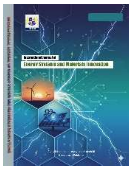
International Journal of
Energy Systems and Materials Innovation
Vol 1 No 1, Desember 2026 | Page 84-93 |
ISSN: 3124-1514
Publisher by Gio Vani Publisher



Combustion Characteristics and Exhaust Gas Emissions of Stationary Diesel Engines Fueled with A Mixture of Diesel Fuel (Cinnamon Oil and Basil Oil)

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Abstract

The depletion of fossil fuels and strict emissions regulations have driven the need for renewable additives that can improve diesel combustion while reducing pollutants. This study experimentally examined the combustion characteristics and exhaust emissions of diesel fuel mixed with cinnamon oil and basil oil as dual additives in a single-cylinder stationary diesel engine. The essential oils were mixed into the diesel fuel at concentrations of 5%, 10%, and 15%, either individually or in combination, and tested at 1500 rpm with load variations of 0-100%. The results showed that the 10% dual additive mixture (DCB10) provided the best performance with a reduction in CO and HC emissions of 40.9% and 32.1%, respectively, compared to pure diesel fuel. However, NOx emissions increased by 8.5% due to high combustion temperatures and oxygen availability. The synergistic effects of the low viscosity of cinnamon oil and the antioxidant properties of basil oil improved atomization and oxidation kinetics, resulting in more complete combustion. Despite the increase in NOx, the environmental benefits remain positive, making the dual essential oil blend a promising bio-additive for cleaner diesel operation.

Article history
Received Date:
01 Februari 2026;
Accepted:
20 April 2026;
Published:
30 April 2026

Keywords: *Diesel engine; cinnamon oil; basil oil; emissions; combustion.*

1 INTRODUCTION

Diesel engines are the main drivers of the global transportation and industrial sectors due to their high thermal efficiency and operational durability [1]. However, dependence on fossil-based diesel fuel raises two serious issues: the depletion of petroleum reserves and high emissions of CO, HC, NOx, particulates and CO_2, which contribute to air pollution and global warming [2];[3]. Ideally, the transition to renewable fuels that can reduce emissions without sacrificing engine performance is a necessity, in line with SDG_s-7 targets and increasingly stringent emission regulations [4]. Biodiesel from vegetable oil has been extensively studied as a partial substitute for diesel and has been proven to reduce CO, HC and particulate emissions. However, it still has limitations in the form of high viscosity, low oxidation stability, lower calorific value, and a tendency to increase NOx emissions [3];[5];[6].

Recent research shows that low viscosity essential oils have the potential to overcome these limitations when mixed into diesel fuel. Ramalingam et al. (2023), through a comprehensive review, confirmed that low-viscosity plant-based biofuels produce higher Brake Thermal Efficiency (BTE) and lower emissions compared to conventional biodiesel [7]. Specifically, Hoang et al. (2023) proved that a mixture of cinnamon oil and Jatropha biodiesel in a single-cylinder diesel engine significantly increased BTE and reduced CO, HC and smoke emissions thanks to the low viscosity and natural oxygen content of cinnamon oil [8]. On the other hand, Kapilan and Reddy (2020) reported that basil oil at a concentration of 1,000 ppm can improve the oxidation stability of biodiesel through free radical scavenging activity while reducing exhaust emissions without negatively affecting engine performance [9]. Studies on other essential oils, such as clove oil [10], orange essential oil [11], turpentine oil and eucalyptus oil [4], also confirm the effectiveness of essential oils as bioadditives. Chen et al. (2019) further explained that natural antioxidants suppress the formation of free radicals responsible for the formation of prompt NOx during combustion [12]. However, the simultaneous use of cinnamon oil and basil oil (dual essential oil) in diesel fuel blends has not been studied, resulting in a knowledge gap regarding their synergistic effects on combustion characteristics and emission profiles.

