Indian Journal of Engineering & Materials Sciences
Vol. 33, April 2026, pp. 206-222
DOI: 10.56042/ijems.v33i02.19823

Performance, emission, and optimization of CuO-doped ternary biodiesel in CI engines

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Received: 18 May 2025; accepted: 06 January 2026

This research has explored the performance, emission, and combustion properties of a CuO nanoparticle-doped ternary biodiesel mixture containing 90% diesel, 5% rapeseed methyl ester, and 5% linseed methyl ester (RLD10) in a single-cylinder CI engine. To increase efficiency in combustion and decrease emissions, nanoparticles of CuO have been added at different concentrations (25-100 ppm). RLD10CU75 has demonstrated the best brake thermal efficiency (34.04%), lowest specific fuel consumption (0.258 kg/kWh) and greatest mechanical efficiency (70.10) at full load of all the tested blends. The emission analysis has shown high percentages of CO (19.2%), HC (13.6%), and smoke (17.3) reduction over the diesel, and the NO Cs have not exceeded the allowable limit. The diagnostics of combustion has shown that RLD10CU75 has a better in-cylinder pressure and a higher heat release rate, which proves better combustion dynamics. It has been used to optimize statistically with Response Surface Methodology (RSM) and desirability function has found the optimal condition of 63.2% load and 99.99 ppm CuO which predicts a brake thermal efficiency of 29.20% with reduced emissions. The results have made CuO-doped RLD10 a promising bio-nano fuel, which has provided a good trade-off between the engine performance and the environmental impact without necessitating any adjustments to the engine. This work has supported the advancement of sustainable fuel technologies aligned with clean energy and emission reduction goals.

Keywords: Combustion analysis, CuO nanoparticles, Diesel engine performance, Emission reduction, Heat release rate, Optimization, Rapeseed methyl ester, Response surface methodology (RSM), Ternary biodiesel blend

1 Introduction

Rising energy needs, harm to the environment and unstable fossil fuel prices have made alternative fuels more important in discussions on sustainable energy and this is very true in places like India that need energy security and are dedicated to fighting climate change. In sectors such as transportation, agriculture and industry, IC engines—especially diesel engines—have played a key role because of their durability, high energy density and low fuel requirements by Nguyen[1]& Babu[2]. However, it’s important to know that diesel engines contribute greatly to air pollution and as a result emit greenhouse gases, carbon monoxide, hydrocarbons, nitrogen oxides and particulate matter by Wu[3]. Due to these environmental concerns, people are looking for new types of fuel that would supply enough energy for transportation without modifying the engine. There is growing interest in biodiesel, since it is considered one of the top renewable fuels reported by Zulqarnain[4]. Since biodiesel is made from renewable sources such as vegetable oils and animal fats, it is biodegradable, less harmful, offers good lubrication and improves combustion as it contains more oxygen reported by Kumar[5]. Various regions around the world have used first-generation biodiesel, mostly made from rapeseed, sunflower and soybean by Malode[6]. At the same time, using B100 or high concentrations of biodiesel in unaltered engines results in drawbacks, including thicker liquid and low temperature stability, leading to difficulty in atomizing, burning incompletely, deposits on injection parts and an increase in NOx emissions reported by Mofijur[7].

People are using biodiesels in combination with diesel more often in order to overcome these challenges. Ternary mixtures are prepared to take

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advantage of the best features from several feedstocks such as a high cetane number, low density, stronger resistance to oxidation and more unsaturated compounds addressed by Garg[8]& Ranjit[9]. Reduced oxidation and good lubricity are known features of rapeseed oil biodiesel, whereas the high unsaturated levels in linseed oil biodiesel can improve the burning process reported by Pantoja[10]&Brahma[11]. A blend of rapeseed methyl ester (RME), linseed methyl ester (LME) and conventional diesel allows for a well-balanced fuel that shares similar properties with diesel and adds green elements by Ranjit[9]. Yet such blends of biodiesel can't sufficiently handle problems caused by inefficient engine operation and toxic emission concerns by Modi[12]. Adding nanoparticles to biodiesel blends has proven to be a modern method that addresses the problems of conventional biodiesel. It is particularly advantageous to use CuO, Al_2O_3, CeO_2 or TiO_2 nanoparticles as they are very active catalysts, have a large surface area and conduct heat better than most other materials reported by Upadhyay[13]. Among all of them, Copper Oxide (CuO) nanoparticles stand out due to their excellent potential. During combustion, CuO particles release oxygen, speed up oxidation, improve the process of fuel atomization and help ignition become more stable and occur earlier. These factors enable the flame to move more rapidly and make combustion more total, helping to control emissions and maximize how the engine works. The mixing of nanoparticles in the fuel is achieved through ultrasonic treatment to avoid aggregation addressed bySingh[14]. Moreover, using such nanoparticles may raise the cetane number in biodiesel which improves its quality and how it functions in the engine reported by Basha[15].

Numerous studies have confirmed the performance enhancement and emission reduction potential of biodiesel blends enriched with nanoparticles by Borthakur[16]. For instance, Azad[17] reported that ternary biodiesel blends derived from Mandarin, Crambe, Avocado, and Bush nut oils—when modified with paraffin—exhibited combustion and emission characteristics comparable to those of conventional diesel fuel. Similarly, Fareed[18] investigated hybrid biodiesel blends formulated from palm and waste cooking oils and observed notable improvements in brake thermal efficiency (BTE), along with significant reductions in hydrocarbons (HC), carbon monoxide (CO), and smoke opacity. However, a slight increase in NO_x emissions remained a challenge. In addition, blending strategies incorporating oxygenated additives such as diethyl ether (DEE) or catalytic nanoparticles like cerium oxide have been shown to enhance the cold flow properties and combustion quality of biodiesel blends. Several researchers have also documented measurable gains in thermal efficiency with the inclusion of nanoparticles, reinforcing their value in biofuel optimization strategies reported by Fayaz[19].

Various studies reveal that adding nanoparticles to biodiesel can help improve its performance and allow for less emission reported byBorthakur[16]. As an example, Azad[17]indicated that blending Mandarin, Crambe, Avocado and Bush nut oils with paraffin made the modified biodiesel behave and perform similarly to conventional diesel in terms of combustion and emissions. In addition, Fareed[18]examined hybrid biodiesel blended from palm and cooking oil waste and noticed an improvement in brake thermal efficiency, as well as less HC, less CO and less gas opacity. Nonetheless, there was still a challenge in keeping NO_x emissions low. Additionally, including diethyl ether (DEE) or cerium oxide nanoparticles during blending improves the cold flow properties and the efficiency of biodiesel fuels. A number of researchers have demonstrated that adding nanoparticles leads to improved efficiency in various biofuels reported by Fayaz[19]. While studies on nanoparticle-enhanced biodiesel keep increasing, an important issue is that engineering the performance and emissions of engine using ternary fuel with copper oxide (CuO) nanoparticles has not yet been fully addressed. Although a lot of research uses experimental data, only a few researchers include Response Surface Methodology (RSM) to study and improve many important engine characteristics together. RSM is an effective approach for studying, analyzing and improving different engineering designs. It allows researchers to understand how various input variables such as engine load and nanoparticle level affect the performance and emissions of an internal combustion engine. The use of nanoparticles in biodiesel enhances fuel performance and helps the fuel to burn cleanly. Oxygen supplied by CuO particles and their catalytic effect make fuel burn faster and more completely addressed by Ağbulut[20].

This research closes the existing gap by suggesting a ternary biodiesel blend named RLD10 that consists of 90% diesel, 5% rapeseed biodiesel and 5% linseed biodiesel. Copper oxide (CuO) nanoparticles at concentrations of 25, 50, 75 and 100 ppm are used to test how they impact the performance, combustion and emissions of a diesel engine at different amounts. Critical performance metrics such as brake thermal efficiency (BTE), specific fuel consumption (SFC), and mechanical efficiency (ME) are assessed, alongside key emissions including CO, CO_2, HC, NO_x, and smoke opacity, across varying engine loads. To gain mechanistic insights, advanced combustion diagnostics—namely in-cylinder pressure and heat release rate (HRR) analyses—are conducted to interpret combustion intensity, ignition delay, and thermodynamic efficiency. A statistically driven response surface methodology (RSM) model, employing central composite design (CCD), is developed to examine the combined effects of engine load and nanoparticle dosage. Analysis of variance (ANOVA) validates model reliability and identifies significant factors. A multi-objective desirability function is employed to determine the optimal operating condition, which was experimentally found to be 63.2% load with 99.99 ppm CuO, yielding maximum BTE with minimal emissions.

The novelty of this study lies in its integrated approach that combines biodiesel ternary blending, nanoparticle enhancement, engine experimentation, and statistical optimization. It clearly demonstrates the dual advantage of RLD10CuO blends in significantly improving thermal and mechanical efficiency while concurrently reducing harmful emissions such as CO, HC, and smoke. The catalytic behaviour of CuO nanoparticles is effectively leveraged to enhance combustion quality by accelerating oxidation reactions and promoting more complete fuel burn.

2 Materials and Methods

2.1 Raw materials and feedstock oils

This study relied on linseed oil and rapeseed oil for making biodiesel. All the oils we used were bought from trusted vendors and tested to confirm they were pure. The paper used commercial-grade diesel (B0) as the benchmark fuel. Copper oxide nanoparticles of 30–50 nanometers in size and 99.9% purity were obtained from Nano Labs India for the samples. Methanol (99.5% purity) and potassium hydroxide (KOH) were used as the alcohol and catalyst, respectively, in the transesterification process.

