



Performance, Combustion, and Emission Characteristics of CeO₂-doped Cottonseed Biodiesel in a Non-road Diesel Engine

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ABSTRACT

The present study investigates the effect of incorporating cerium oxide (CeO₂) nanoparticles on the performance, combustion, and emissions of a cottonseed biodiesel–diesel blend in a constant-speed, non-road diesel engine. CeO₂ nanoparticles were synthesized using a precipitation–ultrasonic method and introduced into a 30% cottonseed biodiesel blend (CSO30) at three concentrations: 20, 40, and 60 ppm. All experiments were conducted on a single-cylinder, 4-stroke, water-cooled, direct-injection diesel engine at 1500 rpm with loads ranging from 0 to 16 kg. Evaluations were based on key performance parameters, including brake thermal efficiency (BTE) and brake-specific fuel consumption (BSFC), combustion characteristics including in-cylinder pressure and cumulative net heat release rate, and exhaust emissions including CO, HC, NO_x, and smoke opacity. CSO30 exhibited lower brake thermal efficiency and a higher brake-specific fuel consumption than diesel at full load, due to its lower calorific value and higher viscosity. Adding CeO₂ nanoparticles improved combustion quality and fuel conversion efficiency. Among the tested blends, CSO30-N60 (with 60 ppm CeO₂ nanoparticles) exhibited optimal performance, achieving a BTE of 30.8% compared to 30.2% for CSO30, while improving BSFC by approximately 13% at full load, thus approaching diesel performance (32% BTE). Emissions analysis showed that CeO₂-doped blends significantly reduced regulated exhaust emissions. The CSO30-N60 blend showed reductions of 11.9% in hydrocarbons, 17.7% in nitrogen oxides, and 17% in smoke opacity under full-load conditions compared to diesel. The maximum reduction in carbon monoxide was observed for the CSO30-N20 blend, reaching 43.8%. The findings indicate that CeO₂ nanoadditives significantly enhance the combustion efficiency of cottonseed biodiesel blends, achieving performance levels close to diesel while reducing exhaust emissions, making them suitable for non-road diesel engine applications. The addition of CeO₂ nanoparticles improved the performance of the cottonseed biodiesel blends, enabling near-diesel performance, while neat diesel still exhibited the highest brake thermal efficiency. Overall, the results demonstrate that CeO₂ nanoadditives substantially improve the combustion efficiency of cottonseed biodiesel blends, enabling near-diesel performance while simultaneously reducing exhaust emissions, making them suitable for non-road diesel engine applications.

Keywords: Energy efficiency; Engine; Nanoparticles; Cerium oxide; Cottonseed oil; NO_x; Smoke.

1. INTRODUCTION

Non-road compression-ignition (CI) engines, primarily diesel engines, are widely used across various off-highway applications, including agricultural machinery (tractors, harvesters), construction equipment (excavators, bulldozers), industrial vehicles (forklifts, cranes), marine vessels, railway locomotives, and mining equipment. These engines play a vital role in supporting infrastructure development, transportation of goods, and food production (Dwivedi *et al.* 2014). Their widespread use is primarily due to their high efficiency, torque

characteristics, robustness, and ability to operate under severe conditions.

In a direct-injection compression-ignition engine, only air is inducted and compressed to high pressure and temperature (Shankar *et al.* 2017). Near the end of the compression stroke, finely atomized fuel is injected directly into the combustion chamber, where it undergoes evaporation, mixing, and chemical pre-reactions during the ignition delay period. Auto-ignition occurs once local temperature conditions are satisfied, followed by a premixed combustion phase and a diffusion-controlled combustion phase, which together

govern in-cylinder pressure development, heat release, and pollutant formation (Esonye *et al.* 2019).

Carbon dioxide (CO₂) emitted during diesel and biodiesel combustion contributes to climate change, while nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), and particulate matter are primarily responsible for photochemical smog formation, ozone generation, and degradation of local air quality. Therefore, improving CI-engine combustion through fuel modification is essential for both emission control and energy sustainability. In response to these emission and sustainability challenges associated with non-road compression-ignition engines, fuel modification strategies have gained increasing attention, particularly the partial substitution of diesel with biodiesel and the use of advanced fuel additives.

Among the fuel modification strategies to address the combined challenges of emission control and energy sustainability associated with non-road CI engines, the use of biodiesel as a partial substitute for diesel and the incorporation of nano-scale additives have emerged as promising approaches for improving combustion efficiency while mitigating regulated exhaust emissions. Globally, governments have promoted the sale of biodiesel or blended biodiesel. These fuels aim to reduce emissions, improve combustion characteristics, and promote energy sustainability. Another scientific finding is the use of nanoparticles as fuel additives. A recent innovation to improve CI engine performance and reduce emissions is the addition of nanoparticles to fuel. These particles, typically in the 1–100 nm size range, can enhance combustion through catalytic activity, improved thermal conductivity, and better fuel atomization.

2. MATERIALS AND METHODS

2.1 Nanoparticle Synthesis

CeO₂ nanoparticles were prepared through the precipitation–ultrasonic method. Cerium nitrate hexahydrate (Ce(NO₃)₃·6H₂O) was dissolved in deionized water to prepare a 0.05 M solution, and NaOH was dissolved in deionized water to prepare a 0.15 M solution. Under continuous stirring, the NaOH solution was added dropwise to the cerium nitrate solution under ultrasonic irradiation (20 kHz). The pH of the reaction mixture was monitored with a calibrated digital pH meter (±0.01), and it was maintained at pH 12 by controlled addition of NaOH solution. Polyethylene glycol (0.01 M, PEG-2000) was added at 5-min intervals for 60 min of ultrasonication (12 equal additions) to serve as a surfactant and prevent nanoparticle agglomeration. The resultant precipitate was centrifuged at 10,000 rpm for 15 min, washed twice with deionized water and once

with ethanol, and dried at 80 °C for 8 h before calcination at 450 °C for 3 h to produce CeO₂ nanoparticles. Fig. 3 shows the procedure for the synthesis of nanoparticles.

