



Performance and Emission Optimization of *Spirulina platensis* Biodiesel Blends with Green-synthesized CeO₂ Nanoparticles for Low-emission Diesel Engines

Shruti A Gomkale¹, Merlyn Stephen², S. Mayakannan^{3*}, R. Suresh⁴, Kallakunta Ravi Kumar⁵ and K. Vinukumar⁶

¹Department of Applied Chemistry, Yeshwantrao Chavan College of Engineering, Nagpur, MH, India

²Department of Botany, A.V.V.M. Sri Pushpam College (Autonomous), Affiliated to Bharathidasan University, Poondi, Thanjavur, TN, India

³Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, TN, India

⁴Department of Mechanical Engineering, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Tiruvallur, TN, India

⁵Department of Electronics and Communication Engineering, Koneru Lakshmaiah Education and Foundation, Guntur, AP, India

⁶Department of Mechanical Engineering, Francis Xavier Engineering College, Tirunelveli, TN, India

Received: 19.03.2026 Accepted: 22.03.2026 Published: 30.06.2026

*kannanarchievs@gmail.com



ABSTRACT

Biomass-derived biodiesel is a sustainable and renewable fuel alternative with significant potential for sustainable energy applications. The depletion of fossil fuels and stringent emission regulations necessitate the development of high-efficiency alternative fuels for compression ignition engines. *Spirulina platensis* microalgae biodiesel was produced through transesterification and blended with diesel at 25% and 45% proportions, followed by the incorporation of green-synthesized CeO₂ nanoparticles derived from *Moringa oleifera* leaf extract. The bio-assisted synthesis yielded uniformly distributed nanocrystalline CeO₂ particles with an average particle size of 40 ± 5 nm, confirmed by FTIR and SEM analyses. The novelty of this work lies in the combined application of *Spirulina platensis* biodiesel, bio-mediated CeO₂ nano-additives, and statistical optimization to enhance diesel engine combustion and emission characteristics. Engine performance and emission characteristics were evaluated in a single-cylinder, 3.7 kW diesel engine operating at 1500 rpm under varying load conditions, and statistical optimization was performed using Response Surface Methodology with Central Composite Design. The optimized blend achieved a minimum specific fuel consumption of 0.275 kg/kWh and carbon monoxide (CO) emission of 0.105 vol%, along with significant hydrocarbon reduction. The optimized blend achieved a minimum specific fuel consumption of 0.275 kg/kWh and carbon monoxide (CO) emission of 0.105 vol%, along with significant hydrocarbon reduction. ANOVA results confirmed CeO₂ dosage as the most influential parameter governing combustion improvement and emission mitigation. The integrated fuel formulation improved combustion characteristics and reduced harmful emissions, demonstrating its potential for cleaner diesel engine applications.

Keywords: *Spirulina platensis* microalgae; *Moringa oleifera* leaf extract; CeO₂ nanoparticles; Combustion; Response surface methodology.

1. INTRODUCTION

The escalating environmental contamination and the finite supply of fossil fuel resources have resulted in an increased need for renewable energy alternatives. CeO₂ nanoparticles were synthesized via a green route using *Azadirachta indica* leaf extract, with the process optimized using RSM coupled with a genetic algorithm. The synthesized CeO₂ nanoparticles demonstrated enhanced fuel properties and suitability for biodiesel applications (Manimaran, 2023). CeO₂ nanoparticles were synthesized using an eco-friendly solution combustion technique with *Butea monosperma* seed powder fuel and characterized through XRD, FTIR, and SEM. The nanoparticles exhibited good crystallinity, tunable band gap, antibacterial activity, and catalytic

efficiency (Rudreshappa *et al.* 2022). To further improve biodiesel production efficiency and engine operating conditions, advanced optimization and decision-making approaches have also been increasingly applied. *Spirulina platensis* biomass was utilized for biodiesel production through acid-catalyzed transesterification, optimizing methanol ratio, temperature, reaction time, catalyst concentration, and stirring speed. Response Surface Methodology (RSM) was employed to optimize the biodiesel production process (Chhikara *et al.* 2024).

Spirulina platensis DRH 20 was cultivated at four photobioreactors under controlled CO₂ and pH conditions to enhance biomass and lipid productivity. The highest biomass (20.7 g L⁻¹) and lipid productivity (0.581 g L⁻¹ day⁻¹) were obtained with CO₂

supplementation (De Souza *et al.* 2023). *Enteromorpha flexuosa* macroalgae was evaluated for biodiesel suitability and compared with *Nannochloropsis oceanica* and *Spirulina platensis* using cell disruption methods. Acid treatment showed higher lipid recovery than bead milling, achieving up to 136.36% recovery for *Nannochloropsis* (Elnajjar *et al.* 2023). *Spirulina platensis* was cultivated at diluted palm oil mill effluent to enhance biomass, lipid, and phycocyanin production under controlled environmental conditions. The highest lipid yield (28.6%) was obtained using ultrasound extraction, with major FAMES including stearic, palmitoleic, and palmitic acids (Palanisamy *et al.* 2023). In addition to nanoparticle-assisted fuel enhancement, microalgae-based biodiesel has emerged as a sustainable alternative feedstock due to its high lipid productivity and carbon sequestration potential. Microalgae biodiesel (B20) blended with 50 and 100 ppm CeO₂ nanoparticles was evaluated in a 3.5 kW diesel engine under varying loads. CeO₂ addition significantly reduced harmful exhaust emissions and improved combustion behavior (Jayabal, 2025).

Beyond biodiesel production, several studies have investigated the influence of nanoparticle additives on combustion, engine performance, and emission characteristics of biodiesel-fueled CI engines. Palmyra oil methyl ester (POME20) was tested with varying EGR rates and compression ratios, with nano-additives (Al₂O₃ and CeO₂) in a diesel engine. At CR 20:1 with 6% EGR and 100 ppm nanoparticles, BSFC reduced significantly, and CO, HC, and smoke emissions decreased, though NO_x initially increased before EGR control (Vijaya *et al.* 2022). Cottonseed biodiesel blended with 50 and 75 ppm CeO₂ nanoparticles was tested in a three-cylinder diesel engine under four load conditions. However, NO_x emissions increased due to improved combustion performance and higher in-cylinder temperatures (Çelik *et al.* 2022). B20 biodiesel derived from Used Temple Oil Methyl Ester (UTOME) was enhanced with 100 ppm CeO₂ nanoparticles and tested under varying loads. Machine learning models demonstrated strong predictive capability for biodiesel engine performance (Jegan *et al.* 2023). Jackfruit biodiesel–camphor blends were doped with ZnO, CeO₂, and Al₂O₃ nanoparticles (100 ppm each) to enhance emissions and combustion in a CI engine. Nano-additives increased calorific value and improved BTE by up to 15.3% (ZnO), while reducing CO, HC, NO_x, and smoke emissions at full load (Rajasekaran *et al.* 2025). Waste cooking oil biodiesel blends were doped with Al₂O₃ and CeO₂ nanoparticles and evaluated under varying loads with exhaust gas recirculation (EGR). The addition of 70 ppm Al₂O₃ with 10% EGR enhanced BTE and reduced BSFC, CO, and HC emissions, while 60 ppm CeO₂ reduced NO_x and HC emissions at part load (Sathish *et al.* 2023b).

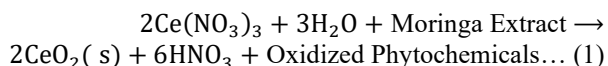
The study implemented Reactivity Controlled Compression Ignition (RCCI) using *Jatropha* biodiesel as high-reactivity fuel and gasoline as low-reactivity fuel to improve CI engine efficiency and reduce emissions. Multi-response optimization using the VIKOR method identified B15 + 2 ms gasoline injection at 80% load as the optimal operating condition (Sengodan *et al.* 2025). The magnetic nanocatalyst (CaFe₂O₄) was employed for transesterification of cottonseed, pongai seed oils, and rubber seed to produce biodiesel with yields exceeding 95%. Central composite design optimization minimized methanol and catalyst usage while maintaining efficient conversion at 70 °C. The produced biodiesel met EN and ASTM standards, confirming suitability for diesel engine applications without modification (Saravanan *et al.* 2024). Four biodiesel feedstocks—microalgae, palm oil, soybean oil, and coconut oil—were ranked using five weighting methods (EQUAL, CRITIC, ENTROPY, AHP, FAHP) and five MCDM techniques including PROMETHEE, WSM, WPM, TOPSIS, and VIKOR (Anwar, 2021b). Sixteen biodiesel feedstocks were analysed based on fifteen economic, technical, and environmental uses by WSM, PROMETHEE-GAIA, TOPSIS, and WPM methods with multiple weighting approaches. Coconut oil consistently ranked as the best alternative, while soybean was identified as the least suitable feedstock. The results highlight the importance of multi-dimensional decision analysis in biodiesel feedstock selection (Anwar, 2021a).

Although several studies have explored nanoparticle-assisted biodiesel combustion and microalgal biofuel production, limited research has focused on the integrated use of green-synthesized rare-earth nanoparticles with microalgal biodiesel under statistically optimized operating conditions. Furthermore, the combined evaluation of bio-mediated CeO₂ nanoparticles, *Spirulina platensis* biodiesel blends, and multi-response optimization for simultaneous enhancement of engine performance and emission reduction remains insufficiently investigated. The novelty of this study lies in the integrated application of green-synthesized CeO₂ nanoparticles derived from *Moringa oleifera* leaf extract and *Spirulina platensis* biodiesel to enhance diesel engine performance and emission characteristics. Unlike conventional chemically synthesized nano-additives, the bio-mediated CeO₂ nanoparticles exhibited nanocrystalline stability of 40 ± 5 nm with high catalytic activity. Response Surface Methodology coupled with Central Composite Design was employed to optimize CeO₂ dosage (10–70.35 mg/L) and engine responses. The optimized condition, SB25 with 70.35 mg/L CeO₂, achieved minimum specific fuel consumption (0.275 kg/kWh) and CO emission (0.105 vol%). This integrated approach provides a statistically validated and sustainable framework for developing

next-generation low-carbon combustion systems using green nanotechnology and microalgal biodiesel.

2. MATERIALS AND METHODOLOGY

CeO₂ nanoparticles were synthesized using a green and environmentally benign approach employing *Moringa oleifera* leaf extract as a reducing and stabilizing agent. Fresh *Moringa oleifera* leaves were collected, thoroughly washed with distilled water, and air-dried. Approximately 10 g of cleaned leaves were boiled in 100 mL of deionized (DI) water for 20 min to extract bioactive phytochemicals. The obtained extract was cooled to room temperature (25 ± 2 °C) and filtered using Whatman filter paper to remove residual solids. Separately, 0.1 M cerium nitrate hexahydrate [Ce(NO₃)₃·6H₂O] solution was prepared in 50 mL of distilled water, and the pH was adjusted to 7–8 using dilute sodium hydroxide solution to facilitate nanoparticle formation (Azam and Park, 2024). The leaf extract was then added dropwise into the cerium nitrate solution under continuous magnetic stirring. The phytochemical constituents present in the extract reduced Ce³⁺ ions into CeO₂ nanoparticles while simultaneously acting as capping and stabilizing agents to minimize agglomeration.