2.2 Biodiesel synthesis via transesterification

The oils were first filtered and preheated to 60 ± 2 °C to remove moisture. The transesterification reaction was conducted in a batch reactor equipped with a mechanical stirrer and heating mantle. For both linseed and rapeseed oils, a methanol-to-oil molar ratio of 6:1 and a catalyst concentration of 1 wt% KOH were employed. The reaction was maintained at 60 °C for 90 minutes under constant stirring at 600 rpm. The resulting biodiesel was separated from glycerol via decantation and subsequently washed with warm deionized water until a clear layer was obtained. The purified biodiesel was dried and stored in airtight containers for further use.

2.3 Fuel blend preparation

In this study, various ternary biodiesel blends and their nanoparticle-enriched variants were prepared and evaluated to assess their impact on diesel engine performance, combustion, and emissions. The base biofuels used were rapeseed biodiesel (RB) and linseed biodiesel (LB), selected for their complementary physicochemical properties—rapeseed biodiesel offers better cetane number and oxidative stability, while linseed biodiesel contributes higher unsaturation and improved combustion characteristics. These biodiesels were blended with commercial diesel in specific volumetric proportions to create a series of ternary fuel blends. The blending process was performed using a magnetic stirrer to ensure homogeneous mixtures. Initially, five ternary blends were prepared by mixing diesel, RB, and LB at the following ratios: 90:5:5 (RLD10), 80:10:10 (RLD20), 70:15:15 (RLD30), 60:20:20 (RLD40), and 50:25:25 (RLD50) by volume. Figure 1 shows the sample of ternary blended bio-diesel.

Among these, RLD10 was selected as the base ternary blend for nanoparticle enhancement due to its closer match to diesel fuel properties and operational stability. Subsequently, RLD10 was doped with CuO

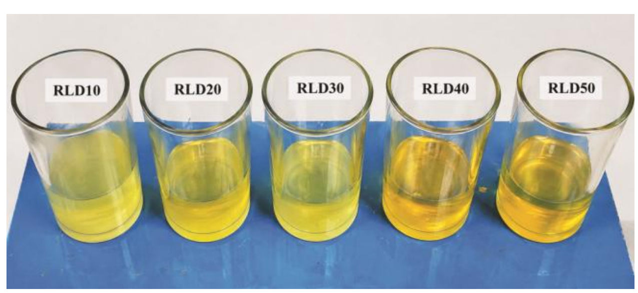

Fig. 1 — Sample of triple blended biodiesel.

nanoparticles at concentrations of 25, 50, 75, and 100 ppm, resulting in blends RLD10CU25, RLD10CU50, RLD10CU75, and RLD10CU100, respectively. The CuO nanoparticles were dispersed into the fuel using probe ultrasonication for 30 minutes to ensure uniform distribution and prevent agglomeration. The blends were then allowed to rest for 24 hours to test stability, and no phase separation was observed. The test engine was initially operated using neat diesel at 1500 rpm until it reached steady-state conditions (about 30 minutes). This provided a performance and emission baseline. Thereafter, each blend was tested under the same conditions, and the engine was run for at least 20 minutes per fuel before measurements were taken across variable load conditions (0 to 100%). Table 1 provides the experimental matrix values for fuel blends.

2.4 Experimental set-up and test procedure

The experimental investigation was conducted using a single-cylinder, four-stroke, water-cooled Kirloskar diesel engine, which was coupled to an eddy current dynamometer as illustrated in Fig. 2. The detailed specifications of the engine are provided in Table 2.

Performance parameters including brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and mechanical efficiency (ME) were systematically measured during the tests. Emission characteristics—specifically carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO_2), nitrogen oxides (NO_x), and smoke opacity—were monitored using an AVL gas analyzer and a smoke meter. For combustion analysis, in-cylinder pressure data was captured using a piezoelectric pressure transducer integrated with a data acquisition (DAQ) system, enabling precise evaluation of combustion dynamics.

2.5 Design of experiments and optimization methodology

To optimize the fuel blends and engine functioning, response surface methodology (RSM) was applied together with a central composite design (CCD). The study examined how three independent variables engine load, CuO nanoparticle concentration and ternary blend ratio—affect fuel combustion. The

Table 1 — Experimental matrix for fuel blends.

Fuel and Blends	Notation
Diesel	D
Rapeseed biodiesel	RB
Linseed biodiesel	LB
90% Diesel + 5% RB + 5% LB	RLD10
80% Diesel + 10% RB + 10% LB	RLD20
70% Diesel + 15% RB + 15% LB	RLD30
60% Diesel + 20% RB + 20% LB	RLD40
50% Diesel + 25% RB + 25% LB	RLD50
RLD10 + 25 ppm CuO nanoparticles	RLD10CU25
RLD10 + 50 ppm CuO nanoparticles	RLD10CU50
RLD10 + 75 ppm CuO nanoparticles	RLD10CU75
RLD10 + 100 ppm CuO nanoparticles	RLD10CU100

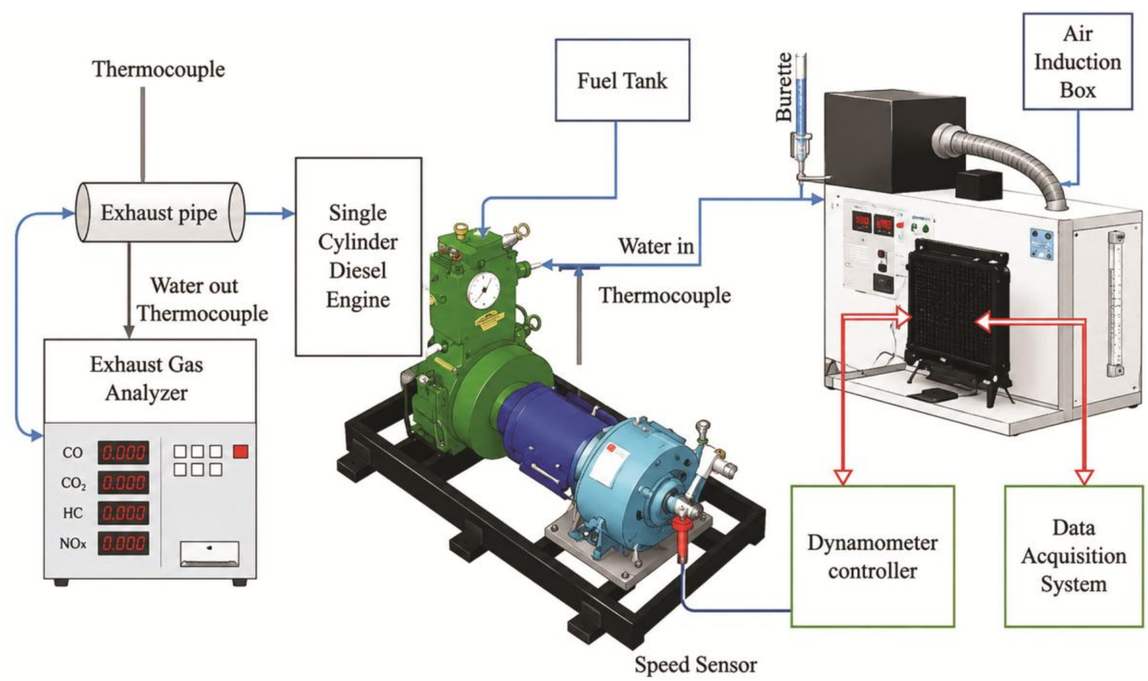

Fig. 2 — Schematic view of the test rig.

evaluated response variables were brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), NO_x emissions and smoke opacity. In this study, design-expert software (Version 10, provided by Stat-Ease Inc., USA) was used for model development, regression analysis and numerical optimization. The CCD matrix was used to design 20 experimental trials to ensure all possible interactions were measured. The statistical significance of the models and the effects between variables were tested using Analysis of Variance (ANOVA). Finally, the desirability function approach was applied to identify the optimal combination of input parameters that would yield maximum performance benefits while minimizing exhaust emissions.

3 Results and Discussion

3.1 Engine performance parameters

The performance evaluation of the ternary biodiesel blends and nano-additive fuels was carried out by analysing three major parameters: Brake thermal efficiency (BTE), specific fuel consumption (SFC), and mechanical efficiency (ME). The performance data reveals the direct impact of CuO nanoparticles and bio-diesel proportions under varying load conditions. Figure 1 comprises three subplots that illustrate the variation of key engine performance parameters—brake thermal efficiency (BTE), specific fuel consumption (SFC), and mechanical efficiency (ME)—across different load conditions (20% to 100%) for various fuel blends: neat diesel, RLD10 (rapeseed-linseed-diesel blend), and nano-enhanced versions of RLD10 with CuO concentrations ranging from 25 ppm to 100 ppm.

Table 2 — Specifications of the experimental engine.

Parameter	Specification
Engine Type	Kirloskar AV1
No. of Cylinders	Single
Stroke	4-Stroke, CI Engine
Bore × Stroke	87.5 mm × 110 mm
Compression Ratio	17.5:1
Rated Power	5.2 kW @ 1500 rpm
Cooling Type	Water-Cooled
Injection Pressure	200 bar

3.1.1 Brake thermal efficiency (BTE) versus Load

Figure 3(a) reveals that BTE increases consistently with engine load for all fuel types. Among the fuels tested, RLD10CU75 achieved the highest BTE of 34.04% at full load, surpassing diesel (31.32%) and RLD10 (29.89%). The enhanced BTE for RLD10CU75 is attributed to the synergistic effects of the ternary blend and CuO nanoparticles. The catalytic activity of CuO promotes faster and more complete combustion, thereby increasing the thermal efficiency. Notably, RLD10CU100 exhibits a slight drop in BTE compared to RLD10CU75, suggesting that excessive nanoparticle concentration can increase fuel viscosity, negatively impacting spray atomization and combustion completeness.