2.2 Characterization

Fig. 1(a) presents the X-ray diffraction (XRD) pattern of the synthesized nanoparticles. XRD analysis was performed using a Bruker diffractometer with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) over a 2θ range of 20°–80°, using a step size of 0.02° and a scan rate of 1° min⁻¹. Crystallite size was calculated using the Debye–Scherrer equation. Surface morphology was examined using a TESCAN VEGA field-emission scanning electron microscope operated at 5–15 kV, with magnifications ranging from 10,000 $\times$ to 100,000 $\times$. The average crystalline size, calculated according to the Debye–Scherrer equation, is about 25 nm. The irregular morphology with an average of 100 nm can be seen in Fig. 1.

2.3 Fuel Preparation

Biodiesel was synthesized from cottonseed oil via alkaline transesterification, employing methanol and potassium hydroxide (KOH) as the catalyst (Fig. 2). The molar ratio of methanol to oil was set at 6:1, accompanied by 1 wt.% KOH. The oil was subjected to heating at 60 °C and agitated at a speed of 500 rpm. A distinct preparation of potassium methoxide was subsequently introduced in increments to the heated oil (Fan *et al.* 2021). The mixture underwent stirring for approximately 60 min to confirm completion of the reaction. Following the mixing process, phase separation was permitted to take place by allowing the mixture to settle for a duration of 12 h (Hoque *et al.* 2025). The glycerol was isolated, and the biodiesel underwent a washing process with hot distilled water until the pH of the water was neutral, followed by drying with anhydrous Na₂SO₄. Table 1 presents the measured properties of the fuel.

Table 1. Properties of diesel and cottonseed biodiesel

Fuel Properties	Diesel	Cottonseed Biodiesel
Calorific value, kJ/kg	444512	39520
Density, kg/m ³	832	863
Cetane Number	449	58
Kinematic Viscosity at 40 °C, cSt	33.32	6.91
Specific gravity at 15 °C	00.85	0.8817
Flash Point, °C	772	173
Fire Point, °C	779	187

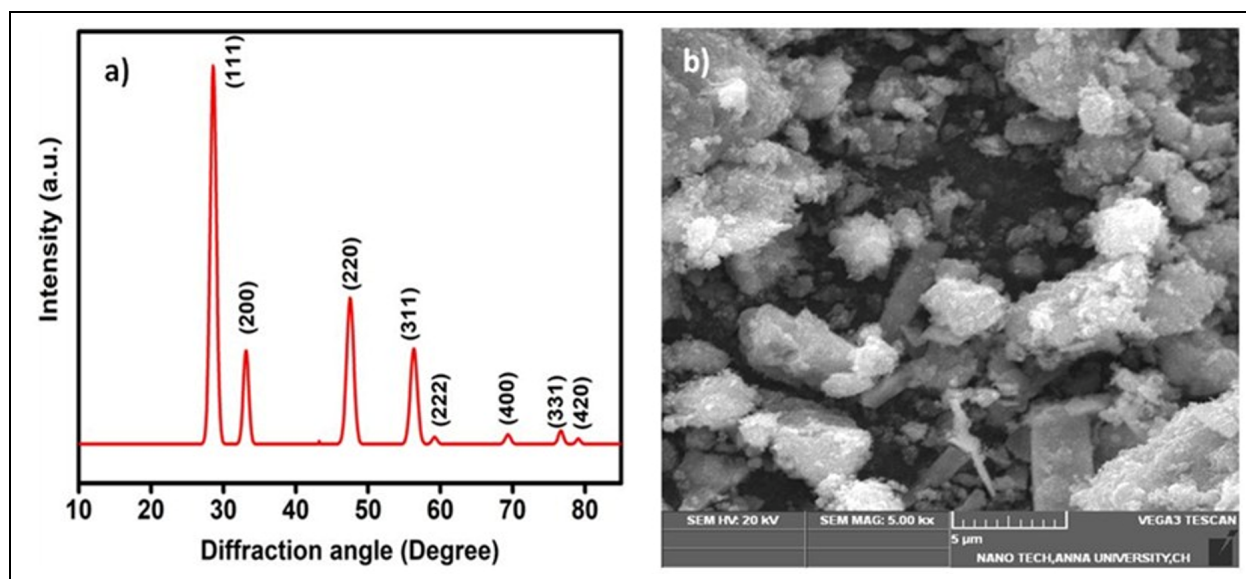


Fig. 1: (a) XRD pattern and (b) SEM image of CeO_2 nanoparticles



Fig 2: Biodiesel preparation

2.4 Nanoadditive Fuel Preparation

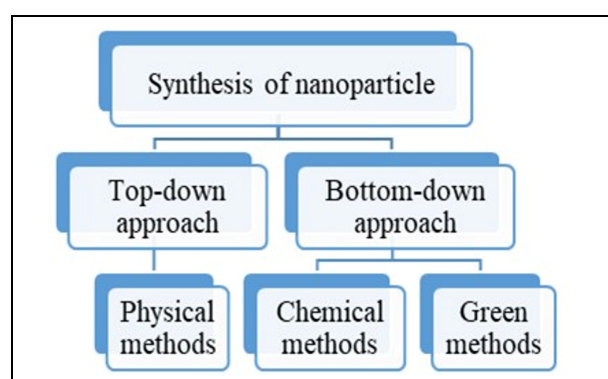


Fig. 3: Synthesis of nanoparticles

Various methods of nanoparticle synthesis are shown in Fig. 3. The synthesized CeO_2 nanoparticles were dispersed into CSO30 biodiesel at concentrations of 20, 40, and 60 ppm. The required mass of nanoparticles was weighed using an analytical balance (± 0.1 mg) and added to the biodiesel. To enhance dispersion stability,

0.1 vol.% PEG-2000 was added as a surfactant. The mixture was subjected to ultrasonication at 20 kHz for 30 min, followed by magnetic stirring for 60 min (Sabri *et al.* 2026). The resulting nanofuel blends were designated as CSO30-N20, CSO30-N40, and CSO30-N60. All blends were allowed to stand for 24 h before testing to confirm the absence of visible sedimentation. Fig. 4 shows the prepared nanoadditive biodiesel.