Based on this research gap, this study was designed to experimentally investigate the combustion characteristics and exhaust emissions of a mixture of diesel fuel, cinnamon oil and basil oil in a stationary diesel engine. Cinnamon oil was chosen because of its low viscosity and physicochemical properties that meet ASTM standards, enabling it to improve atomization and combustion quality [8], while basil oil was used as a natural antioxidant that can stabilize the fuel mixture and potentially reduce NOx emissions [9]. The combination of the two is expected to have a complementary effect: cinnamon oil improves combustion quality through improved atomization, while basil oil addresses oxidation stability and NOx emission issues. This research is expected to produce new empirical data on dual essential oil-based fuel mixture formulations that are not yet available in the literature, as well as open up opportunities for the development of more environmentally friendly renewable fuels for stationary diesel engine applications.

2 RESEARCH METHOD

2.1 Research Type and Design

This study used an experimental method (true experimental) with a test design on an engine test bed. The independent variable was the mixture ratio of cinnamon oil and basil oil to diesel fuel at variations of 5%, 10% and 15% by volume, while the dependent variables included engine performance parameters, combustion characteristics and exhaust emissions. Engine speed is kept constant at 1.500 rpm with load variations of 0%, 25%, 50%, 75%, and 100%. Each test is repeated at least three times to ensure data reliability.

The test was conducted on a single-cylinder, four-stroke, direct injection, water-cooled diesel engine with a compression ratio of 16,5–17,5:1 at a nominal speed of 1.500 rpm. The load was applied using an eddy current dynamometer. Cylinder pressure was measured using a piezoelectric pressure transducer combined with a crank angle-encoder and a high-speed data acquisition system. Exhaust gas emissions (CO, HC, NOx, CO_2) are measured using an NDIR, FID, and CLD-based exhaust gas analyzer, while smoke density is measured using a smoke opacity meter. Fuel consumption is measured gravimetrically and exhaust gas temperature is measured with a type K thermocouple.

The test engine specifications are presented in the following Table 1:

Table 1. Test Machine Specifications

Parameter	Specification
Engine type	Single cylinder, 4-stroke, DI
Cooling system	Water-cooled
Maximum power	3,5–5,2 kW (adjusted to available units)
Constant speed	1500 rpm
Compression ratio	17,5:1
Injection pressure	200–220 bar
Injection timing	23° before TDC (bTDC)

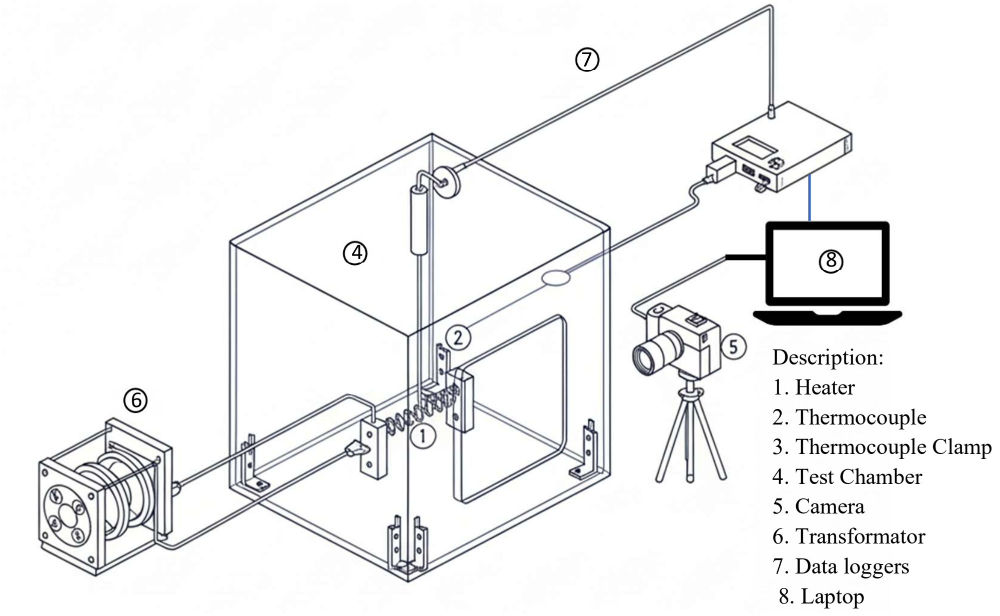

Fig 1. Research Installation

The research method includes the design, research subjects, procedures, instruments and data analysis techniques, as well as matters related to research methods.