The reaction mixture was continuously stirred and heated at 80°C for 1 h to promote nanoparticle nucleation and crystallization. After completion of the reaction, the mixture was cooled to 25 ± 2 °C, and the synthesized nanoparticles were collected by centrifugation. The obtained particles were repeatedly washed with DI water and ethanol to remove residual impurities and dried at 80–100°C. The synthesized CeO₂ nanoparticles were subsequently utilized as fuel additives for biodiesel blend enhancement.

2.1 Characterization of Cerium Oxide (CeO₂)

The synthesized CeO₂ nanoparticles were characterized using Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM) analyses to evaluate functional groups, surface morphology, and particle characteristics. FTIR spectra were recorded within the range of 4000–400 cm⁻¹, while SEM analysis was performed to examine nanoparticle surface topology and particle distribution.

2.2 Preparation of *Spirulina platensis* Algae Biodiesel

Spirulina platensis, a photosynthetic cyanobacterium, is recognized as a promising feedstock for sustainable biodiesel production due to its rapid growth kinetics, appreciable lipid accumulation, and

adaptability to diverse cultivation environments, including wastewater systems (Maheswaran and Uthranarayan, 2022). Its lipid content typically ranges between 20–50% (dry weight basis) depending on strain and culture conditions, making it suitable for biodiesel production via transesterification. For this investigation, standardized *Spirulina platensis* algal oil was procured from a certified supplier in Chennai to ensure experimental reproducibility. Base-catalyzed transesterification was carried out using a 6:1 methanol-to-oil ratio with 1 wt% KOH at 60 ± 2 °C for 90 min, followed by 12 h gravitational separation. The resulting esters were thoroughly washed and subsequently dried at 110 °C, yielding a fatty acid methyl ester (FAME) conversion efficiency of approximately 92.4%. GC–MS analysis identified major constituents including palmitic (C16:0, 29.5%), oleic (C18:1, 27.8%), linoleic (C18:2, 20.3%), and stearic acids (C18:0, 11.6%), indicating a balanced saturation–unsaturation profile favorable for ignition quality and oxidative stability.

Biodiesel blends were prepared volumetrically as SB25 (25% biodiesel + 75% diesel) and SB45 (45% biodiesel + 55% diesel) under magnetic stirring at 500 rpm for 30 min at 25 °C. Green-synthesized CeO₂ nanoparticles derived from *Moringa oleifera* extract were incorporated at 25 and 50 mg L⁻¹ to formulate SB25CeO₂25, SB25CeO₂55, SB45CeO₂25, and SB45CeO₂55 blends. Uniform nanoparticle dispersion was achieved using a probe-type ultrasonicator (20 kHz, 500 W) for 30 min, with temperature controlled below 40 °C to prevent thermal degradation (Oni *et al.* 2022). Ultrasonication enhanced nanoparticle stability and fuel–additive interaction, ensuring homogeneous suspension and consistent physicochemical properties across the prepared test fuels (Table 1).

2.3 Experimental Setup

Comprised a vertically oriented, water-cooled, single-cylinder, four-stroke compression ignition engine with a rated power output of 3.7 kW (Sathish *et al.* 2023a). The engine featured a bore diameter of 70 mm and a stroke length of 120 mm, resulting in a total displacement of 0.6 L. It was designed to operate at a constant speed of 1500 rpm with a compression ratio of 17:1. A direct fuel injection system was employed, and the engine was manually started using a hand crank mechanism. Performance and emission characteristics were evaluated under standard operating conditions with injection timing maintained at 21° before top dead center (bTDC) and injection pressure set to 210 bar (Kumar *et al.* 2021). The engine was coupled to an eddy current dynamometer, which enabled controlled loading from no-load to full-load conditions (0–100%). Torque output was measured using the dynamometer system, while in-

cylinder pressure data were recorded through a piezoelectric pressure transducer. Exhaust emissions and smoke opacity were quantified by an AVL 437C smoke meter and an AVL DI GAS 444 gas analyzer. Engine

performance parameters and emission data were processed and analyzed by AVL software to assess combustion stability and pollutant formation.

Table 1. Physicochemical properties of prepared test fuels

Property	Diesel	SB25	SB45	SB25 CeO ₂ 25	SB45 CeO ₂ 25	SB25 CeO ₂ 55	SB45 CeO ₂ 55	ASTM Standard
Cetane Number	47	52.0	53.9	52.8	53.2	54.6	55.1	ASTM D613
Viscosity (mm ² /s)	2.88	2.58	2.72	2.56	2.69	2.52	2.66	ASTM D975 (Farrokheh <i>et al.</i> 2022)
Calorific value (kJ/kg)	41,248	37,200	36,420	38,200	37,350	38,850	37,580	ASTM D240
Density (g/cm ³)	0.722	0.758	0.768	0.762	0.779	0.764	0.782	ASTM D4052
Fire Point (°C)	58	69	71	72	74	73	76	ASTM D93
Flash Point (°C)	55	65	67	69	71	70	73	ASTM D93

For each fuel variant, experiments were conducted independently, and a minimum of three repetitions were performed to assess repeatability. The experimental campaign commenced with neat diesel operation. Once the engine attained steady-state conditions, baseline performance and emission data were documented. Engine evaluations were carried out under five discrete loading conditions by systematically adjusting the dynamometer load. Subsequently, experiments were executed for all test fuels in the following order: Diesel, SB25, SB45, SB25CeO₂25, SB25CeO₂55, SB45CeO₂25, and SB45CeO₂55, with every operating condition repeated three times to ensure consistency. After maintaining steady-state operation for a minimum duration of 5 minutes at a constant speed of 1500 rpm, all pertinent efficiency and emission parameters were recorded. The reported data were presented as mean values accompanied by SD (mean $\pm$ SD), ensuring statistical robustness. The overall experimental uncertainty, accounting for instrumentation accuracy and ambient variations was estimated to be approximately $\pm 1\%$, as summarized in Table 2. This uncertainty margin aligns with established reporting norms for combustion-based experimental investigations. Additionally, the inclusion of error bars facilitates improved visualization of data dispersion and strengthens the reliability and reproducibility of the findings.

Table 2. Experimental variables and measurement uncertainty

Testing Factors	Accuracy	Percentage of Uncertainty
CO emissions	$\pm 0.5\text{vol}\%$	± 0.50
HC emissions	$\pm 5\text{ppm}$	± 0.50
Fuel quantity	$\pm 0.10 \text{ cm}^3$	± 0.50
Engine speed	$\pm 5\text{rpm}$	± 0.50
Engine load	$+0.25 \text{ kg}$ to -0.25 kg	± 0.50

2.4 Multi Criteria Decision Making

2.4.1 CRITIC Approach

The CRITIC–TOPSIS integrated multi-criteria decision-making approach was employed to identify the optimal fuel blend considering both engine performance and emission characteristics. The CRITIC method was utilized to determine objective weights of the selected criteria based on data variability and inter-criteria correlation, whereas the TOPSIS method was applied to rank the fuel blends according to their closeness to the ideal solution. The CRITIC is a goal-of-weighting tool. The procedure adopted for attribute weight determination using the CRITIC method is given as follows (Sriariyanun *et al.* 2025). Brake thermal efficiency and cetane number were treated as beneficial criteria,

whereas brake specific fuel consumption, CO, HC, NO_x emissions, and smoke opacity were considered non-beneficial criteria during decision analysis.

Step 1: The first step in decision-making is to construct a matrix. A set of q criteria and p options, which were part of multi-criteria models, are defined to form a decision matrix.

$$[Z_{ij}]_{p \times q} = \begin{matrix} & \begin{matrix} C_1 & C_2 & \dots & C_j & \dots & C_q \end{matrix} \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_p \end{matrix} & \begin{bmatrix} Z_{11} & Z_{12} & \dots & Z_{1j} & \dots & Z_{1q} \\ Z_{21} & Z_{22} & \dots & Z_{2j} & \dots & Z_{2q} \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ Z_{i1} & Z_{i2} & \dots & Z_{ij} & \dots & Z_{iq} \\ \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ Z_{p1} & Z_{p2} & \dots & Z_{pj} & \dots & Z_{pq} \end{bmatrix} \end{matrix} \quad \dots (2)$$

The following formulas (3-4) were used to construct the decision matrix for CRITIC weighting method:

$$X_{ij} = \frac{z_{ij} - z_j^{\min}}{z_j^{\max} - z_j^{\min}}, \text{ if } j \in \text{beneficial attribute} \quad \dots (3)$$

$$X_{ij} = \frac{z_j^{\max} - z_{ij}}{z_i^{\max} - z_i^{\min}}, \text{ if } j \in \text{non - beneficial attribute} \dots (4)$$

The standard deviation, (δ_j) for each attribute is then calculated as follows:

$$\delta_j = \sqrt{\frac{\sum_{i=1}^h (x_{ij} - \Lambda_j)^2}{h-1}}; j = 1, \dots, \lambda \quad \dots (5)$$

Here, Λ_j is mean of j th attributes were as;

$$\Lambda_j = \frac{\sum_{i=1}^h x_{ij}}{h}; j = 1, 2, \dots, \lambda \quad \dots (6)$$

Subsequently, a correlation coefficient (ρ_{jk}) is established for each attribute pair utilizing the following formula:

$$\rho_{jk} = \frac{\sum_{i=1}^h (x_{ij} - \Lambda_j)(x_{ik} - \Lambda_k)}{\sqrt{\sum_{i=1}^h (x_{ij} - \Lambda_j)^2 \sum_{i=1}^h (x_{ik} - \Lambda_k)^2}} \quad \dots (7)$$

The mean of the k th attribute, denoted as (Λ_k) is calculated using Equation (6) for the k th attribute.

For all attributes, the information measure denoted as (σ_j) were calculated as follows:

$$\sigma_j = \delta_j \sum_{k=1}^{\lambda} (1 - \rho_{jk}); j = 1, \dots, \lambda \quad \dots (8)$$

The objective weight (ω_j) of all attribute is obtained by CRITIC approach as follows:

$$\omega_j = \frac{\sigma_j}{\sum_{j=1}^{\lambda} \sigma_j}; j = 1, \dots, \lambda \quad \dots (9)$$

2.4.2 TOPSIS Method

TOPSIS technique was applied to rank changes of the study. According to the principle of the TOPSIS method, the best rank of the alternative is obtained when it has the shortest distance from the ideal solution and the longest distance from the negative ideal solution (Abirami and Das, 2025). Eqn (10) is used to calculate matrix (n_{ij}) .