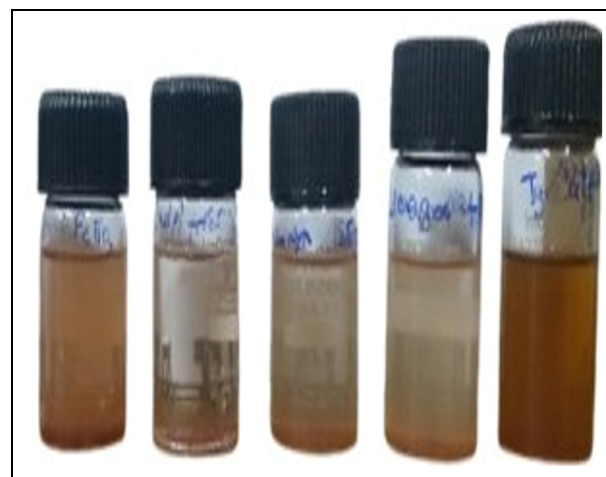


Fig. 4: Nanoadditive biodiesel

3. EXPERIMENTAL SETUP

The experimental setup consists of a single-cylinder, four-stroke, water-cooled, direct-injection (DI) compression-ignition engine (Kirloskar TV1) (Shaisundaram, *et al.* 2025). With an 87.5 mm bore and a 110 mm stroke, the engine displaced 661 cm^3 and had a compression ratio of 17.5:1. The engine was connected to a water-cooled eddy-current dynamometer for load control and operated at a constant rated speed of 1500 rpm.

In a mechanical inline fuel pump, fuel was injected at an injection pressure of 220 bar with a fixed injection timing of 23° bTDC. To minimize temperature fluctuations, cooling water was circulated with a flow rate of 200 L h^{-1} throughout the experimental run.

The consumption of fuel was evaluated using a calibrated graduated burette ($\pm 0.1 \text{ mL}$) and a digital stopwatch to determine the time required to consume a known volume of fuel, and the mass flow rate was calculated accordingly. A calibrated rotameter ($0\text{--}100 \text{ L min}^{-1}$) was used to measure the intake air flow. Air–fuel ratio calculations were corrected for ambient temperature and humidity. The engine was run at five

different load conditions (0, 4, 8, 12, and 16 kg). The engine was maintained at steady-state conditions for 10 min at each load before recording performance and emission data. Before each test series, the engine was preconditioned at 1500 rpm and no-load for 30 min with diesel fuel to ensure stable lubrication and coolant temperatures.

All baseline and test data were obtained directly from the experimental setup with diesel, CSO30, and nano-fuel blends; no data points from the literature were used for performance or emission comparisons. Figures 5 and 6 show the experimental and schematic setup.

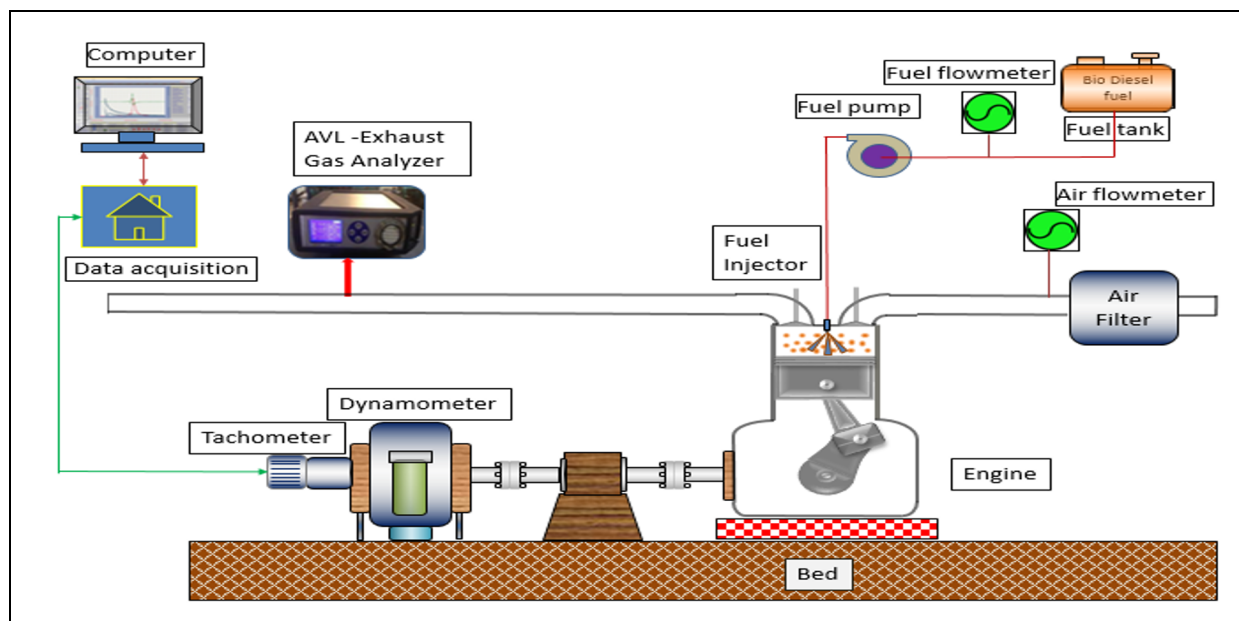


Fig. 5: Schematic diagram of a non-road engine setup



Fig. 6: Non-road engine test rig with electrical dynamometer

Table 2. Specification of the test rig

Make	Kirloskar TV1
Bore	87.5 mm
Stroke	110 mm
Compression Ratio (CR)	17.5
Rated Power	5.2 kW
Rated Capacity	661 cc
Rated speed	1500 rpm
Dynamometer	Eddy current; water-cooled

