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Impact of diethyl ether on emissions of groundnut soapstock biodiesel-diesel blends in a VCR engine

S S Ragit[1], Rachan Karmakar[2*], Debasis Mitra[3], Krishnendu Kundu[4], Vijay Tripathi[3,5*]
[1]Department of Mechanical Engineering, Mahesh Institute of Engineering and Technology, Nagpur, Maharashtra, India.
[2]Departments of Environmental Science, Graphic Era (Deemed to be University), 566/6 Bell Road, Clement Town, Dehradun-248002, Uttarakhand, India; rachan.in.air@gmail.com (R.K.).
[3]Departments of Microbiology, Graphic Era (Deemed to be University), 566/6 Bell Road, Clement Town, Dehradun-248002, Uttarakhand, India; vijaytripathi84@gmail.com (V.T.).
[4]Department of Biofuel, Centre of Excellence for Farm Machinery (CSIR CMERI), Ludhiana, Punjab, India.
[5]Department of Molecular and Cellular Engineering, Jacob Institute of Biotechnology and Bioengineering, Sam Higginbottom University of Agriculture Technology and Sciences, Prayagraj, Uttar Pradesh, India.

Abstract: Growing concerns over diesel engine emissions have increased interest in cleaner and more sustainable fuel blends. This study aimed to evaluate the emission behavior of diethyl ether (DEE) when blended with groundnut soapstock oil methyl ester (GSOME) and diesel fuel in a variable compression ratio (VCR) engine. Experimental investigations were conducted using pure diesel and three GSOME–DEE blended fuels at compression ratios of 14:1, 16:1, and 18:1, while maintaining a constant engine speed of 1500 rpm under varying load conditions. Emissions of nitrogen oxides, carbon monoxide, and unburned hydrocarbons were measured and analyzed. The results indicated that the D80GSOME10-DEE10 blend exhibited the most favorable emission performance among the tested fuels. At full load, this blend achieved significant reductions in NO_x and CO emissions compared to diesel across all compression ratios, with the highest reductions observed at 18:1. However, an increase in hydrocarbon emissions was also recorded, attributed to rapid fuel vaporization and localized quenching effects. Overall, the study concludes that GSOME–DEE blends, particularly at optimized ratios, can serve as a viable alternative fuel. These findings support the use of DEE-assisted biodiesel blends for emission reduction strategies in VCR diesel engines.

Keywords: *Biofuel optimization, Combustion efficiency, Emission mitigation, Exhaust after-treatment, Renewable energy sources.*

1. Introduction

The incorporation of fuel additives into biodiesel has attracted significant attention as an effective strategy to enhance engine durability, operational performance, and fuel efficiency. These additives are often used in biodiesel formulations for compression ignition (CI) engines to improve combustion dynamics, reduce pollutant emissions, and refine fuel properties. Among various additives, diethyl ether (DEE) is notable for its high cetane number, excellent volatility, and low self-ignition threshold, all of which promote faster combustion and cleaner exhaust gases.

In light of growing concerns about the depletion of fossil energy resources and increasingly strict environmental regulations, the importance of alternative fuels and performance-boosting additives like DEE has increased. DEE contributes to more complete combustion by reducing ignition lag and improving air-fuel mixing, making it a valuable addition to biodiesel blends.

Extensive research has been conducted to evaluate DEE's influence when blended with biodiesel sourced from different origins. For example, a study by Prasada Rao and Appa Rao [1] analyzed the behavior of Mahua Methyl Esters (MME) when mixed with various DEE percentages [1]. Their

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* Correspondence: rachan.in.air@gmail.com

results indicated that a blend containing 10% DEE provided optimal performance, demonstrating better thermal efficiency, lower brake-specific fuel consumption, and notable reductions in carbon dioxide, nitrogen oxides (NO_x), and smoke emissions. Similarly, Iranmanesh et al. [2] investigated blends of Karanja Oil Methyl Ester (KOME) with DEE at concentrations of 5%, 10%, 15%, and 20% [2]. Their findings revealed that while smoke levels decreased slightly, NO_x emissions showed a significant drop when DEE content exceeded 10%. In another study, Selvaraj and Thangavel [3] evaluated mixtures of diesel fuel, waste cooking oil methyl ester (FM), and DEE [3]. They observed that lower DEE concentrations contributed to reductions in carbon monoxide (CO) and unburned hydrocarbon (HC) emissions. However, NO_x emissions tended to increase with higher DEE percentages. Sezer [4] offered a broader review of DEE's function in diesel fuel applications, concluding that DEE plays a significant role in lowering CO output [4]. Meanwhile, Subramanian and Ramesh [5] reported that DEE-diesel combinations enhanced brake thermal efficiency under heavy engine loads and consistently lowered both smoke density and CO emissions Subramanian and Ramesh [5]. Anand and Mahalakshmi [6] also found that combining DEE (10–30%) with 5% exhaust gas recirculation (EGR) effectively reduced both NO_x and smoke emissions [6]. However, some studies observed slight increases in CO emissions at certain DEE levels due to incomplete combustion in lean mixtures, Singh et al. [7], Karmakar et al. [8] and Karmakar R. [9]. Madhu et al. [10] similarly reported that DEE-diesel blends containing 5% and 15% DEE led to 3% and 8% increases in CO emissions, respectively Madhu et al. [10]. Prasad Rao and Haribabu [11] concluded that most biodiesel-DEE blends emitted less CO than diesel alone at higher loads, thanks to the oxygen content in both DEE and biodiesel that promoted better combustion Prasad Rao and Haribabu [11]. Patnaik et al. [12] found that a DEE15 blend reduced CO emissions by as much as 62% compared to diesel at full load Patnaik et al. [12]. Sivalakshmi and Balusamy [13] observed a 25% reduction in CO emissions using a DEE5 blend, attributing this to enhanced fuel-air mixing and improved spray atomization [13]. According to Kumar et al. [14], CO emissions in CI engines are typically low due to the reliance on lean mixtures and higher air-fuel ratios [14].

Despite this extensive body of work, studies investigating DEE as an additive in Groundnut Soapstock Oil Methyl Ester (GSOME) fuel blends remain scarce. GSOME, produced via methyl esterification of groundnut soapstock, a by-product of vegetable oil refining, is an economically attractive and sustainable biodiesel source. It offers the dual advantages of waste valorization and reduced fuel costs, making it highly relevant for developing biofuels. However, the application of DEE in GSOME-based blends has been minimally explored [7].

This study investigates the effects of DEE concentrations (5%, 10%, and 15%) in GSOME-diesel blends, specifically D90GSOME5-DEE5, D80GSOME10-DEE10, and D70GSOME15-DEE15, on exhaust emissions (HC, CO, and NO_x). Engine tests are conducted at 1500 rpm with varying compression ratios (14:1, 16:1, and 18:1) and loads. The goal is to identify the optimal DEE content that produces the most favorable emission characteristics when blended with GSOME-diesel fuel.

Previous investigations into biodiesel and dual-fuel systems reveal notable variations in emission characteristics depending on fuel composition and combustion conditions (Table 1). Studies involving Mahua and Karanja methyl esters blended with diethyl ether (DEE) demonstrated a significant decrease in nitrogen oxide emissions at moderate additive levels, primarily due to DEE's ability to enhance fuel–air mixing and reduce ignition temperature [15]. Similarly, experiments with biogas and producer gas showed lower CO and NO_x emissions but increased unburned hydrocarbons, attributed to incomplete oxidation [15-17]. A comparable trend was observed where DEE improved CO oxidation while slightly raising hydrocarbon emissions due to accelerated fuel vaporization. Research on ethanol–diesel blends with aluminium-oxide nanoparticles and studies on Calophyllum inophyllum biodiesel confirmed that both compression ratio and load significantly influence emission performance [18].

Table 1.
Comparison between different biodiesels and biodiesel-diesel blends.