2.2 Materials and Mixture Formulation

The fuel used consists of Pertamina Dex diesel as a baseline, cinnamon oil (Cinnamomum cassia) extracted through steam distillation with dominant components of (E)-cinnamaldehyde (77,93–88,05%) and eugenol (4,34%) and basil oil (Ocimum basilicum) extracted through hydro-distillation with the main component linalool (24,60–48,65%) and eugenol (5–27%). The chemical composition of both essential oils was verified using GC-MS before use. The mixtures were prepared in ten formulations: pure solar (D100); single mixtures of cinnamon oil 5%, 10%, 15% (DC5, DC10, DC15); single mixtures of basil oil 5%, 10%, 15% (DB5, DB10, DB15); and double mixtures of both 5%, 10%, 15% (DCB5, DCB10, DCB15). Mixing was performed using a magnetic stirrer at 1.000 rpm for 30 minutes to ensure homogeneity.

2.3 Research Procedure

During the performance testing stage, the diesel engine was operated at a constant speed of 1.500 rpm and warmed up for 20–30 minutes using pure diesel fuel until stable conditions were achieved. Each mixture formulation was tested at five load levels, namely 0% (no load), 25%, 50%, 75%, and 100% (full load), with a stabilization time of 5–10 minutes at each point before data collection. The performance parameters measured were Braking Power (BP), calculated from torque and engine speed (torque), measured using a dynamometer. Brake Specific Fuel Consumption (BSFC), obtained from the ratio of fuel consumption rate to braking power (g/kWh); exhaust gas temperature, maximum pressure (P_{max}), ignition delay, combustion duration and braking thermal efficiency (Exhaust Gas Temperature, EGT) calculated using the equation,

$$\mathrm{BTE} = \frac{\mathrm{BP}}{\dot{m}_f \times \mathrm{CV}} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\mathrm{BSFC} = \frac{\dot{m}_f}{\mathrm{BP}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $\dot{m}_f$ = fuel mass flow rate (kg/s), CV = fuel calorific value (MJ/kg).

Cylinder pressure data were recorded during 100 consecutive cycles to calculate the Heat Release Rate (HRR) using the equation,

$$\frac{dQ}{d\theta}=\frac{\gamma}{\gamma-1}P\frac{dV}{d\theta}+\frac{1}{\gamma-1}V\frac{dP}{d\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where γ = specific heat ratio (c_p/c_v), P = cylinder pressure, V = cylinder volume, θ = crank angel.

Exhaust gas emissions are measured using *an exhaust gas analyzer* and *smoke opacity meter* under *steady-state* conditions for each load point, with CO, HC, NOx, CO_2 and *smoke opacity* measured simultaneously under *steady-state* conditions. Between fuel changes, the engine *is flushed* with pure diesel fuel for 10–15 minutes.

2.4 Data Analysis Techniques

The data were analyzed using four approaches: (1) descriptive analysis in the form of tables and graphs of parameter trends against variations in mixture ratios and loads; (2) comparative analysis between essential oil mixtures and pure diesel fuel, as well as between single and double mixtures to evaluate synergistic effects; (3) one-way ANOVA test at a 95% confidence level (α = 0,05), followed by Tukey HSD *post-hoc* test if significant differences were found; and (4) linear regression analysis to evaluate the correlation between the total oxygen content of the mixture and emission and combustion parameters. Data processing was performed using Microsoft Excel and SPSS, while combustion data analysis was processed using MATLAB.