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}, i = 1, \dots, m, j = 1, \dots, n \quad \dots (10)$$

The weighted matrix was calculated by Eqn (11). In Eqn (11), w_j were the weight of the j th criterion and $\sum_{j=1}^n w_j = 1$.

$$v_{ij} = w_j n_{ij}, i = 1, \dots, m, j = 1, \dots, n \quad \dots (11)$$

Eqn (7) and (8) were used to calculate negative and positive solutions.

$$A^+ = \{v_1^+, \dots, v_n^+\} = \left\{ \left(\max_{i \in I} \right), \left(\min_{i \in J} \right) \right\} \dots (12)$$

$$A^- = \{v_1^-, \dots, v_n^-\} = \left\{ \left(\min_{i \in I} \right), \left(\max_{i \in J} \right) \right\} \dots (13)$$

Distance of all alternative from ideal solutions were calculated by Eqn (14) and (15).

$$d_i^+ = \left\{ \sum_{j=1}^n (v_{ij} - v_j^+)^2 \right\}^{\frac{1}{2}}, i = 1, \dots, m \quad \dots (14)$$

$$d_i^- = \left\{ \sum_{j=1}^n (v_{ij} - v_j^-)^2 \right\}^{\frac{1}{2}}, i = 1, \dots, m \quad \dots (15)$$

Relative to ideal solution were calculated by Eqn (16).

$$R_i = \frac{d_i^-}{(d_i^+ + d_i^-)} i = 1, \dots, m \quad \dots (16)$$

since $d_i^- \geq 0$ and $d_i^+ \geq 0$, then $R_i \in [0, 1] \dots (17)$

Initially, the experimental response data were normalized to eliminate dimensional differences among the criteria. Subsequently, objective weights obtained from the CRITIC method were incorporated into the weighted decision matrix. Finally, the relative closeness coefficient obtained through TOPSIS analysis was used to rank the fuel blends and identify the optimum operating condition.

3. RESULTS AND DISCUSSIONS

3.1 FTIR Analysis of CeO₂ Nanoparticles

The FTIR spectrum of green-synthesized CeO₂ nanoparticles using *Moringa oleifera* leaf extract confirms successful formation of CeO₂ and presence of

surface-bound phytochemicals. FTIR spectrum obtained from 4000 to 400 cm^{-1} were presented in Fig. 1. A IR spectra of CeO_2 exhibits broad band at 2401 and 1487 cm^{-1} , indicative of bending vibration and hydroxyl stretching frequency associated with water. This may result from absorbed hydroxide at nanoparticles owing to elevated reactivity. A bands observed at 748 cm^{-1} attributed to bending vibration of Ce-O-Ce. The peak at 1289 cm^{-1} to the C-O stretching vibration. The peak about 1487 cm^{-1} vibrational stretching of CO_2 , potentially resulting from unvented CO_2 generated during burning. The peak at 682 cm^{-1} corresponds Ce-O stretching, whereas peaks at 1045 cm^{-1} and 1289 cm^{-1} . It were inferred hydroxyl ions were at surface, while C-O confined within pores of produced materials. Overall, the FTIR spectrum demonstrates that the CeO_2 nanoparticles are successfully reduced, crystallized, and capped by the phytochemicals of *Moringa oleifera* leaves, providing stable, high-surface-area nanoparticles suitable for applications in biodiesel enhancement.

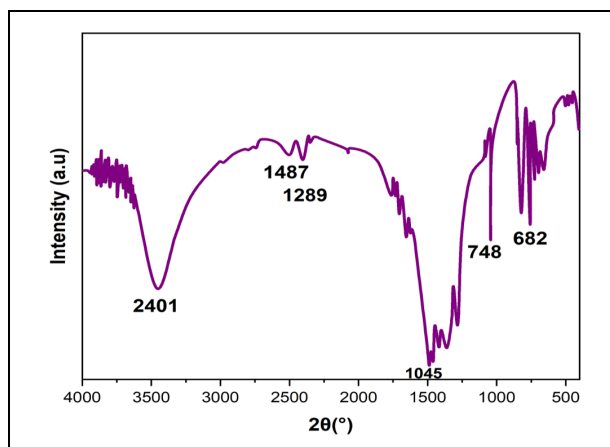


Fig. 1: FTIR spectrum of synthesized CeO_2 nanoparticles

3.2 SEM Analysis of CeO_2 Nanoparticles

The SEM image of green-synthesized CeO_2 reveals uniformly distributed polyhedral particles with slight aggregation attributed to interparticle van der Waals forces.

The synthesized CeO_2 nanoparticles exhibited an average particle size of approximately 70nm - 120nm, indicating successful nanoscale particle formation. The surface morphology reveals well-defined polyhedral crystallites with sharp facets, indicating efficient nucleation and growth during bio-assisted synthesis using *Moringa oleifera* leaf extract. A crystallite size estimated from the Debye–Scherrer equation was approximately 37 nm, closely matching the SEM-derived particle size and validating dimensional consistency. The polycrystalline nature of CeO_2 nanoparticles enhances surface area-to-volume ratio, thereby raising catalytic and thermal stability, consistent with previously reported green-synthesized CeO_2 systems.

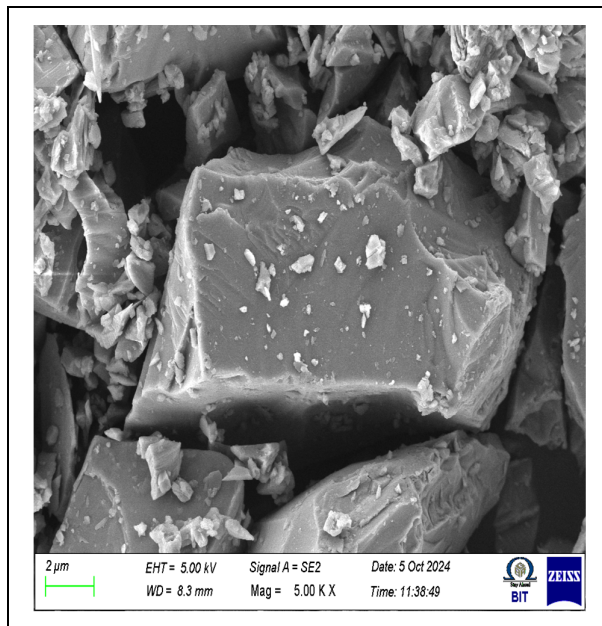


Fig. 2: SEM micrograph of CeO_2

3.3 Performance Characteristics

Figure 3 shows the variation of brake thermal efficiency with engine load for diesel, SB25, SB45, and CeO_2 -doped biodiesel blends. BTE increases steadily with raising load for fuels due to high in-cylinder temperature and improved combustion on elevated loads. Compared to diesel, SB25 and SB45 exhibit slightly lower efficiency because of higher viscosity and lower calorific value of biodiesel. However, addition of CeO_2 (30 and 55 mg/L) enhances BTE across all load conditions, with SB25 + 55 mg/L CeO_2 showing the highest efficiency at 75–100% load. The improvement was attributed to the catalytic oxidation capability and oxygen buffering property of CeO_2 ($\text{Ce}^{3+}/\text{Ce}^{4+}$ redox cycle), which promotes better atomization, faster oxidation reactions, reduced ignition delay, and more combustion, thereby compensating for the efficiency loss associated with higher biodiesel content. The improvement in BTE obtained with SB25 + 55 mg/L CeO_2 was comparatively higher than several previously reported nano-additive biodiesel systems. Unlike conventional biodiesel blends, the *Spirulina platensis* methyl ester exhibited improved combustion compatibility with CeO_2 due to its oxygenated molecular structure and enhanced oxidation kinetics. Similar enhancement trends were reported by (Savaş *et al.* 2025); however, the present study demonstrated superior efficiency recovery at higher engine loads, indicating stronger catalytic interaction between CeO_2 nanoparticles and *Spirulina*-derived fuel components. The improvement also confirms that nanoparticle-assisted combustion can effectively compensate for the lower calorific value limitation generally associated with biodiesel fuels.

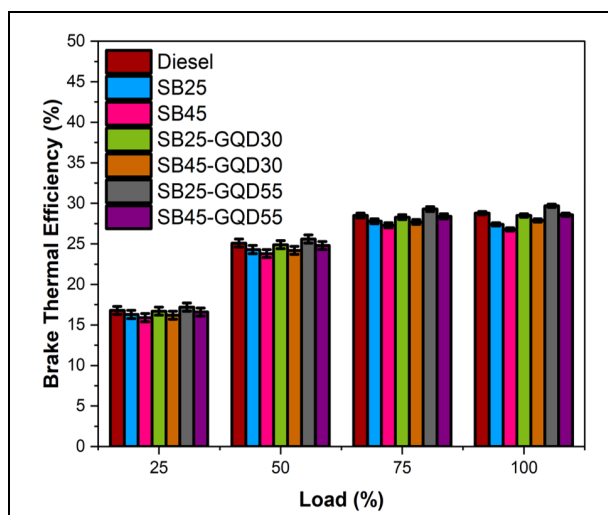


Fig. 3: Effect of CeO₂ nanoparticles on Brake Thermal Efficiency (BTE)

Figure 4 shows the variation of BSFC with engine load of diesel, SB25, SB45, and CeO₂-doped blends. BSFC decreases progressively with raising load for all tested fuels because of improved combustion efficiency and higher brake power output at loads. Compared to neat diesel, SB25 and SB45 exhibit relatively higher BSFC, mainly because of higher viscosity and lower calorific value of biodiesel, which require more fuel to produce equivalent power. However, the addition of CeO₂ nanoparticles (30 and 55 mg/L) significantly reduces BSFC across all load conditions, with SB25 + 55 mg/L CeO₂ showing the lowest fuel consumption at medium and higher loads. The reduction in BSFC is associated with improved combustion efficiency after CeO₂ addition. In a previous study, the addition of CeO₂ with sunflower oil methyl ester (B20) and hydrogen improved BTE up to 7.01% and reduced BSFC up to 7.19%. Hydrogen-assisted nano-doping also increased in-cylinder pressure and heat release rate, demonstrating improved combustion characteristics (Polat *et al.* 2024). Compared with earlier sunflower and waste-oil biodiesel investigations, the present Spirulina biodiesel system achieved a comparatively lower BSFC reduction at moderate nanoparticle concentration without requiring secondary gaseous fuel support. This indicates that the catalytic oxygen buffering behavior of CeO₂ alone was sufficient to enhance combustion efficiency under optimized blend conditions. The reduction in fuel consumption further validates the role of nanoparticle-assisted micro-explosion phenomena and improved atomization characteristics during combustion.