Table 3. Emission measurement specifications

Instrument	Measuring Parameter	Range
Gas Analyzer (AVL)	NO	0–6000 ppm
	CO ₂	0–22% vol.
	CO	0–16% vol.
	HC	0–3000 ppm
Smoke Meter (AVL)	Smoke opacity	0–100% opacity

4. RESULTS AND DISCUSSION

4.1 Performance Analysis

4.1.1 Brake Specific Fuel Consumption (BSFC)

The lower BSFC of all test fuels with increasing load can be attributed to the better combustion at higher operating conditions (Nabi *et al.* 2020). The marginally greater BSFC of CSO30 is due to its lower CV, whereas the CeO₂ nanoparticle addition decreased BSFC by improving combustion efficiency by catalytic oxidation.

For all fuels, the BSFC decreased with increasing load due to lower relative frictional losses and improved temperature conditions. At full load, diesel achieved the lowest (0.18 kg/kWh) and CSO30 the highest (0.23 kg/kWh) BSFC, with CSO30-N60 having an intermediate BSFC of 0.20 kg/kWh. This indicates that CeO₂ enhances fuel conversion compared with CSO30 (Venkatesan *et al.* 2019).

4.1.2 Brake Thermal Efficiency (BTE)

Fig. 7 presents the change in BTE with respect to engine load for diesel, CSO30, CSO30-N20, CSO30-N40, and CSO30-N60. BTE improved with CeO₂ nanoparticle addition due to enhanced combustion efficiency and improved fuel–air interaction (Odufuwa, *et al.* 2014). The highest BTE was observed for CSO30-N60 at full load, indicating the positive catalytic influence of CeO₂ nanoparticles. The cottonseed biodiesel blend reduced the BTE of diesel by about 5.62%, due to its lower calorific value and inferior physicochemical properties. BTE increased with load for all fuels. Diesel reached 32% at full load. CSO30 showed reduced efficiency (30.2%), while CSO30-N60 improved BTE to 30.8%, indicating partial performance recovery due to CeO₂-assisted combustion (Onukwuli *et al.* 2017). Hence, the diesel, CSO30, and CSO30-N60 exhibited BTE values of 32, 30.2, and 30.8%, respectively, at full load.

4.2 Combustion Analysis

4.2.1 In-cylinder Pressure

Fig. 8 illustrates the in-cylinder pressure profiles for the tested fuels. The higher peak cylinder pressure observed with CeO₂-blended fuels is attributed to improved premixed combustion, driven by enhanced oxidation and reduced ignition delay (Mohammed *et al.* 2024). The combustion process is analyzed by examining the correlation between in-cylinder pressure and crank angle throughout the compression and expansion strokes of a 4-stroke diesel engine with various fuel blends (Papadopoulos *et al.* 2010). (Qi *et al.* 2010) examined the variations in cylinder pressure with crank angle at full load for diesel, a biodiesel blend, and a nanoadditive biodiesel.

In-cylinder pressure traces show earlier combustion phasing for CSO30 and nanoparticle blends, due to their higher cetane numbers. Diesel exhibited the lowest peak pressure, while CSO30-N60 produced the highest peak pressure under full load.

4.2.2 Heat Release Rate (HRR)

The net heat release rate increased with CeO₂ addition due to improved oxidation and better fuel–air mixing. At full load, the peak heat release was ~36 J/deg for CSO30-N60 compared to ~24 J/deg for diesel (Fig. 9).