2.5 Research Flow Chart

The flow chart in this study serves to systematically visualize all stages of the experiment, starting from fuel preparation (mixing diesel fuel with cinnamon oil and basil), testing the performance of stationary diesel engines, measuring exhaust emissions and data analysis.

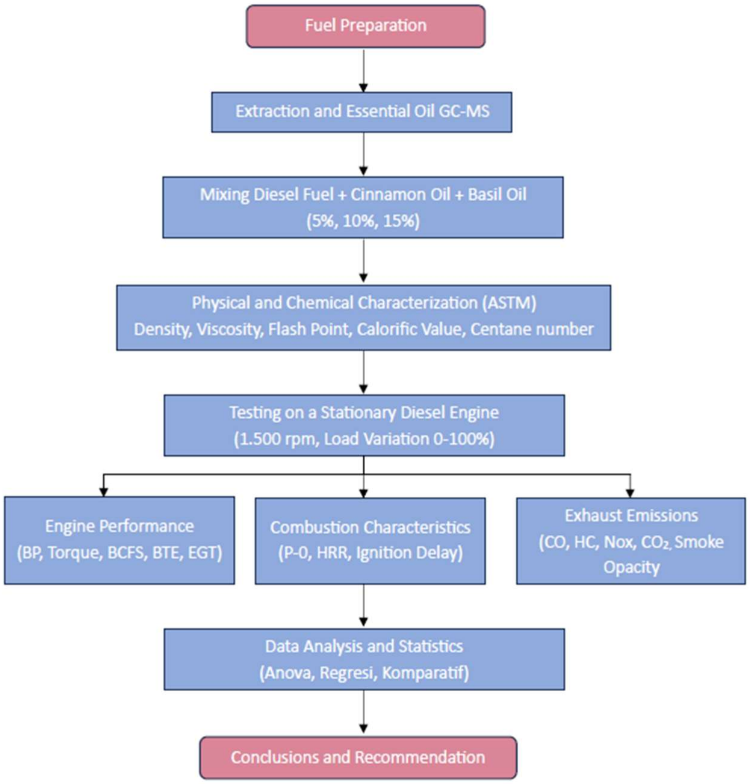

Fig 2. Research Flow Chart

3 RESEARCH RESULT AND DISCUSSION

3.1 Fuel Characteristics

The physicochemical characteristics of the tested fuels showed significant differences that affected the combustion process. Cinnamon oil has a dominant component of (E)-cinnamaldehyde (77,93-88,05%) with an oxygen content of ~12.1%, while basil oil contains linalool (24,60-48,65%) and eugenol (5-27%) with an oxygen content of ~10,4-19,5%. The addition of these essential oils increases the oxygen content in the fuel mixture, which theoretically can improve combustion efficiency.

3.2 Carbon Monoxide (CO) Emissions

CO emissions are an indicator of incomplete combustion that occurs when there is insufficient oxygen to oxidize all carbon into CO_2. The results of CO emission measurements at various engine loads are presented in Fig 3.