3.1.2 Specific fuel consumption (SFC) versus Load

Figure 3(b) shows a declining trend with increasing load, consistent with typical diesel engine behavior. RLD10CU75 again stands out by offering the lowest SFC across the tested load range, particularly at full load where it records a 23.3% and 26.9% reduction compared to diesel and RLD10, respectively. This indicates that the energy extraction per unit mass of fuel is more efficient with RLD10CU75. The improvement is due to enhanced combustion facilitated by the high thermal conductivity and catalytic oxidation potential of CuO, which enables better utilization of the fuel's calorific content.

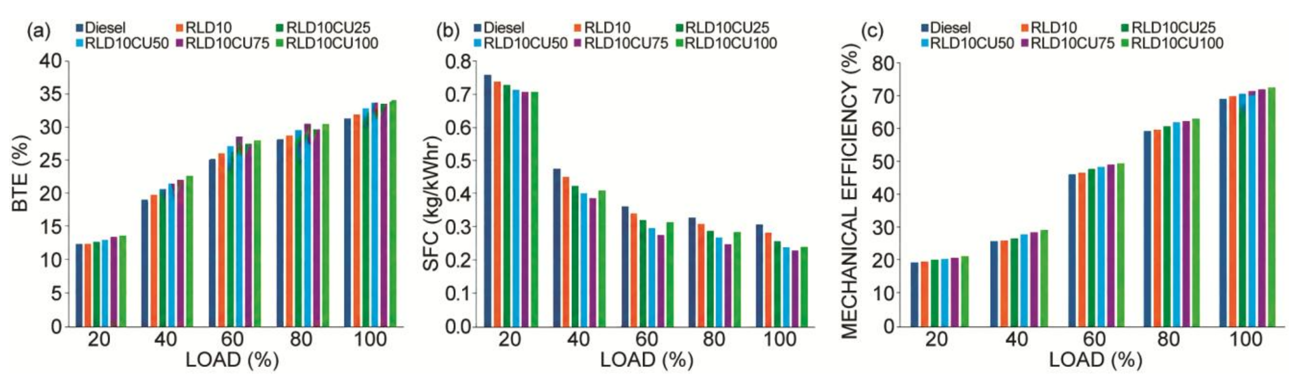

Fig. 3 — Variation of engine performance parameters with load for different fuel blends (a) Brake thermal efficiency (BTE), (b) Specific fuel consumption (SFC), and (c) Mechanical efficiency (ME) for diesel, RLD10, and CuO nanoparticle-enriched ternary biodiesel blends (RLD10CU25–RLD10CU100).

3.1.3 Mechanical efficiency (ME) versus Load

Figure 3(c) shows a strong positive correlation with load across all blends. RLD10CU75 consistently achieves the highest mechanical efficiency at each load level, peaking at 70.1% at full load, which is slightly above diesel (68.41%). This improvement is likely due to the better combustion quality induced by the nanoparticles, leading to a smoother transfer of energy from combustion to the crankshaft with reduced frictional and thermal losses reported by Kamble[21]. The high efficiency of RLD10CU75 suggests that it enables more effective conversion of indicated power to brake power.

Overall, RLD10CU75 emerges as the most optimized blend, offering a balanced enhancement in all three-performance metrics. The presence of CuO nanoparticles at 75 ppm concentration appears to be the threshold for maximizing combustion efficiency without adversely affecting fuel properties such as viscosity. This figure provides visual and analytical evidence of the suitability of nano-biodiesel blends as sustainable and high-performance alternatives to conventional diesel fuel.

This performance evaluation validates the synergistic effect of ternary blends and CuOnano-additives, particularly at a 75-ppm dosage, offering an optimal balance between energy conversion efficiency and fuel economy. Table 3 summarizes the engine performance at full load, presenting clear numerical evidence that supports the trends observed in Fig. 1. It shows that the RLD10CU75 blend delivers the highest brake thermal efficiency (34.04%), lowest specific fuel consumption (0.258 kg/kWh), and maximum mechanical efficiency (70.10%) among all tested fuels. These values correlate directly with the graphical trends in Fig. 3(a, b &c), where RLD10CU75 consistently outperforms neat diesel and other biodiesel blends. The enhanced performance is attributed to the catalytic and thermal effects of CuO nanoparticles, which improve combustion efficiency, reduce frictional losses, and optimize energy conversion, especially at full engine load.

3.2 Emission characteristics

The emission behaviour of the diesel engine fueled with ternary biodiesel blends enhanced with CuO nanoparticles was assessed by monitoring CO, CO_2, HC, NO_x, and smoke emissions. These parameters were analyzed in relation to varying engine loads and nanoparticle concentrations. The results confirm the environmental advantages of incorporating nanoadditives into biodiesel blends, demonstrating their potential to reduce harmful exhaust emissions.

Figure 4 provides insights into the variation of Carbon Monoxide (CO) and Carbon Dioxide (CO_2) emissions with engine load for different fuel types, including neat diesel, RLD10 (a ternary blend of rapeseed, linseed, and diesel), and RLD10 blends enhanced with various concentrations of CuO nanoparticles (25–100 ppm).

3.2.1 CO emission versus Load

Figure 4(a) shows that CO emissions decrease with increasing CuO nanoparticle concentration, especially

Table 3 — Summary of engine performance at full load conditions.

Fuel Type	BTE (%)	SFC (kg/kWh)	ME (%)
Diesel	31.32	0.287	68.41
RLD10	29.89	0.301	69.70
RLD10CU25	32.11	0.295	69.82
RLD10CU50	33.14	0.280	70.00
RLD10CU75	34.04	0.258	70.10
RLD10CU100	33.52	0.272	69.40

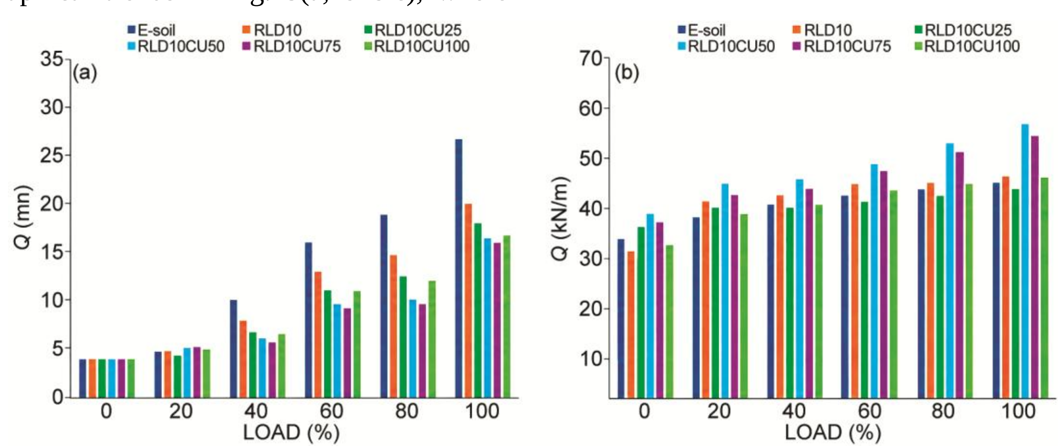

Fig. 4 — Variation of (a) Carbon monoxide (CO) and (b) Carbon dioxide (CO_2) emissions with engine load for diesel, RLD10, and CuO nanoparticle-enhanced ternary biodiesel blends (RLD10CU25–RLD10CU100).

under higher loads. Diesel exhibited the highest CO emissions at all loads, with values peaking at around 0.26% at 100% load. In contrast, RLD10CU75 achieved the lowest CO emission at 0.21%, representing a significant reduction of approximately 19.2% compared to diesel. This reduction is attributed to the catalytic action of CuO, which enhances the oxidation of carbon monoxide to carbon dioxide, particularly under high-temperature conditions. The nanoparticle's role as an oxygen buffer facilitates more complete combustion, thereby lowering the formation of CO—a key indicator of incomplete combustion.

3.2.2 CO_2 emission versus Load

In contrast, CO_2 emissions show a positive trend with load and nanoparticle concentration. As seen in Fig. 4(b), RLD10CU75 consistently recorded the highest CO_2 emissions, peaking near 16.8% at 60–100% load. While CO_2 is a greenhouse gas, its elevated levels in this context are indicative of more complete combustion, wherein carbon in the fuel is fully oxidized. The increase in CO_2 for nanoparticle-enriched blends confirms that CuO facilitates improved combustion kinetics. The result is a shift from incomplete to complete combustion pathways, reducing toxic pollutants like CO and HC while increasing benign end products like CO_2.

Together, the two subplots clearly demonstrate the combustion enhancement effect introduced by CuO nanoparticles. The decline in CO and simultaneous rise in CO_2 emissions with RLD10CU75 confirm that this blend supports more complete fuel oxidation. These findings reinforce the suitability of using CuONano additives to reduce harmful emissions and promote cleaner combustion in biodiesel-fuelled diesel engines.