Fuel / Reference System	**Experimental or Additive Condition**	**Observed NO_x Behaviour**	**Observed CO Behaviour**	**Observed HC Behaviour**	**Technical Explanation**	**Relevance to Present GSOME–DEE Findings**	**Reference**
Mahua methyl ester with diethyl ether	Biodiesel blended with 5–15% DEE	Notable drop in NO_x at moderate DEE addition	Lower CO concentration	Slight rise in HC levels	Oxygen supplied by DEE improved oxidation; the latent heat effect reduced peak flame temperature.	The present work shows a similar decline in NO_x up to 10% DEE, although higher proportions increased it due to increased heat release.	Prasada Rao and Appa Rao [1] and Mohapatra et al. [15]
Karanja oil methyl ester with diethyl ether	Addition of 5–20% DEE	Decrease in NO_x beyond 10% DEE content	Reduction in CO output	Slight rise in HC levels	Better fuel–air mixing and milder combustion limit NO_x generation.	GSOME's higher heating value and lower viscosity caused faster combustion and slightly higher NO_x emissions.	Iranmanesh et al. [2] and Mohapatra et al. [16]
Biogas–diesel dual-fuel operation	Constant gas flow under varying engine loads	Lower NO_x than diesel	Drop in CO	Noticeable increase in HC	Lean operation reduced NO_x but caused incomplete fuel combustion.	Comparable HC rise found here; DEE, however, improved CO oxidation due to its oxygen-rich nature.	Mohapatra et al. [16] and Nayak et al. [17]
Producer gas–diesel dual-fuel system	Partial substitution of diesel with producer gas	Higher NO_x emissions	Decline in CO	Increase in HC	Hydrogen-rich gas raises in-cylinder temperature, leading to increased thermal NO_x.	GSOME–DEE shows a milder NO_x increase and greater CO reduction due to oxygenated DEE blending.	Nayak et al. [17]
Ethanol–diesel blend with Al_2O_3 nanoparticles	15 wt% ethanol with 25–75 ppm nanoparticles	Lowest NO_x at 50 ppm; increase at higher loading	Lower CO emission	Reduced HC formation	Nanoparticles improved combustion and heat transfer efficiency.	Optimum 10% DEE in GSOME–diesel showed comparable, balanced control of NO_x and CO.	Mishra et al. [18]
Calophyllum inophyllum biodiesel with producer gas	Load 4–12 kg, compression ratio 14–18	NO_x increased with engine load	CO declined at higher compression	HC rose with load	Load-governed NO_x behavior; blend composition affects CO and HC.	Similar pattern observed; higher CR (18:1) in GSOME–DEE blends helped limit NO_x at 10% DEE.	Mishra et al. [18]

2. Materials and Methods

2.1. Material

Groundnut soapstocks were collected from local oil refineries in Ludhiana, produced by acidulation of the feedstock. For the experimental procedure, catalysts including potassium hydroxide (KOH), methanol, and diethyl ether (DEE) were obtained from Sardar Lamichems Pvt. Ltd., Patiala, India.

2.2. Method

The Center of Excellence in Farm Machinery (CMERI-COEFM), CSIR Lab, located on Gill Road in Ludhiana, developed biodiesel from groundnut soapstock. This biodiesel was used as an oxygenated additive in a Diesel-GSOME blend. The study aimed to replace conventional diesel fuel with a Diesel-GSOME-DEE blend. Diethyl ether (DEE) was added at concentrations of 5%, 10%, and 15%, creating three fuel samples: D90GSOME5-DEE5, D80GSOME10-DEE10, and D70GSOME15-DEE15, representing their respective proportions of diesel, biodiesel (GSOME), and DEE. Before testing, each mixture was thoroughly agitated to ensure uniformity. Engine performance and emission tests were carried out at the Internal Combustion Engine Laboratory of Thapar Institute of Engineering & Technology, Patiala, using a variable compression ratio (VCR) diesel engine.

2.3. Fuel Properties

To evaluate the fuel characteristics, a series of instruments was employed, including a hydrometer for density measurement, a Redwood viscometer for viscosity assessment, apparatuses for determining cloud and pour points, flash and fire point testing equipment, and a bomb calorimeter for measuring calorific value [19, 20]. The study aimed to identify a cost-effective and environmentally sustainable alternative to conventional diesel by analyzing and comparing the properties of standard diesel, groundnut soapstock oil, and its methyl ester. Throughout the experimentation process, key physical and chemical attributes of diesel, diethyl ether (DEE), groundnut soapstock oil (GSO), and groundnut soapstock oil methyl ester (GSOME) were systematically measured, as presented in Table 2.

Table 2.
Physicochemical properties of Diesel, GSO, GSOME, and DEE (experimental value).

Parameters	**Instrument/ Method used**	**EN14214**	**ASTM D6751**	**GSO**	**GSOME**	**DEE**	**Diesel**
Density at 15 °C, kg/m^3	Pycnometer	860-900	-	922.17	880.2	713.4	820-860
FFA content, %	Titration	-	-	0.60	0.18	-	-
Kinematic viscosity (40°C) (cSt)	Redwood Viscometer	3.5-5.0	1.9-6.0	26.92	4.14	0.24	3.12
Flash point, °C	Flash and Fire point apparatus	>101	100-170	250.7	174	-45	>55
Fire point, °C		-	-	262	182	-	-
Cloud point, °C	Cloud and pour point apparatus	<3	-3-12	-7	-5	-	-16
Pour point, °C		-	-15-10	-4	-6	-	-33
CV(MJ/)	Bomb calorimeter	-	-	37.7	39.52	33.9	42.7
Water content (mg/kg)	Moisture meter	Maximum 500	-	390.8	202.50	-	-

2.4. Engine Set- Up and Procedure

The experimental arrangement used in the investigation is illustrated in Figures 1(a) and 21(b), with specific details of the equipment provided in Table 3. At the start of testing, the engine was filled with methyl ester extracted from bitter almond oil. It was then run at a constant speed of 1500 RPM without applying any load, maintaining this condition for approximately 20 to 30 minutes. This initial run allowed the engine to reach a uniform operating temperature, which was crucial before beginning any performance evaluations. The approach closely followed the procedure described by [21]. Subsequently, the emission characteristics were manually measured without a load. After establishing steady working conditions, observations were conducted, and the process was repeated with varying loads. Water circulation was maintained to keep the engine cool. Additionally, all experimental data were recorded and replicated at least three times to enhance precision and repeatability, with average values used for analysis.

Figure 1.
(a): VCR Engine.

Figure 1.
(b): AVL Di-gas Emission analyzer.

Table 3.
Specifications of the engine.

Parameter	**Details**
Engine Type	Variable Compression Ratio, Four-Stroke
Number of Cylinders	One (Single-Cylinder Configuration)
Displacement Volume	661 cubic centimeters
Cylinder Bore	87.5 Millimeters.
Piston Stroke Length	110 Millimeters.
Compression Ratio Range	Adjustable between 14:1 and 20:1
Rated Power Output	3.5 kilowatts at 1500 revolutions per minute
Load Measurement System	Eddy Current Dynamometer with Water Cooling
Performance Monitoring Software	"Engine Soft LV" Analysis Tool

Therefore, the summarized setup can be explained as follows (Figure 2). The experimental work was carried out using a single-cylinder, four-stroke variable compression ratio (VCR) diesel engine, with a displacement of 661 cm^3, a bore of 87.5 mm, and a stroke length of 110 mm. The engine operated at a rated power of 3.5 kW at 1500 RPM, with the compression ratio adjustable between 14:1 and 20:1. Fuel testing included pure diesel and three blends: 90% diesel with 5% GSOME and 5% DEE, 80% diesel with 10% GSOME and 10% DEE, and 70% diesel with 15% GSOME and 15% DEE. Engine performance was monitored using a water-cooled eddy current dynamometer integrated with "Engine soft LV" software. Exhaust emissions such as nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) were recorded under varying loads, from no-load to full-load conditions. To ensure consistent and reliable data, well-established calibration protocols and standardized emission testing procedures were carefully followed throughout the study. Emissions were measured using both a di-gas analyzer and a flue gas analyzer. The test results indicated that incorporating diethyl ether (DEE) slightly increased nitrogen oxide (NO_x) levels, especially under heavy engine loads, likely due to more complete combustion. In contrast, hydrocarbon (HC) emissions showed a moderate rise, which can be linked to DEE's higher latent heat, tending to hinder full combustion. Carbon monoxide (CO) emissions, however, were noticeably lower, attributed to DEE's oxygen-enriched composition and high cetane number, both of which promote cleaner combustion. Including a schematic or flowchart of the setup is advisable for better representation of the experimental layout and measurement systems.