Figure 6 shows the variation of CO by engine load for diesel, SB25, SB45, and CeO₂-doped blends. CO raise with increasing load for tested fuels because of fuel–air mixtures and lower oxygen availability at high loads, leading to incomplete oxidation of carbon species. Compared to diesel, SB25 and SB45 exhibit slightly

higher CO emissions, particularly at medium and full load conditions, mainly due to high viscosity and altered spray characteristics of biodiesel blends. However, the addition of CeO₂ nanoparticles (30 and 55 mg/L) significantly reduces CO emissions across all load levels, with SB25 + 55 mg/L CeO₂ showing the lowest CO values. The lower CO emissions indicate improved oxidation efficiency during combustion. In a prior study, engine tests showed that adding 100 ppm CeO₂ to ARME20 (*A. reticulata* seed oil) reduced CO (42%), HC (35.59%), and NO_x (5.94%) while improving BTE and lowering BSFC at full load condition. Lower CO emissions confirm improved oxidation behavior and reduced incomplete combustion after CeO₂ addition. The CO reduction achieved in the present investigation was comparatively higher than several reported non-catalytic biodiesel blends under similar operating conditions. This improvement highlights the strong oxidation-promoting capability of CeO₂ nanoparticles through reversible Ce³⁺/Ce⁴⁺ redox reactions. Furthermore, the reduction pattern suggests that optimized nanoparticle dosage plays a critical role in minimizing incomplete combustion products without negatively affecting combustion stability (Arun *et al.* 2024).

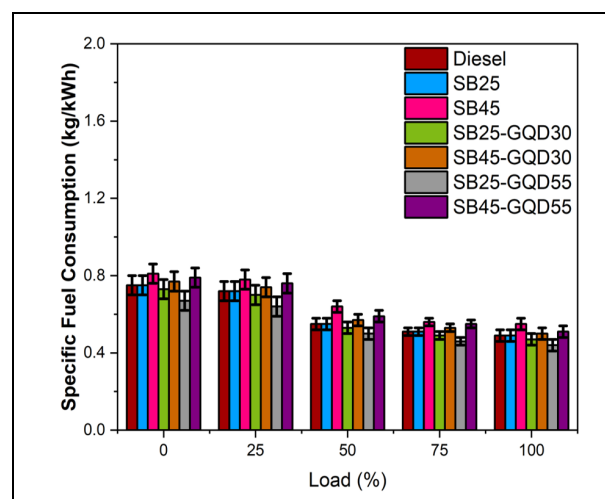


Fig. 4: Effect of CeO₂ nanoparticles on Brake Specific Fuel Consumption (BSFC)

3.4 Emission Behavior Under Test Conditions

Figure 5 shows the variation of HC emissions by engine load for diesel, SB25, SB45, and CeO₂-doped blends. HC emissions increase progressively with raising load for tested fuels because of richer fuel–air mixtures and incomplete combustion on high load conditions. Compared to neat diesel, SB25 and SB45 exhibit relatively high HC, particularly at medium and full load, owing to higher viscosity and lower volatility of biodiesel, which affect atomization and evaporation characteristics. However, the incorporation of CeO₂ nanoparticles (30 and 55 mg/L) significantly reduces HC emissions across all load conditions, with SB25 + 55

mg/L CeO₂ showing the lowest HC levels. The reduction in HC emissions is attributed to enhanced combustion behavior in the nanoparticle-blended fuel. The reduction trend observed in HC emissions was more significant at medium and higher loads, where incomplete combustion generally becomes dominant in biodiesel-fueled engines. Compared with previous CeO₂-assisted biodiesel studies, the present work demonstrated improved HC oxidation efficiency, which may be attributed to the synergistic interaction between fuel-bound oxygen in *Spirulina* biodiesel and lattice oxygen released from CeO₂ nanoparticles. This confirms that nanoparticle-assisted catalytic oxidation becomes increasingly effective under elevated combustion temperature conditions.

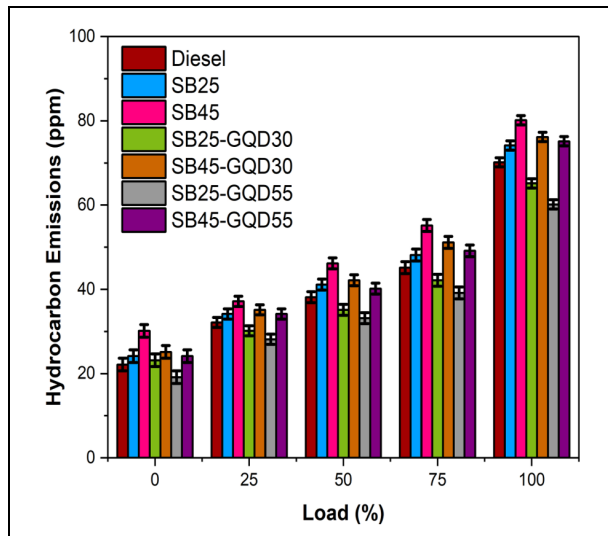


Fig. 5: Effect of CeO₂ nanoparticles on Hydrocarbon (HC) emissions

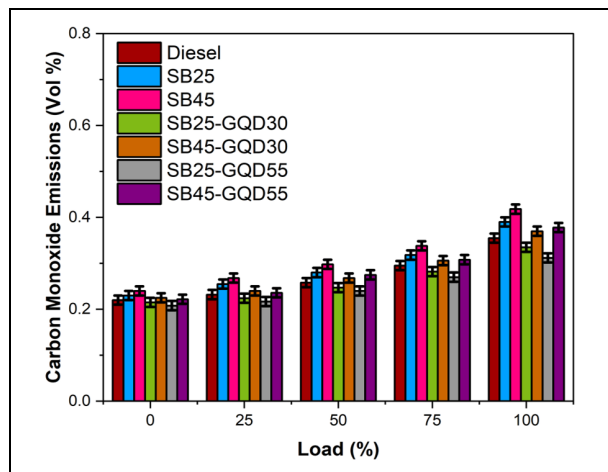


Fig. 6: Effect of CeO₂ on carbon monoxide emissions

3.5 Effect of CeO₂

Effect of CeO₂ on *Spirulina platensis* blends was investigated to improve engine performance by reducing HC, BSFC, and CO emissions. RSM employing

Central Composite Design (CCD) was implemented with two independent variables: blend ratio (SB10–SB45%) and CeO₂ concentration (10–60 mg/L), as defined in Table 3. A total of thirteen experimental runs were conducted according to the CCD matrix. The obtained responses were statistically analyzed using ANOVA to determine factor significance, and interaction effects were illustrated through contour and response surface plots to identify optimal operating conditions. ANOVA results demonstrated that the blend ratio and CeO₂ nanoparticle concentration significantly influenced engine performance and emission characteristics ($p < 0.05$). Furthermore, the interaction effects analyzed through RSM contour and response surface plots confirmed the optimal operating conditions for minimizing HC, BSFC, and CO emissions (Alotaibi *et al.* 2025).

Table 3. Experimental Variables and its Levels

Factors	Unit	Low	High
SB	%	10	40
CeO ₂	mg/L	10	60

Table 4 summarizes the 13 CCD experimental trials conducted with SB biodiesel (3.78–46.21%) and CeO₂ (10–70.35 mg/L). The minimum SFC (0.275 kg/kWh) with reduced CO (0.105%) and HC emissions was obtained at SB25 with 70.35 mg/L CeO₂. Center-point runs showed consistent results (SFC $\approx$ 0.305 kg/kWh), confirming model reliability.

Table 4. Trial-based optimization results

Std Run	Run	SB Biodiesel	CeO ₂	SFC	CO	HC
1	1	10	10	0.355	26	0.182
12	2	25	35	0.305	28.2	0.132
7	3	25	0.35	0.41	24	0.22
10	4	25	35	0.306	28.1	0.133
11	5	25	35	0.304	28.3	0.131
3	6	10	60	0.295	29	0.12
6	7	46.2132	35	0.38	25	0.2
5	8	3.7868	35	0.42	23.5	0.225
13	9	25	35	0.305	28.2	0.132
8	10	25	70.35	0.275	30.2	0.105
4	11	40	60	0.31	27.8	0.138
9	12	25	35	0.305	28.2	0.132
2	13	40	10	0.39	24.8	0.208

The findings indicated strong interactive effects between *Spirulina platensis* biodiesel blends and CeO₂

nanoparticles, significantly influencing engine performance characteristics. Contour plot analysis enabled determination of optimal operating conditions and offered clearer understanding of the parameters governing reductions in fuel consumption and exhaust emissions, thereby supporting performance optimization (Elumalai *et al.* 2023).

3.6 Fuel Consumption Analysis

Table 5 presents the quadratic ANOVA results for fuel consumption. The overall model was statistically

the same, with an F-value of 8.56 and a p-value of 0.0068. Among factors, CeO₂ dosage (B) significantly influenced fuel consumption ($p = 0.0018$), while the *Spirulina* blend ratio (A) showed no same effect ($p = 0.9256$). The quadratic of blend ratio (A²) was also significant ($p = 0.0036$), indicating curvature in the response. However, the interaction term (AB) and B² were statistically insignificant. The same lack of fit ($p < 0.0001$) suggests that model refinement may required for better prediction accuracy.

Table 5. ANOVA results for fuel consumption

Source	SS	df	MS	F-value	p-value	
Model	0.0246	5	0.0049	8.56	0.0068	significant
A- <i>Spirulina</i> blend	5.393E-06	1	5.393E-06	0.0094	0.9256	
B-CeO ₂ dosage	0.0137	1	0.0137	23.81	0.0018	
AB	0.0001	1	0.0001	0.1740	0.6891	
A ²	0.0106	1	0.0106	18.47	0.0036	
B ²	0.0007	1	0.0007	1.29	0.2940	
Residual	0.0040	7	0.0006			
Lack of Fit	0.0040	3	0.0013	2681.22	< 0.0001	significant
Pure Error	2.000E-06	4	5.000E-07			
Cor Total	0.0286	12				

The statistical indicators in table 6 demonstrate satisfactory model performance for fuel consumption prediction. The COD ($R^2 = 0.8594$) that 85.94% of variability at fuel consumption were explained by model. Adjusted R^2 (0.7590) confirms reasonable explanatory capability after accounting for model terms. However, the predicted R^2 (0.0008) shows weak predictive agreement with the adjusted R^2 , suggesting limited external prediction strength. Adequate precision of 8.1527, which were greater than desirable threshold of 4, indicates acceptable S/N ratio and adequate model discrimination within the design space.

