

Article

Engine Response and Emission Optimization of Ceramic-Oxide-Doped Diesel Blends with Reclaimed Waste Energy

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Abstract

Without changing any of its constituents, tyre pyrolysis oil energy (TPOE) has frequently been subjected to Diesel-RK (D-RK) analyses in diesel engines in an effort to serve as a substitute for diesel fuel. Environmentally beneficial TPOE features, such as biodegradability, renewability, and ease and safety of handling, are highly sought after. In addition to its beneficial aspects, TOPE also has drawbacks. The BTE and SFC of performance metrics, as well as the smoke and NO_x of emission parameters of alternative fuel, do not meet the emission limits specified by regulatory authorities. Nano-additions have been shown to be effective for boosting fuel quality for improved performance and production characteristics. In this study, TPOE–diesel blends are blended with ceramic oxide (CeO₂ of 50 and 100 ppm) nanoparticles and subjected to a performance and production investigation of engine working physiognomies in diesel engines. For the blend TPOE10CDF80 + D, the numerical results show a positive outcome of a 1.0% rise in BTE, a 2.0% decrease in SFC, a 17.7% decrease in smoke emission, and an 18.2% increase in NO_x emission as compared to diesel fuel (CDF).

Keywords: diesel engine; tyre pyrolysis oil energy; ceramic oxide; performance; NO_x production



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1. Introduction

Internal combustion engine emissions that are harmful are a problem worldwide. Therefore, in addition to traditional exhaust gas treatment technologies like diesel particle filters and catalytic converters, scientists and engineers are searching for alternate production control mechanisms. Utilizing nano-additives is a common alternative method now in use to meet the rising need for energy [1]. Yasar et al. [2] examined the effects of copper nitrate, titanium dioxide, and cerium acetate hydrate on diesel fuel to reduce exhaust gas discharges from diesel engines. It was determined that diesel emissions of NO_x are significantly reduced by the addition of cerium acetate hydrate, titanium dioxide, and copper nitrate. The outcome of coconut shell nanoparticles on diesel engine features through various blends was established by Vinukumar et al. [3]. It is significant to note that the CO, CO₂, and NO_x discharges are decreased when coconut shell nanoparticles are added to diesel-alternative fuel blends. Ghanbari et al. [4] suggested adding cerium oxide nanoparticles (80 ppm) to blended gasoline to improve performance and reduce discharge (HC and CO). Ardebili et al. [5] evaluated the effects of sugarcane nano-biochar particles (25,

50, 75, 100, and 125 ppm) with fuel oil–diesel blends on a diesel engine. According to their research, adding fuel oil reduced NO_x and UHC discharges while raising CO discharges.

Gharehghani and Pourrahmani [6] investigated the influence of adding carbon nanotubes (120, 80, and 40 ppm) as nano-additives to diesel–alternative blends, as well as the physiognomies of diesel engines. According to their findings, the blending of diesel and alternatives with nanoparticles improved engine performance by 2.0% and decreased fuel ingestion by 7.08%. The addition of nanoparticles causes a rise in CO₂ and NO_x discharges and a reduction in HC and CO discharges when associated with diesel and alternative blends. Khalife et al. [7] examined how diesel–alternative aqueous additives affected diesel engine performance. The results showed an increase in BTE and a significant decrease in CO, HC, and NO_x emissions when the blends were considered. Perumal and Ilangukumar conducted studies on the usage of pongamia as an alternative to copper oxide in diesel engines [8]. It was discovered that the B20CuO100 mix had a 4.01% gain in thermal efficiency, a 1.0% decrease in fuel consumption, a 9.8% decrease in NO_x discharges, and a 12.8% decrease in smoke discharges. Örs et al. [9] evaluated the effects of adding a titanium dioxide nano-additive to diesel, used cooking oil, and n-butanol alternative fuel mixes. According to their findings, blending diesel and alternatives increased engine power, brake torque, and NO_x discharges while lowering fuel consumption, HC, and CO discharges.

Ettefaghi et al. [10] looked into how adding carbon quantum dots, an alternative–water–diesel–biodegradable nano-additive, affected engines. The outcomes demonstrated that the addition of the titanium dioxide nano-additive reduced engine power, brake torque, and fuel consumption. In comparison to B₁₅ pure fuel (85% diesel fuel + 15% alternative), the HC and NO_x discharges were reduced for the titanium dioxide nano-additive (5% water + B₁₅ fuel containing + 60 ppm carbon quantum dots). Hasannuddin et al. [11] examined the possessions of adding various nano-additives including water to diesel, including zinc oxide, copper oxide, aluminium oxide, magnesium oxide, and manganese oxide. The outcomes demonstrated that the sample with 10% water and aluminium oxide led to lower fuel consumption and better engine performance. Nano-additives reduced NO_x and CO outputs. Dhanasekar et al. [12] used CeO₂ and CeO₂: Gd nanoparticles in diesel and pongamia oil alternative mixes to improve compression ignition engine performance. CeO₂ and CeO₂: Gd reduced CO output and smoke opacity in diesel and pongamia oil alternatives. Kumaravel et al. [13] added cerium oxide to a diesel–tyre oil alternative as a nano-additive with the aim of enhancing the oil characteristics of the diesel–tyre mixes. The outcomes demonstrated that CeO₂ greatly decreases smoke emission and improves thermal efficiency in a diesel–tyre oil alternative blend. Table 1 displays the results of an earlier investigation on alternative mixtures with nanoparticles and diesel.

Table 1. The findings of an earlier study that was conducted.

Authors	Nano-additives	Performance				Discharge			
		Power	Torque	BTE	SFC	CO	HC	NO _x	Smoke
Yaşar et al. [2]	TiO ₂ , (Cu(NO ₃) ₂), (Ce(CH ₃ CO ₂) ₃ ·H ₂ O)	-	-	-	↓	↓	↓	↑	-
Vinukumar et al. [3]	Coconut shell (CS)	↑	↑	-	↑	↓	-	↓	-
Gharehghani et al. [6]	Cerium oxide (CeO ₂)	-	-	-	-	↓	↓	-	-
Ardebili et al. [5]	Sugarcane nano-biochar (SNB)	↑	↑	-	↑	↑	↓	↓	-
Ghanbari et al. [4]	Carbon nanotubes (CNTs)	↑	↑	-	↓	↓	↓	↑	-

Table 1. Cont.

Authors	Nano-additives	Performance				Discharge			
		Power	Torque	BTE	SFC	CO	HC	NO _x	Smoke
Khalife et al. [7]	Aqueous nano cerium oxide [7]	-	-	↑	↓	↓	↓	↓	-
Perumal and Ilangkumaran [8]	Copper oxide (CuO) [8]	-	-	↑	↓	↓	-	↓	↓
Örs et al. [9]	Titanium dioxide (TiO ₂)	↑	↑		↓	-	↓	↑	↓
Ettefaghi et al. [10]	Carbon quantum dots	↑	↑	-	↓	↓	↓	-	-
Hasannuddin et al. [11]	Aluminium oxide (Al ₂ O ₃)	↑	-	-	↓	↓		↓	-
Dhanasekar et al. [12]	CeO ₂ and CeO ₂	-	-	-	-	↓	-	-	↓
Kumaravel et al. [13]	CeO ₂	-	-	↑	-	-	-	↑	↓
Present investigation	Cerium oxide (CeO ₂) with tyre oil–diesel fuel at different loads	-	-	↑	↓	-	-	↑	↓

↑ = Increase value of parameter and ↓ = decrease value of parameter.