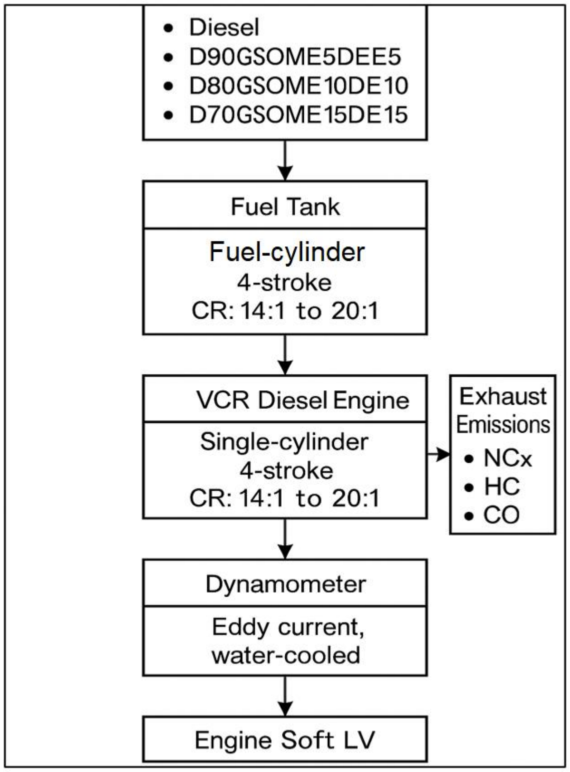

Figure 2.
Flow-diagram of the experimental setup.

3. Results and Discussion

3.1. Engine Exhaust Emissions

An experimental study was conducted using four different fuel blends in a VCR diesel engine: base diesel, D90GSOME5DEE5 (90% diesel + 5% GSOME + 5% DEE), D80GSOME10DEE10 (80% diesel + 10% GSOME + 10% DEE), and D70GSOME15DEE15 (70% diesel + 15% GSOME + 15% DEE). The engine's rated speed of 1500 rpm was used for testing, with brake power ranging from 0 kW to 3.5 kW. The emission characteristics of all gasoline blends were examined in the laboratory. During testing, NOx, HC, and CO exhaust emissions were calculated, and each emission parameter was thoroughly analyzed in subsequent sections.

3.2. NO_x Emissions

Figures 3, 4, and 5 demonstrate the variation in nitrogen oxide (NO_x) emissions as a function of engine load from biodiesel blends employing DEE (GSOME5%DEE5%, GSOME10%DEE10%, and GSOME15%DEE15%) in contrast with diesel fuel at different compression ratios. Figure 4 indicates that the GSOME15%DEE15% blend at a 14:1 compression ratio has the highest NO_x value, 193 ppm. This value exceeds the NO_x emissions from pure diesel fuel and other biodiesel mixes, such as GSOME5%DEE5% and GSOME10%DEE10%. The NO_x emissions for diesel, GSOME5%-DEE5%, GSOME10%-DEE10%, and GSOME15%-DEE15% were 187, 179, 172, and 193 ppm at full load and a 14:1 compression ratio, respectively. Under full load, the NO_x emissions for the same mixtures were 167, 162, 155, and 173 ppm, respectively, at a compression ratio of 16:1. Similarly, the NO_x emissions for these mixes were 148, 135, 131, and 164 ppm, respectively, with a compression ratio of 18:1 under full load. Compared with pure diesel fuel, the NO_x emissions from the GSOME and DEE mixes were consistently higher. Because DEE has a higher latent heat of evaporation, it facilitates more thorough combustion at lower temperatures, which slightly decreases NO_x emissions when added. However, at the maximum DEE concentration (DEE15), NO_x emissions improved somewhat across all compression ratios, ranging from 3.21% to 10.81%. As more fuel is burned at higher loads, combustion is enhanced, and the engine's cylinder temperature rises, increasing NO_x production. The rise in NO_x emissions under higher engine load conditions can be mainly attributed to elevated combustion temperatures. Conversely, blending diethyl ether (DEE) with gasoline enhances fuel evaporation and lowers the intake charge temperature. This cooling effect helps suppress peak combustion temperatures, ultimately leading to a noticeable reduction in NO_x formation.

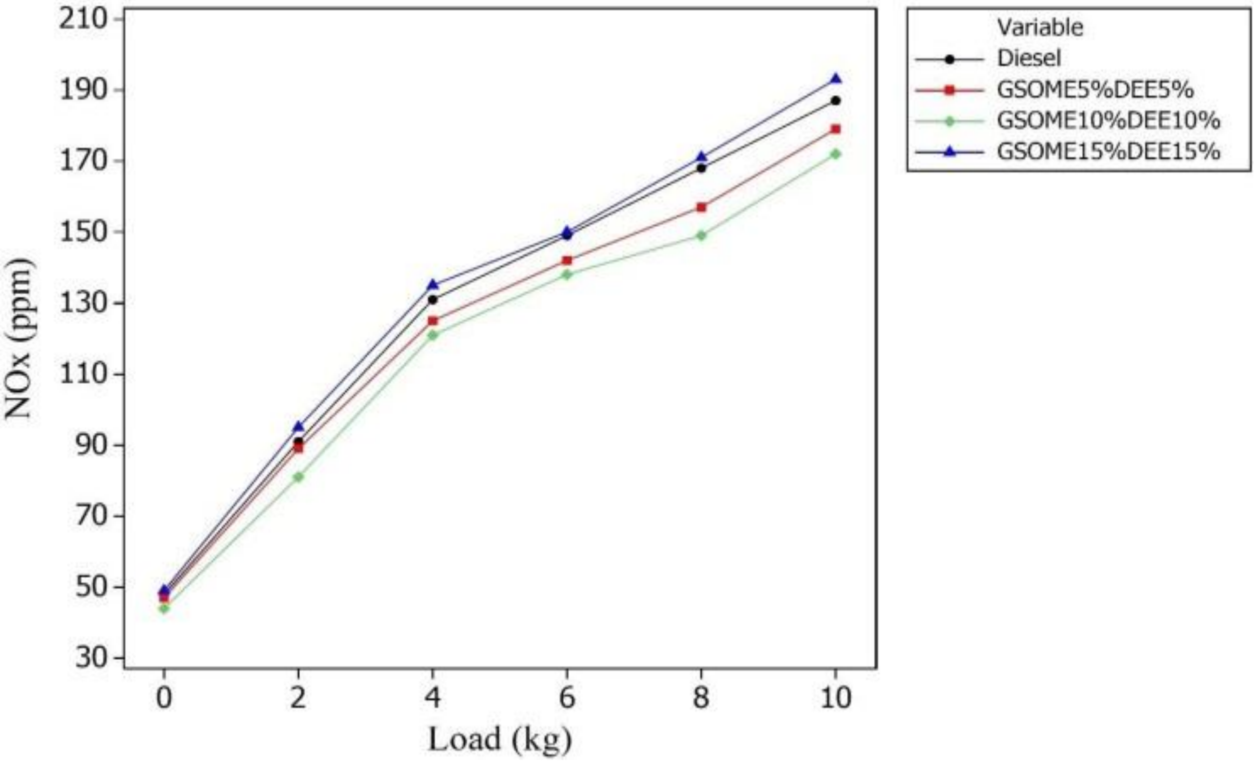

Figure 3.
Trend of NO_x Emissions Across Different Loads for GSOME-DEE Blends and Conventional Diesel at a Compression Ratio of 14:1.