Table 6. ANOVA validation for fuel consumption

Std. Dev.	0.0240	R ²	0.8594
Mean	0.3354	Adj. R ²	0.7590
C.V. %	7.15	Pre. R ²	0.0008
Adeq Precision		8.1527	

Although the developed quadratic model exhibited acceptable R^2 and Adeq Precision values, the comparatively low predicted R^2 and significant lack-of-fit indicate limited predictive capability outside the investigated experimental domain. This may be

attributed to experimental variability, nonlinear interaction effects, and the restricted number of CCD experimental runs. The CCD-RSM model provided a reasonable prediction of favorable operating conditions within the experimental domain. RSM-based regression equations are articulated in dimensionless coded variables to ensure consistent scaling; all factor (X_i) were appropriately normalized using equ (17):

$$\frac{X_i - X_0}{\Delta X_j} \quad \dots (17)$$

In this context, X_i denotes the actual factor value, X_0 signifies the midpoint and ΔX_i indicates the increment; hence, the quadratic coefficients are dimensionless inside the coded range.

$$\text{SFC (kg/kWh)} = 0.305 - 0.0008A - 0.0413B - 0.004 AB + 0.03906 A^2 + 0.0103 B^2 \quad \dots (18)$$

In this context, X_i denotes the actual factor value, X_0 signifies the midpoint, and ΔX_i indicates the increment; hence, the quadratic coefficients are dimensionless within the specified coded range.

Figures 7 illustrate the contour and 3D surface plots showing combined presence of *Spirulina* blend ratio and CeO₂ dosage on SFC. Response surface

indicates a minimum SFC of approximately 0.275 kg/kWh, achieved at around SB25 with 70 mg/L CeO₂. The downward curvature toward higher nanoparticle concentration confirms that increasing CeO₂ enhances combustion efficiency and reduces fuel consumption, while extreme low or high blend ratios tend to increase SFC.

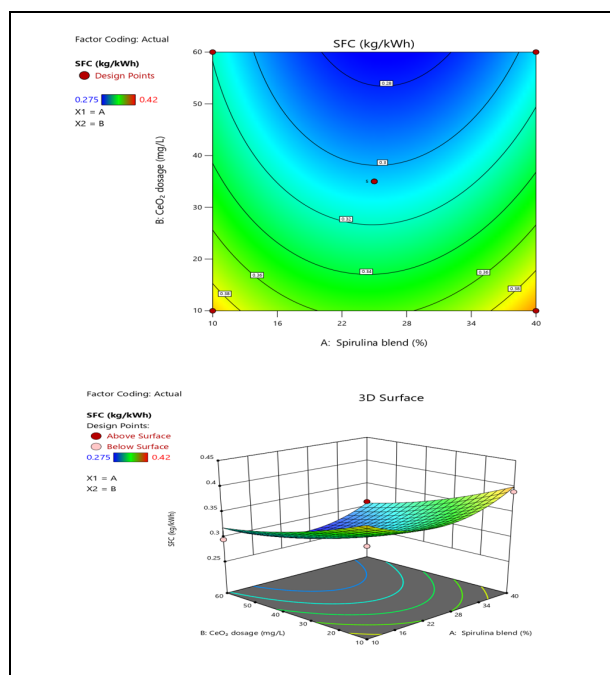


Fig. 7: CeO₂ nanoparticle effect on SFC

Figure 8 shows the comparison among experimental and predicted SFC values. The data points were distributed closely around 45° reference line, showing reasonable agreement among observed and model-estimated results. Minor deviations are visible at higher SFC values, suggesting slight prediction error at extreme conditions. Overall, the scatter pattern demonstrates acceptable model accuracy without significant systematic deviation, confirming that the developed quadratic RSM model provides a satisfactory fit within the studied operating range.

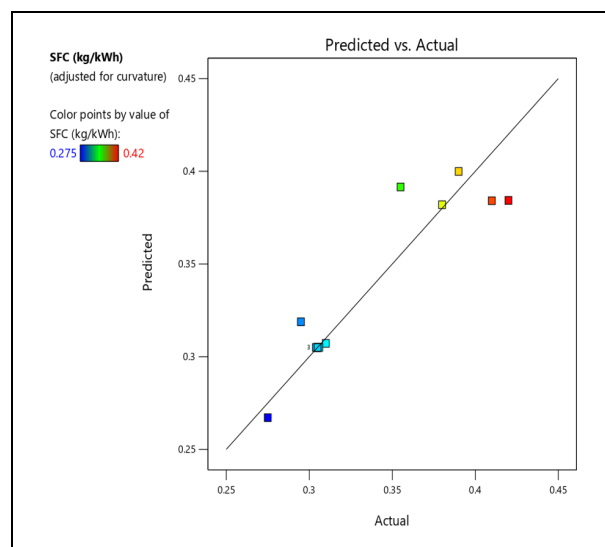


Fig. 8: Residual analysis of SFC model

Table 7. Statistical significance of HC emissions

Source	SS	d _f	MS	F-value	p-value	
Model	46.65	5	9.33	9.99	0.0043	significant
A- Spirulina blend	0.0097	1	0.0097	0.0104	0.9216	
B-CeO ₂ dosage	27.26	1	27.26	29.20	0.0010	
AB	0.0000	1	0.0000	0.0000	1.0000	
A ²	19.37	1	19.37	20.75	0.0026	
B ²	0.4133	1	0.4133	0.4428	0.5271	
Residual	6.53	7	0.9335			
Lack of Fit	6.51	3	2.17	434.29	< 0.0001	significant
Pure Error	0.0200	4	0.0050			
Cor Total	53.18	12				

3.7 Analysis of HC Emission

Table 7 presents the quadratic ANOVA results for HC emissions. The overall model were statistically same with F-value of 9.99 and p-value of 0.0043. Among input factors, CeO₂ dosage (B) significantly influences HC emissions ($p = 0.0010$), whereas the Spirulina blend

ratio (A) shows no significant individual effect ($p = 0.9216$). The quadratic term of blend ratio (A²) is also significant ($p = 0.0026$), indicating a nonlinear response. However, the interaction term (AB) and B² are statistically insignificant. The significant lack of fit ($p < 0.0001$) suggests that further refinement may improve predictive accuracy.

The statistical indicators demonstrate satisfactory model adequacy for HC emission prediction. The standard deviation (0.9662) is low compared to the mean value (27.02), reflected by a modest coefficient of variation (3.58%), indicating good experimental precision. The coefficient of determination ($R^2 = 0.8771$) shows 87.71% of variability at HC emissions explained by model, while adjusted R^2 (0.7894) confirms reasonable explanatory strength after correction for model terms. However, the predicted R^2 (0.1284) suggests limited external capability. The Adeq Precision of 9.0138, being greater than 4, shows an adequate S/N ratio and acceptable model discrimination within the design space.

Table 8. Analysis of variance for hydrocarbon emissions

Std. Dev.	0.9662	R^2	0.8771
Mean	27.02	Adj. R^2	0.7894
C.V. %	3.58	Pre. R^2	0.1284
Std. Dev.	0.9662	Adeq Precision	9.0138

The variation between adjusted and predicted R^2 values suggests moderate prediction accuracy of the developed model. Additional experimental observations may further improve model reliability.

$$\text{HC (\%)} = 28.2 - 0.0348 A + 1.8460 B + 0 = AB - 1.668 A^2 - 0.2437 B^2 \quad \dots (19)$$

Figures 9 illustrate the contour and 3D surface plots showing combined presence of *Spirulina* blend ratio and CeO_2 dosage on HC. Response surface indicates that HC increases with rising CeO_2 concentration and moderate blend ratios. The maximum HC (~30%) is observed at approximately SB25–30 with higher CeO_2 levels (around 60–70 mg/L), whereas lower efficiency (~23–24%) occurs at minimal blend and nanoparticle dosage. The upward curvature confirms that optimized biodiesel blending with adequate CeO_2 enhances combustion efficiency and thermal performance. In another study, a 20% Coconut oil biodiesel blend with 35 ppm CeO_2 provided optimal performance, increasing efficiency by 5% and reducing HC (45%) at higher loads (George *et al.* 2024).

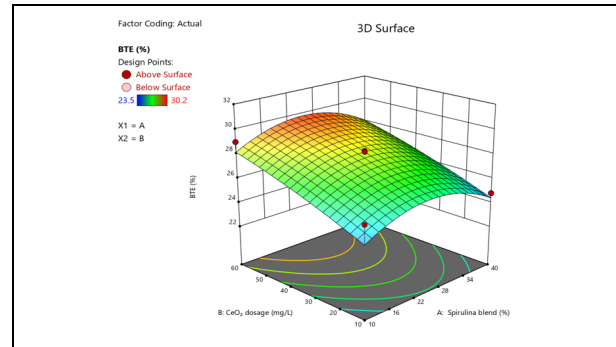
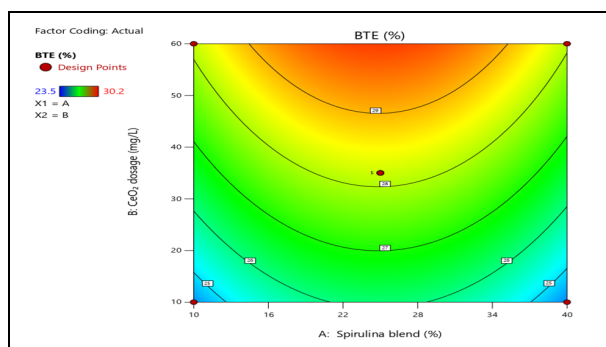


Fig. 9: Effect of CeO_2 on HC emissions

Figure 10 presents the predicted versus actual values of HC. Data points are distributed to 45° reference line, providing good agreement among experimental and model-predicted results. Minor changes are observed at intermediate efficiency levels; however, no systematic bias is evident. The overall clustering of points near the reference line confirms satisfactory model accuracy and reliable prediction of HC within the investigated operating range. High R^2 values confirmed model accuracy, demonstrating that nanoparticles enhance combustion and emission performance (Canan, 2025).

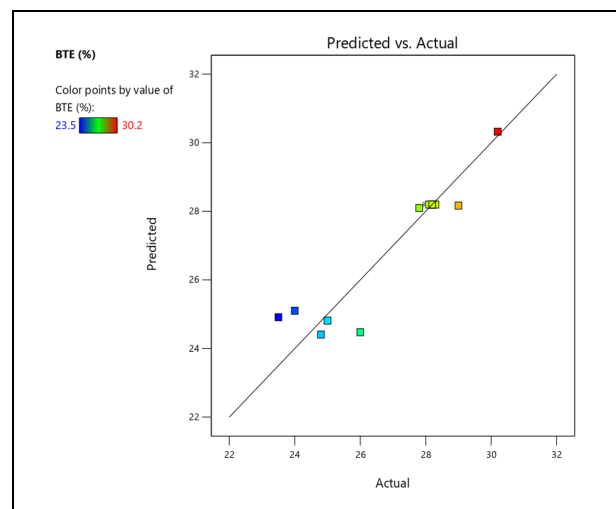


Fig. 10: Residual plots for HC model

3.8 Evaluation of Carbon Monoxide Emissions

Table 9 presents the quadratic ANOVA results for carbon monoxide (CO) emissions. The model were same, with an F-value of 12.05 and a p-value of 0.0025. CeO_2 dosage (B) significantly affects CO emissions ($p = 0.0006$), while the *Spirulina* blend ratio (A) shows no significant individual influence ($p = 0.8682$). The quadratic term of blend ratio (A^2) is also significant ($p = 0.0015$), indicating a nonlinear effect on CO formation. However, the interaction term (AB) and B^2 are statistically insignificant. The lack of fit ($p < 0.0001$) suggests that although the model explains variation well, further refinement may improve prediction accuracy.