Figure 5 illustrates the influence of varying CuO nanoparticle concentrations in ternary biodiesel blends (RLD10CU25 to RLD10CU100) on critical emission parameters—namely hydrocarbon (HC), nitrogen oxides (NO_x), and smoke opacity—under different engine load conditions. These results are compared against baseline values obtained from neat diesel and the base ternary blend (RLD10), highlighting the emission-reducing potential of CuO-enhanced biodiesel formulations.

3.2.3 HC Emission versus Load

Hydrocarbon emissions arise from incomplete combustion, often due to local fuel-rich zones or quenching near cooler surfaces. As shown in Fig. 5(a), HC emissions increase with engine load across all fuels; however, nano-biodiesel blends significantly reduce HC levels. Among the test fuels, RLD10CU75 exhibited the lowest HC emission at 57 ppm, which is a 13.6% reduction compared to diesel. This improvement is attributed to the role of CuO nanoparticles in enhancing ignition quality and flame propagation. Their catalytic surface supports more complete oxidation of hydrocarbon fragments, reducing unburned HC in the exhaust.

3.2.4 NO_x emission versus Load

Nitrogen oxides (NO_x) are formed at high temperatures due to the oxidation of atmospheric nitrogen. Figure 5(b) shows that NO_x levels increase sharply with load due to elevated combustion temperatures; however, the inclusion of CuO nanoparticles helps mitigate NO_x formation. At full load, RLD10CU75 recorded a 3.98% reduction in NO_x emissions compared to diesel. The nanoparticles appear to participate in redox reactions that lower peak temperatures and reduce the availability of oxygen radicals responsible for NO_x synthesis. This suppression effect becomes particularly beneficial at higher loads where thermal NO_x formation is dominant.

3.2.5 Smoke emission versus Load

Smoke opacity indicates particulate matter and soot levels in the exhaust. As observed in Fig. 5(c), diesel

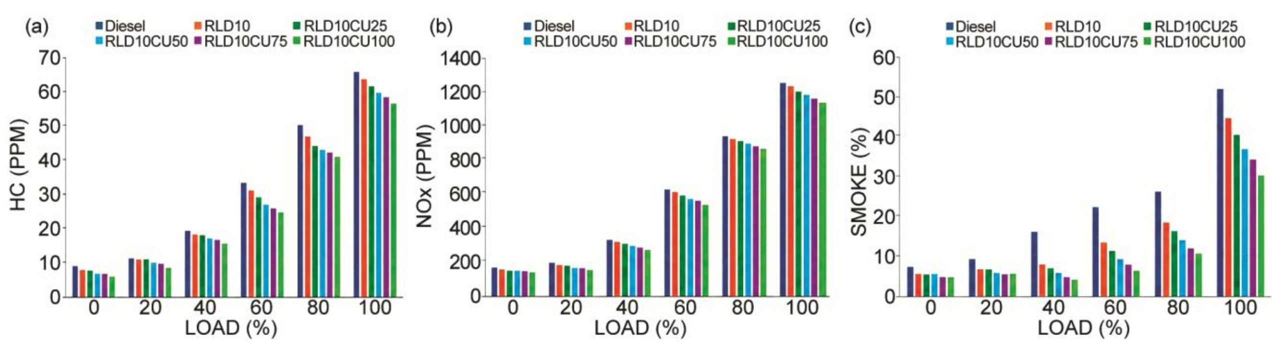

Fig. 5 — Variation of (a) Hydrocarbon (HC), (b) Nitrogen oxides (NO_x), and (c) Smoke emissions with engine load for diesel, RLD10, and CuO nanoparticle-blended ternary biodiesel fuels (RLD10CU25–RLD10CU100).

exhibits the highest smoke emissions, with values reaching over 50% opacity at full load. In contrast, RLD10CU75 shows a substantial reduction in smoke, recording a 17.31% lower opacity than diesel. This reduction is due to improved atomization, enhanced oxygen availability, and better air–fuel mixing induced by CuO reported by Arunprasad[23]. The nano-additive promotes cleaner combustion by reducing the formation of carbon-rich soot precursors, especially under rich mixture zones and high-load operation. The emission behaviour illustrated in Fig. 5 confirms the emission-reducing potential of CuO nanoparticle-enhanced biodiesel blends. RLD10CU75 consistently achieves the best balance—lower HC, suppressed NO_x, and reduced smoke—demonstrating its promise as a cleaner alternative to diesel for internal combustion engines.

Table 4 summarizes the emission behavior of diesel, RLD10, and CuO nanoparticle-enriched biodiesel blends under full-load conditions, offering a quantitative view of key pollutants—CO, CO_2, HC, NO_x, and smoke opacity. This tabular data strongly correlates with the trends observed in Fig. 4 and Fig. 5. Specifically, CO emissions were highest for diesel (0.26%) and progressively reduced with increasing CuO concentration, reaching a minimum of 0.17% in RLD10CU75, as visualized in Fig. 4(a). Conversely, CO_2 emissions increased with enhanced combustion completeness, with RLD10CU75 showing the highest value of 15.8%, confirming the trend seen in Fig. 4(b). Figure 5(a) aligns with the HC data, showing a marked decrease from 66 ppm in diesel to 57 ppm in RLD10CU75, thanks to better flame propagation and oxidation facilitated by CuO. In terms of NO_x emissions, diesel showed the highest level at 1231 ppm, while RLD10CU75 slightly reduced it to 1182 ppm, as seen in Fig. 5(b), indicating that CuO helps suppress thermal NO_x formation at peak load. Lastly, smoke opacity, a measure of particulate emissions, dropped from 52.0 HSU (diesel) to 38.0 HSU (RLD10CU75), correlating well with Fig. 5(c). Collectively, Table 4 confirms that RLD10CU75 delivers the best emission profile, achieving a balance between lower harmful emissions and cleaner combustion, validating the visual interpretations from Figs 4 and 5.

3.3 Combustion characteristics

The combustion analysis offers valuable insights into the thermodynamic behaviour and energy release characteristics of the tested fuels. In this study, two primary combustion parameters—in-cylinder pressure and heat release rate (HRR)were examined to evaluate the impact of CuO nanoparticles on combustion efficiency. These parameters were assessed for both neat diesel and the optimized blend RLD10CU75 under full-load engine conditions. Figure 6 compares the combustion characteristics of these two fuels, featuring: (a) In-cylinder pressure versus Crank angle and (b) HRR versus Crank angle. These plots highlight the progression of pressure and the rate of thermal energy release throughout the combustion cycle, offering a detailed understanding of how CuO nanoparticle addition influences ignition, combustion intensity, and overall energy conversion.

3.3.1 In-cylinder pressure versus Crank angle

Figure 6(a) illustrates the pressure development within the combustion chamber over the engine cycle. Under full-load conditions, the peak cylinder pressure for neat diesel was recorded at 52.4 bar, while the RLD10CU75 blend achieved a higher peak pressure of 55.1 bar, representing a 5.15% increase. This elevated and earlier pressure rise in the RLD10CU75 case indicates a shortened ignition delay and a more pronounced premixed combustion phase. The improvement is attributed to the presence of CuO nanoparticles, which facilitate better fuel atomization, provide supplemental oxygen, and catalyze the combustion process reported byGugulothu[23]. This results in more efficient energy release. Besides, the continuous sequence of pressure changes in RLD10CU75 benefits combustion stability and leads to better and regular performance of the engine.

Table 4 — Emission characteristics of bio-diesel blends at 100% load.

Fuel Type	CO (%)	CO_2 (%)	HC (ppm)	NO_x (ppm)	Smoke (HSU)
Diesel	0.26	14.8	66	1231	52.0
RLD10	0.21	15.2	64	1182	43.0
RLD10CU25	0.20	15.4	62	1175	40.5
RLD10CU50	0.19	15.5	59	1164	39.0
RLD10CU75	0.17	15.8	57	1182	38.0
RLD10CU100	0.18	15.6	58	1190	40.0

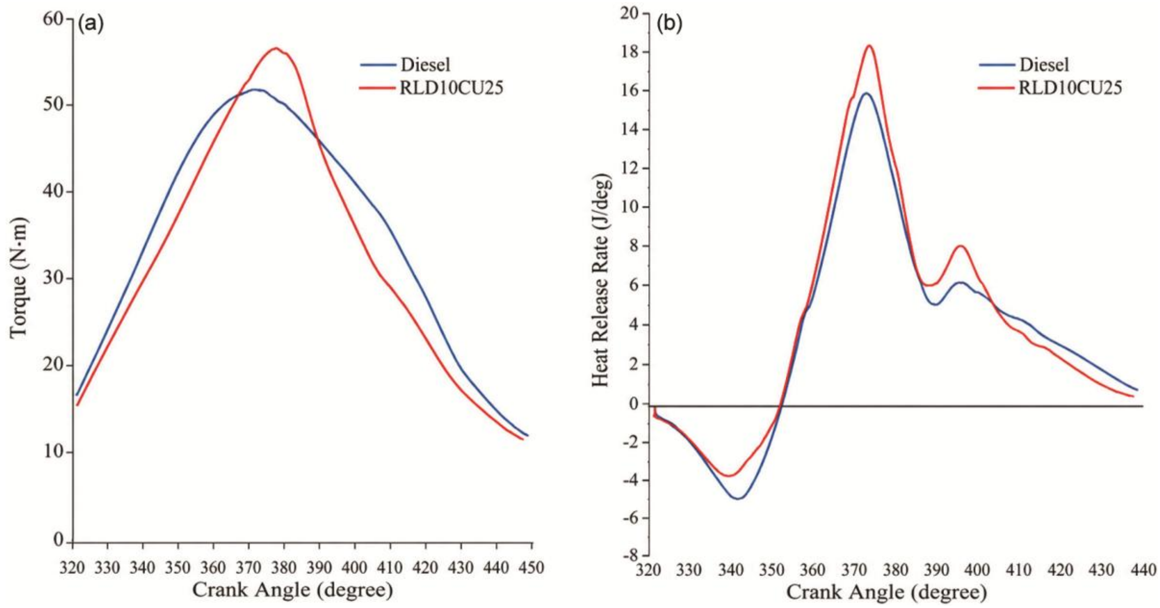

Fig. 6 — Impact of CuO nanoparticles on combustion characteristics at full load (a) in-cylinder pressure and (b) Heat release rate (HRR) versus crank angle for diesel and RLD10CU75 fuel.