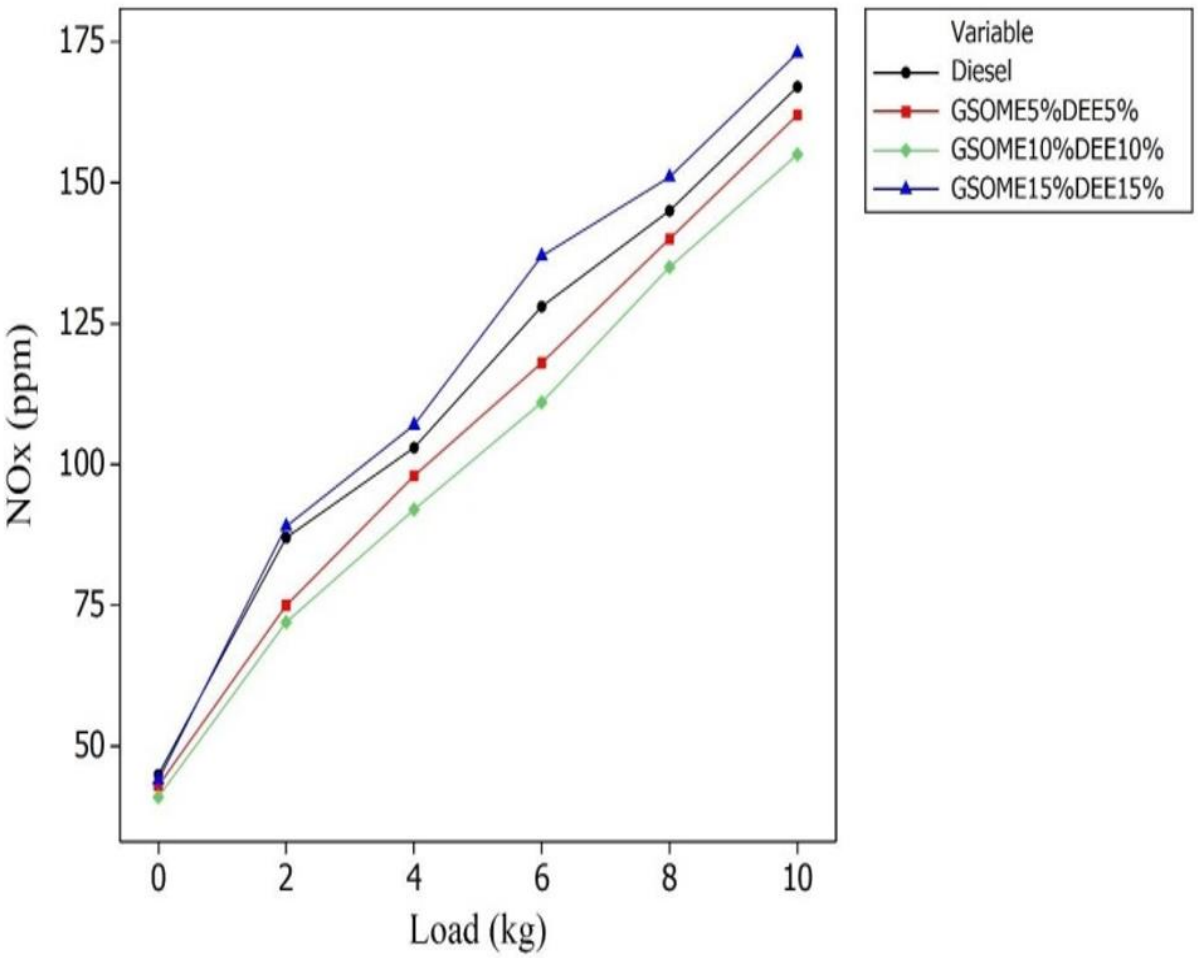

Figure 4.
NO_x Emission Behavior of GSOME-DEE Mixtures Compared to Diesel Across Varying Load Conditions at a Compression Ratio of 16:1.

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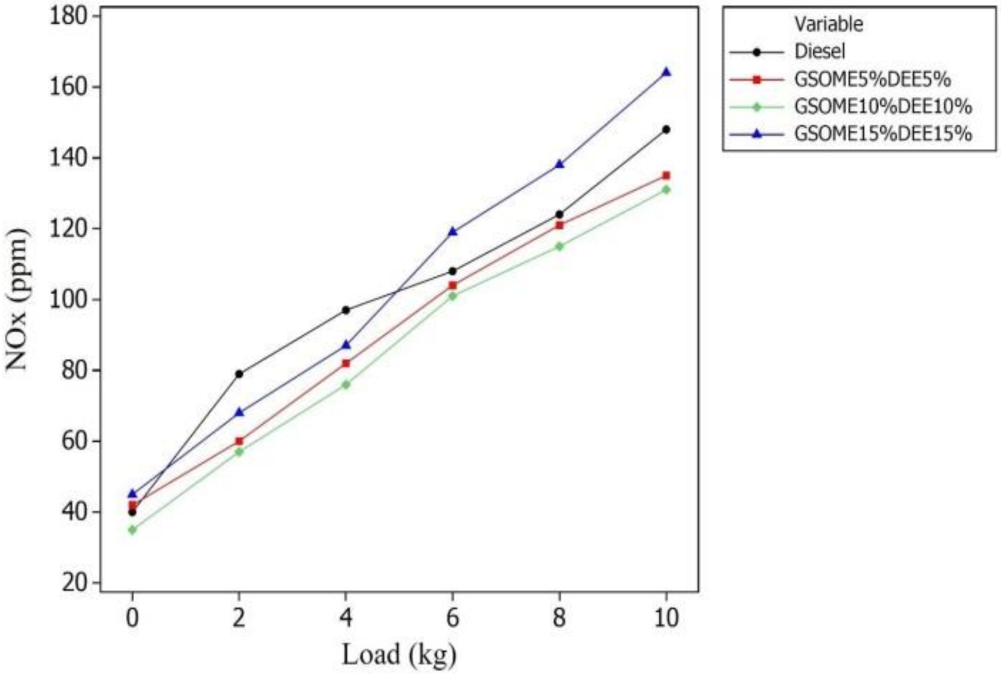

Figure 5.
Comparative Analysis of NO_x Emissions from GSOME-DEE Blends and Standard Diesel Under Different Load Conditions at a Compression Ratio of 18:1.

3.3. HC Emissions

Figures 6 through 8 illustrate how hydrocarbon (HC) emissions respond to increasing engine load when using biodiesel blends enhanced with diethyl ether (DEE). The tested fuel combinations include GSOME5%-DEE5%, GSOME10%-DEE10%, and GSOME15%-DEE15%, which are compared against pure diesel fuel across different compression ratios. Hydrocarbon emissions are primarily linked to incomplete fuel combustion, which leaves unburned fuel particles in the exhaust. At a compression ratio of 14:1 under full engine load, HC emission levels were approximately 1124 ppm for conventional diesel (D100), 1299 ppm for the GSOME5%-DEE5% blend, 1524 ppm for GSOME10%-DEE10%, and 1397 ppm for the GSOME15%-DEE15% blend. Under full loading, HC emissions for the same blends were 1016, 1185, 1225, and 1219 ppm at a compression ratio of 16:1. At a compression ratio of 18:1 under full load, emissions were 899, 1241, 1301, and 1262 ppm. For all fuel blends, HC emissions increased as engine load increased. HC emissions improved when DEE was introduced into diesel and biodiesel blends. This increase is explained by slower evaporation and air-fuel mixing caused by DEE's higher latent heat of vaporization. Limited oxygen supply also contributes to incomplete combustion under full-load conditions, further increasing HC emissions. A noticeable rise in hydrocarbon emissions occurs when diethyl ether is used in the fuel mix. However, this can be reduced by fine-tuning injection timing to promote more complete fuel oxidation. Controlled exhaust gas recirculation helps maintain appropriate in-cylinder temperatures, and adding small amounts of oxygen-bearing or catalytic agents can further assist in burning unoxidized hydrocarbons.