Table 9. ANOVA summary for carbon monoxide emissions

Source	SS	d _f	MS	F-value	p-value	
Model	0.0190	5	0.0038	12.05	0.0025	significant
A- Spirulina blend	9.341E-06	1	9.341E-06	0.0296	0.8682	
B-CeO ₂ dosage	0.0109	1	0.0109	34.42	0.0006	
AB	0.0000	1	0.0000	0.0507	0.8282	
A ²	0.0080	1	0.0080	25.32	0.0015	
B ²	0.0005	1	0.0005	1.74	0.2289	
Residual	0.0022	7	0.0003			
Lack of Fit	0.0022	3	0.0007	1469.98	< 0.0001	significant
Pure Error	2.000E-06	4	5.000E-07			
Cor Total	0.0212	12				

Table 10 summarizes the statistical adequacy of the CO emission model. The standard deviation (0.0178) relative to the mean (0.1583) yields a C.V. of 11.22%, indicating acceptable experimental variability. The COE ($R^2 = 0.8959$) shows 89.59% of variation in CO emissions was explained by the model, while the adjusted R^2 (0.8216) confirms good explanatory capability after correction. However, the predicted R^2 (0.2605) indicates moderate predictive strength. The Adeq Precision value of 9.6987, well above the threshold of 4, confirms an adequate S/N ratio and satisfactory model discrimination within the design space.

$$\text{CO (vol\%)} = 0.132 + 0.0010 \text{ A} - 0.036 \text{ B} - 0.0019 \text{ AB} + 0.0338 \text{ A}^2 + 0.008875 \text{ B}^2 \dots (20)$$

Table 10. ANOVA validation for CO emission model

Std. Dev.	0.0178	R ²	0.8959
Mean	0.1583	Adj. R ²	0.8216
C.V. %	11.22	Pre. R ²	0.2605
		Adeq Precision	9.6987

Despite satisfactory regression statistics, the significant lack-of-fit indicates that certain nonlinear combustion interactions may not be fully captured within the present model

Figure 11 illustrates the contour and 3D surface plots showing the combined presence of Spirulina blend ratio and CeO₂ dosage on CO emissions. The response surface indicates that CO emissions decrease significantly with increasing CeO₂ concentration, particularly at moderate blend ratios. The minimum CO value (~0.105 vol%) is observed around SB25 with higher nanoparticle dosage (~70 mg/L). At lower additive levels and extreme blend ratios, CO emissions increase. Overall, optimized biodiesel blending with sufficient

CeO₂ enhances oxidation reactions and effectively reduces CO formation.

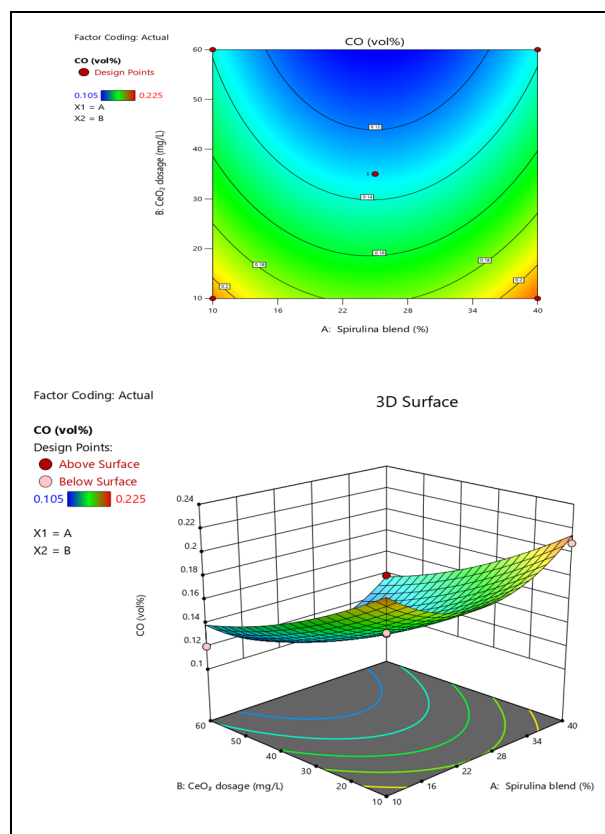
**Fig. 11: Effect of CeO₂ on CO emissions**

Figure 12 illustrates the predicted versus actual values of CO emissions. The data points were distributed near 45° reference line, showing reasonable agreement among experimental and model-predicted results. Slight deviations are observed at higher CO levels; however, no clear systematic trend is evident. The overall scatter pattern confirms acceptable model accuracy and

satisfactory predictive capability for CO emissions within the studied operating range.

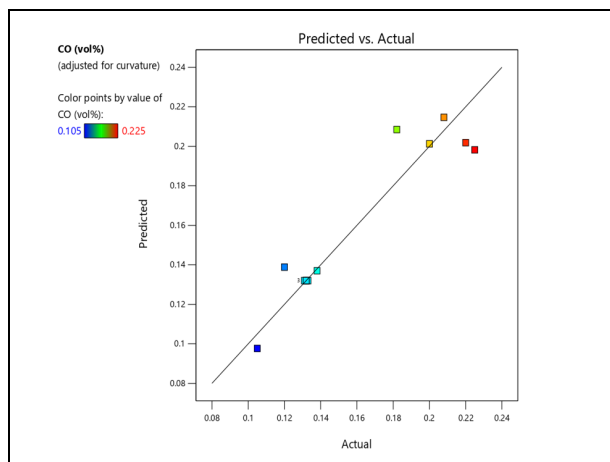


Fig. 12: CO residual analysis

3.9 Validation of ANOVA Results

Table 11 presents the ANOVA results for carbon monoxide (CO) emission model. The quadratic model were statistically same with F-value of 15.28 and p-value

of 0.0012. Among factors, CeO₂ dosage (B) significantly affects CO emissions ($p = 0.0003$), while the *Spirulina* blend ratio (A) has no significant individual influence ($p = 0.9604$). The quadratic term of blend ratio (A^2) is also significant ($p = 0.0008$), indicating a nonlinear relationship with CO formation. However, the interaction term (AB) and B^2 are statistically insignificant. The significant lack fit ($p = 0.0002$) suggests that although model explains a major portion of variability, further refinement may improve predictive accuracy.

Table 12 presents the validation statistics of the developed ANOVA model. The standard deviation (3.33) relative to the mean (63.62) yields a C.V. of 5.24%, indicating good experimental consistency. The COE ($R^2 = 0.9161$) shows 91.61% of response variability was explained by the model, while adjusted R^2 (0.8561) confirms strong explanatory capability after correction. However, the predicted R^2 (0.4078) suggests moderate predictive agreement. Adeq Precision of 11.4591, which was well above the threshold of 4, confirms adequate S/N and reliable model discrimination within the design space.

$$\text{HC (ppm)} = 58.8 - 0.060 A - 7.91941 B + 0.50000 AB + 7.0375 A^2 + 0.7875 B^2 \quad \dots (21)$$

Table 11. ANOVA summary for carbon monoxide emissions

Source	SS	d_f	MS	F-value	p-value	
Model	847.42	5	169.48	15.28	0.0012	significant
A- <i>Spirulina</i> blend	0.0294	1	0.0294	0.0027	0.9604	
B-CeO ₂ dosage	501.74	1	501.74	45.23	0.0003	
AB	1.00	1	1.00	0.0901	0.7727	
A^2	344.53	1	344.53	31.06	0.0008	
B^2	4.31	1	4.31	0.3889	0.5527	
Residual	77.66	7	11.09			
Lack of Fit	76.86	3	25.62	128.10	0.0002	significant
Pure Error	0.8000	4	0.2000			
Cor Total	925.08	12				

Table 12. ANOVA results validation

Std. Dev.	3.33	R^2	0.9161	R^2	
Mean	63.62	Adj. R^2	0.8561	Adj. R^2	
C.V. %	5.24	Pre. R^2	0.4078	Pre. R^2	
	Adeq Precision	11.4591	Adeq Precision		

The statistical analysis demonstrates acceptable model adequacy; however, the lower predicted R^2 value indicates limited extrapolation capability beyond the investigated operating conditions.

The diagnostic plots for CO, HC, and BSFC indicate that the residuals follow an approximately linear pattern in the normal probability plots, confirming normal distribution. The absence of structured patterns in residual-versus-predicted plots suggests no systematic

bias. Durbin–Watson values near 2 imply independence of errors, and homoscedastic behavior confirms constant variance. Overall, these statistical checks validate the ANOVA assumptions and confirm model reliability.

Figures 13 illustrate the contour and 3D surface plots for CO emissions as a function of Spirulina blend ratio and CeO₂ dosage. CO emissions decrease notably with increasing CeO₂ concentration, particularly at moderate blend levels. The minimum CO (~0.105 vol%) is observed around SB25 with higher nanoparticle dosage (~70 mg/L). At lower additive levels and extreme blend ratios, CO emissions increase. These results confirm that optimized biodiesel blending combined with sufficient CeO₂ enhances oxidation reactions and effectively reduces CO formation.

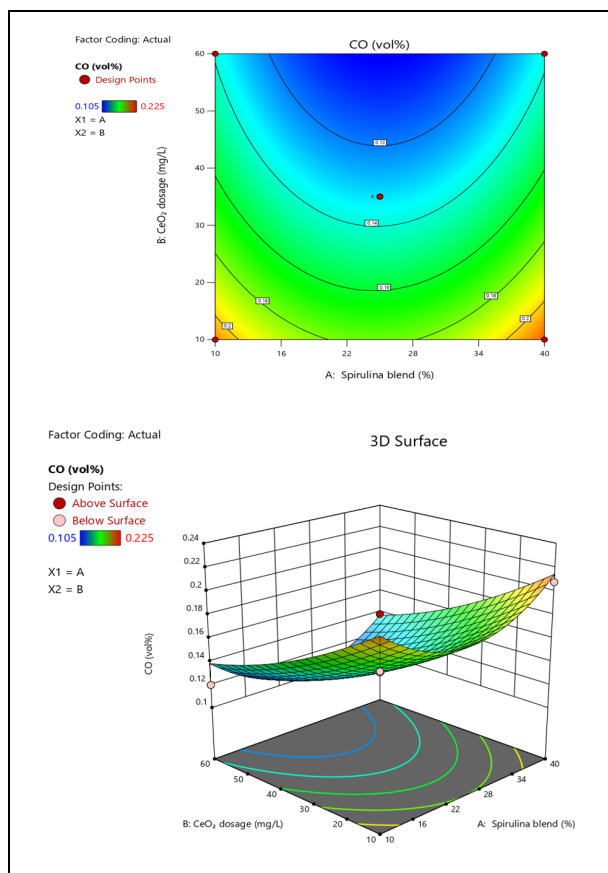


Fig. 13: Effect of CeO₂ on CO emissions

Figure 14 illustrates predicted versus CO emission values. Data points were distributed to 45° reference line, providing good agreement among experimental and model-estimated results. Slight deviations are observed at higher CO levels, but no consistent systematic trend is evident. The overall clustering near the reference line confirms satisfactory

model accuracy and reliable predictive performance within the investigated operating range.