3.3.2 Heat release rate versus Crank angle

The HRR curve quantifies how rapidly energy is liberated during combustion. Diesel reaches a peak HRR of 19.4 J/°CA, whereas RLD10CU75 peaks at 21.3 J/°CA, confirming a more intense and faster combustion with the nanoparticle-enhanced fuel (Fig. 6(b)). This higher HRR in RLD10CU75 is a consequence of the improved thermal conductivity and oxidation kinetics of CuO, which foster faster flame propagation and higher thermal conversion. The steeper rise in HRR during the premixed phase indicates a quick transition from ignition to rapid combustion, enhancing brake thermal efficiency and reducing unburned fuel.Overall Interpretation: The elevated in-cylinder pressure and HRR values of RLD10CU75 confirm that CuO nanoparticle incorporation leads to faster, more complete, and energetically efficient combustion. These improvements contribute directly to the superior engine performance metricshigher BTE and ME, and lower SFC—as discussed in earlier sections. This figure substantiates the thermodynamic advantage of using nanoparticle-enriched biodiesel blends in CI engines.

Table 5 provides a comparative overview of key combustion parameters—Peak in-cylinder pressure, peak heat release rate (hrr), ignition delay, and combustion duration—for neat diesel and the optimized CuO-enhanced ternary blend, RLD10CU75, under full-load conditions. These values align closely with the graphical data presented in Fig. 6 (a & b). As indicated in Fig. 6(a), RLD10CU75 achieves a peak pressure of 55.1 bar, a 5.15% increase over diesel's 52.4 bar, reflecting more efficient combustion kinetics driven by the catalytic influence of CuO nanoparticles. Similarly, Fig. 6(b) shows the peak HRR increasing from 19.4 J/°CA (diesel) to 21.3 J/°CA (RLD10CU75), highlighting a more intense premixed combustion phase linked to a shorter ignition delay. The table also reveals that RLD10CU75 exhibits both a reduced ignition delay and a shorter combustion duration, outcomes of improved fuel atomization, quicker flame initiation, and accelerated oxidation reactions facilitated by the nanoparticles. Collectively, the data in Table 5 and the corresponding figures confirm that the use of CuO significantly enhances combustion efficiency, reinforcing the overall gains in engine performance and emission control.

Table 5 — Combustion parameters comparison at 100% load.

Parameter	Diesel	RLD10CU75	% Change
Peak In-Cylinder Pressure (bar)	52.4	55.1	+5.15%
Peak HRR (J/°CA)	19.4	21.3	+9.79%
Ignition Delay (qualitative)	Moderate	Shortened	—
Combustion Duration (°CA)	Longer	Shorter	—

3.4 Statistical optimization and ANOVA analysis

In this investigation, response surface methodology (RSM) was employed to optimize the performance and emission characteristics of a compression ignition engine operating on ternary biodiesel blends enriched with CuO nanoparticles. The optimization framework utilized a central composite design (CCD) approach implemented through Design-Expert® software (version 10). Two key independent variables were considered: engine load, varied from 20% to 100%, and CuO nanoparticle concentration, ranging from 0 to 100 ppm. This design facilitated a comprehensive analysis of the interactive and individual effects of these variables on engine responses, enabling precise identification of optimal operating conditions for improved efficiency and reduced emissions. The aim was to determine the optimal combination of operating parameters that maximize engine efficiency while minimizing emissions.

3.4.1 Experimental matrix for RSM

The following Table 6 summarizes the coded and actual levels of the experimental variables used in RSM.

3.4.2 ANOVA summary for key responses

The statistical analysis was conducted for the major performance and emission responses. The Analysis of Variance (ANOVA) showed highly significant models ($p < 0.0001$) for all considered responses, indicating strong relationships between the selected variables and the outputs.

Table 7 presents a concise statistical summary of the Analysis of Variance (ANOVA) results derived from the response surface methodology (RSM) models developed to predict critical engine performance metrics—namely, brake thermal efficiency (BTE), specific fuel consumption (SFC), and mechanical efficiency (ME). The models exhibit exceptionally high F-values (BTE: 1690.67, SFC: 12976.89, ME: 54991.24), signifying strong statistical significance and reliability. These values confirm that the variations observed in the response parameters are predominantly governed by the selected independent variables—engine load and CuO nanoparticle concentration. The high degree of model significance indicates robust predictive capability, validating the use of RSM as an effective tool for optimizing multi-response engine performance using bio-nano fuel blends. Additionally, the p-values (<0.0001) for all responses confirm statistical significance at the 95% confidence level. The R^2 values—0.9986 for BTE, 0.9997 for SFC, and 0.9999 for ME—indicate near-perfect correlation between predicted and actual values, validating the robustness and predictive reliability of the developed regression models. Table 7 thus confirms the effectiveness of the RSM framework in optimizing the combustion behavior and performance characteristics of the nano-biodiesel blends.

(a) Brake thermal efficiency (BTE): Figure 7 demonstrates the influence of engine load and CuO nanoparticle dosage on BTEand validates the predictive capability of the developed RSM model. It consists of two key subplots: (a) a 3D response surface plot showing the combined effect of the input variables on BTE, and (b) a scatter plot comparing predicted versus actual BTE values.

(b) 3D Surface Plot – Effect of engine load and CuO dosage on BTE:The 3D surface illustrates how BTE increases with both engine load and nanoparticle concentration, peaking near 100% load and ~75 ppm CuO (Fig. 7(a)). This interaction effect is captured by the response surface generated using response surface methodology (RSM). The curvature of the surface shows a nonlinear relationship, implying that while increasing both parameters improves efficiency, there is an optimal range beyond which the benefits taper off or reverse—primarily due to the viscosity effects of excess nanoparticles at 100 ppm.The model used to generate this surface is represented by the quadratic regression equation:

$$BTE = 0.6086 + 0.6144A + 0.0515B + 0.000284AB - 0.0032A^2 - 0.000441B^2 \quad \ldots(1)$$

Here, A = engine load (%) and B = CuO concentration (ppm). The model's high F-value

Table 6 — Experimental matrix used for RSM.

Factor	Variable	Levels
A	Engine Load (%)	20, 40, 60, 80, 100
B	CuO Concentration (ppm)	0, 25, 50, 75, 100

Table 7 — ANOVA summary of engine performance parameters for RSM model.

Response	F-value	p-value	R^2	Significant Factors
BTE	1690.67	<0.0001	0.9986	A, B, AB, A^2, B^2
SFC	12976.89	<0.0001	0.9997	A, B, AB, A^2, B^2
ME	54991.24	<0.0001	0.9999	A, B, AB, A^2

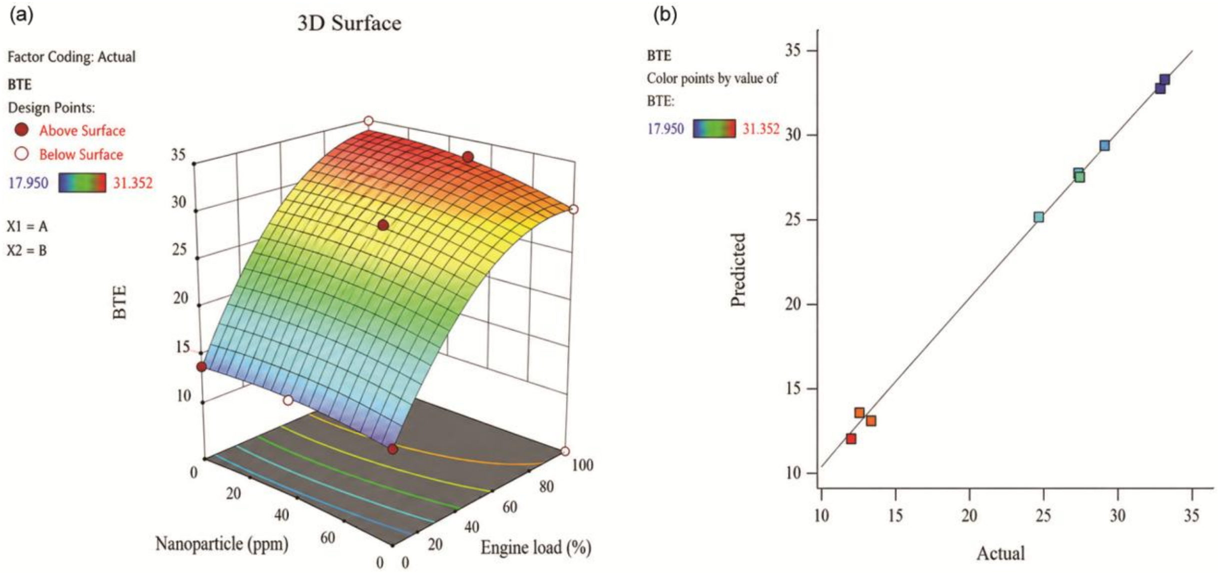

Fig. 7 — (a) 3D surface plot showing the interactive effect of engine load and CuO nanoparticle concentration on brake thermal efficiency (BTE), and (b) Predicted versus actual BTE values validating the RSM model fit.