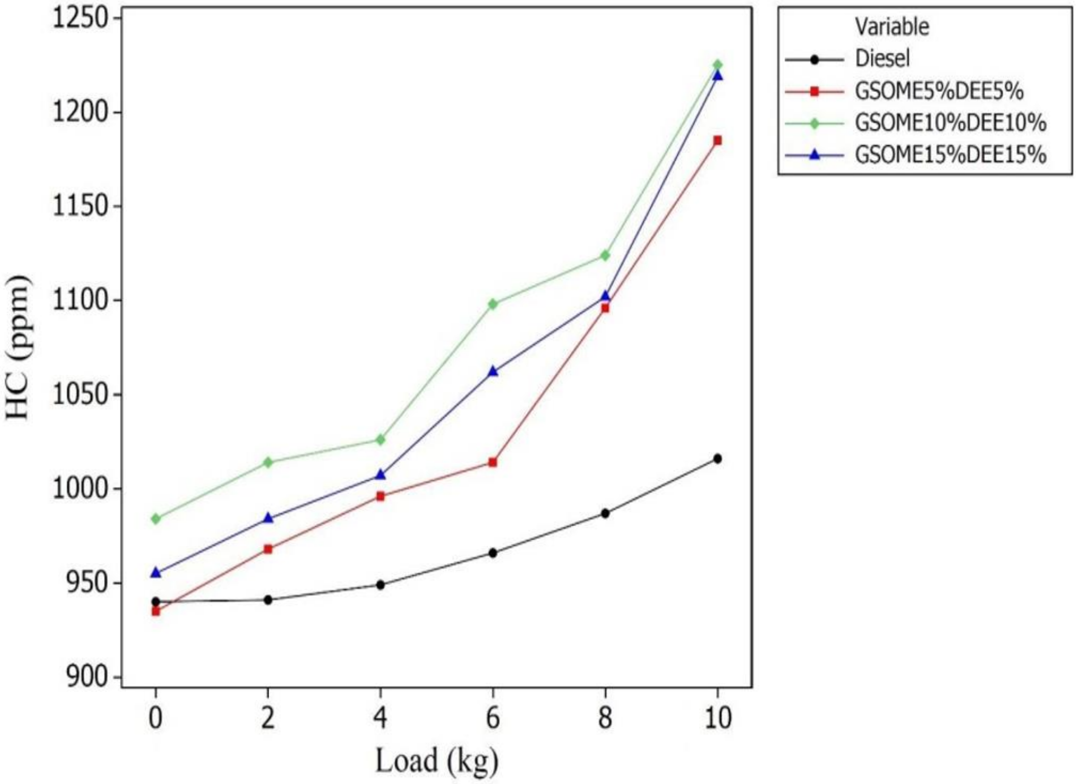

Figure 6.
Load-Dependent Changes in Hydrocarbon Emissions for GSOME-DEE Blends Compared to Diesel Fuel at a Compression Ratio of 14:1.

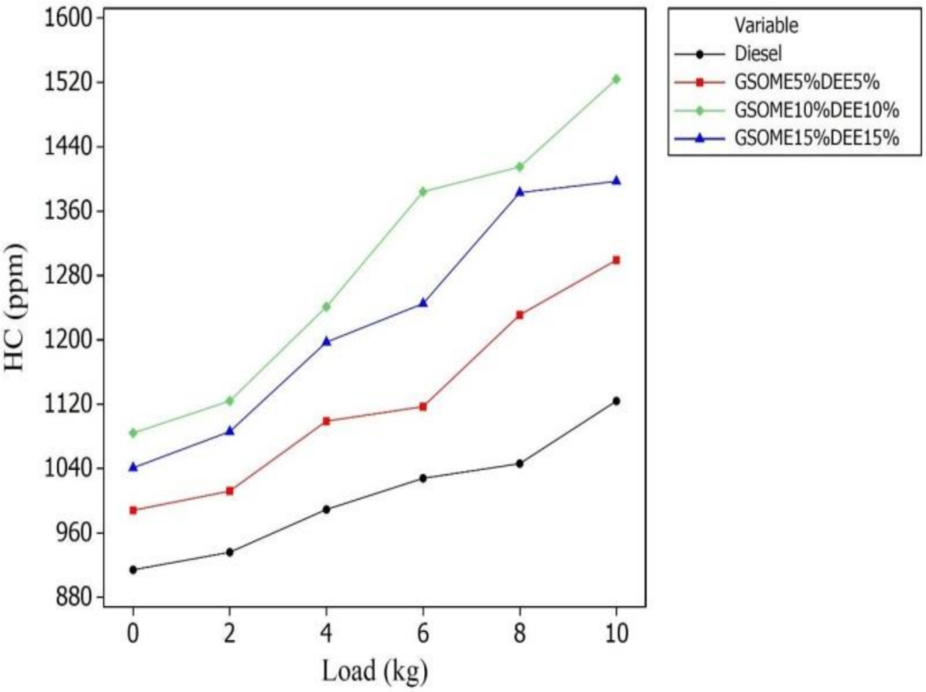

Figure 7.
Comparative Assessment of Hydrocarbon Emissions from GSOME-DEE Fuel Mixtures and Diesel Under Varying Load Conditions at a Compression Ratio of 16:1.

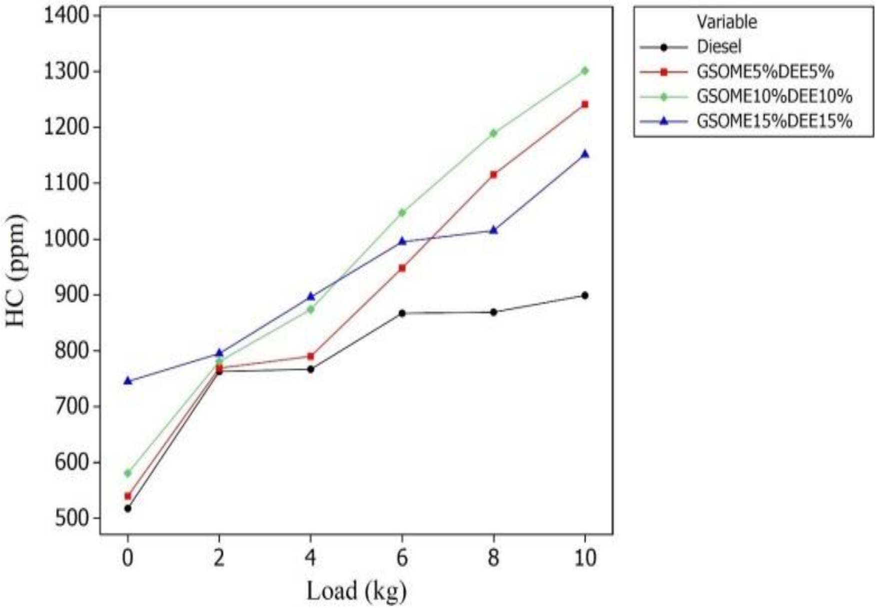

Figure 8.
Hydrocarbon Emission Trends of GSOME-DEE Blended Fuels Versus Conventional Diesel at Different Engine Loads and a Compression Ratio of 18:1.

3.4. CO Emissions

As a function of engine load at different compression ratios, Figures 9, 10, and 11 show the changes in carbon monoxide (CO) emissions from blends with DEE additives (GSOME5%-DEE5%, GSOME10%-DEE10%, and GSOME15%-DEE15%) compared to diesel fuel. As the percentage of biodiesel increased, CO emissions decreased. This reduction is explained by the higher in-built O_2 content of the biodiesel-DEE blends, which promotes combustion quality and increases brake thermal efficiency. From no load to full load conditions, the GSOME10%DEE10% blend had the lowest average CO emissions (385.33 ppm) at an 18:1 compression ratio. For all fuel mixes, the graphs illustrate a steady decrease in CO emissions as engine brake power rises. Additionally, larger DEE fractions in the Diesel-GSOME-DEE mixes led to lower CO emissions because DEE contains oxygen, which accelerates the combustion of the GSOME blend. Since DEE includes more oxygen, more oxygen is available in the cylinder, minimizing CO emissions. Moreover, DEE's high cetane number contributed to a decline in CO emissions by improving combustion efficiency and reducing burning time.