Research on the combustion, performance, and emission characteristics of a single-cylinder diesel engine powered by tyre-derived oil, diesel blends, and CeO₂ nanoparticles is still scarce, despite the recent explosion in interest in alternative fuels. The majority of the current research focuses on traditional biodiesel or fuels made from trash, but little is known about the combined effects of tyre oil and nanomaterials on pollutant reduction, heat release properties, and ignition delay. Moreover, despite its critical function determining thermal efficiency and emissions, the impact of loads on these blends has not been thoroughly investigated. The optimization of such fuel blends for real-world diesel engine applications is limited by this gap.

Goals of the research: Through the combination of theoretical simulation and real-world experimentation, the current work aims to fill the aforementioned research gap:

- To examine the performance and combustion properties of a single-cylinder diesel engine running on blends of tyre oil, diesel, and CeO₂ under various load scenarios.
- To forecast cylinder pressure, the heat release rate, and emission behaviour by simulating an engine cycle with the Diesel-RK (D-RK) tool.
- To assess how various loads affect pollution reduction, combustion stability, and efficiency and to validate the model and optimize performance by contrasting simulation and experimental data.
- To determine the ideal blend composition and compression ratio in order to maximize efficiency and reduce hazardous emissions.

2. Material and Procedure

2.1. Material and Properties

Cerium oxide (CeO₂) nanoparticles, diesel fuel, and tyre oil pyrolytic extract (TPOE) were used for the current study in order to create innovative alternative fuel mixes for diesel engine testing. Four tyre oil–diesel combinations, TPOE5D95, TPOE10D90, TPOE15D85, and TPOE20D80, were first created with replacement amounts of 5%, 10%, 15%, and 20% by volume. By adding CeO₂ nanoparticles to particular blends, the fuel properties were further improved, resulting in the formulations TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + c, and TPOE10D80 + D. The CeO₂ nanoparticles were obtained from a

specialized manufacturer of metal oxide nanomaterials, as shown in Figure 1a [13], and the blending strategy was directed by techniques documented in earlier research, as shown in Figure 1b. Equation (1) can be used to calculate the surface tension of blends based on fuel density (constant $C_1 = 49.6$ and $C_2 = 14.92$) [14]. Tables 2–4 display the fuel characteristics and properties of the mixture.

$$\sigma = (C_1\rho - C_2) \times 10^{-3} \quad (1)$$

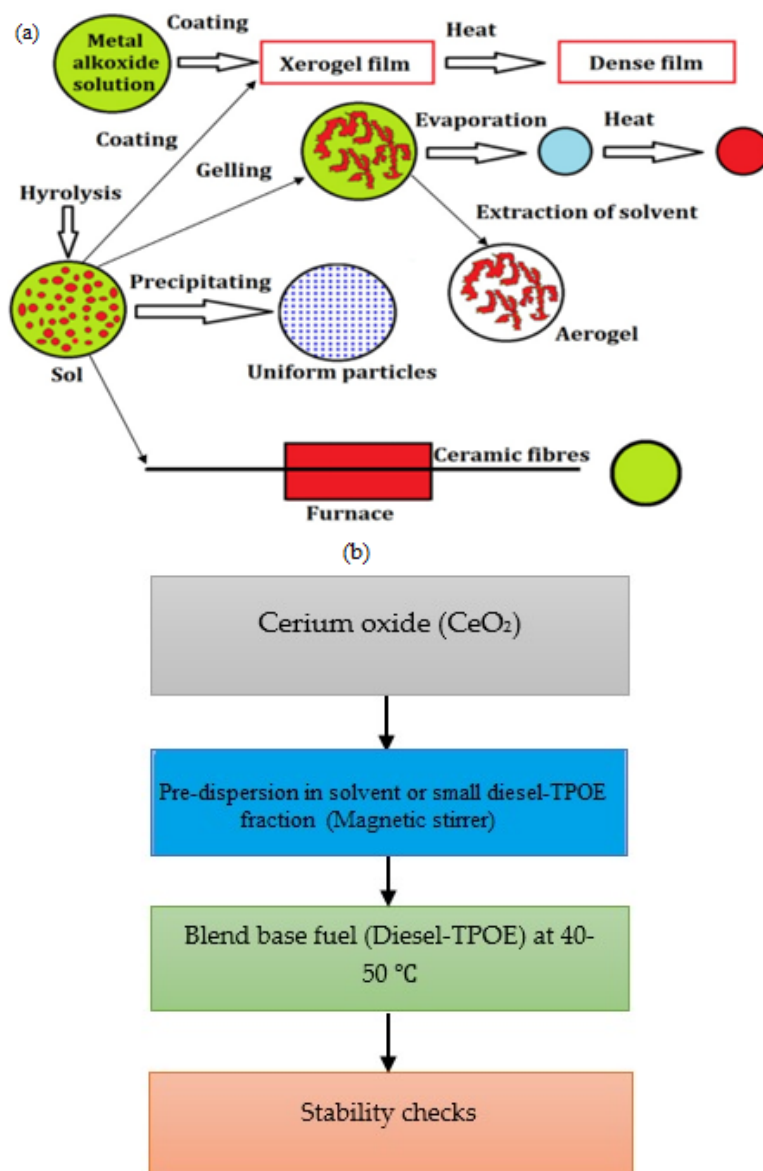


Figure 1. (a). displays a manufacturer of metal-based nanoparticles [13]. (b) Nanoparticles dispersion and fuel blending.

Because of its remarkable oxygen storage and release capabilities, which result from the reversible redox transition between Ce^{4+} and Ce^{3+} , cerium oxide (CeO_2) is an essential catalytic component in the processing of diesel and pyrolysis oil. The breakdown of heavy hydrocarbons and the conversion of oxygenated chemicals found in pyrolysis oils are facilitated by the capacity of CeO_2 s to provide active oxygen for oxidation processes, even in oxygen-lean environments. Therefore, by encouraging full combustion and lowering the creation of unwanted byproducts like soot and coke, CeO_2 makes it easier to produce

cleaner fuels. CeO_2 also works very well in deoxygenation reactions, assisting in the removal of oxygenates from pyrolysis oil, which enhances the stability and calibre of the fuel that it produces. CeO_2 improves dispersion, redox activity, and resistance to deactivation when combined with other catalysts to improve overall catalytic performance. Because of these characteristics, CeO_2 is an essential catalyst for improving pyrolysis and diesel oil, which enhances fuel quality and lowers emissions into the atmosphere.

Table 2. Specifics of CeO_2 .

Sr. No.	Name	Values
1.	Compound	Cerium oxide (CeO_2)
2.	Colour	Pale yellow-white
4.	Producer	M/s. Sigma–Aldrich (Burlington, MA, USA)
5.	Purity	99.97%
6.	Surface area	11–17 m^2/g

Table 3. Properties of fuels derived from waste plastics and municipal solid waste.

Properties/Fuel	TPOE	Diesel
Heating value (MJ/kg)	36.5	43.5
Flash point ($^{\circ}\text{C}$)	35	51
Fire point ($^{\circ}\text{C}$)	40	56
Surface tension (N/m)	0.0451	0.028
Density (kg/m^3)	910	810
Viscosity (cSt.)	12.74	5.665

Table 4. Properties of blends and combustion behaviour characteristics.