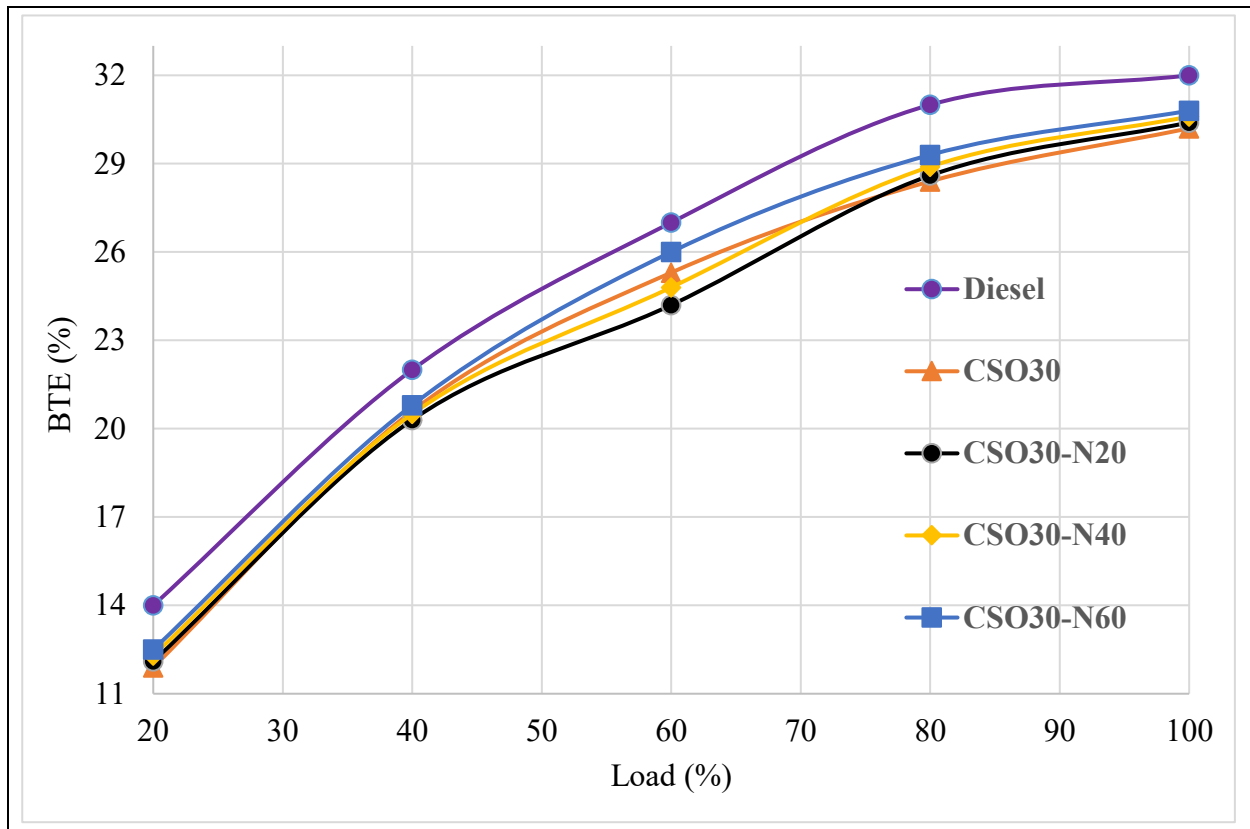


Fig. 7: Brake thermal efficiency under various loads

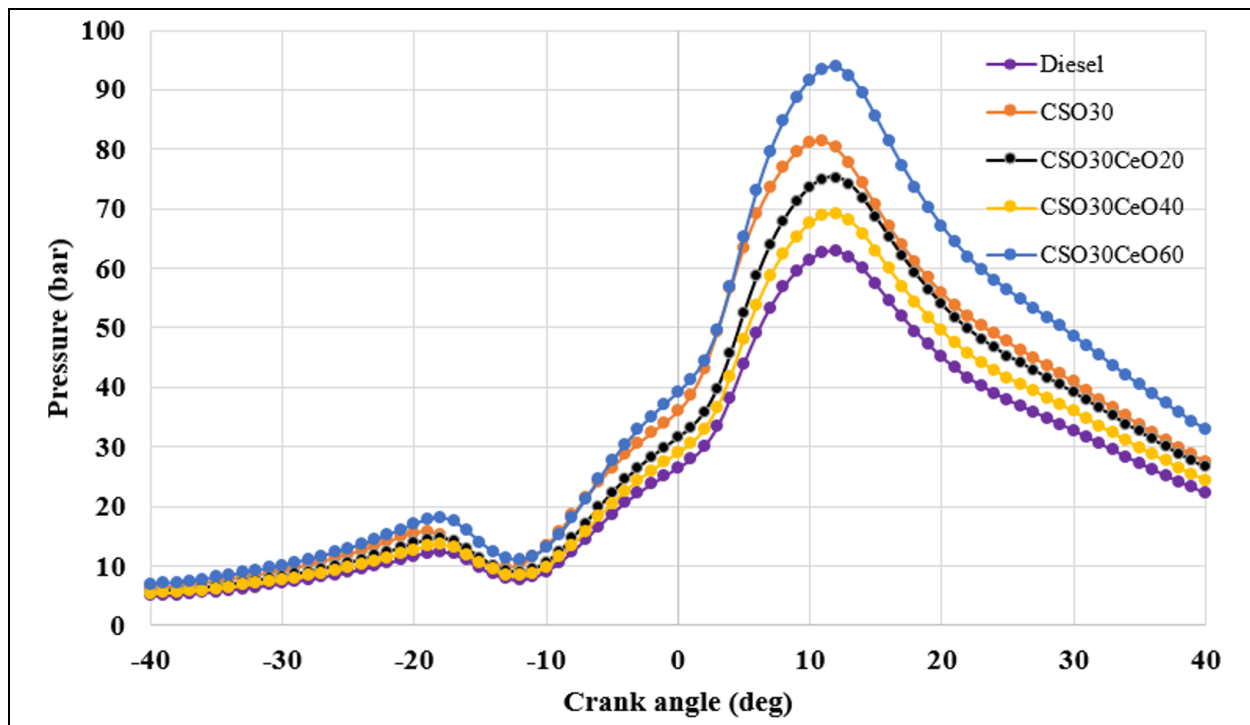


Fig. 8: Pressure vs. crank angle

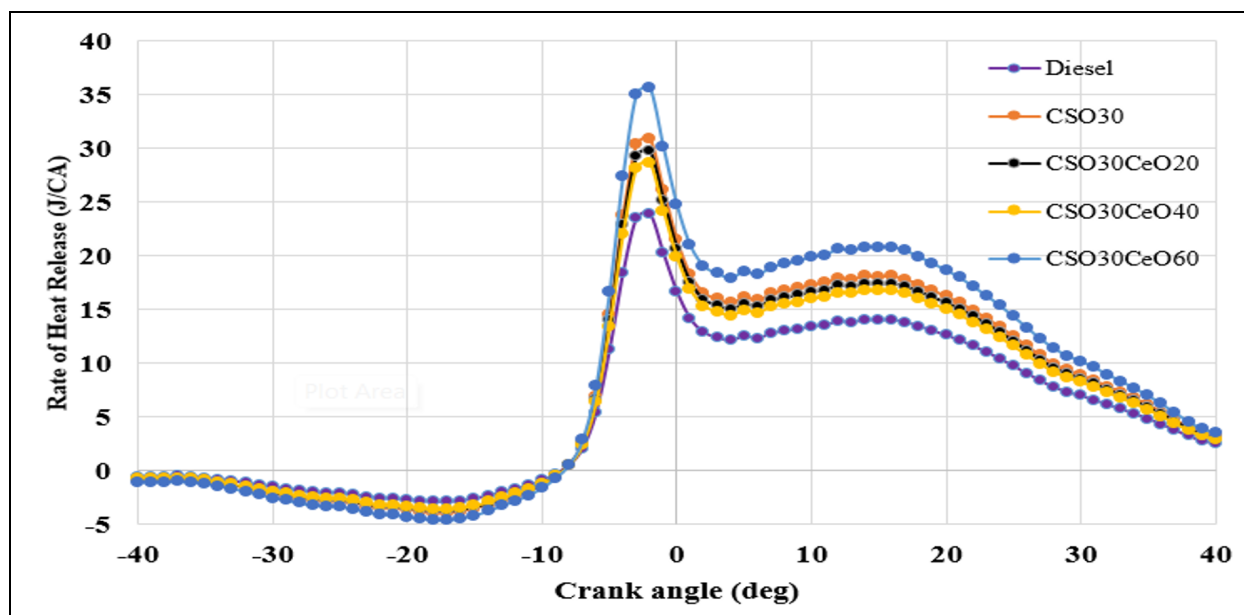


Fig. 9: HRR vs. crank angle

(Ramalingam *et al.* 2020) studied the variations in HRR with respect to crank angle for cottonseed biodiesel with and without different nanoparticles at 0.1 ppm under full-load conditions.

4.3 Emission Analysis

4.3.1 Unburnt HC Emissions

Variation in HC emissions of diesel, CSO30, and CeO₂-doped blends with engine load is shown in Fig. 10. Diesel emitted the highest HC at full load (109 ppm) among the test fuels, attributable to diffusion-controlled combustion that contributed to incomplete oxidation. CSO30-N60 decreased HC with 11.9% relative to diesel. The reduction in HC emissions with CeO₂ addition is attributed to the oxygen storage–release capability of CeO₂ nanoparticles, which enhances post-flame oxidation of unburned hydrocarbons. At higher loads, where diffusion-controlled combustion dominates, the presence of CeO₂ promotes more complete oxidation, resulting in a 11.9% reduction in HC emissions for CSO30-N60 compared to diesel. The monotonic decrease in HC with increasing nanoparticle concentration indicates that catalytic oxidation (and not just the fuel oxygen content) determines HC reduction in nano-blended fuels (Sundar *et al.* 2020).

4.3.2 Carbon Monoxide Emission

Fig. 11. Under diffusion-controlled combustion at higher fueling rates, all fuels exhibited increasing CO emissions with load because of oxygen deficiency. For CO, diesel displayed the highest emission at full load with 0.13%, while CSO30–N20 showed the lowest value of CO emission with a value of 0.073%, having to a reduction of 43.8% compared to diesel. The decrease of