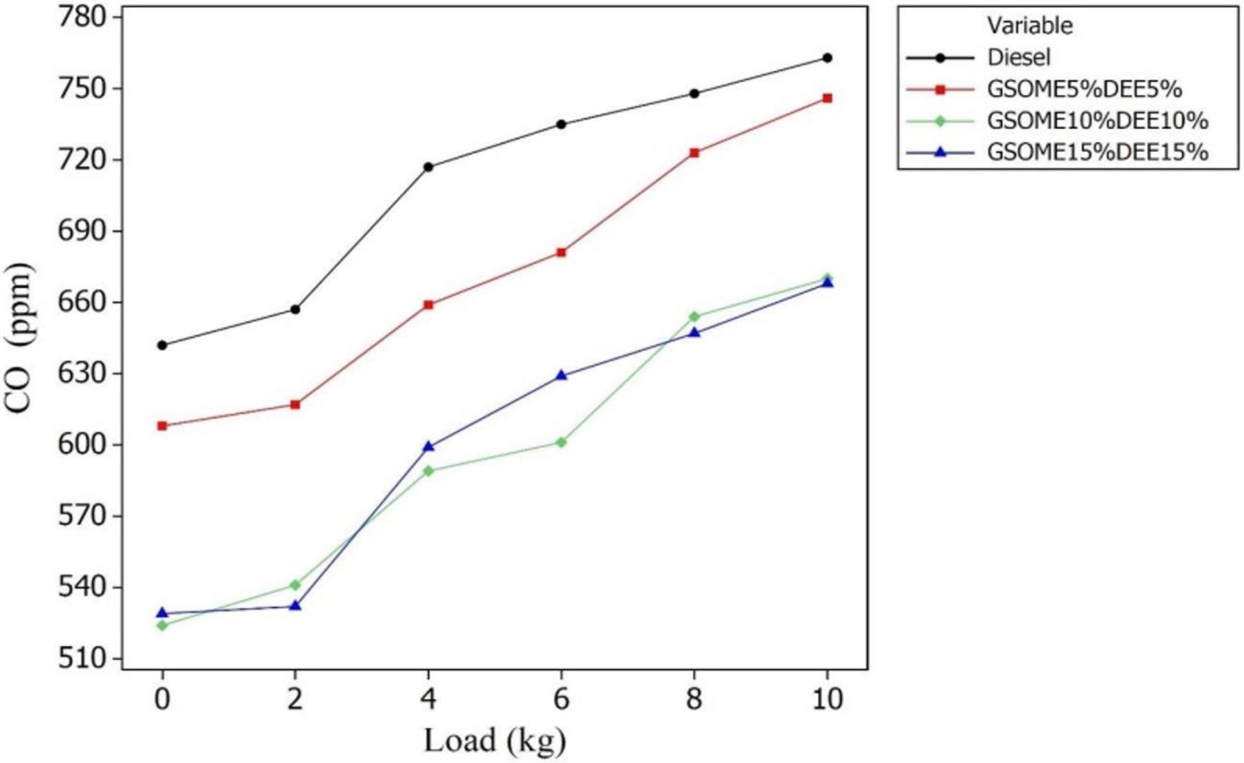

Figure 9.
Analysis of Carbon Monoxide Emissions from GSOME-DEE Fuel Combinations and Diesel Under Varying Engine Loads at a Compression Ratio of 14:1.

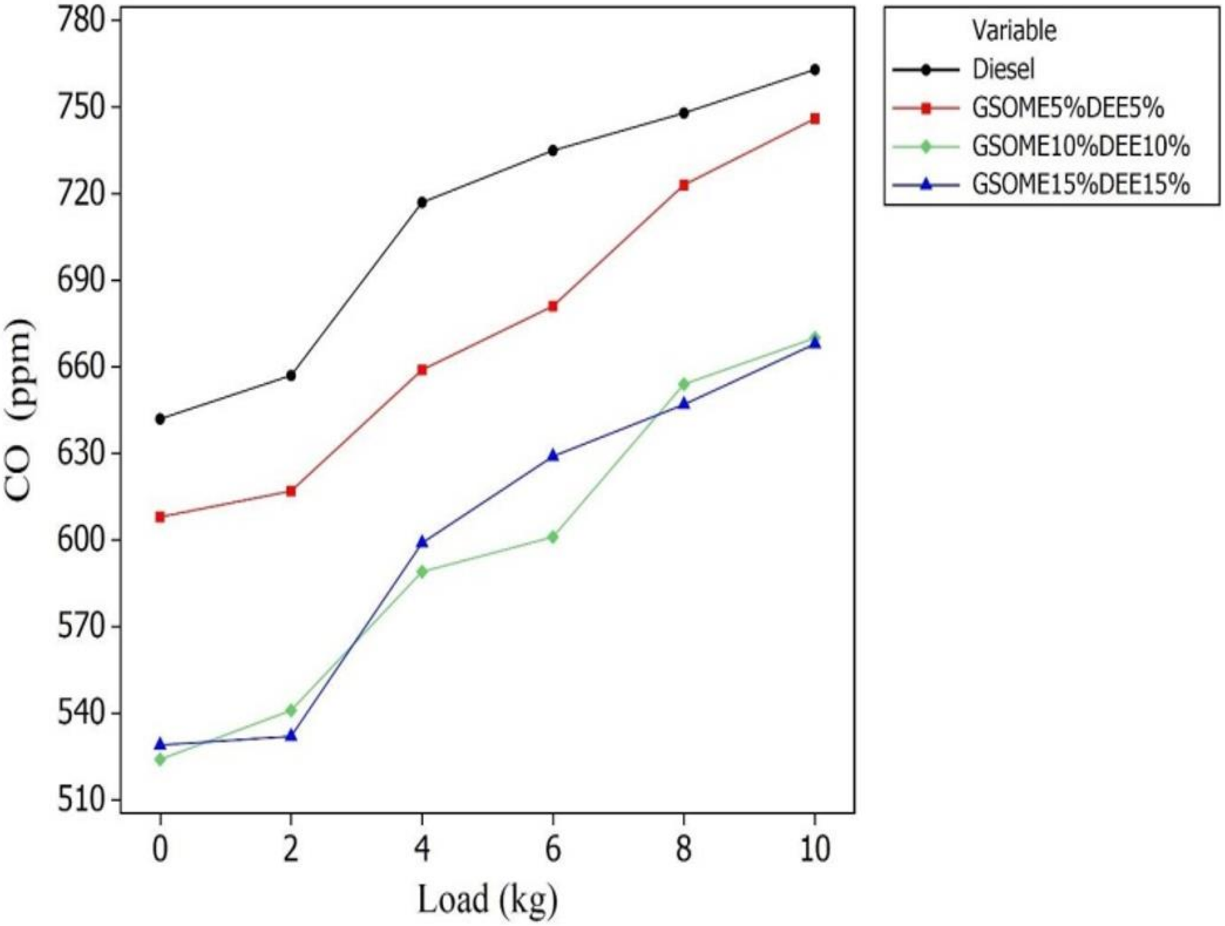

Figure 10.
Load-Based Evaluation of Carbon Monoxide Emissions for GSOME-DEE Blends Compared to Diesel Fuel at a Compression Ratio of 16:1.

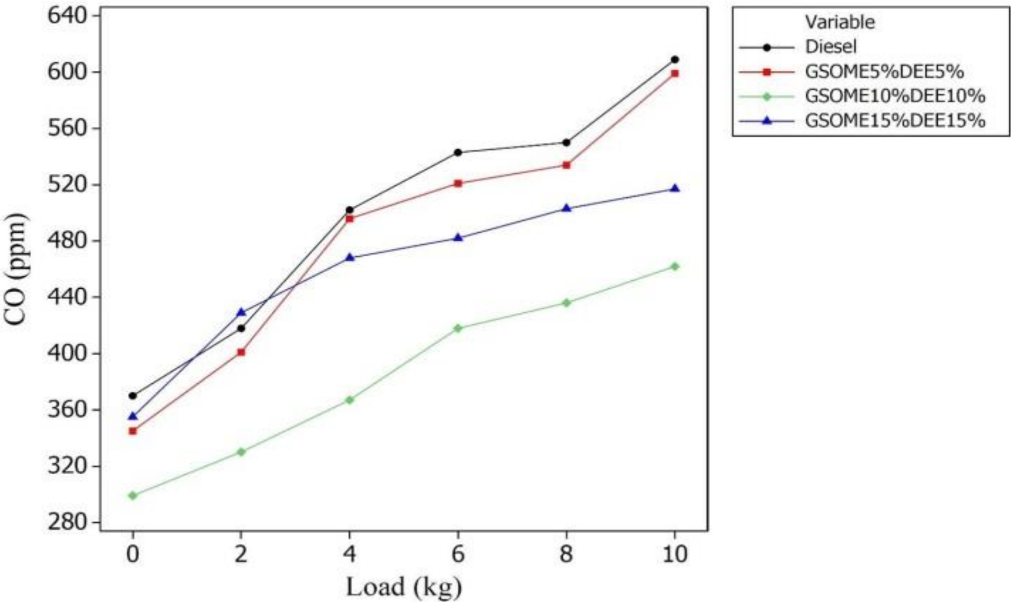

Figure 11.
Comparative Study of Carbon Monoxide Emissions from GSOME-DEE Blended Fuels and Conventional Diesel Across Various Load Conditions at a Compression Ratio of 18:1.