Fuel	TPOE5D90 + A	TPOE5D85 + B	TPOE10D85 + C	TPOE10D80 + D
Density (kg/m^3)	817	819	822	824
Flash point ($^{\circ}\text{C}$)	51	52	50	51
Fire point ($^{\circ}\text{C}$)	55	56	54	56
Heating value (MJ/kg)	43.28	43.28	42.94	42.98
Viscosity (cSt.)	6.35	6.4	6.65	6.72

2.2. Experimental Setup

A diesel engine was used for the experiment. For the D-RK tool [15,16], validation against chamber pressure and the heat release rate for diesel fuel was used while preserving injection time and speed (as shown in Figure 2). Table 5 highlights and illustrates the technical details of the different testing equipment employed, as well as the largest unknowns prior to the experiment. Using the equipment and the study's standard deviation equation, error deviations were estimated [17,18]. On the basis of the uncertainty shown in Table 6, the total uncertainty of the experimental data was then computed using the standard deviation equation. The calculated uncertainty was 2.68% overall, as per Equation (2). Four load levels, 25%, 50%, 75%, and 100%, of the rated load were used to operate the engine. An eddy current dynamometer was used to regulate the brake power, and torque was measured with an accuracy of $\pm 0.5\%$. Because 1500 rpm is a common operating point for small stationary diesel engines used in power generation and agricultural applications, this speed was maintained throughout the experiments. Small variations (± 5 rpm) were noted and adjusted for in the analysis. The crank angle before the top dead centre (b TDC) was set at 23.5° for the baseline injection time. Initially, no changes were made to the injection timing for blended fuels; however, trends in heat release and ignition delay were

tracked to guarantee stable combustion. Depending on the impacts of nanoparticles, future optimization might entail moving the timing forward by 1–2° CA. The total uncertainty was calculated using Equation (2) [19] and was found to be 2.68%.

$$\text{Uncertainty} = \sqrt{(\text{Air flow rate})^2 + (\text{Dynamometer})^2 + (\text{Encoder})^2 + (\text{Consumption of fuel})^2 + (\text{CO}_2)^2 + (\text{NO}_x)^2 + (\text{CO})^2 + (\text{Load cell})^2 + (\text{Pressure sensor})^2 + (\text{Smoke meter})^2 + (\text{Temperature sensor})^2 + (\text{speed sensor})^2 + (\text{BTE})^2 + (\text{Density})^2 + (\text{Flash point})^2 + (\text{Fire point})^2 + (\text{Heating value})^2 + (\text{Viscosity})^2} \quad (2)$$



Figure 2. Experiment setup.

Table 5. Apparatus configuration summary.

Parameter	Value
Engine type	Single-cylinder, 4-stroke, DI diesel
Bore × stroke	87.5 mm × 110 mm
Compression ratio	18.5:1
Rated power	5.2 kW @ 1500 rpm
Cooling system	Water-cooled
Injection pressure	220 bars
Injection timing	23.5° b TDC
speed	Constant 1500 rpm
Load conditions	25%, 50%, 75%, and 100% of rated load
Intake air temperature	30 ± 2 °C
cooling water temperature	80 ± 2 °C
Lubricating oil temperature	75 ± 3 °C
Test repetitions	3 per load condition

This study's uncertainty analysis is mostly restricted to formulaic computations and does not provide a more thorough assessment of how these errors affect the dependability of the findings. A more thorough approach that addresses the impact and propagation of errors is required. One important concern is the in-cylinder pressure. Combustion analysis is directly impacted by even minor sensor errors that can skew the heat release rate and ignition delay. Regarding brake power and fuel consumption, measurement mistakes can spread to the BTE and SFC, making efficiency gains less certain. Regarding emission data, results for NO_x, CO, and HC are extremely sensitive to analyser calibration; even little variations could obscure the impacts of nanoparticles.

Table 6. Sources of uncertainty.

Instrument	Uncertainty (%)
Air flow	±1.0
Encoder	±0.2
Dynamometer	±0.15
Fuel consumption	±0.6
CO ₂	±1.0
NO _x	± 0.5
CO	±1.2
Load cell	±0.2
Pressure sensor	±0.5
Smoke meter	±1.0
Speed sensor	±1.0
Temperature sensor	±0.15
Thermal efficiency	±0.9

There is also the issue of the spread of uncertainty, as error propagation should be measured rather than just the main sensor errors. For example, a ±1–3% variation in SFC could be caused by a ±1% inaccuracy in fuel flow. In the absence of this, performance trends could seem more or less robust than they truly are.

2.3. Model Descriptions

2.3.1. Governing Equations

The first rule of thermodynamics is the foundation of the Diesel-RK tool, which analyses engine performance, combustion, and emission data. This model incorporates the conservation equations from Land and Assanis, which utilize the Diesel-RK program [20,21]. The following equations are linked to the Diesel-RK program: conservation of energy (5); conservation of mass (3); conservation of species (4); modelling of engine friction (6); the rate of heat release computed using Tolstov's equation (ignition delay time; premixed combustion phase, mixing-controlled ignition phase, and late ignition phase) (7); and NO_x production via the Zeldovich mechanism (8). Table 7 provides the formation of soot and particulate matter by alkydas (9), HSL (10), and BSN (11).

Table 7. General structure of a model equation.

Equation	Equation
(3)	$\frac{dm}{dt} = \sum_j \dot{m}_j$
(4)	$SFC = \frac{\dot{m}_f}{P_b}$
(5)	$\frac{d(mu)}{dt} = -p \frac{dv}{dt} + \frac{dQ_{ht}}{dt} + \sum_j \dot{m}_j h_j$
(6)	$FMEP = \alpha + \beta P p_{max}$
(7)	$\tau = 3.8 \times 10^{-6} (1 - 1.6 \times 10^{-4} \times n) \sqrt{\frac{T}{p}} \exp\left(\frac{E_a}{8.312T} - \frac{70}{CN+25}\right)$ $\frac{dx}{d\tau} = \Phi_0 \times \left(A_0 \left(\frac{m_f}{v_i} \right) \times (\sigma_{ud} - x_0) \times (0.1 \times \sigma_{ud} + x_0) \right) + \Phi_1 \times \left(\frac{d\sigma_u}{d\tau} \right)$ $\frac{dx}{d\tau} = \Phi_1 \times \left(\frac{d\sigma_u}{d\tau} \right) + \Phi_2 \times \left(A_2 \left(\frac{m_f}{v_c} \right) \times (\sigma_u - x) \times (\alpha - x) \right)$ $\frac{dx}{d\tau} = \Phi_3 A_3 K_T (1 - x) (\zeta_b \alpha - x)$
(8)	$[N_2] + [O] \leftrightarrow [NO] + [N] \quad [N] + [O_2] \leftrightarrow [NO] + [O]$ $\frac{d[NO]}{d\theta} = \frac{P \times 2.333 \times 10^{-7} \cdot e^{-\frac{38020}{T_b}} [N_2]_e [O]_e \left\{ 1 - \left(\frac{[NO]}{[NO]_e} \right)^2 \right\}}{R \cdot T_b \cdot \left(1 + \frac{2365}{T_b} \cdot e^{\frac{2365}{T_b}} \cdot \frac{[NO]}{[NO]_e} \right)} \cdot \frac{1}{\omega}$

Table 7. Cont.