CO emissions with CeO₂ addition is closely correlated with the redox behavior of cerium oxide (Ce⁴⁺/Ce³⁺ cycle), which increases the oxygen buffering capacity and benefits good combustion of CO to CO₂ through oxidation during combustion. While all nanoparticle blends produced less CO than diesel and neat CSO30, the lowest result was seen for CSO30–N20 at full load. Such an evidence indicates that intermediate concentration of the nanoparticles may yield the best catalytic activity without causing a stifled spray or deteriorating the combustion properties. Yet, neither agglomeration nor dispersion stability was explicitly examined, so the trend is interpreted in terms of combustion behavior rather than dispersion constraints. (Yeneneh and Sufe, 2025; Sinha *et al.* 2016).

4.3.3 Oxides of Nitrogen

NO and NO₂ emissions are among the most significant environmental and health concerns associated with compression-ignition engines (Saravanan *et al.* 2020). These nitrogen oxides (NO_x) are formed when atmospheric nitrogen reacts with oxygen in the high-temperature combustion chamber. The oxides formed by this reaction are all gases, and they are toxic. The oxides contribute substantially to air pollution. Fig. 12 shows the percentage change in NO_x with respect to the engine load. From these results, it is observed that as load increases, NO_x emissions also increase, following the trend in engine power output. NO_x emissions were minimal at low loads and increased as the load approached full load (Soosai *et al.* 2022). Compared with neat diesel, the CSO30 blend showed slightly higher NO_x emissions (Shaisundaram *et al.* 2025). NO_x increased with load for all fuels. CSO30 produced slightly higher NO_x than diesel at high load. However, CeO₂ addition reduced NO_x, with CSO30-N60 showing a ~17.7% reduction compared to diesel at full load (Woldetensy *et al.* 2025).