The comparative graphs ((Figure 12, Figure 13 and Figure 14) for CO, HC and NO$_x$ emissions across varying compression ratios (14:1, 16:1, and 18:1) and fuel blends clearly demonstrate that incorporating DEE (diethyl ether) into diesel-biodiesel mixtures significantly reduces CO emissions, particularly at higher DEE concentrations and compression ratios (Table 4, Table 5 and Table 6). At all compression ratios, diesel (D100) exhibits the highest CO emissions, followed by D90GSOME5DEE5. D80GSOME10DEE10 and D70GSOME15DEE15 show noticeably lower values, with D80GSOME10DEE10 achieving the lowest emissions at full load under CR 18:1 (480 ppm). The reduction in CO emissions with increasing DEE content is primarily due to DEE's high oxygen content, which enhances the oxidation of carbon monoxide into carbon dioxide, promoting more complete combustion. Additionally, DEE has a high cetane number, shortening ignition delay and leading to smoother, more efficient combustion. Its high volatility and latent heat of vaporization also aid in better air-fuel mixing and cooling of the intake charge, lowering peak combustion temperatures and reducing incomplete combustion products like CO. As the compression ratio increases, combustion becomes more efficient, amplifying the emission-reducing effects of DEE and resulting in a cleaner exhaust profile. The graphical trends from the data show how different compression ratios and biodiesel fuel blends influence engine emission characteristics. Regarding nitrogen oxides (NOx), a consistent decline is observed as the compression ratio increases, especially for most biodiesel-diesel mixtures.

The data suggests that increasing the compression ratio generally reduces NOx emissions. Among the tested fuel blends, D90GSOME5DEE5 and D80GSOME10DEE10 consistently showed lower NOx output than standard diesel fuel (D100). Interestingly, this trend does not apply to D70GSOME15DEE15, which tends to produce higher NOx levels, especially at higher compression ratios.

In contrast, the behavior of hydrocarbon (HC) and carbon monoxide (CO) emissions differs noticeably. HC emissions typically increase when biodiesel blends are used, particularly at elevated compression ratios, likely due to incomplete combustion under those conditions. CO emissions, however, show a downward trend with biodiesel use, with the D80GSOME10-DEE10 blend providing the most significant reduction. Additionally, increasing the compression ratio helps lower CO emissions across all tested fuels.

These patterns underscore a complex trade-off in engine performance: while certain biodiesel blends can effectively reduce specific emissions like CO and, to a lesser extent, NOx, they may inadvertently cause an increase in unburned hydrocarbons. This highlights the need to balance blend composition and engine settings to optimize overall emission profiles.

Table 4.
NO_x Emissions (ppm) from Biodiesel blends and petrodiesel.

Compression Ratio	Diesel (D100)	D90GSOME5DEE5	D80GSOME10DEE10	D70GSOME15DEE15
14:1	187	179	172	**193**
16:1	167	162	155	**173**
18:1	148	135	131	**164**

Table 5.
HC Emissions (ppm) from Biodiesel blends and petrodiesel.

Compression Ratio	Diesel (D100)	D90GSOME5DEE5	D80GSOME10DEE10	D70GSOME15DEE15
14:1	1124	1299	**1524**	1397
16:1	1016	1185	**1225**	1219
18:1	899	1241	**1301**	1262

Table 6.
CO Emissions (ppm) from Biodiesel blends and petrodiesel.

Compression Ratio	Diesel (D100)	D90GSOME5DEE5	D80GSOME10DEE10	D70GSOME15DEE15
14:1	**755**	715	662	660
16:1	**750**	705	654	657
18:1	**600**	560	**480**	520

The emission data trends clearly indicate that both the compression ratio and biodiesel blend composition significantly influence engine exhaust characteristics (Tables 7, 8, 9). Generally, nitrogen oxide (NO_x) emissions tend to decrease as the compression ratio increases, especially for most biodiesel-diesel blends. This suggests that higher compression ratios may create conditions that suppress NO_x formation. Blends such as D90GSOME5DEE5 and D80GSOME10DEE10 often produce lower NO_x levels than standard diesel (D100). However, the D70GSOME15DEE15 blend deviates from this trend, frequently showing increased NO_x emissions at higher compression ratios.

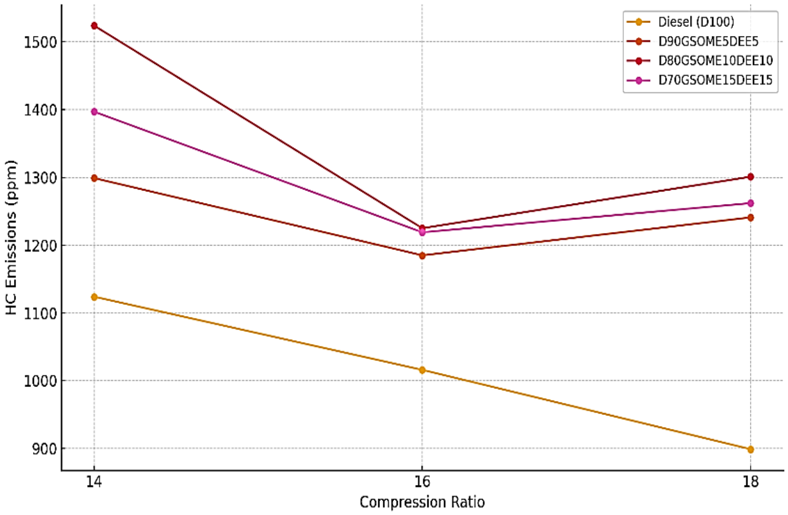

Figure 12.
Variation of hydrocarbon emissions for GSOME-DEE Blends Compared to Diesel Fuel with varying compression ratios.

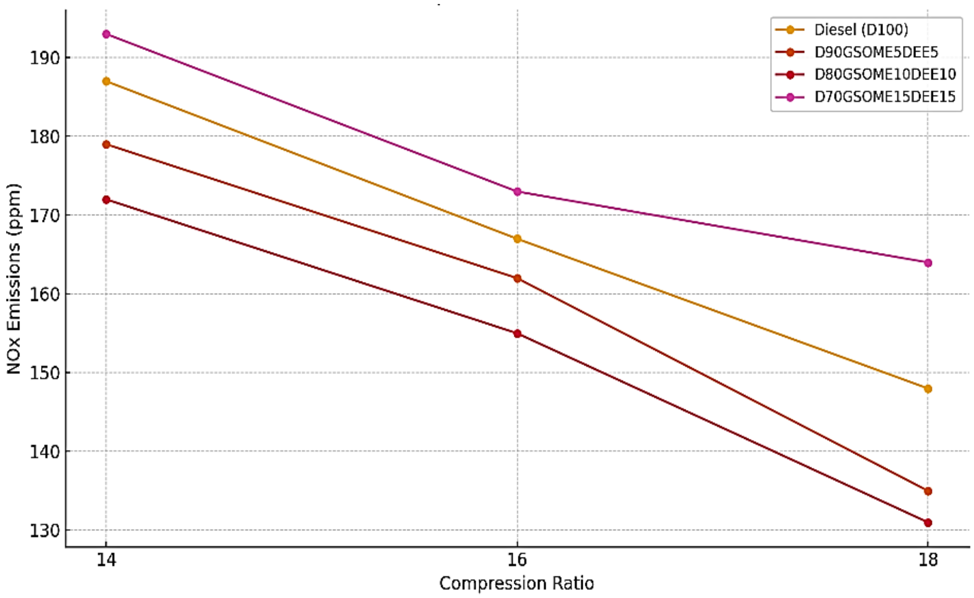

Figure 13.
NO_x emissions for GSOME-DEE Blends Compared to Diesel Fuel with different compression ratios.

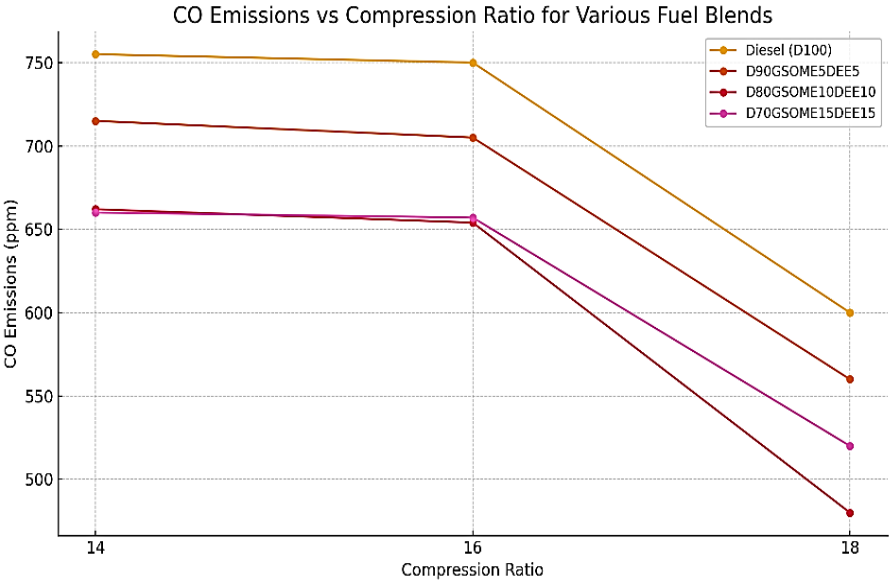

Figure 14.
Carbon monoxide emissions were measured across varying compression ratios for each fuel blend.