Equation	Equation
(9)	$\left(\frac{d[C]}{dt}\right)_K = 0.004 \frac{q_c}{V} \frac{dx}{dt}$
(10)	$HSL = 100\{1 - 0.9545\exp(-2.4226[C])\}$
(11)	$[PM] = 565\left(\ln \frac{10}{10-BN}\right)^{1.206}$

2.3.2. Validation Tool

In this work, the D-RK tool was used to quantitatively evaluate the engine characteristics of a CI engine operating on CDF, TPOE as a substitute, and CeO₂ with 50 and 100 ppm. The chamber pressure shown in Figures 3 and 4 demonstrates the degree of concordance between simulation and experiment results (chamber pressure and heat release rate). The observed error deviation is a consequence of the interactions between the experimental and simulation hypotheses. Because the error deviation for in-chamber pressure was found to be 9.37% and for the in-heat release rate was found to be 7.18%, in the current investigation, as per the literature, the graph clearly demonstrates that the chamber pressure and heat release rate are operating under the same conditions as those listed in Table 5. The experimental findings of a single-chamber diesel engine working under identical circumstances are validated by comparing them to the predicted Diesel-RK results, as per [22]. At a higher load scenario (100%), the rate of heat escape decreased, and the discrepancy between the numerical and experimental chamber pressure values widened. The experimental and numerical data for in-chamber pressure (94.7 bar and 104.5 bar) and the heat release rate in the chamber (75.85 J/degree and 70.4 J/degree) are supplied as per the literature.

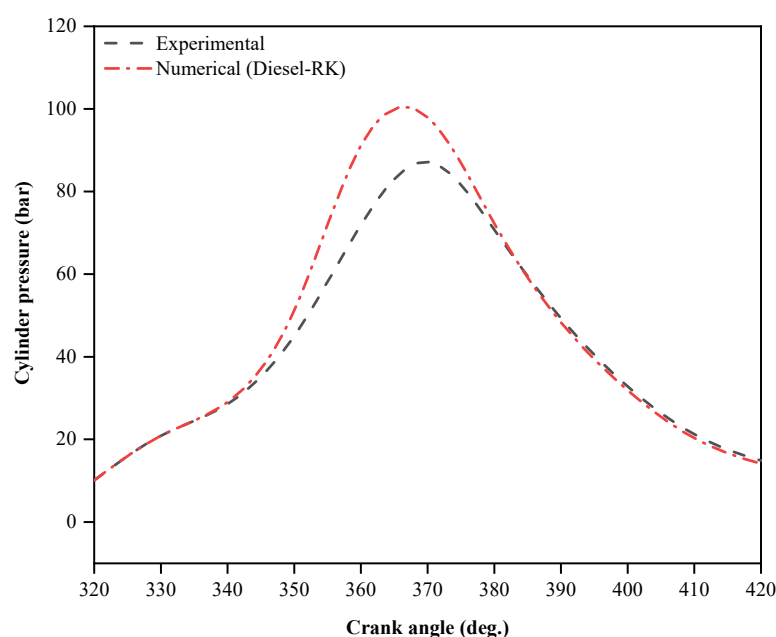


Figure 3. Cylinder pressure with crank angle.

2.3.3. Optimization Results

Using diesel–TPOE alternative–CeO₂ ternary mixes, the engine characteristics of a CI engine were optimized with the use of the D-RK tool. As shown in Figure 5, compression ratios of 15.5, 16.5, 17.5, 18.5, and 19.5 yielded better outcomes than compression ratios of 18.5 (Figure 5a–d). The current investigation revealed that higher compression ratios led to higher chamber pressure, NO_x discharges, and reduced ignition delay and fuel consumption. The graph in Figure 5 clearly illustrates these findings (Figure 5a–d). When

compared to 15.5, 16.5, 17.5, 18.5. and 19.5, it was discovered that at a CR18.5 chamber pressure, engine power is higher and fuel consumption is lower. In comparison to 15.5, 16.5, 17.5, and 19.5, CR18.5 is an effective compression ratio. Using TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + nano-additives A, TPOE5D85 + nano-additives B, TPOE10D85 + nano-additives C, TPOE10D80 + nano-additives D, diesel fuel (CDF), and tyre oil (TPOE) fuel blends, CR18.5 was used to assess ignition, performance, and discharge characteristics.

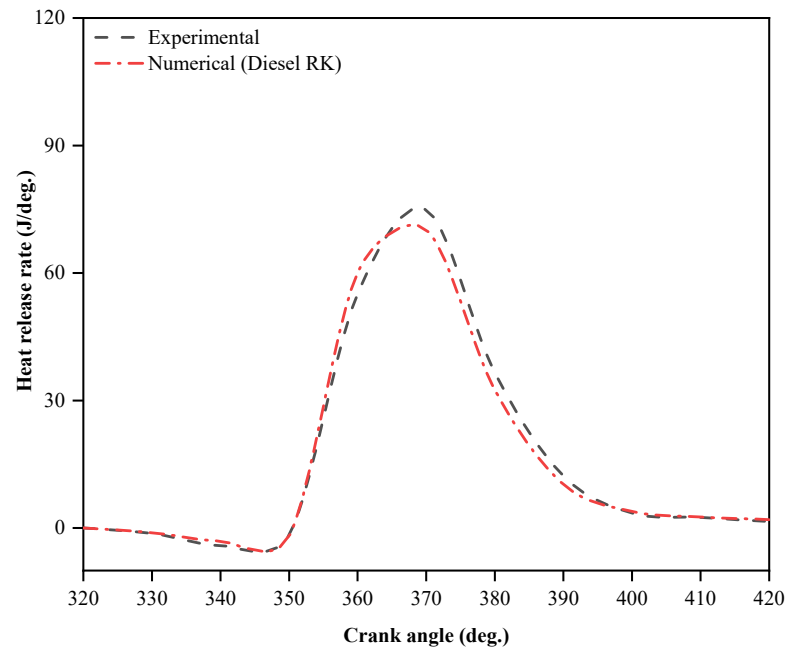


Figure 4. HRR with crank angle.

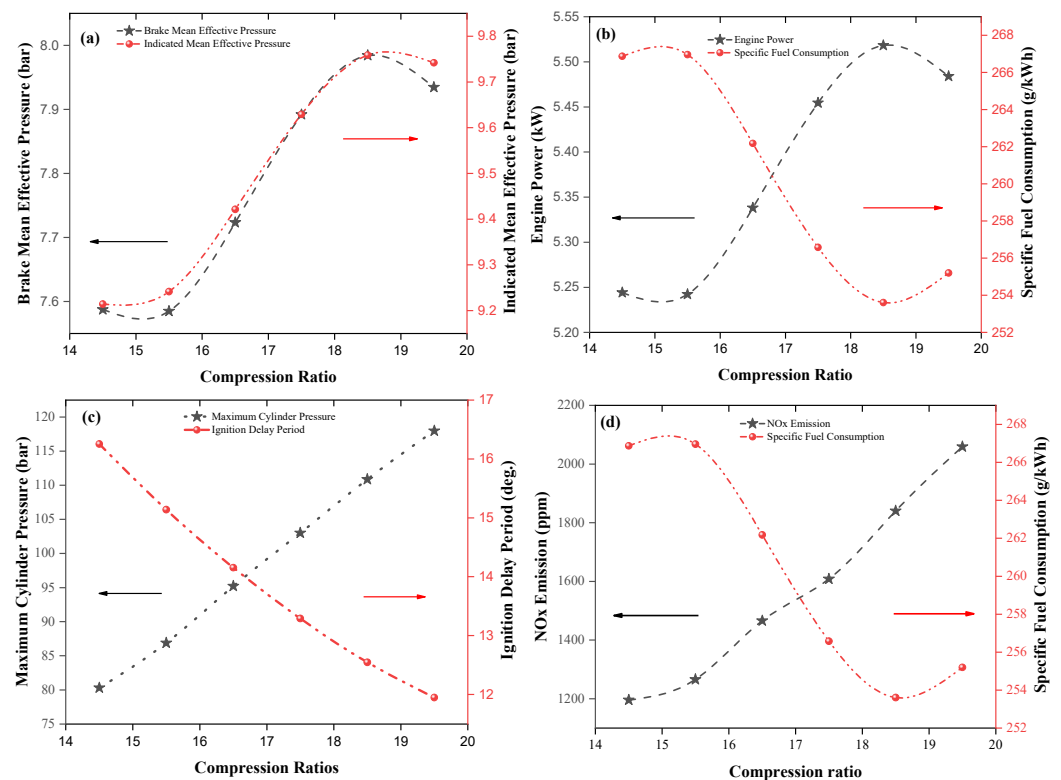


Figure 5. Optimizing outputs by varying parameters vs compression ratios for (a) BMEP and IMEP, (b) Engine power and SFC, (c) Cylinder pressure and Ignition delay, and (d) NO_x emission and SFC.

