 to maintain its particulate reduction advantages while specifically mitigating the temperature-dependent NOx formation pathways characteristic of oxygenated biodiesel blends.

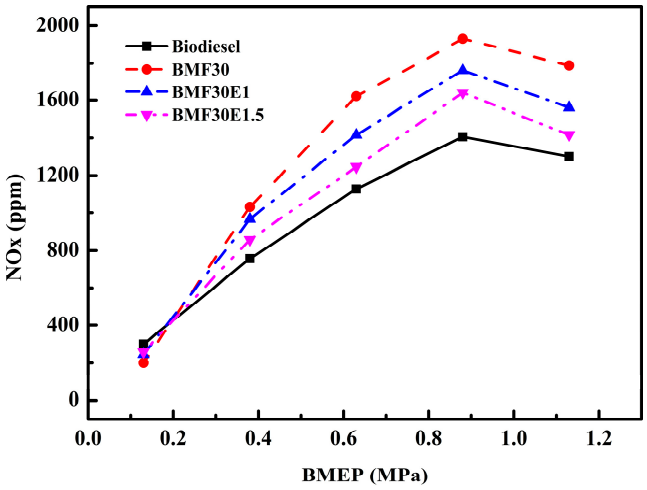



**Figure 5.** Effect of addition 2-EHN concentration on the NOx emissions to BMF30 blend at different BMEP levels.

Figure 6 depicts the influence of varying 2-EHN concentrations on HC emissions for the BMF30 fuel mixture under different engine operating conditions. At low load (0.13 MPa BMEP), elevated HC emissions were observed, attributable to reduce in-cylinder temperatures and incomplete combustion [48]. As the load increased, HC emissions progressively declined, reaching their lowest levels at 0.88 MPa BMEP, followed by a resurgence at 1.13 MPa BMEP. This behavior is linked to variations in the air-fuel equivalence ratio and localized oxygen depletion within the combustion zone. Under high-load conditions, diminished oxygen availability contributes to less efficient oxidation, leading to increased HC formation. Compared to the BMF30, neat biodiesel displayed the highest HC emissions despite exhibiting the shortest ID among the evaluated fuels. The elevated CN ≈ 46 of pure biodiesel promotes earlier autoignition relative to BMF30 (CN ≈ 35). However, its greater kinematic viscosity (4.24 $mm^2/s$ compared to ~3.1 $mm^2/s$ for BMF30) adversely affects spray atomization [49], impairing mixture preparation and thus elevating HC emissions. In contrast, the BMF30 blend exhibited reduced HC emissions due to its enhanced oxygen content, which facilitates more thorough combustion [50]. The addition 1% and 1.5% concentration of 2-EHN to the BMF30 mixture significantly suppressed HC emissions. The BMF30E1 and BMF30E1.5 formulations reduced HC emissions by 14.56% and 24.90%, respectively, compared to the baseline BMF30 blend. The improved volatility of 2-EHN promotes superior fuel vaporization, enhancing premixing before combustion initiation. Furthermore, 2-EHN elevates the cetane index of the BMF30 mixture, shortening the ID period and improving combustion efficiency, thereby further curtailing HC emissions. These observations align with the existing literature, which highlights the role of cetane improvers in optimizing combustion dynamics and reducing unburned hydrocarbon output in compression-ignition engines [40].