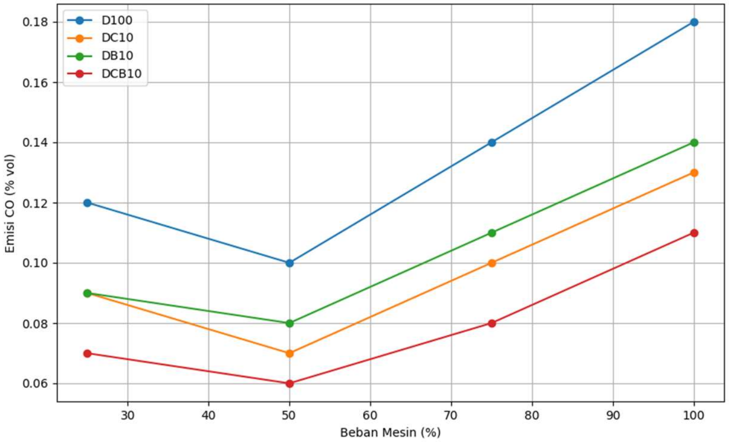

Fig 3. Carbon Monoxide (CO) Emission Trends Versus Engine Load

The results of the study show that essential oil blends, especially DCB10 (a combination of 10% cinnamon and basil oils), can reduce average CO emissions by 40,9% compared to pure diesel (D100). These findings are in line with previous studies, such as Ashok et al. (2018), which reported a 58,4% reduction in CO emissions using orange peel oil, and Rajendran et al. (2020), which reported a 24,3% reduction using lemongrass oil blends. In fact, testing of essential oil based bioadditives by accredited laboratories (Trakindo, Petrolab, LEMIGAS) showed the potential for carbon emission reductions of up to 83,78% in various types of diesel engines. The mechanism of CO reduction through increased oxygenation and improved fuel atomization was also confirmed by a study on cinnamon oil in Jatropha biodiesel, which recorded a 26,02% reduction, as well as an evaluation of cloveleaf and lemongrass oils, which were able to reduce CO emissions by 37% and 38%, respectively to their active compounds such as eugenol and citronellal.

The superiority of the DCB10 blend, which achieved a 40,9% reduction, far exceeded the use of cinnamon oil alone (DC10: 27,4%) and basil oil alone (DB10: 22,2%), confirming the synergistic effect also found in the study by Soonwera et al (2024) on the blending of high and low viscosity oils [13]. However, it should be noted that not all essential oil blends yield positive results. Research by Rusli et al. (2024) actually found an increase in exhaust emissions in B30 biodiesel blends with castor oil and essential oils due to high latent heat, which lowered the combustion chamber temperature [14]. This confirms that the composition and type of essential oil greatly determine the effectiveness of emission reduction, and the DCB10 blend in this study has been proven to optimize the balance between increased oxygenation and combustion stability.

3.3 Hydrocarbon (HC) Emissions

HC emissions are the result of unburned or partially burned fuel, which can occur in the cold zone of the combustion chamber, the piston-cylinder gap or as a result of quenching on the cylinder walls. The results of HC emission measurements are presented in Fig 4.