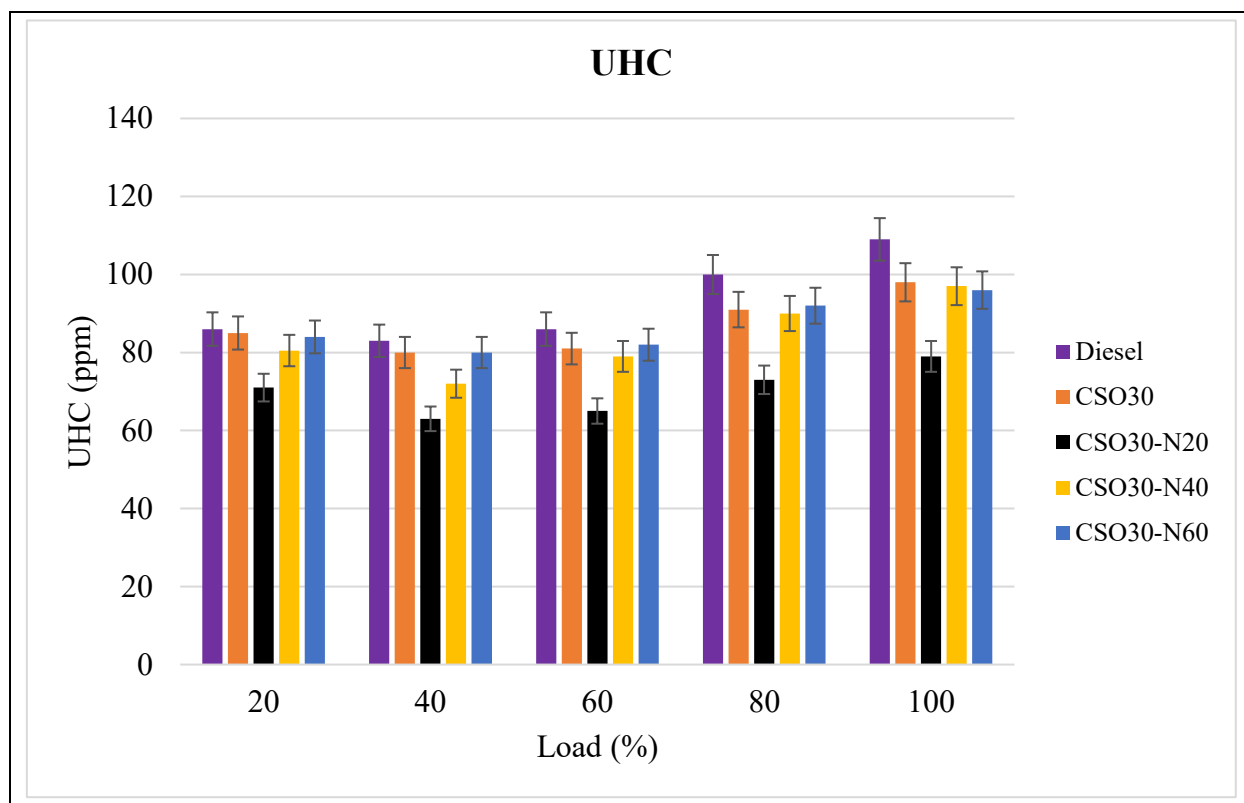


Fig. 10: HC emissions under various loads

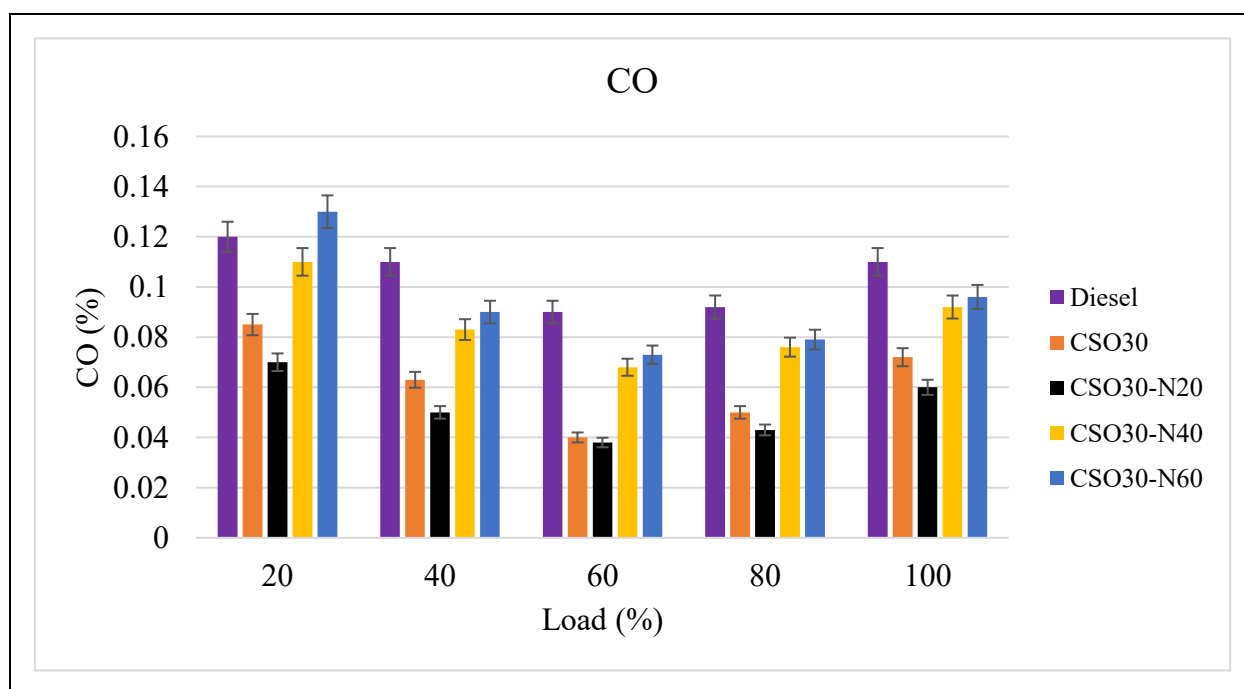


Fig. 11: CO emissions under various loads

4.3.4 Smoke Opacity

Smoke opacity increased with load for all fuels. CSO30 produced more smoke than diesel due to higher viscosity and larger droplet size. CeO₂ significantly reduced

smoke, with CSO30-N60 showing a 17% reduction relative to diesel, as shown in Fig. 13. Like other exhaust parameters, smoke emissions increase progressively with load. This is primarily due to greater fuel burn at elevated loads, which creates an oxygen deficiency in the

combustion chamber (Kumar *et al.* 2020). The CSO30 blend exhibited higher smoke emissions than diesel fuel.

The introduction of CeO_2 nanoparticles into the fuel significantly reduced smoke levels, owing to

improved combustion efficiency and enhanced fuel oxidation (Dhairiyasamy *et al.* 2025). The measured smoke opacity at full-load conditions for CSO30-N60 was reduced by 20.9% and 17.07% compared to CSO30 and diesel, respectively.