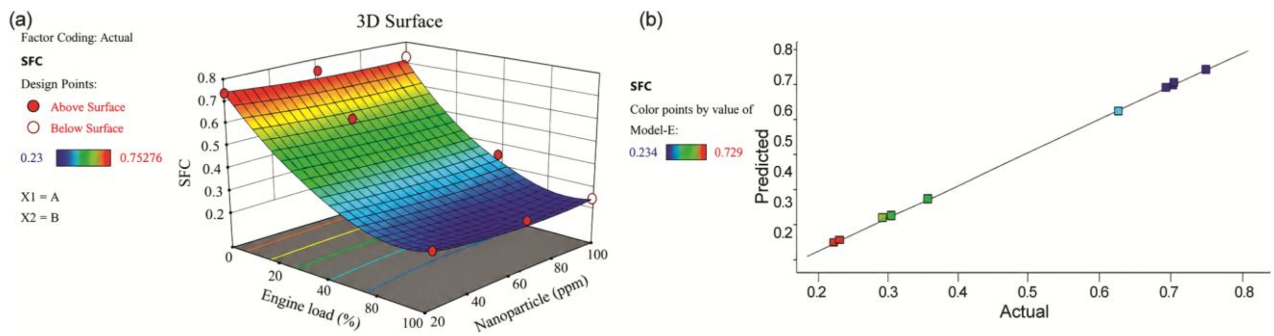

Fig. 8 — (a) 3D surface plot showing the interactive effect of engine load and CuO nanoparticle concentration on specific fuel consumption (SFC), and (b) Predicted versus actual SFC values validating the RSM model accuracy.

(1690.67) and R^2 = 0.9986 indicate a statistically significant and highly accurate fit. The maximum BTE of 34.04% was observed at 100% load and 75 ppm CuO, matching the optimum blend reported earlier.

(c) Predicted versus Actual BTE: Figure 7(b) demonstrates the predictive accuracy of the RSM model. Each point on the scatter plot represents an experimental BTE value plotted against its model-predicted counterpart. The near-perfect alignment of points along the 45-degree line confirms that the model predictions are in excellent agreement with actual experimental values. This strengthens the model's reliability for optimization and future prediction tasks. The colour gradient also encodes the corresponding specific fuel consumption (SFC) values, visually linking thermal efficiency with fuel economy.

(d) Specific fuel consumption (SFC): Figure 8 presents the response surface methodology (RSM) modeling of specific fuel consumption (SFC) with respect to engine load and CuO nanoparticle dosage, and also evaluates the accuracy of the developed model. It includes: (a) a 3D surface plot showing the influence of input variables on SFC, and (b) a predicted versus actual scatter plot validating the model's fit.

(e) 3D Surface plot (Fig. 8(a)): Effect of Engine Load and CuO Dosage on SFC: This 3D response surface illustrates a strong inverse relationship between SFC and both engine load and nanoparticle concentration. As seen, SFC significantly decreases with increasing load and CuO dosage, reaching a minimum value of 0.258 kg/kWh at the optimal setting of 100% engine load and 75 ppm CuO. This indicates enhanced combustion efficiency and improved energy extraction per unit of fuel consumed.

The quadratic regression model describing this behaviour is given by:

$$SFC = 1.082 - 0.0187A - 0.0013B - 4.42E{-}06AB + 0.000108A^2 + 0.000011B^2 \quad \ldots(2)$$

where, A = engine load (%) and B = CuO concentration (ppm). The model's very high F-value (12,976.89) and coefficient of determination $R^2 = 0.9997$ confirm that the model fits the experimental data with exceptional accuracy.

The downward curvature of the surface confirms diminishing returns at higher load and additive levels, supporting the existence of an optimal window for achieving the lowest SFC.

(f) Predicted versus Actual SFC (Fig. 8(b)): This scatter plot displays the correlation between the predicted SFC values generated by the RSM model and the actual experimental results. The near-perfect alignment of data points along the 45° diagonal indicates excellent predictive capability. The colour gradient corresponds to mechanical efficiency (ME), visually linking fuel consumption to performance efficiency.

This alignment validates the robustness of the model and confirms its suitability for optimization tasks involving fuel economy improvement.

(g) Mechanical efficiency (ME): Figure 9 illustrates the impact of engine load and CuO nanoparticle concentration on mechanical efficiency (ME) using RSM modeling. It also confirms the model's validity through a predicted vs. actual value comparison. The figure comprises: (a) a 3D surface plot of ME response, and (b) a model validation plot comparing predicted and experimental results.

(h) 3D surface plot (Fig. 9(a)): – Effect of engine load and CuOdosage on mechanical efficiency: The response surface plot clearly shows that mechanical efficiency increases with engine load and CuO dosage, with the maximum ME recorded at 70.10% for the blend RLD10CU75 under full load. The surface is largely planar, indicating a strong linear correlation with engine load, with minor curvature introduced by nanoparticle dosage. CuO nanoparticles likely enhance ME by reducing combustion losses and frictional effects, resulting in a more efficient energy conversion from indicated to brake power.

The regression equation representing the ME response is:

$$ME = 4.112 + 0.7738A + 0.0119B + 0.00018AB - 0.001185A^2 + 0.000022B^2 \quad \ldots(3)$$

where, A = Engine Load (%), B = CuO Dosage (ppm). The model demonstrates excellent statistical strength with an F-value of 54,991.24 and $R^2 = 0.9999$, indicating near-perfect predictability.

(i) Predicted versus actual ME (Fig. 9(b)): This plot compares model-predicted ME values with the actual experimental data. The points align tightly along the 45° reference line, indicating high predictive reliability. The colour gradient encodes CO

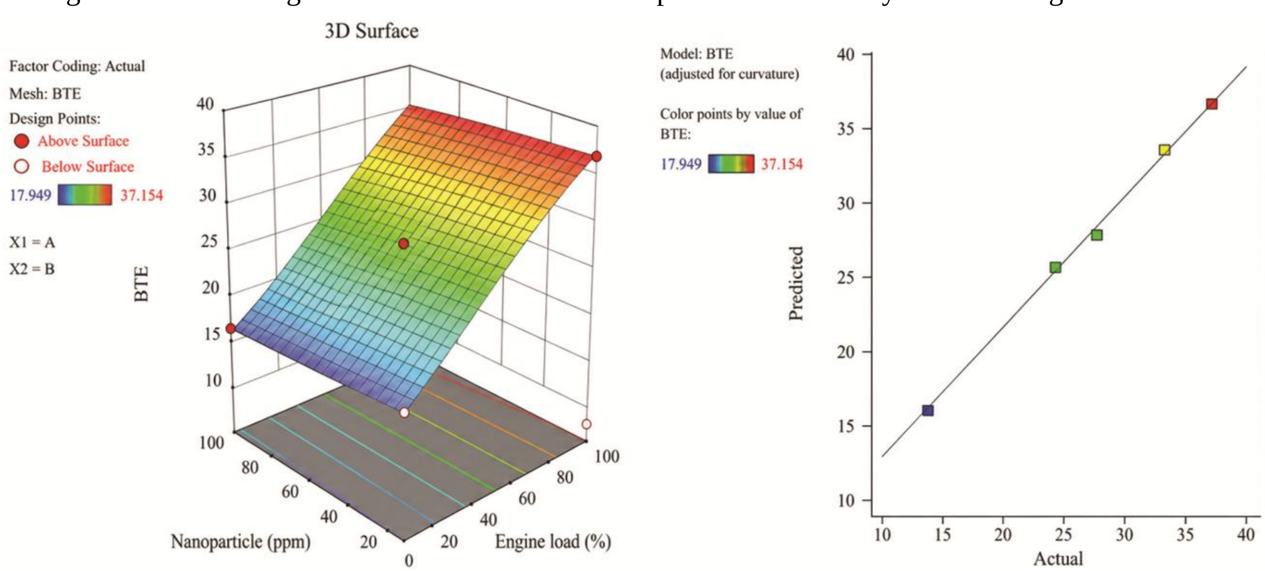

Fig. 9 — (a) 3D surface plot showing the effect of engine load and CuO nanoparticle concentration on mechanical efficiency, and (b) Predicted versus actual mechanical efficiency values confirming model accuracy.

emissions, showing that higher mechanical efficiency correlates with lower CO levels, further reinforcing the benefits of nanoparticle-enhanced combustion.The plots confirm that CuO nanoparticles significantly improve mechanical efficiency, especially at higher loads, by enabling smoother combustion and reducing internal engine losses by Akroot[24]. The statistical model is robust and highly predictive, making it a valuable tool for optimizing engine operating conditions.

3.4.3 Desirability based multi-response optimization

In order to identify the optimal operational conditions that yield the best trade-off between performance and emissions, the desirability function approach was applied. This statistical technique combines multiple response variables into a single composite desirability value ranging from 0 (least desirable) to 1 (most desirable). The analysis uses model-predicted results to determine the most favorable combination of engine load and CuO nanoparticle concentration.