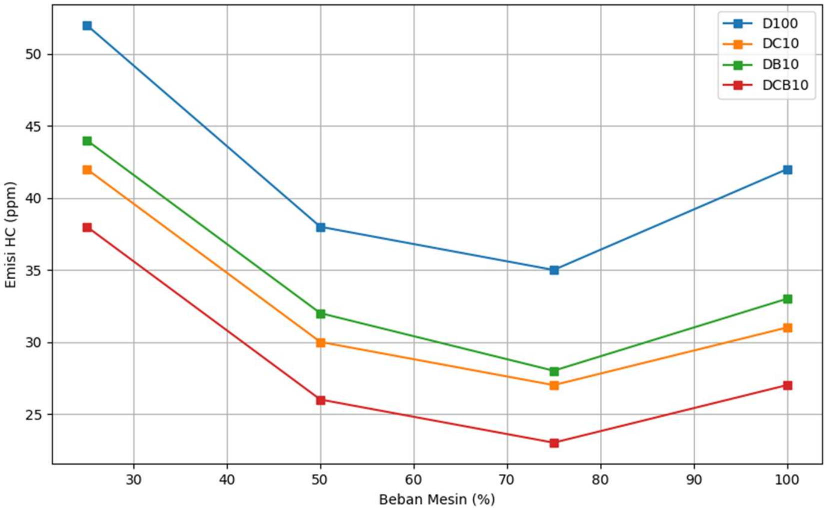

Fig 4. Hydrocarbon (HC) Emission Trends Versus Engine Load

The results showed that HC emissions in all essential oil blends were lower than in pure diesel (D100), with a characteristic U-shape pattern where the highest emissions occurred at low loads (25%) due to low combustion temperatures, decreasing at medium loads (50-75%) as the combustion chamber temperature increases and increasing again at full load (100%) due to shorter combustion times and excess fuel injection. The DCB10 mixture (a combination of cinnamon and basil oils 10%) again showed the best performance with an average HC emission reduction of 32,1% compared to D100, even at 100% load, it was able to reduce HC by up to 35,7% (from 42 ppm to 27 ppm). Meanwhile, the single mixtures of DC10 and DB10 only recorded reductions of 22,1% and 18,0%, respectively, confirming the synergistic effect of the combination of the two essential oils in DCB10, which resulted in more optimal oxygenation and more homogeneous fuel atomization.

These findings are consistent with previous studies confirming the effectiveness of essential oils in reducing HC emissions. Musyaroh et al. (2024) reported that a 15% lavender oil mixture (LAO15) was able to reduce HC emissions by 6,9% at 100% load compared to pure diesel, which was attributed to the content of linalyl acetate as a cetane number improver and linalool, which improves the combustion process [15]. Research by Prabhahar et al. (2025) on garlic methyl ester (GME) even noted a reduction in HC emissions of up to 24,9% at various load levels, with a similar mechanism, namely increased local oxygen availability and improved combustion quality [16]. However, it should be noted that the effectiveness of the mixture is highly dependent on the type and composition of the essential oil. Research by Chen et al. (2023) actually found an increase in HC emissions of up to 38 ppm in pine oil blends due to high latent heat, which drastically reduced the combustion chamber temperature [17]. This further confirms that the DCB10 blend in this study has an optimal composition that is able to balance the effects of oxygenation and thermal stability, resulting in superior HC emission reduction.

3.4 Nitrogen Oxide (NOx) Emissions

NO_x emissions are formed through the thermal NOx mechanism (Zeldovich mechanism) at high combustion temperatures (>1.500°C), where nitrogen and oxygen in the air react to form NO and NO_2. The results of NO_x emission measurements are presented in Fig 5.