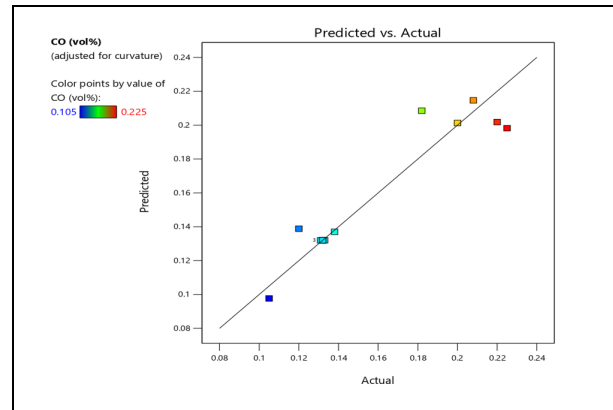


Fig. 14: Residual plot for CO emissions

Table 13 presents the CRITIC-based objective weighting results for multi-response optimization. The weights were calculated using the CRITIC method, where the data of each criterion is determined based on standard deviation and correlation with criteria. Based on the computed weights, HC (0.305932) and SFC (0.296914) exhibit the highest importance, indicating their dominant influence in the decision-making process. CO (0.215666) shows moderate significance, while BTE (0.181488) has comparatively lower weight. These results confirm that emission reduction and fuel consumption parameters play a major role in the overall optimization framework.

Table 13. CRITIC weight result

Criterion	Weight
SFC	0.296914
BTE	0.181488
CO	0.215666
HC	0.305932

The normalized and weighted normalized decision matrices were developed for the TOPSIS analysis using SFC, BTE, CO, and HC as evaluation criteria. Initially, vector normalization was performed as given in Eq. (2), followed by weighted normalization using the CRITIC-derived weights as expressed in Eq. (3). The separation distances from these ideal solutions were computed using Eq. (6) and Eq. (7). Finally, the relative closeness coefficient was determined using Eq. (8) to rank the alternatives. The alternative with the highest closeness value is considered optimal solution, representing best trade-off among fuel consumption, efficiency, and emission characteristics.

Table 14. Normalization and weighted normalization result for TOPSIS

Normalization				Weighted Normalization			
SFC	BTE	CO	HC	SFC	BTE	CO	HC
0.2907	0.2661	0.3090	0.3025	0.0863	0.0483	0.0666	0.0926
0.2498	0.2886	0.2241	0.2550	0.0742	0.0524	0.0483	0.0780
0.3358	0.2456	0.3735	0.3241	0.0997	0.0446	0.0805	0.0992
0.2506	0.2876	0.2258	0.2550	0.0744	0.0522	0.0487	0.0780
0.2490	0.2896	0.2224	0.2507	0.0739	0.0526	0.0480	0.0767
0.2416	0.2968	0.2037	0.2377	0.0717	0.0539	0.0439	0.0727
0.3112	0.2559	0.3395	0.3112	0.0924	0.0464	0.0732	0.0952
0.3440	0.2405	0.3820	0.3371	0.1021	0.0437	0.0824	0.1031
0.2498	0.2886	0.2241	0.2550	0.0742	0.0524	0.0483	0.0780
0.2252	0.3091	0.1782	0.2161	0.0669	0.0561	0.0384	0.0661
0.2539	0.2845	0.2343	0.2593	0.0754	0.0516	0.0505	0.0793
0.2498	0.2886	0.2241	0.2550	0.0742	0.0524	0.0483	0.0780
0.3194	0.2538	0.3531	0.3155	0.0948	0.0461	0.0762	0.0965

The TOPSIS results present the separation distances from positive (D^+) and negative (D^-), along with relative closeness coefficient (CC_i) and corresponding ranks. The first alternative achieved $D^+ = 0$ and $D^- = 0.068549$, resulting in the highest closeness coefficient ($CC_i = 1.000$) and securing Rank 1, indicating it is the optimal solution. As D^+ increases and D^- decreases, the closeness coefficient progressively declines, reflecting reduced performance. The lowest-ranked alternative (Rank 11) exhibits $D^+ = 0.068549$ and $D^- = 0$, yielding $CC_i = 0$, which indicates maximum deviation from the ideal solution. Overall, the ranking clearly distinguishes the best compromise solution based on combined fuel consumption, efficiency, and emission criteria. Comparative TOPSIS analysis identified the first alternative as the optimal solution with the highest closeness coefficient ($CC_i = 1.000$). The lower-ranked alternatives exhibited greater deviation from the ideal solution, indicating comparatively inferior efficiency and emission characteristics (Zhu *et al.* 2026).

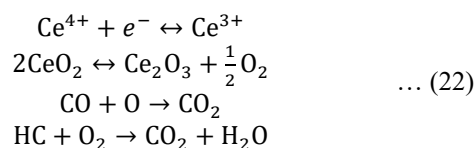
3.10 Mechanism of CeO₂ Nanoparticles

3.10.1 Proposed combustion pathway of CeO₂

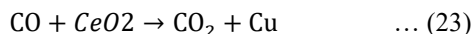
Alterations in combustion and emission characteristics after adding CeO₂ to *Spirulina platensis* biodiesel result from the combined influence of the fuel's inherent oxygen content and CeO₂'s catalytic behavior. CeO₂ acts as an oxygen-buffering catalyst by reversible Ce⁴⁺/Ce³⁺ redox cycling, enhancing oxidation reactions during combustion.

Table 15. D⁺, D⁻ and CC_i normalization result for TOPSIS

D ⁺	D ⁻	CC _i	Rank_Topsis
0	0.068549	1	1
0.010124	0.058574	0.852636	2
0.016269	0.052525	0.763509	3
0.017503	0.051465	0.746219	4
0.017503	0.051465	0.746219	4
0.017503	0.051465	0.746219	4
0.017853	0.05106	0.740931	5
0.020325	0.048582	0.705039	6
0.04397	0.025122	0.363605	7
0.052925	0.015782	0.229704	8
0.056828	0.011895	0.173086	9
0.063841	0.005085	0.07378	10
0.068549	0	0	11



Oxidation of incomplete combustion intermediates is typically kinetically limited; however, this catalytic system promotes rapid and near-complete CO oxidation to CO₂ by continuously supplying lattice oxygen to the reaction interface, even at elevated temperatures. Additionally, alternative cooperative pathways facilitate oxidation under oxygen-deficient conditions.



Beyond catalytic oxidation, CeO₂ nanoparticles enhance combustion through superior thermal conductivity (~33–36 W/m·K), improving heat transfer and accelerating droplet vaporization. They promote flame propagation and act as heterogeneous nucleation centers, inducing micro-explosions that reduce droplet size by 25–40%, resulting in finer atomization.

The inherent oxygen content (8–12 wt%) of *Spirulina platensis* biodiesel enhances oxidation of CO and HC intermediates. The SB25CeO₂50 blend achieved 20.81% CO and 14.49% HC reductions due to synergistic catalytic oxygen release, improved atomization, superior heat transfer, and oxygenated FAME structure, promoting more complete combustion.

Optimal combustion and emission characteristics were achieved with 50 mg/L CeO₂ and a 20% biodiesel blend. Higher concentrations induce agglomeration, droplet coalescence, and increased mass-transfer resistance, diminishing catalytic effectiveness and offsetting the benefits of nanoparticle-assisted oxidation.

The reduction in emissions arises from the synergistic coupling of CeO₂ catalytic activity and the intrinsic oxygen of biodiesel. CeO₂ nanoparticles supply lattice oxygen via Ce⁴⁺/Ce³⁺ redox cycling, enhancing hydrocarbon oxidation and CO intermediates at the droplet interface. Simultaneously, the oxygenated FAME structure promotes more complete bulk-phase combustion. This combined fuel-bound oxygen mechanism and surface-catalytic accounts for the consistent decline in CO and HC emissions across varying engine loads.

In contrast, SB45CeO₂50 exhibited inferior full-load performance, with increased BSFC and reduced BTE. Elevated biodiesel viscosity and nanoparticle agglomeration impaired atomization. Excess oxygenated content prolonged ignition delay and intensified in-cylinder pressure gradients, ultimately lowering thermal efficiency despite adequate oxygen availability.

4. CONCLUSION

The investigation shows that green-synthesized CeO₂ nanoparticles derived from *Moringa oleifera* leaf extract significantly enhance the emission and combustion characteristics of *Spirulina platensis* biodiesel blends in a compression ignition engine. The bio-mediated synthesis route successfully produced nanocrystalline CeO₂ particles with an average size of 40 ± 5 nm, ensuring high surface activity and effective catalytic functionality. Engine experiments confirmed that nano-additive incorporation improves brake thermal efficiency while reducing specific fuel and regulated

emissions. The RSM-predicted condition corresponding to SB25 with 70.35 mg/L CeO₂ exhibited comparatively lower SFC (0.275 kg/kWh) and CO emission (0.105 vol%), which showed reasonable agreement with experimental observations. Statistical analysis using RSM and ANOVA verified the significant influence of CeO₂ dosage (*p* < 0.01) on performance enhancement, with strong model adequacy (*R*² > 0.85). Overall, the synergistic integration of microalgal biodiesel and green-synthesized rare-earth nano-additives provides an effective strategy for improving fuel economy and emission control, offering a sustainable pathway for next-generation low-carbon diesel engine applications. However, the present study was limited to short-term engine operation and selected nanoparticle concentrations under laboratory conditions. Future investigations may focus on long-term engine durability, nanoparticle stability, combustion optimization, and real-time engine applications under varying operating environments.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Alotaibi, B., Gaafar, S. S., Aljuailan, R., Alawadhi, H. L. A., Alsalhi, H., Alharbi, H., Alfaraidey, R. S., Smran, A. A. A. and Niazi, F. H., Photochemically Activated Microbubble Emulsion, Nd: Yap Laser, and Cerium Oxide Nanoparticles as Canal Disinfectants on Push-Out Bond Strength of Sealer to Root Dentin, Smear Layer, and Antibacterial Efficacy, *Micros. Res. Tech.*, 88(6), 1654–1663(2025).
<https://doi.org/10.1002/jemt.24802>
- Anwar, M., Biodiesel feedstocks selection strategies based on economic, technical, and sustainable aspects, *Fuel*, 283, 119204(2021a).
<https://doi.org/10.1016/j.fuel.2020.119204>