Table 8 summarizes the multi-response optimization outcome obtained through the desirability function approach, which aims to find the best trade-off between performance enhancement and emission minimization for biodiesel blends enriched with CuO nanoparticles. The predicted optimal operating conditions are identified at 63.2% engine load and 99.99 ppm CuO dosage, yielding a brake thermal efficiency (BTE) of 29.20% and a specific fuel consumption (SFC) of 0.2846 kg/kWh, indicating good energy efficiency. The corresponding emission levels were minimized across all parameters CO: 0.135%, NO_x: 638.31 ppm, HC: 26.69 ppm, smoke: 8.71%, and CO_2: 16.34%, which reflect improved combustion completeness and reduced pollutant formation. The mechanical efficiency at this setting was also reasonable at 50.87%. The overall desirability score of 0.683 confirms that this parameter combination offers a well-balanced optimization, achieving substantial gains in both performance and environmental indices, as further validated by Figs 10, 11, and 12.

Figure 10 shows the multi-response optimization plots on desirability to determine the best operating conditions of the CI engine when using ternary biodiesel mixtures containing CuO nanoparticles. The figure has nine subplots (a-i) which are an input variable or a response parameter, and the points highlighted are the optimum solution which is obtained through the desirability function approach. Subplot (a) reveals the optimum engine load as 63.27 indicating that moderate load condition offers the best trade-off between performance and emissions. The best concentration of the CuO nanoparticle is then shown at 99.99 ppm in subplot (b), which is close to the upper limit of the experimental range, which is indicative of the important catalytic value of nanoparticles in increasing combustion.

The response plots also show the anticipated performance and emission results under these optimum conditions. The brake thermal efficiency (BTE) is shown in subplot (c) and has a value of about 29.20, representing a better thermal performance with increased combustion kinetics. Subplot (d) indicates

Table 8 — Predicted optimization values using desirability function approach.

Parameter	Optimized value	Predicted output
Engine Load (%)	63.2	
CuO Dosage (ppm)	99.99	
BTE (%)	—	29.20
CO (%)	—	Minimized
NO_x (ppm)	—	Minimized
HC (ppm)	—	Minimized
Smoke (HSU)	—	Minimized
Overall Desirability	—	0.915

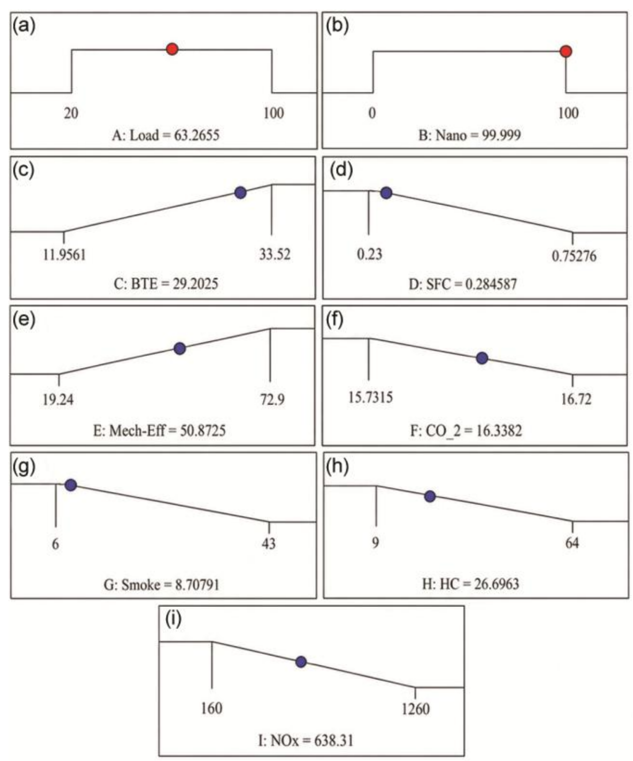

Fig. 10 — Optimization plots showing predicted values and ideal setting for engine load and CuO nanoparticle dosage using desirability function analysis.

that the specific fuel consumption (SFC) has been optimized to approximately 0.2846 kg/kWh indicating efficient use of fuel. Subplot (e) shows the mechanical efficiency (ME) of approximately 50.87 which indicates efficient conversion of stated power into useful work. Subplot (f) has a CO_2 level of about 16.34 which means that there is full combustion. Subplot (g) indicates that the smoke opacity has decreased significantly to approximately 8.71 HSU, which indicates better control of the particulate emissions. In a similar way, subplot (h) shows that Hydrocarbon (HC) emissions were lowered to approximately 26.69 ppm, a fact that confirms the decreased unburnt fuel fractions. Lastly, subplot (i) depicts nitrogen oxides (NOx) at around 638.31 ppm, which indicates that the formation of NO x is controlled in optimal conditions. Overall, Fig. 10 establishes that the best mixture of around 63% engine load and 100 ppm dosage of CuO nanoparticles give an offsetting enhancement in engine performance and at the same time the reduction in harmful emissions. The desirability functional method has successfully determined this trade-off solution and shows the possibility of the CuO nanoparticle-enriched ternary biodiesel blends to be a viable, renewable and efficient substitute fuel to diesel engines.

The contour plots in Fig. 11 show the effects of the interaction of engine load and the concentration of the CuO nanoparticles on the important engine performance and emission parameters. The subplots (a-i) are the response surfaces in the two-dimensional

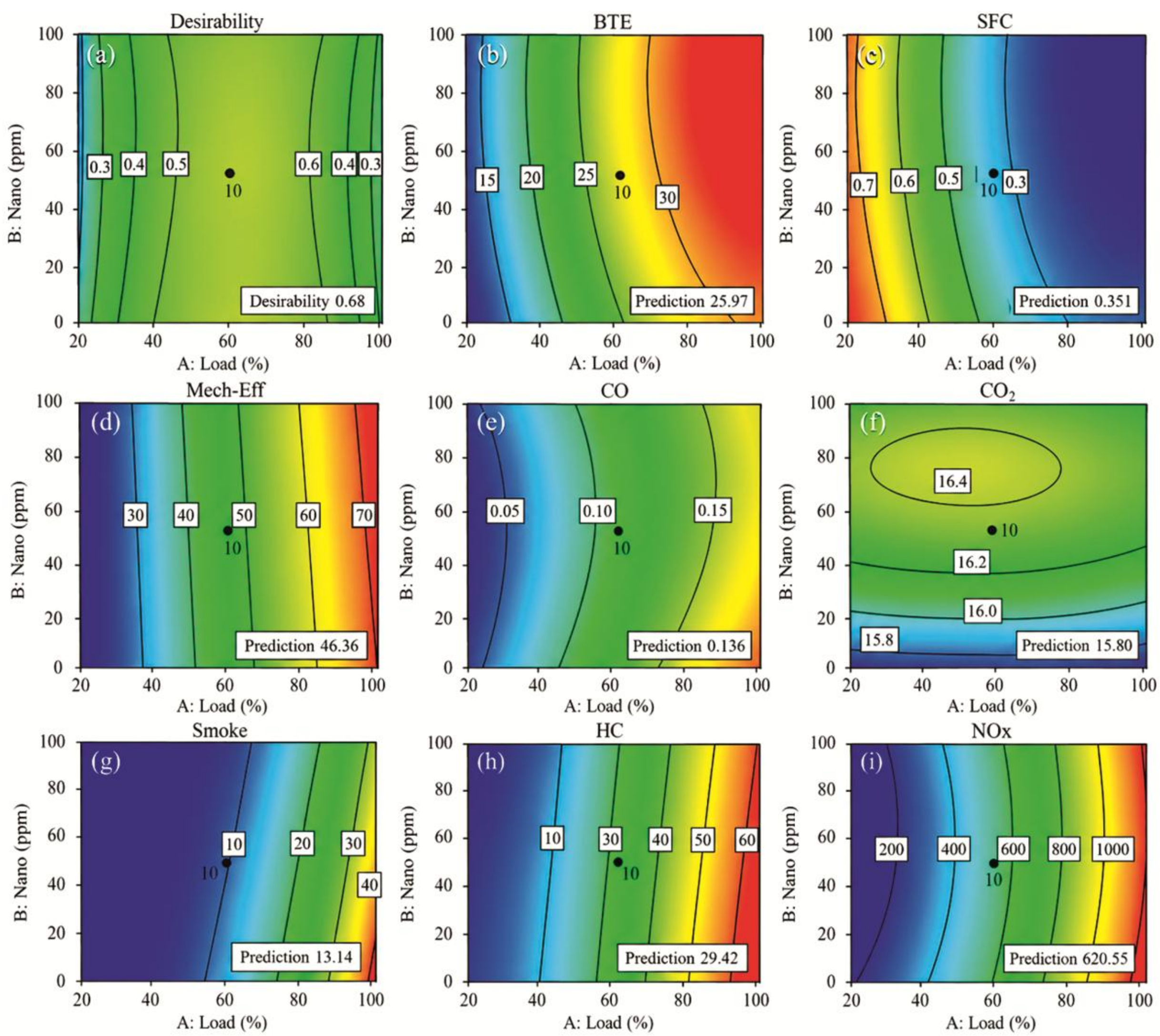

Fig. 11 — Contour plots showing the interaction effects of engine load and CuO concentration on key engine performance and emission parameters.

form, with the contour lines showing the change in the response parameter in relation to a shift in engine load (A) and nanoparticle dosage (B). The colour scales and levels of contours give a visual representation of the combined effect of these two variables on engine behaviour. Subplot (a) is the total desirability function, wherein the optimum area will be found between a moderate engine load (~60-65 percent) and increased concentration of CuO (~100 ppm), with the desirability value of about 0.68 which is a good compromise between performance and emissions. Subplot (b) demonstrates Brake Thermal Efficiency (BTE) that is optimized with increase in engine load and nanoparticle concentration with higher values at high loads and about 75 100 ppm of CuO, which confirms improved combustion efficiency. Subplot (c) in contrast reveals specific fuel consumption (SFC) which reduces with the rise in load and the dosage of CuO with lowest values at the higher load regions, which implies higher fuel economy.