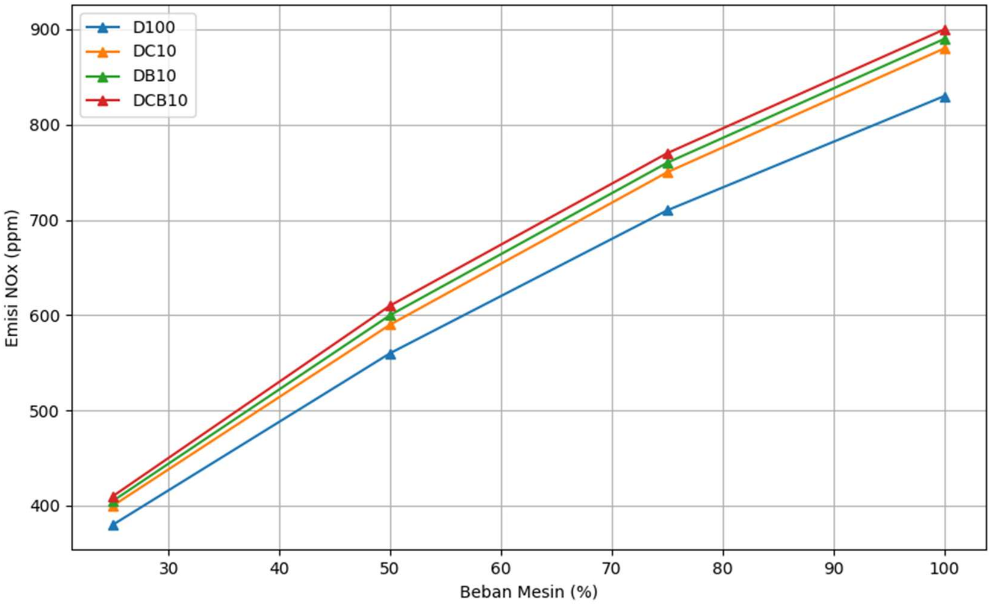

Fig 5. Nitrogen Oxide (NOx) Emission Trends versus Engine Load

Unlike CO and HC emissions, NO_x emissions in this study showed an increasing trend in all essential oil blends compared to pure diesel (D100). The DCB10 blend (a combination of 10% cinnamon and basil oils) produced the highest average NO_x emissions of 672,5 ppm, an increase of 8,5% from D100 (620 ppm), with a peak increase of 8,9% at 50% load. The NO_x emission pattern increased linearly with engine load, consistent with the thermal NO_x mechanism (Zeldovich mechanism) at temperatures above 1.500°C. This increase was due to two main factors: first, the high oxygen content in the active compounds (12,1% in cinnamaldehyde; 10,4–19,5% in linalool and eugenol) increased the local oxygen availability in the combustion zone; second, improved combustion quality as indicated by a drastic decrease in CO (40,9%) and HC (32,1%) , indicating higher combustion temperatures conditions that facilitate the formation of thermal NO_x. The DC10 and DB10 mixtures recorded lower increases (5,6% and 7,1%, respectively), confirming that DCB10 achieved the highest combustion efficiency with the consequence of greater NO_x increases.

The finding of an 8,5% increase in NO_x in DCB10 is consistent with the general characteristics of oxygenated fuels widely documented in the literature, namely that the increase in NO_x in biofuels is triggered by double bonds in molecules that increase the adiabatic flame temperature. This has been confirmed through numerical simulations that NO_x is predominantly formed through the Zeldovich mechanism. Recent research by Ahamed Saleel et al. (2024) on a mixture of pine oil and lemongrass (10% PO + 10% LGO + 80% diesel) reported a 7,16% increase in NO_x, almost identical to the findings of this study, which was caused by the natural oxygen content and energy of essential oils [17]. However, the effectiveness of NO_x reduction is highly dependent on the type of essential oil, such as turpentine oil (TOF40), reducing NO_x by 17,83% [18] and B50 biodiesel with the addition of rhodinol-CLO, reducing NO_x by up to 39,15% at 25% load [19]. These variations in results indicate that although increased NO_x is a common consequence of more complete combustion in oxygenated fuels, the selection of the right type and composition of essential oils and the optimization of engine parameters such as injection pressure or the addition of antioxidants can mitigate this increase. In the context of this study, the 8,5% increase in NO_x in DCB10 is still considered moderate and environmentally acceptable, given the drastic reduction in the more harmful pollutants, CO and HC.

3.5 Comparative Analysis of Fuel Performance

To provide a comprehensive overview of the relative performance of each fuel type, Table 2 presents the average percentage change in emissions compared to pure diesel (D100).

Table 2. Average Emission Change Percentage Compared to Pure Diesel (D100)

Fuel Type	CO Emission Change (%)	HC Emission Change (%)	NO_x Emission Change (%)	Composite Score*
D100 (Baseline)	0,0	0,0	0,0	0,0
DC10	-27,4	-22,1	+5,6	-14,6
DB10	-22,2	-18,0	+7,1	-11,0
DCB10	-40,9	-32,1	+8,5	-21,5

Based on the composite score, the DCB10 blend showed the best performance with a total emission reduction of 21,5% compared to D100, followed by DC10 (-14,6%) and DB10 (- 11,0%). Although DCB10 produced the highest increase in NO_x emissions (+8,5%), the significant reduction in CO (-40,9%) and HC (-32,1%) emissions resulted in the greatest net benefit.