3. Result and Discussion

3.1. Performance Characteristics

3.1.1. Specific Fuel Consumption

Figure 6 depicts the connection between specific fuel consumption (SFC) and load for the formulations TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE. Due to its lower calorific value than diesel and tyre oil (TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, and TPOE), CeO_2 nano-additions had a lower SFC. CeO_2 nano-additions are slightly more expensive than diesel fuel. The viscosity and surface tension of the TPOE5D95, TPOE10D90, TPOE15D85, and TPOE20D80 blends rose as the fraction of alternatives increased. In this experiment, CeO_2 (50–100 ppm) was combined with CDF-TPOE at a concentration of 10% by volume. SFC declines with load in all fuel mixtures with unmodified engine characteristics [21,23]. Increased fuel input to the chamber reduces oxygen for ignition [24,25]. Oxide nano-additions to blends lowered fuel usage at full load. At a 100% load, the SFC values of TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE were 299.4, 288.6, and 296.9.

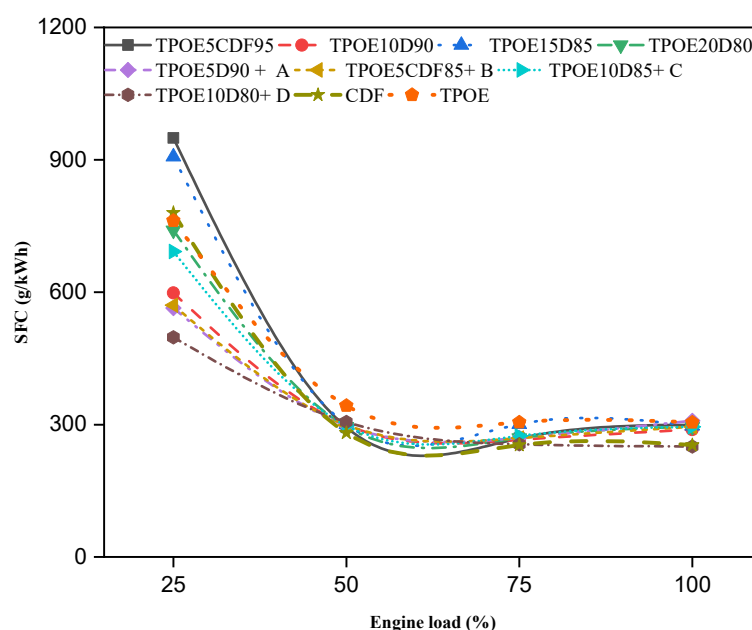


Figure 6. Analysis of SFC under varying load conditions.

3.1.2. Brake Thermal Efficiency

Figure 7 illustrates the brake thermal efficiency (BTE) as a function of load for the following materials: TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE. In published descriptions of diesel engines, the BTE is defined as the connection between braking force and the total amount of heat generated during fuel ignition [26,27]. Compared to diesel fuel, the TPOE5D90, TPOE5D85, TPOE10D85, and TPOE10D80 fuel combinations with nano-additives at 50 ppm and 100 ppm exhibited lower brake thermal efficiency. This effect is because adding nano-additives to the fuel mixture decreases the fuel's calorific value. The presence of oxygen molecules in TPOE5D95, TPOE10D90, TPOE15D85, and TPOE20D80 improved ignition as the amount of alternative fuel increased in the blends. The properties of the spray are influenced by factors such as viscosity, surface tension, and the concentration of oxygen molecules [28]. In this experiment, CeO_2 (50–100 ppm) was combined

with CDF-TPOE up to 10% by volume. At an increasing load, the BTEs of diesel, tyre oil substitute, and TPOE10D80 + CeO₂ 100 ppm tested fuel mixes are greater. Adding more oxide nano-additives to the blends enhances the BTE at the full-load condition. At a 75.0% load, the BTE values for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE were found to be 30.98 and 31.73. Although the direction of this increase is positive, it is as significant as earlier research employing fuels augmented with nano-additives. Increased oxygen availability, catalytic activity in soot oxidation, and improved atomization characteristics are the main reasons for the up to 1% BTE improvements reported in studies employing cerium oxide nanoparticles in diesel and alternative blends. This study's comparatively modest improvement may be due to a number of factors: blend formulation limit, as it is possible that the CeO₂ concentrations chosen were not the best for catalytic activity; and dispersion stability, as during burning, the agglomeration of nanoparticles may result in decreased surface activity. When compared to transitory or higher-load circumstances, the benefits of nanoparticles may not have been as evident in engine operating conditions, which are characterized by steady speed and a fluctuating load. Therefore, even though the findings support the ability of CeO₂ to affect thermal efficiency, a higher dosage, dispersion, and operating strategy tuning are needed to produce gain on par with that reported in earlier studies.

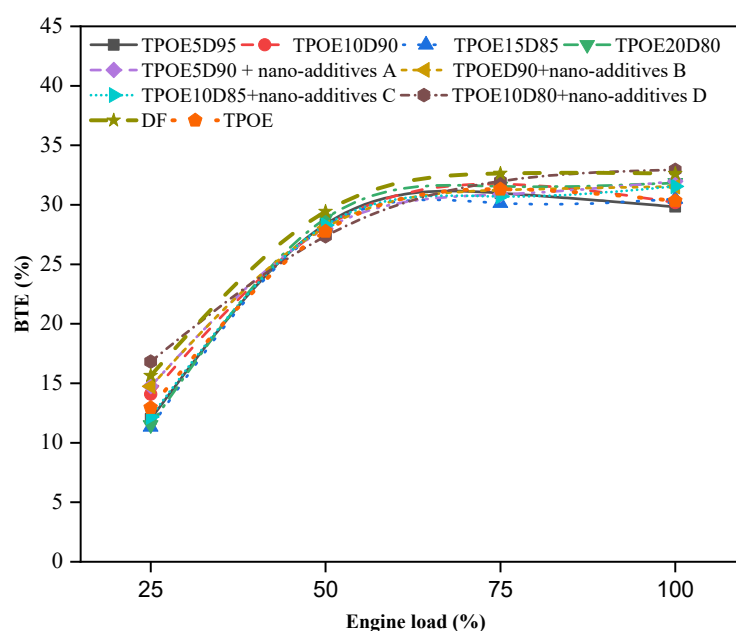


Figure 7. Analysis of BTE under varying load conditions.