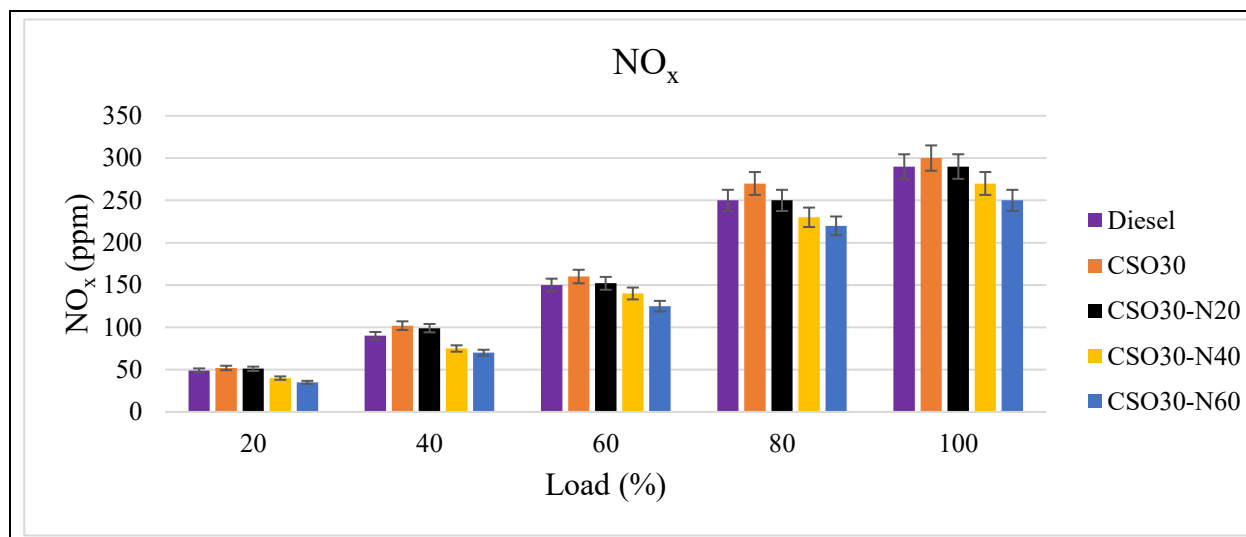


Fig. 12: Nitric oxide emissions under various loads

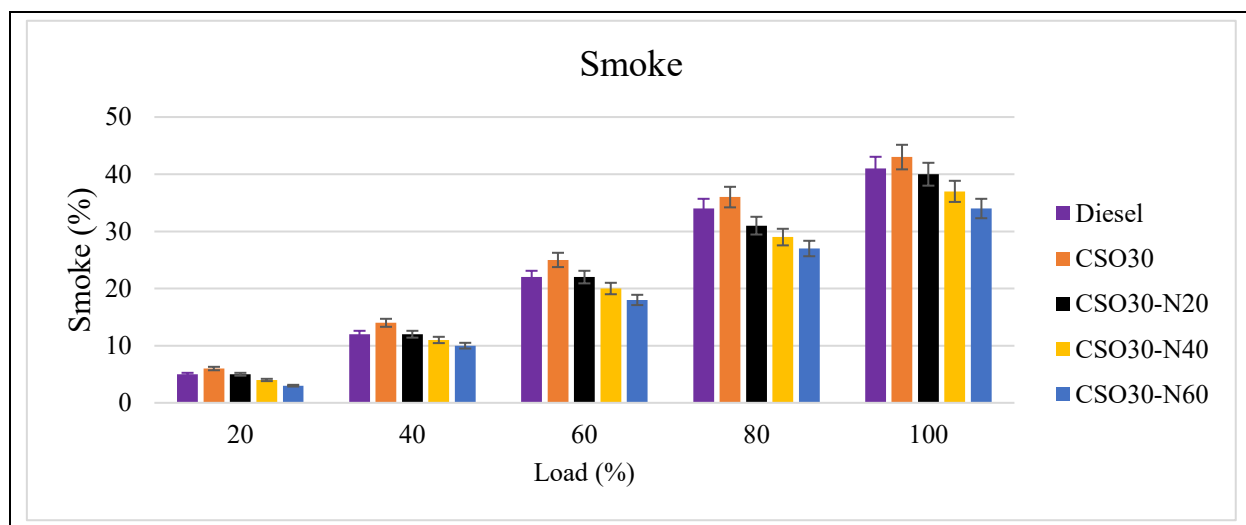


Fig. 13: Smoke opacity under various loads

5. CONCLUSION

This work examined the influence of adding 20, 40, and 60 ppm of CeO_2 nanoparticles to a 30% cottonseed biodiesel–diesel blend (CSO30) in a direct-injection diesel engine operated under non-road, constant-speed operation. The results showed that the addition of CeO_2 nanoparticles improved BTE and reduced fuel consumption compared with neat CSO30. However, neat diesel exhibited the highest BTE (32% at full load). The incorporation of CeO_2 nanoparticles enhanced the performance of CSO30, increasing BTE up

to 30.8% and reducing BSFC by approximately 13% at full load for CSO30-N60, compared with a lower BTE of 30.2% for CSO30 at full load.

Results of exhaust emission measurements indicated that, in general, CeO_2 -doped blends resulted in lower emissions than diesel under most operating conditions. Compared to diesel, the reductions in hydrocarbon emissions, smoke opacity, and NO_x emissions at full load were 11.9%, 17%, and 17.7%, respectively, for CSO30-N60. The CSO30–N20 blend exhibited the lowest carbon monoxide (CO) emission at

full load, achieving a 43.8% reduction compared with diesel. This reduction is attributed to the oxygen storage–release capability and catalytic oxidation effect of CeO₂ nanoparticles, which enhance post-flame oxidation under locally oxygen-deficient conditions.

Diesel exhibited the highest HC emissions under part-load conditions due to incomplete combustion, whereas the addition of CeO₂ nanoparticles significantly reduced HC emissions across all loads. For all nano-blended fuels, post-flame oxidation was enhanced, as evidenced by reduced HC and CO levels resulting from the addition of CeO₂ nanoparticles.

In summary, CeO₂ nanoadditives enabled CSO30 to achieve diesel-like performance while reducing regulated exhaust emissions. Among the tested blends, CSO30-N60 was identified as the optimal formulation for non-road engines, offering the best trade-off between efficiency and emission reduction.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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