When examining hydrocarbon (HC) and carbon monoxide (CO) emissions, a distinct trend becomes apparent. HC emissions tend to increase when biodiesel blends are used, particularly at higher compression ratios, which may indicate that combustion is not fully complete with these fuels. In contrast, CO emissions generally decrease with the introduction of biodiesel, with the blend D80GSOME10DEE10 showing the greatest reduction. Additionally, increasing the compression ratio helps reduce CO emissions across all tested fuel types.

These findings highlight a trade-off: while some biodiesel blends effectively reduce certain pollutants like CO and, to a lesser extent, NO_x, they can also cause an increase in unburned hydrocarbons, indicating complex interactions in how these fuels burn.

Table 7.
Percentage change in NO_x emissions relative to Diesel (D100).

Compression Ratio	D90GSOME5DEE5 vs Diesel (D100) (% Change)	D80GSOME10DEE10 vs Diesel (D100) (% Change)	D70GSOME15DEE15 vs Diesel (D100) (% Change)
14:1	-4.28	-8.02	3.21
16:1	-2.99	-7.19	3.59
18:1	-8.78	-11.49	10.81

Table 8.
Percentage change in HC emissions relative to Diesel (D100)

Compression Ratio	D90GSOME5DEE5 vs Diesel (D100) (% Change)	D80GSOME10DEE10 vs Diesel (D100) (% Change)	D70GSOME15DEE15 vs Diesel (D100) (% Change)
14:1	15.57	35.59	24.29
16:1	16.63	20.57	19.98
18:1	38.04	44.72	40.38

Table 9.
Percentage Change in CO Emissions relative to Diesel (D100).

Compression Ratio	D90GSOME5DEE5 vs Diesel (D100) (% Change)	D80GSOME10DEE10 vs Diesel (D100) (% Change)	D70GSOME15DEE15 vs Diesel (D100) (% Change)
14:1	-5.3	-12.32	-12.58
16:1	-6	-12.8	-12.4
18:1	-6.67	-20	-13.33

3.5. Mechanistic Interpretation of Emission Characteristics of the Fuel

The lower emission levels observed for the D80GSOME10-DEE10 blend result from the combined effects of fuel chemistry, vaporization behavior, and combustion temperature. Diethyl ether, with its high cetane value and low ignition temperature, aids in early ignition and faster flame development. When mixed at about ten percent, it improves fuel dispersion and enhances interaction between fuel and air, allowing more oxygen to participate in combustion reactions [8]. Consequently, carbon in the fuel is more completely oxidized, leading to lower carbon monoxide levels in the exhaust. The oxygen in groundnut soapstock methyl ester also supports this process by facilitating continuous oxidation and maintaining a steadier flame. When the ether content increases to fifteen percent, its cooling effect becomes dominant due to its high latent heat of evaporation [22]. This reduces in-cylinder temperature and may interrupt the final oxidation phase, resulting in slightly higher hydrocarbon emissions [23].

With an increase in compression ratio, the temperature and pressure inside the cylinder rise, which helps improve thermal efficiency and reduce specific fuel consumption. In the current study, the ten percent DEE blend performed best because it maintained a balance between oxygen enrichment and charge cooling. The mixture burned evenly without creating local rich zones, and the combustion temperature remained below the range where thermal NO_x is produced in significant quantities. This explains the simultaneous reduction in carbon monoxide and nitrogen oxides for this blend [24]. A smaller addition of DEE was insufficient to improve mixture uniformity, while a higher addition increased cooling to the point that part of the fuel did not burn completely. Therefore, the ten percent blend represented a favorable balance between ignition timing, mixture preparation, and available oxygen.

The pattern aligns with observations from earlier studies on biodiesel mixed with oxygenated additives, where moderate amounts of DEE generally produced the most consistent combustion and emission results [25]. However, this work shows that groundnut soapstock methyl ester behaves slightly differently from other biodiesels due to its composition and viscosity, which support smooth vaporization and stable burning under high compression conditions. These factors contribute to cleaner exhaust and steadier engine operation for the D80GSOME10-DEE10 fuel.

3.6. Contextualization of The Performance and Emission Characteristics of GSOME DEE With Prior Research Works

It has been revealed that adding diethyl ether (DEE) to groundnut soapstock methyl ester (GSOME)–diesel blends significantly improves exhaust emissions, especially in the D80GSOME10DEE10 blend, which showed approximately 20% lower carbon monoxide and about 11–12% less nitrogen oxides compared to pure diesel at a compression ratio of 18:1. Similar results have been reported for other biodiesel systems, although the extent of emission reduction varies depending on the feedstock and engine condition. Experiments with waste cooking oil biodiesel mixed with 10% DEE demonstrated about a 21% decrease in NO_x emissions and a 15–20% reduction in CO at constant engine speed [26]. Blends made from Mahua methyl ester with comparable additive levels achieved around 25% lower hydrocarbon emissions and a 30% reduction in CO compared to base diesel [27]. The values obtained with GSOME therefore fall within the same performance range, but the use of an industrial by-product feedstock introduces a more sustainable dimension.

In a previous test by Satapathy et al. [28] with Karanja methyl ester and 15 % DEE, a decline of roughly 20 % in CO but a mild rise in NO_x was reported when the engine was operated under full load [28]. In contrast, NO_x formation in the GSOME blends continued to decrease as the compression ratio increased, indicating more complete combustion and improved thermal utilization of oxygen within the mixture. For hydrocarbon emissions, rice-bran and cottonseed biodiesel blends containing DEE typically showed reductions of about 40–45% compared to diesel [29]. In this case, hydrocarbon values were somewhat higher at certain loads, possibly due to the cooling effect caused by the high latent heat of DEE, which occasionally inhibits full oxidation in localized regions of the combustion chamber. Nonetheless, the overall emission pattern remained cleaner than that of standard biodiesel–diesel mixtures.

Brake thermal efficiency for biodiesel fuels is often 2–5% lower than that of diesel due to their lower calorific value, but studies suggest oxygenated additives can offset much of this difference [30]. In this work, adding 10% DEE brought the efficiency of GSOME blends close to diesel, especially at higher compression ratios, confirming DEE's positive effect on ignition quality and energy release. Unlike earlier studies limited to fixed compression ratios, this research examined a range from 14:1 to 18:1. Results showed that higher compression improved combustion uniformity and further reduced CO emissions, aspects rarely quantified in previous biodiesel research.

Taken together, these comparisons show that the GSOME–DEE blends yield emission and efficiency responses comparable to or better than those reported for other biodiesel systems using DEE. The results demonstrate that effective emission control can be achieved without compromising performance, while simultaneously converting a low-value refinery by-product into a clean, usable fuel. This broadens the applicability of DEE as an oxygenated additive and highlights the technical and environmental merits of GSOME as a sustainable alternative to conventional diesel.

4. Conclusions

The experimental study conducted on a single-cylinder variable compression ratio (VCR) diesel engine explored the use of diethyl ether (DEE) as an additive to diesel and GSOME blends. Among the various fuel mixtures tested, the combination labeled D80GSOME10-DEE10 delivered the most promising results, especially regarding emission performance. This particular blend consistently showed a marked decrease in carbon monoxide emissions under all loads and compression ratio settings, indicating more efficient combustion. While the influence on nitrogen oxide emissions varied depending on the compression ratio applied, the general trend suggested that adding DEE can help reduce NO_x emissions in certain operating conditions. These outcomes demonstrate the practical advantages of incorporating DEE into biofuel blends, helping to lower harmful exhaust pollutants and support cleaner engine operation. However, to establish the broader applicability of these fuels, additional research is necessary. Future investigations should examine the long-term durability of engines running on these blends, assess environmental impacts over extended periods, and perform thorough economic evaluations to understand the feasibility of widespread adoption.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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