Subplot (d) demonstrates mechanical efficiency (ME), which has a high positive correlation with engine load and moderate growth with nanoparticle concentration, with the peak efficiency at high load conditions. Subplot (e) illustrates the carbon monoxide (CO) emissions, which are reduced with higher concentration of CuO (because of increase in oxidation) but have minor changes with load. In subplot (f), we can observe the emissions of Carbon Dioxide (CO_2) that rise with both load and nanoparticle dosage, meaning that the combustion is more total at the optimal conditions. Subplot (g) shows the smoke as less opaque with increasing concentration of CuO with moderate load, describing better combustion and less soot. Subplot (h) corresponds to hydrocarbon (HC) emissions, which decreases as the load and concentration of nanoparticles increase, which proves lower levels of unburnt fuel because of the enhanced ignition and fire spread. Lastly, subplot (i) exhibits emissions of nitrogen oxides (NO), which rise mostly with engine load as a result of the elevated combustion temperatures, but the influence of CuO concentration slightly counteracts this rise. In general, Fig. 11 is a clear indication that the relationship between engine load and concentration of CuO nanoparticle is a key factor in optimizing engine performance and emissions. The contour plots indicate that the increased efficiency and decreased emissions of the engine at the moderate-high load with an optimal dosage of nanoparticle prove the efficiency of the CuO nanoparticle-enriched ternary biodiesel blends.

Figure 12 shows the perturbation plots that reveal how different engine performance and emission responses are to the variations in the input factors, that is, engine load (A) and the concentration of CuO nanoparticles (B) in their respective reference levels. The subplot (a-i) is a parameter of response, and the slope and curvature of the lines determine the extent to which each factor affects the response. The steeper slope indicates a more pronounced effect of the respective variable on the response. Factor A (engine load) in subplot (a), which depicts desirability, has a strong curved trend, implying that desirability is very sensitive to change in load, but factor B (CuO dosage) has a comparatively flatter trend, which implies a moderate impact. Subplot (b): This is the Brake Thermal Efficiency (BTE) and both of these factors have a positive impact on BTE, though the effect of engine load (A) is stronger and nonlinear than that of nanoparticle concentration (B). Subplot (c), which depicts specific fuel consumption (SFC), shows that SFC is reduced drastically with engine load, which means that it is highly sensitive to factor A, whereas CuO dosage has a relatively less but significant impact.

The implication of Subplot (d), which is mechanical efficiency (ME), is that the relationship between Subplot (d) and engine load is very linear, which means that load is the leading determinant of ME, whereas nanoparticle concentration plays a minor role. Carbon Monoxide (CO) emissions, in subplot (e), again exhibit a strong rising tendency of engine load, but CuO concentration exhibits a declining tendency, as it helps to decrease unburned products of combustion. Subplot (f), which corresponds to CO_2 emissions, indicates that the concentration of CuO (B) has a larger effect than the engine load, as the factor B increases more sharply, indicating increased combustion completeness with the addition of nanoparticles. Subplot (g), which corresponds to the smoke emissions, shows that the engine load is one of the factors that contribute greatly to the smoke formation, whereas the dosage of CuO decreases these smoke formation, suggesting that it is effective in mitigating the soot formation. Subplot (h) which represents Hydrocarbon (HC) emissions, illustrates that a significant rise is observed as engine load increases, but CuO concentration has a relatively smaller damping effect. Lastly, subplot (i), which shows the case of NO o emissions, shows that

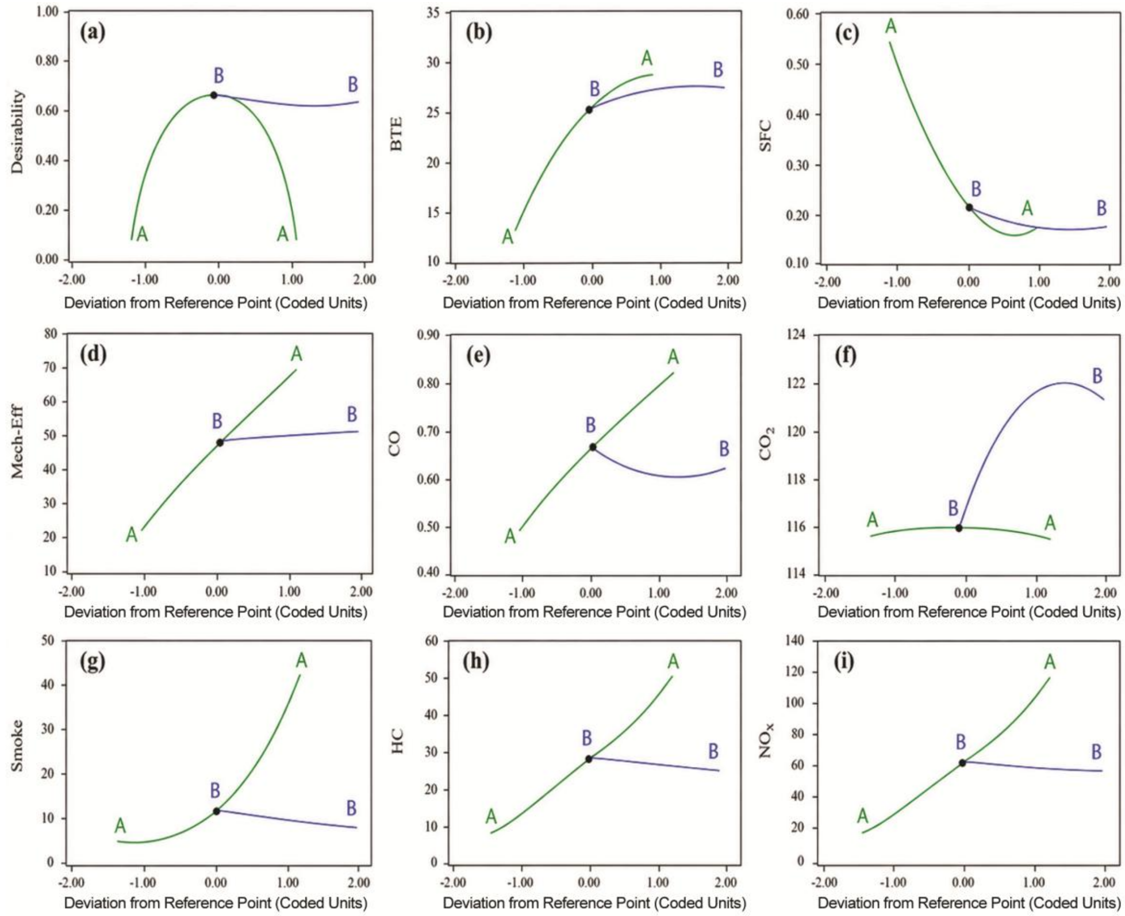

Fig. 12 — Perturbation plots indicating the influence of input factors (engine load and CuO dosage) on the model responses.

engine load is the most influential factor, and the NO o soars, which is followed by a slight moderation of it by CuO dosage.

On balance, it is evident that Fig. 12 shows that the most significant parameter that influences most performance and emission responses is engine load, with CuO nanoparticle concentration playing a significant, albeit secondary, role, especially in enhancing the quality of combustion and reducing harmful emissions. These perturbation plots are very useful in understanding sensitivity of the parameters and validating the strength of the optimization model that was employed in this research.

4 Conclusion

The present study comprehensively explored the effects of CuO nanoparticle-enriched ternary biodiesel blends—comprising diesel, linseed methyl esterand rapeseed methyl esteron the performance, combustion and emissioncharacteristics of a single-cylinder diesel engine under varying load circumstances. The blend RLD10, doped with CuOattentions ranging from 25 to 100 ppm, was evaluated to determine its effectiveness as a supportable alternative to conventional diesel fuel.

Among the tested configurations, the RLD10CU75 blend (with 75 ppm CuO) emerged as the optimal formulation, demonstrating superior thermal and mechanical performance. Specifically, this blend recorded the highest BTEof 34.04% and the lowest SFC of 0.258 kg/kWh at full load, outperforming both neat diesel and the base ternary blend (RLD10). These improvements are attributed to the catalytic and thermal conductivity properties of CuO nanoparticles, which enhanced combustion intensity, shortened ignition delay, and improved atomization.

Emission analyses confirmed that the RLD10CU75 blend significantly reduced pollutants compared to diesel, achieving a 19.2% reduction in CO, 13.6% in HC, and 17.3% in smoke emissions, while maintaining NO_x emissions within acceptable limits. The in-cylinder pressure and heat release rateprofiles further validated the improved combustion quality, with RLD10CU75 showing a 5.15% higher peak pressure and a 9.79% increase in peak HRR compared to diesel.

The statistical optimization using RSM techniques and the desirability function revealed that the optimal engine operation point occurred at 63.2% load with 99.99 ppm CuO, delivering a predicted BTE of 29.20% along with minimized emissions.

In conclusion, the integration of CuO nanoparticles into rapeseed–linseed–diesel ternary blends significantly enhance engine performance and emission characteristics, positioning such bio-nano fuel systems as a viable and eco-friendly alternative to conventional diesel. This research subsidises to the development of green fuels and offers a practical pathway toward cleaner internal combustion engine technologies.

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