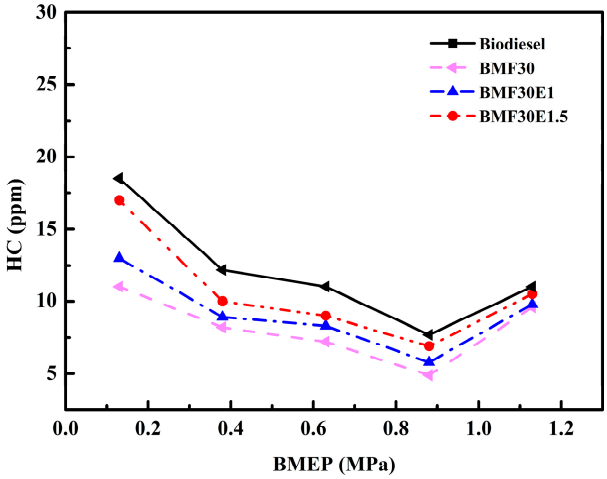



**Figure 6.** Effect of addition 2-EHN concentration on the HC emissions to BMF30 blend at different BMEP.

Figure 7 presents the impact of varying concentrations of 2-ethylhexyl nitrate (2-EHN) on carbon monoxide (CO) emissions for the BMF30 fuel blend at different engine loads. At BMEP of 0.13 MPa, all tested fuel showed elevated CO emissions, which can be attributed to reduce in-cylinder pressures and temperatures, leading to incomplete combustion [51]. As the BMEP increased from 0.13 to 0.38 MPa, a notable reduction in CO emissions was observed, primarily due to the rise in in-cylinder temperatures, which facilitated more complete combustion. Nevertheless, the BMF30 blend consistently produced higher CO emissions than pure biodiesel throughout this load range. This discrepancy can be attributed to three main factors: (1) the furan-ring oxygen in 2-MF is released more gradually than the ester-bound oxygen in biodiesel, which delays CO oxidation; (2) its higher volatility (boiling point ~64 °C compared to biodiesel's ~350 °C) induces the formation of fuel-lean zones during low-load operation; and (3) the lower cetane number of the BMF30 blend (CN ≈ 35 vs. ~46 for pure biodiesel) extends the ignition delay (ID), resulting in incomplete combustion. These effects are further amplified at lighter loads, where naturally lower temperatures hinder the conversion of CO-to-$CO_2$. However, at higher loads, the increased combustion temperatures overcome these limitations, allowing the oxygen content in the blend to fully enhance combustion efficiency, thereby reducing CO emissions. The fuel blends doped with 2-EHN, labeled as BMF30E1 and BMF30E1.5, demonstrated significant reductions in CO emissions, achieving decreases of 45.1% and 85.5%, respectively. This reduction can be attributed to the enhanced combustion characteristics imparted by the addition of 2-EHN, which elevates the CN of the blend, shortens the ID period, and facilitates the chain reaction initiation within the fuel mixture. Moreover, 2-EHN contributes to an increase in the oxygen content of the fuel, thereby fostering more complete combustion of hydrocarbons. Collectively, these improvements in combustion dynamics lead to a notable reduction in CO formation and, consequently, lower CO emissions [40]. At moderate engine loads, CO emissions were found to be minimal for all fuels tested, owing to sufficient oxygen supply and elevated combustion temperatures, which enabled the complete oxidation of CO. However, as the engine load increased to 1.13 MPa BMEP, the equivalence ratio also increased, resulting in a reduction of local oxygen concentrations within the combustion chamber. This decline in available oxygen led to an increase in CO emissions across all fuel types.

Figure 8 demonstrates the influence of 2-EHN on soot emissions across varying engine loads. Among the tested fuels, neat biodiesel exhibits higher soot emissions compared to BMF30 blends (including 2-EHN modified variants) due to several inherent physicochemi-

cal properties. The terminal positioning of oxygen in biodiesel's ester groups (-$COOCH_3$) limits its effectiveness in suppressing soot formation during pyrolysis [52], whereas 2-MF heterocyclic oxygen actively participates in radical quenching throughout combustion [53]. Biodiesel's long aliphatic chains (C16–C18) readily polymerize into polycyclic aromatic hydrocarbons, while 2-MF within the blend disrupts soot growth pathways. Additionally, biodiesel's higher viscosity (4.24 $mm^2/s$) impairs atomization, promoting fuel-rich zones and pool fires that enhance soot nucleation [54]. The BMF30 blend's lower CN extends ID period, improving air-fuel mixing and reducing diffusion flame dominance—the primary soot production regime. This suggests that the cetane number (CN) and ID period of BMF30 are key factors responsible for the observed reduction in soot emissions compared to biodiesel [55]. In 2-EHN modified blends, the additive further suppresses soot through radical donation ($NO_2$) that oxidizes precursors and shortened combustion duration that limits soot growth time. Previous research has shown that the presence of oxygen in the fuel plays a significant role in reducing soot emissions by enhancing combustion completeness [56]. As shown in Figure 8, the BMF30E1 and BMF30E1.5 blends achieved the lowest soot emissions. This reduction is primarily attributed to the positive effects of 2-EHN on the fuel's properties. The addition of 2-EHN enhances fuel atomization and fuel-air mixing, which improves combustion efficiency, reduces incomplete combustion, and minimizes soot formation.