- Anwar, M., Potential vs prevalent vs popular vs proven biodiesel feedstocks: A critical 4P selection process, *Fuel*, 298, 120712(2021b). <https://doi.org/10.1016/j.fuel.2021.120712>
- Arun, A., Maleki, B., Prakash, R. M., Mounesh, N., Pramoda, P. and Kalanakoppal, V. Y., Exploitation of *Annona reticulata* leaf extract for the synthesis of CeO₂ nanoparticles as catalyst for the production of biodiesel using seed oil thereof, *Energy*, 298, 131335(2024). <https://doi.org/10.1016/j.energy.2024.131335>
- Azam, S. and Park, S. S., Impact of Biosynthesized CeO₂ Nanoparticle Concentration on the Tribological, Rheological, and Thermal Performance of Lubricating Oil, *Lubricant.*, 12(11), 400 (2024). <https://doi.org/10.3390/lubricants12110400>
- Canan, A., Enrichment of 3rd generation biodiesel/diesel blends with optimum boron oxide for cleaner diesel emissions by multi-objective optimization using RSM, *Environ. Res.*, 276, 121472(2025). <https://doi.org/10.1016/j.envres.2025.121472>
- Celik, M., Bayindirli, C. and İlhak, M. İ., Investigation of the Performance and Emissions of an Engine Operated with CeO₂ Nano Additive Doped Biodiesel, *Int. J. Automotive Sci. Technol.*, 6(2), 113–119 (2022). <https://doi.org/10.30939/ijastech..1063986>
- Chhikara, A., Dhingra, A. K., Chhabra, D. and Kumar, P., Optimization of biodiesel production of spirulina-platensis algae biomass using RSM integrated with whale optimization algorithm, *Ind. J. Eng. Mater. Sci.*, 31(5), 750–758 (2024). <https://doi.org/10.56042/ijems.v31i5.10448>
- De Souza, D. S., Lomeu, A., de Oliveira Moreira, O. B., De Oliveira, M. A. L. and Mendonça, H. V. D., New methods to increase microalgae biomass in anaerobic cattle wastewater and the effects on lipids production, *Biomass Bioenergy*, 176, 106915(2023). <https://doi.org/10.1016/j.biombioe.2023.106915>
- Elnajjar, E., Purayil, S. T. P., Alnuaimi, F., Al Khawaja, H., Shaikhoun, L., Arnaoud, N. and Almutawa, S., Mechanistic investigation of efficient cell disruption methods for lipid extraction from various macro and micro species of algae, *Biores. Technol. Rep.*, 22, 101482 (2023). <https://doi.org/10.1016/j.biteb.2023.101482>
- Elumalai, R., Krishnaiah, R., Elumalai, E. P., Saboor, S., C. C. A. and Hussain, F., Investigation into the Ideal Concoction for Performance and Emissions Enhancement of *Jatropha* Biodiesel-Diesel with CuO Nanoparticles Using Response Surface Methodology, *ACS Omega*, 8(42), 39067–39079(2023). <https://doi.org/10.1021/acsomega.3c03890>
- Farrokheh, A., Tahvildari, K. and Nozari, M., Biodiesel production from the *Chlorella vulgaris* and *Spirulina platensis* microalgae by electrolysis using CaO/KOH-Fe₃O₄ and KF/KOH-Fe₃O₄ as magnetic nanocatalysts, *Biomass Convers. Biorefine.*, 12(2), 403–417 (2022). <https://doi.org/10.1007/s13399-020-00688-z>
- George, R. R., Ağbulut, Ü., Preno, K. C., Alex, Y., Sailesh, K. S., Afghan, K. S., Jilte, R., Linul, E. and Asif, M., Impact of synthesizing surfactant-modified catalytic ceria nanoparticles on the performance and environmental behaviors of coconut oil/diesel-fueled CI engine: An optimization attempt, *Energy*, 295, 130825(2024). <https://doi.org/10.1016/j.energy.2024.130825>
- Jayabal, R., Environmental impact of adding hybrid nanoparticles and hydrogen to the algae biodiesel-diesel blend on engine emissions, *Process Safe. Environ. Protect.*, 198, 107102(2025). <https://doi.org/10.1016/j.psep.2025.107102>
- Jegan, C. D., Selvakumaran, T., Karthe, M., Hemachandu, P., Gopinathan, R., Sathish, T. and Ağbulut, Ü., Influences of various metal oxide-based nanosized particles-added algae biodiesel on engine characteristics, *Energy*, 284, 128633(2023). <https://doi.org/10.1016/j.energy.2023.128633>
- Kumar, S., Dinesha, P. and Khan, N., Enhancement of Combustion Behaviour of Waste Cooking Oil Biodiesel Fuelled Engine using Metallic Oxide Nanoparticle with Varying Volume Concentration: An Experimental Study, *Int. J. Renew. Energy Res.*, 11(1), 101–107(2021).
- Abirami, M. and Das, D., Sustainable energy transitions: Evaluating microalgal biodiesel feedstocks using multi-criteria decision-making techniques, 13, 4163–4181(2025). <https://doi.org/10.1016/j.egyr.2025.03.027>
- Maheswaran, R. and Uthranarayan, C., Effect of Photosynthetic Bacteria Based Feedstock and Temperature on Biodiesel Yield Using Microwave Assisted Transesterification with an Application of Box Behnken Supported Response Surface Methodology, *J. Chilean Chem. Soc.*, 67(3), 5636–5642(2022). <https://doi.org/10.4067/S0717-97072022000305636>
- Manimaran, R., Optimization of *Azadirachta indica* leaf extract mediated cerium oxide nanoparticles synthesis, characterization, and its applications, 204, 117304(2023). <https://doi.org/10.1016/j.indcrop.2023.117304>
- Oni, B. A., Sanni, S. E., Ibegbu, A. J. and Oguntade, T. I., Authentication of *Styrax officinalis* L. methyl ester nanoparticulate fuel-system's suitability in powering CI engines, *Indus. Crops Prod.*, 181, 114833(2022). <https://doi.org/10.1016/j.indcrop.2022.114833>
- Palanisamy, K. M., Bhuyar, P., Ab Rahim, M. H., Govindan, N. and Maniam, G. P., Cultivation of Microalgae *Spirulina platensis* Biomass Using Palm Oil Mill Effluent for Phycocyanin Productivity and Future Biomass Refinery Attributes, *Int. J. Energy Res.*, 2023, 1-9(2023). <https://doi.org/10.1155/2023/2257271>

- Polat, F., Sarıdemir, S., Gad, M. S., El-Shafay, A. S. and Ağbulut, Ü., Enhancing diesel engine performance, combustion, and emissions reductions under the effect of cerium oxide nanoparticles with hydrogen addition to biodiesel fuel, *Int. J. Hydrogen Energy*, 83, 884–896(2024).
<https://doi.org/10.1016/j.ijhydene.2024.08.031>
- Rajasekaran, M., Krishnamoorthi, S. and Vijayaragavan, M., An experimental investigation of the effects of blending camphor oil infused with jack fruit biodiesel and nanoparticles on the performance, combustion, and exhaust emissions of a compression ignition engine, *Proce. Institute Mech. Eng. Part E J. Process Mech. Eng.*, 239(6), 3460–3468(2025).
<https://doi.org/10.1177/09544089231225750>
- Rudreshappa, G. E., Chennabasappa, M., Sreenivasa, S., Kumar, S. V., Yatish, K. V., Nagaraju, G., Suresh Kumar, H. M. S. and Kumar, D. B. A., Green Synthesis of Cerium Oxide Nanoparticles, Antibacterial Studies and as Catalyst for the Conversion of Cotton Seed Oil into Biodiesel., *Asian J. Chem.*, 34(9), 2415–2423(2022).
<https://doi.org/10.14233/ajchem.2022.23607>
- Saravanan, A., Kings, A. J., Miriam, L. R. M. and Rimal Isaac, R. S. R., RSM-based comparative experimental study of sustainable biodiesel synthesis from different 2G feedstocks using magnetic nanocatalyst CaFe_2O_4 , *Environ. Develop. Sustain.*, 26(2), 3097–3126(2024).
<https://doi.org/10.1007/s10668-022-02761-1>
- Sathish, T., Ağbulut, Ü., George, S. M., Ramesh, K., Saravanan, R., Roberts, K. L., Sharma, P., Asif, M. and Hoang, A. T., Waste to fuel: Synergetic effect of hybrid nanoparticle usage for the improvement of CI engine characteristics fuelled with waste fish oils, *Energy*, 275, 127397(2023a).
<https://doi.org/10.1016/j.energy.2023.127397>
- Savaş, A., Uslu, S. and Şener, R., Optimization of performance and emission characteristics of a diesel engine fueled with MgCO_3 nanoparticle doped second generation biodiesel from jojoba by using response surface methodology (RSM), *Fuel*, 381, 133658(2025).
<https://doi.org/10.1016/j.fuel.2024.133658>
- Sengodan, N., Selvaraju, M., Venugopal, K. and Raja, T., Performance and Analysis of RCCI Combustion using Gasoline and Jatropha Curcas Biodiesel for Enhanced Efficiency and Reduced Emissions in CI Engines, *Int. J. Veh. Struct. Syst.*, 17(3), 506–519 (2025).
<https://doi.org/10.4273/ijvss.17.3.20>
- Sriariyanun, M., Baranitharan, P., Venkatesh, S., Rajeshkumar, K. and Kavimani, V., Manufacturing and mechanical characterization of alkali-treated Borassus fruit natural fiber with cellulose acetate synthetic fiber reinforced polymer composite: selection of optimum configuration using CRITIC-integrated EDAS soft computing techniques, *J. Mater. Cycles Waste Manage.*, 27(2), 880–897(2025).
<https://doi.org/10.1007/s10163-024-02142-y>
- Sathish, T., Ağbulut, Ü., George, S. M., Ramesh, K., Roberts, K. L., Sharma, P., Asif, M. and Hoang, A. T., Waste to fuel: Synergetic effect of hybrid nanoparticle usage for the improvement of CI engine characteristics fuelled with waste fish oils, *Energy*, 275, 127397 (2023b).
<https://doi.org/10.1016/j.energy.2023.127397>
- Vijaya, K. P., Bragadeshwaran, B., Senthil, K. M., Vignesh, R., Bhasker, J. P. and Kumar, A. N., Evaluation of performance, emissions and combustion attributes of CI engine using palmyra biodiesel blend with distinct compression ratios, EGR rates and nano-particles, *Fuel*, 321, 124092(2022).
<https://doi.org/10.1016/j.fuel.2022.124092>
- Zhu, C., Li, D., Zhang, H., Zhang, D., Su, N. and Xu, F., Effect of montmorillonite-loaded CeO_2 nanocomposites with different CeO_2 contents on thermal-oxidative and ultraviolet aging properties of asphalt, *Constru. Build. Mater.*, 507, 145057 (2026).
<https://doi.org/10.1016/j.conbuildmat.2025.145057>