3.1.3. Exhaust Gas Temperature

Figure 8 illustrates the exhaust gas temperature (EGT) vs. load for the following engines: TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE. The addition of more CeO₂ nano-additives enhances the EGT at a full load compared to diesel fuel but less so for the TPOE10D80 + CeO₂ 100 ppm fuel blend. At 100% load, it was determined that the values of EGT for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D80 + C, TPOE10D80 + D, CDF, and TPOE were 741.6, 696.89, 696.79, 696.91, 746.1, 703.44, 706.88, 673.97, 721.9, and 666.01K. Due to an enhancement in ignition, the EGT reduced as the percentage of nano-additives in the blend increased. Due to improved ignition properties, the EGT falls for the entire load as the number of nano-additive particles in tyre oil–diesel fuel blends increase [29,30]. Because the chamber

gas temperature was lower in the tyre oil alternative–diesel fuel blend than in the diesel fuel, the EGT was reduced [31].

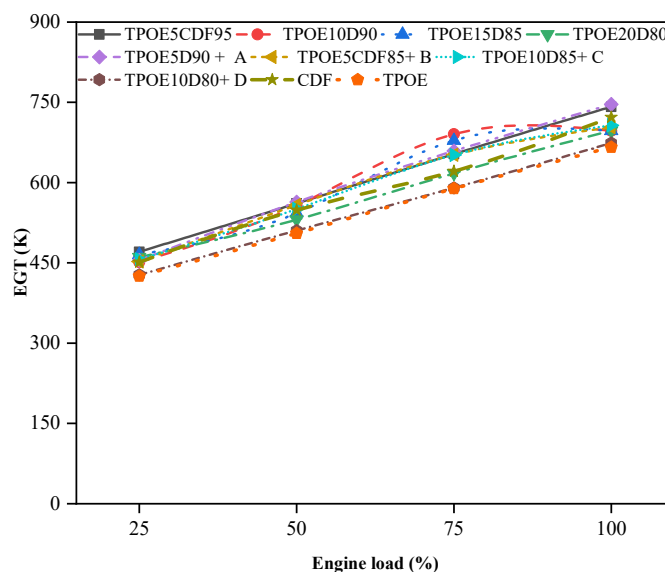


Figure 8. Analysis of EGT under varying load conditions.

3.2. Combustion Characteristics

3.2.1. Chamber Pressure

Figure 9 illustrates the relationship between in-chamber pressure (ICP) and the crank angle for the following: TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE. The heat value decreased with increased TPOE, and the peak chamber pressure was reduced. Because of enhanced ignition, the chamber pressure rises as the load rises [32,33]. The peak chamber pressure for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE was found to be 97.85, 109.97, 105.8, 110.5, 92.72, 103.84, 102.3, 126.1, 110.88, and 97.58 bar. According to the graph, the chamber pressure for 10% of TPOE with 80% of CDF with CeO₂ (100 ppm) is higher than that for TPOE, CDF, and their mixtures. The chamber pressure reduces by 0.34% (TPOE20D80) compared to diesel when the percentage of tyre oil fuel is increased from 0% to 20% but increases by 12.0% with TPOE10D80 + CeO₂ (100 ppm). At higher loads, the peak cylinder pressure was lower with the tyre oil alternative than with diesel fuel due to the calorific value [34].

3.2.2. Heat Release Rate

Figure 10 illustrates the relationship between the in-chamber heat release rate (ICHRR) and the crank angle for the following engine types: TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D80 + C, CDF, and TPOE. At a full load, the peak ICHRR is enhanced in blends with higher oxide nano-additives compared to blends with tyre fuel. PCHRR values for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE were determined to be 46.93, 68.4, 63.24, 62.8, 48.5, 61.2, 60.91, 89.97, 68.7, and 70.3 J/degree. When the amount of TPOE blending is enhanced from 0% to 20%, the chamber heat release rate (TPOE20D80) falls by 8.5% compared to CDF; however, it grows by 23.6% for TPOE10D80 + D. As the load increases, the peak chamber heat release rate rises faster with tyre oil replenishment than with diesel fuel [33,34].

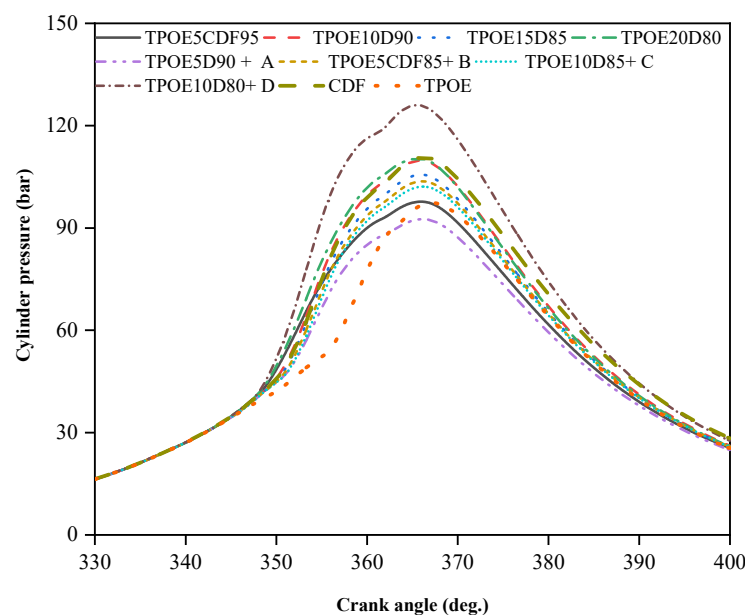


Figure 9. Cylinder pressure with crank angle.

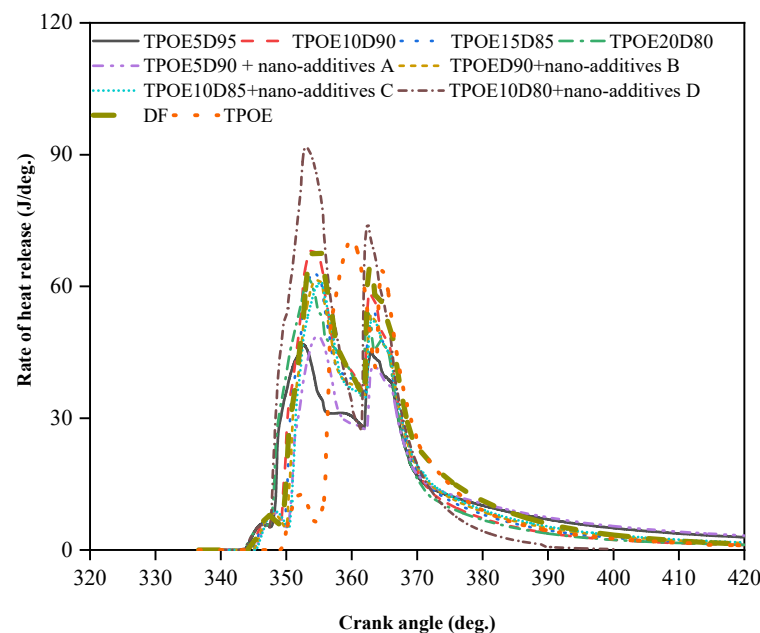


Figure 10. Rate of heat release with crank angle.

3.2.3. Ignition Delay Period

In Figure 11, the assessment of the ignition delay period (IDP) in relation to the loads for the following TPOEs is depicted: TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE. The use of more oxide nano-additives enhances the IDP at a full load, associated with fuel mixtures. At higher loads, it was determined that the values of IDP for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE were 10.88, 12.32, 12.81, 10.9, 13.4, 13.2, 13.66, 10.65, 12.43, and 18.89 degree. The ignition delay increased by 9.0% for TPOE10D80 + D but by 7.23% for TPOE20D80 when the percentage of the tyre oil alternative fuel grew from 0% to 20%. The ignition delay rate increases more rapidly with the tyre oil alternative than with diesel fuel at higher loads [33,34].