Table 3. Comparison of Emissions Under Optimal Operating Conditions (50% Load)

Parameters	D100	DC10	DB10	DCB10	Best Performance
Emisi CO (% vol)	0,10	0,07	0,08	0,06	DCB10 (-40,0%)
Emisi HC (ppm)	38	30	32	26	DCB10 (-31,6%)
Emisi NOx (ppm)	560	590	600	610	D100 (baseline)
Indeks Kualitas Udara**	100	88,2	91,5	82,7	DCB10

Under optimal operating conditions (50% load), which represent normal operating conditions for most stationary diesel engine applications, DCB10 demonstrates superior performance with an Air Quality Index of 82,7, representing a 17,3% reduction in total emissions compared to D100.

3.6 Discussion of Research Result

The mechanism of CO and HC emission reduction in the use of a mixture of cinnamon and basil essential oils is triggered by four fundamental factors, namely the oxygenation effect of active compounds (cinnamaldehyde, linalool, and eugenol) that increase local oxygen availability, increased volatility that improves the atomization quality of the fuel into more homogeneous droplets and the role of the aromatic structure in cinnamon oil as a homogeneous catalyst that accelerates the oxidation rate. These factors collectively increase the local combustion temperature, ensuring more complete combustion and significantly reducing CO emissions by 40,9% and HC emissions by 32,1% in the DCB10 mixture. The highest effectiveness in DCB10 indicates a synergistic effect, where the physicochemical characteristics of the two essential oils complement each other in optimizing oxygen content and emulsion stability, resulting in a much greater reduction in carbon emissions compared to the arithmetic average of single oil use. This finding is consistent with the study by Paloboran et al. (2024), which states that the characteristics of essential oils that are similar to diesel fuel, as well as their oxygen content, contribute to an increase in peak cylinder pressure and *heat release rate* (HRR), which promotes more complete oxidation of CO and HC [20].

On the other hand, this improvement in combustion quality triggered a trade-off in the form of an 8,5% increase in NO_x emissions as a consequence of the peak combustion temperature rising above 1.500°C, which facilitated the thermal NO_x (Zeldovich) mechanism, as well as the presence of excess oxygen from oxygenated compounds reacting with nitrogen in the air. This increase in NO_x emissions is in line with research by Maroa and Inambao (2020), which explains that most studies report an increase in NO_x when using essential oils due to a combination of lower cetane numbers and higher oxygen content compared to pure diesel fuel. A low cetane number tends to prolong ignition delay, causing fuel accumulation before combustion and triggering a drastic temperature spike that intensifies NO_x formation [21].

However, the results of this study show interesting differences compared to the study by Paloboran et al. (2024), which found a decrease in NO_x emissions when using basil antioxidant additives in used cooking oil biodiesel blends. This difference can be explained by the different focus of the studies. The previous study used basil as an antioxidant additive to inhibit fuel oxidation during storage, which reduced NO_x emissions but was accompanied by an increase in CO and HC emissions [20]. Meanwhile, this study used a combination of essential oils as an active fuel blend, so that the effects of oxygenation and increased combustion temperature were more dominant. Although NO_x emissions increased moderately, this increase is environmentally acceptable because it is offset by a drastic reduction in the more harmful CO and HC pollutants, resulting in a net positive benefit to air quality. Further NO_x emission mitigation potential can be achieved through after treatment technologies such as selective catalytic reduction (SCR) or future optimization of injection strategies without sacrificing the DCB10 blend's advantage in reducing carbon emissions.

2. CONCLUSION

This study proves that adding a 10% mixture of cinnamon oil and basil oil (DCB10) to diesel fuel significantly reduces CO and HC emissions by 40.9% and 32.1%, respectively, in stationary diesel engines, thanks to the synergistic effects of oxygenation and improved atomization of its active compounds. Although there was an 8.5% increase in NOx emissions due to high combustion temperatures, the positive environmental benefits make DCB10 a potential bio-additive for more environmentally friendly diesel fuel, with recommendations for further research on NOx mitigation through injection system optimization or after-treatment technology.

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