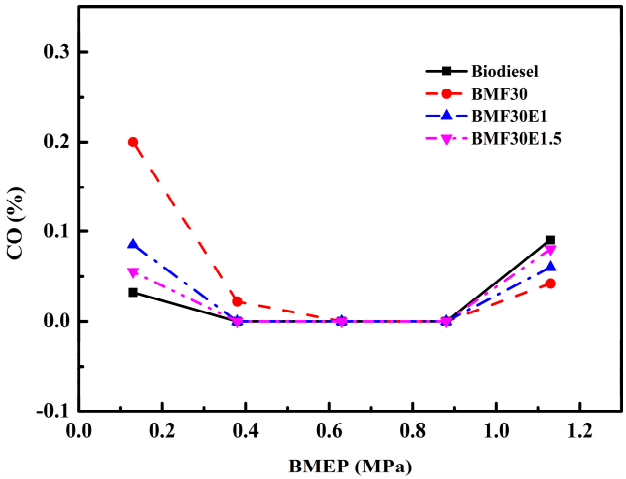



**Figure 7.** Impact of addition of 2-EHN concentration on the CO emissions to BMF30 blend at different BMEP.

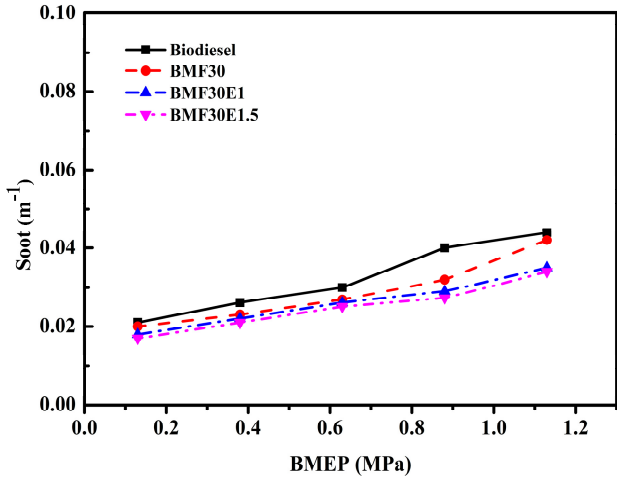



**Figure 8.** Effect of addition 2-EHN concentration on the soot emissions to BMF30 blend at different BMEP.

## 4. Conclusions

This study investigated the effect of incorporating 1% and 1.5% 2-ethylhexyl nitrate (2-EHN) into a 30% 2-methylfuran–biodiesel (BMF30) blend, focusing on combustion behavior, fuel efficiency, and exhaust emissions in a modified direct-injection diesel engine under varied load conditions.

Compared to pure biodiesel, the BMF30 blend exhibited a longer ignition delay (ID) and higher in-cylinder pressure. However, the addition of 2-EHN, particularly at a 1.5% concentration, effectively mitigated these effects. Both ID and peak pressure values approached those of pure biodiesel, confirming the cetane-enhancing effectiveness of 2-EHN. These results demonstrate that cetane number improvement is a viable strategy to enhance the combustion characteristics of low-cetane biofuels.

In terms of fuel economy, 2-EHN addition led to reductions in brake-specific fuel consumption (BSFC) by 5.34% and 7.25% for 1% and 1.5% blends, respectively, along with a notable increase in brake thermal efficiency (BTE). These gains highlight the importance of tailored cetane number tuning in overcoming energy losses associated with low-calorific-value biofuels. The results encourage further exploration of cetane improvers and their synergy with oxygenated fuels to optimize efficiency without increasing system complexity or cost.

Emissions analysis confirmed that the BMF30–2-EHN blends led to substantial reductions in CO and HC emissions—by up to 85.5% and 24.9%, respectively—due to more complete combustion and enhanced ignition characteristics. While CO and HC initially decreased with engine load, they rose again at BMEP = 0.88 MPa, suggesting oxygen depletion under rich conditions. NOx emissions, often a concern with high-temperature combustion of oxygenated fuels, were also reduced by 9.40–17.48% in the presence of 2-EHN. This suggests that the shortened ID and earlier radical formation associated with cetane improvement can offset the NOx-promoting effects of 2-methylfuran. Detailed chemical kinetics modeling is recommended in future work to further investigate the mechanisms behind this suppression and define optimal conditions.

Soot emissions, already reduced in BMF30 due to the intrinsic oxygen content of 2-MF, were further decreased with 2-EHN addition. This improvement is likely a result of enhanced atomization and faster ignition, which together promote more complete combustion. Future investigations should include in-cylinder imaging and spray structure analysis to map soot formation and oxidation zones under varying load and injection conditions.

These findings confirm that adding 2-EHN to BMF30 blends is an effective strategy to enhance ignition quality, improve thermal efficiency, and reduce key pollutant emissions in diesel engines. The study provides strong experimental evidence supporting the viability of biodiesel–MF blends with cetane improvers as a cleaner, high-performance alternative for compression ignition engines. However, the use of 2-EHN was also associated with slightly longer combustion duration at higher concentrations and potential increases in unburned emissions under full-load conditions. Future work should therefore explore long-term engine behavior, cold-start performance, and durability under real-world operating conditions to validate the sustainability of these benefits.

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