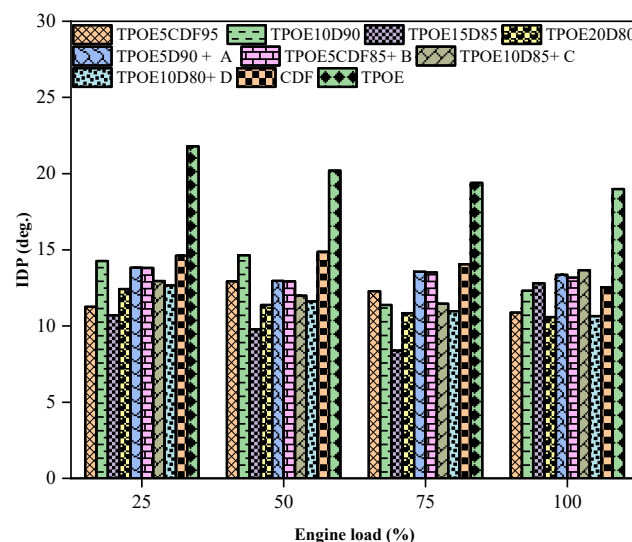


Figure 11. Analysis of IDP under varying load conditions.

3.3. Emission Characteristics

3.3.1. Oxides of Nitrogen Discharge

Figure 12 illustrates the relationship between load and the assessment of nitrogen oxide (NO_x) discharge for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE. When associated with CCDF and TPOE mixtures, NO_x was reduced for TPOE5D90 + A, TPOE5D85 + B, and TPOE10D85 + C at the full load condition due to the increase in CeO_2 in the mixtures. The decreased nitrogen is because the chemicals' functional groups show that the firing process needs to be finished. NO_x values were determined to be 6.04, 9.11, 9.75, 12.54, 4.53, 7.8, 6.61, 26.41, 9.61, and 6.52 g/kWh for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, B, and C, TPOE10D80 + D, CDF, and TPOE, respectively, at a 100% load. Due to an increase in the ignition temperature, NO_x discharges rose as the load increased [34–36]. The use of additives reduced the NO_x discharges from the tyre oil–diesel fuel blends when compared to diesel engine discharges. The TPOE10D80 + nano-additive D emission had the greatest NO_x emission at 26.41 g/kWh. In comparison to other test blend ratios, TPOE5D90 + A had the lowest NO_x emission at 4.53 g/kWh. The shortest NO_x discharges come from a combination of ceramic nano-additives, while the longest come from a combination of diesel that is almost identical to diesel. The main factors impacting NO_x discharges are the fuel ignition temperature, load, and fuel mixtures [37–39]. The NO_x emission figure with engine loads shows that the NO_x emission rises as the engine load increases. The amount of gasoline pumped into the cylinder affects the combustion temperature, which rises with an increased engine load. NO_x production is dynamically influenced by the temperature of combustion and the amount of oxygen present. Greater NO production rates are caused by greater combustion temperatures and the gases' residence time at those temperatures.

Because cerium oxide (CeO_2) serves as both a combustion catalyst and an oxygen buffer, its effects on NO_x emissions in diesel and waste tyre oil mixes show a complex trend. By releasing active oxygen during combustion [40,41] CeO_2 nanoparticles improve the oxidation of hydrocarbons and soot precursors through their $\text{Ce}^{3+}/\text{Ce}^{4+}$ redox cycle. In most cases, this results in lower emissions of CO, HC, and smoke. Because the catalyst facilitates effective oxidation without appreciably increasing in-cylinder temperatures, the enhanced combustion stability and reduced ignition delay at lower blending ratios of tyre oil with diesel (usually 5–10%) lead to decreased NO_x emissions. However, CeO_2 speeds up the oxidation of the heavier material [40].

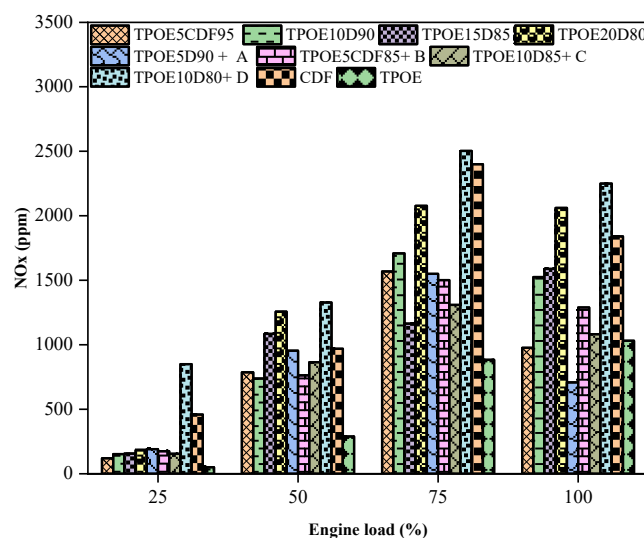


Figure 12. Analysis of NO_x under varying load conditions.

3.3.2. Smoke Emission

Figure 13 depicts smoke emission (1/m) values as a function of load for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE. The addition of CeO_2 to the mixtures enhances the smoke output at a full load. At the full load condition, smoke was determined to be 1.42, 1.00, 0.972, 0.954, 1.511, 1.033, 1.091, 0.63, 3.65, and 1.06 1/m for TPOE5D95, TPOE10D90, TPOE15D85, TPOE20D80, TPOE5D90 + A, TPOE5D85 + B, TPOE10D85 + C, TPOE10D80 + D, CDF, and TPOE, respectively. Due to the oxide nano-additives and TPOE-CDF mixture, smoke emission grows with a greater load. The enhanced complete ignition and longer penetration duration of the blends, compared to diesel fuel, result in reduced smoke emissions. All fuel mixes investigated in the present experiment produce more smoke at higher loads due to TPOE's enhanced ignition [38,42].

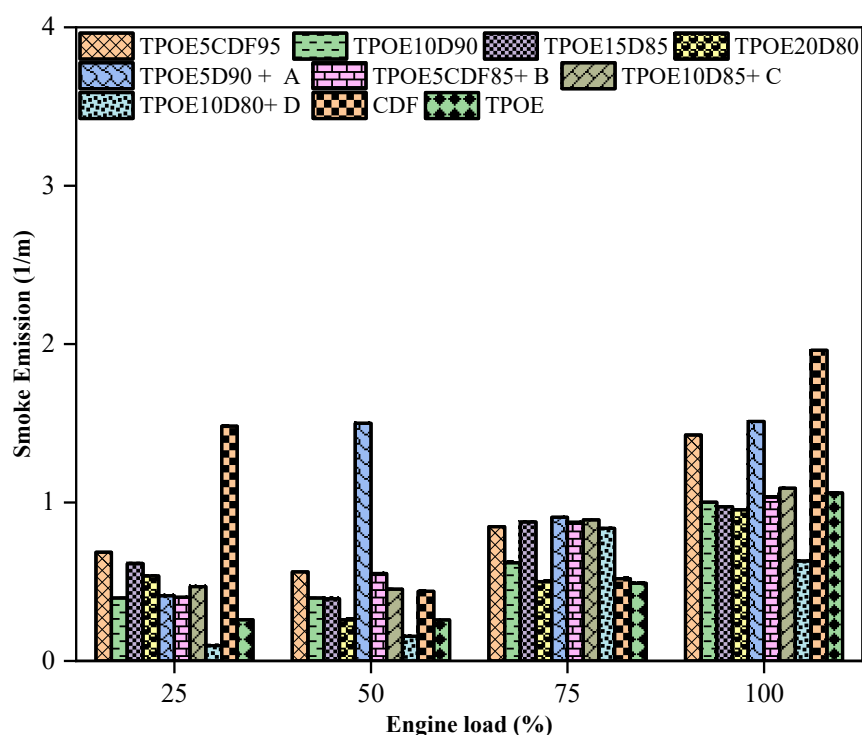


Figure 13. Analysis of smoke emission under varying load conditions.

3.3.3. Summary of Emission

Figure 14 displays the value of the SOE (summary of emission) vs. load for the following compounds: TPOE₅D₉₅, TPOE₁₀D₉₀, TPOE₁₅D₈₅, TPOE₂₀D₈₀, TPOE₅D₉₀ + A, TPOE₅D₈₅ + B, TPOE₁₀D₈₅ + C, TPOE₁₀D₈₀ + D, CDF, and TPOE. The SOE is improved at a full load by the accumulation of more CeO₂ in the mixtures. At a 100.0% load, it was determined that the values of BTE for TPOE₅D₉₅, TPOE₁₀D₉₀, TPOE₁₅D₈₅, TPOE₂₀D₈₀, TPOE₅D₉₀ + A, TPOE₅D₈₅ + B, TPOE₁₀D₈₅ + C, TPOE₁₀D₈₀ + D, CDF, and TPOE were 4.6, 4.04, 4.21, 4.48, 4.68, 3.93, and 5, respectively. Compared to 100% of diesel, the 100 ppm additive particle with tyre oil–alternative fuel has the shortest summary of discharges.

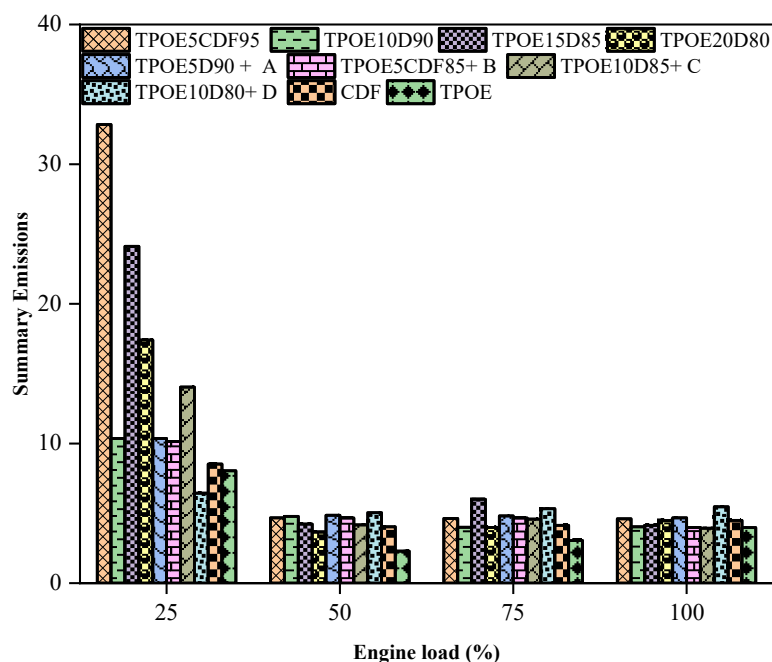


Figure 14. Analysis of summary of emissions under varying load conditions.

4. Conclusions

The impacts of CeO₂ with 50 ppm and 100 ppm and a diesel–tyre pyrolysis oil substitute on engine characteristics were simulated numerically. The concise findings were the following:

- Utilizing tyre pyrolysis oil for alternative production will contribute greatly to environmental compensations and provide an alternative to releasing the tyre pyrolysis oil into the environment.
- Adding nano-additive (CeO₂) particles to diesel–tyre pyrolysis oil enhances brake thermal efficiency and chamber pressure while reducing SFC.
- Increasing the proportion of tyre pyrolysis oil in blends has negative effects, including lengthening the ignition delay duration, increasing SFC, and decreasing EGT.
- With the TPOE₁₀D₈₀ + D nano-additive gasoline sample, reduced fuel consumption and enhanced thermal brake efficiency were observed (100 ppm).
- As the amount of tyre pyrolysis oil in blends increases, emissions of nitrogen oxide and smoke are decreased. Additionally, the addition of CeO₂ to TPOE blends demonstrates an inverse propensity for NO_x emission.
- When increasing volumes of tyre pyrolysis oil are added to blends, the total discharges are lower than when 50 ppm and 100 ppm CDF and ceramic oxide are added, respectively.

- This research may increase the use of compression ignition engines and a unique mix that blends 100 ppm of tyre pyrolysis oil alternative with ceramic oxide.

The limitations of this study should be critically discussed. Specifically, the possibility of nanoparticle aggregation could impair combustion efficiency and decrease dispersion stability. Because nanoparticles are abrasive, they may hasten the wear of cylinder and fuel injector components, raising concerns about long-term engine durability. Furthermore, given the expenses of preparation, stabilization, and large-scale applications, it is still unclear if utilizing CeO₂ additions is economically feasible. A more accurate and balanced evaluation of the study's practical consequences will result from addressing these limitations.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

BTE	Brake thermal efficiency
BMEP	Brake mean effective pressure
IMEP	Indicated mean effective pressure
SFC	Specific fuel consumption
D-RK	Diesel-RK
CDF	Conventional diesel fuel
CeO ₂	Ceramic oxide
CI	Compression ignition
EGT	Exhaust gas temperature
SMD	Diameter of drops
TPOE5D95	5% of TPOE + 95% CDF
TPOE10D90	10% of TPOE and 90% CDF
TPOE15D85	15% of TPOE and 85% CDF
TPOE20D80	20% of TPOE and 80% CDF
TPOE5CDF90 + A	5% of TPOE and 90% CDF + CeO ₂ 50 ppm
TPOE5CDF85 + B	5% of TPOE and 85% CDF + CeO ₂ 100 ppm
TPOE10CDF85 + C	10% of TPOE and 85% CDF + CeO ₂ 50 ppm
TPOE10CDF80 + D	10% of TPOE and 80% CDF + CeO ₂ 100 ppm
TPOE	Tyre pyrolysis oil energy
SOE	Summary of emission
A ₀ , A ₂ , A ₃	Empirical factors
BSN	Bosch Smoke Number
BN	Bosh number
C	Carbon
CN	Cetane number
E _a	Activation energy, kJ/k. mole
K _T	Temperature, K
m	Total mass, kg
$\dot{m}_f$	Mass flow rate, kg/s

n	Speed, rpm
p	Pressure, bar
P_b	Engine power, kW
P_{max}	Maximum chamber pressure, bar
PM	Particulate matter
q_c	Cycle fuel mass
R	Gas constant, J/mole. K
T	Temperature, K
T_b	Burnt gas zone, K
V	Volume chamber, cm ³
V_p	Mean velocity of piston, m/s
x_0	Fraction of burnt fuel (ignition delay)
x	Fraction of fuel burnt
α, β, λ	Constants
τ	Time, s
ξ_b	Air charge usage efficiency
ρ	Density, kg/m ³
$\Phi_0, \Phi_1, \Phi_2, \Phi_3$	Constant
σ_u, σ_{ud}	Fuel fractions evaporated during ignition delay period
dx/dt	Heat release rate, 1/degree
ω	Angular crank velocity, rpm

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