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Synergistic Impact of Alcohol Type and CeO_2 Nanoparticles on the Performance and Emission of an RCCI Engine Fueled with Sapota Biodiesel

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ABSTRACT

This study investigates experimentally the combined effect of alcohol type (hexanol and butanol) and cerium oxide (CeO_2) nanoparticles (at a fixed concentration of 5-15ppm) on performance, combustion and emission of a reactivity-controlled compression ignition (RCCI) engine fueled with sapota oil methyl ester (SOME). Butanol and hexanol were used as low reactivity fuel, while SOME (B20) was the high reactivity fuel with blended CeO_2 nanoparticles at 5–15 ppm. The novelty of this work lies in integrating lower-chain (butanol), higher-chain (hexanol) alcohols and nanoparticle catalysis to deliver the first systematic RCCI comparison to-date. Upto 3% improvement in brake thermal efficiency and a brake specific energy consumption reduction of about 6% were observed with CeO_2 addition. Hydrocarbon, CO and smoke opacity decreased markedly, whereas NO_x emissions increased moderately (4–6%), owing to the higher in-cylinder temperature. Detailed combustion analysis showed the advanced heat release and the increase in peak in-cylinder pressure observed near top dead centre, especially with hexanol–CeO_2 blends. In conclusion, the B20D70HEX10C15 blend showed the most well-balanced trade-off between performance enhancement and emission reduction.

Keywords: Sapota oil methyl ester; Cerium oxide nanoparticles; Butanol; Hexanol; Dual fuel RCCI engine.

1. INTRODUCTION

Due to the high thermal efficiency and life span of CI engines, they are still a popular choice in the transport and power generating sectors (Munimathan *et al.* 2025). The growing concern on greenhouse gases, particulate matter and NO_x has led to the vast amount of research on more clean combustion technologies. One of these new concepts with a potential for simultaneous emission reduction and efficiency improvement is Reactivity-Controlled Compression Ignition (RCCI) engine and it has received significant attention as Low Temperature Combustion (LTC) mode. In RCCI, in-cylinder reactivity stratification is achieved with mixtures of a Low Reactivity Fuel (LRF) and a High Reactivity Fuel (HRF). In general, LRF is pre-mixed by port fuel injection, whereas HRF is injected directly into the cylinder. This concept allows for control of ignition phasing and heat release rate by enabling combustion closer to the ideal lower peak temperatures and a more uniform charge distribution. (Paykani *et al.* 2021; Dwarshala *et al.* 2023)

Research on RCCI has extensively focused on conventional diesel/gasoline mixtures. However, in the quest for sustainable fuels, increasing emphasis has been placed on renewable fuels such as biodiesel, alcohols and gaseous fuels. Vegetable oils and waste feedstock biodiesel are another appealing HRF since they have high cetane number, high oxygen content, and low sulfur concentration, all contributing to a reduced tendency for soot and improved combustion. However, biodiesel also has its issues, including an increased viscosity, slightly lower energy density, and more NO_x emissions in some scenarios. The disadvantages of biodiesel can be eliminated, or the drawbacks can be mitigated by blending biodiesel with alcohols or by using dual-fuel RCCI mode.

Additionally, the use of metal oxide nanoparticles in fuel blends is a new method to enhance the combustion quality and emissions. CeO_2 nanoparticles function as oxidation catalysts that promote the oxidation of hydrocarbons and soot particles. The synergistic introduction of biodiesel, alcohols, and CeO_2 nanoparticles under RCCI mode represents a new strategy for developing sustainable and ultra-efficient combustion. Thus, this study utilizes some of such combinations, namely biodiesel (B20) as the HRF; butanol or hexanol as the LRF; and CeO_2 nanoparticles as catalytic additives; and assesses their concomitant effects on performance, combustion and emission characteristics at three different loading conditions.

Early research established that relative to global combustion mode, RCCI typically has superior brake

thermal efficiency (BTE) and lower soot emissions due to the presence of the distributed combustion, albeit its performance is sensitive to injection timing, Exhaust Gas Recirculation (EGR) rate and fuel composition (Paykani *et al.* 2021; Gharehghani *et al.* 2021)

Due to the favorable cetane number and oxygen content in biodiesel, it acts as an HRF in RCCI operation resulting in reduced soot emissions due to this improved combustion support. The oxygenation of the biodiesel leads to oxidation of the fuel rich regions, leading to lower particulate emissions and unburnt hydrocarbons (HC). Nevertheless, due to the high latent heat of vaporization and viscosity of biodiesel, these mixtures have poor atomization and a delay in ignition that exacerbate the NO_x or fuel consumption (Dwarshala *et al.* 2023).

Previous studies on biodiesel-based RCCI showed that it resulted in higher combustion efficiency and lower soot but seemed to necessitate strict control of combustion phasing to control NO_x emissions (Manivannan and Subramanyan 2024). The use of alcohols as low-reactivity fuels for RCCI systems has been extensively investigated. Various studies state that better BTE along with reductions in smoke emissions were achieved in biodiesel-based RCCI engines with butanol as the LRF, whereas it has been reported that at low loads, using butanol leads to higher CO and HC emissions. Butanol has a moderate volatility (i.e. between ethanol extreme cooling and pentanol bad evaporation) making it the ideal fuel for reactivity stratification control (Manivannan and Subramanyan 2024; Ramachandran *et al.* 2023)

Larger alcohols like 1-hexanol have a lower volatility but they have a higher energy density and are more miscible with diesel and biodiesel fuels. In dual-fuel and RCCI applications, 1-hexanol decreased NO_x and soot emissions with relatively high BTE (especially at medium loads) (Anandavelu *et al.* 2023). The increased C-chain leads to slower evaporation, which will lead to a longer premixing time and a lower temperature gradient in the combustion chamber. But based on fewer studies focused on hexanol, more studies are needed to further identify the performance of hexanol as an LRF under RCCI and its mechanism with biodiesel and the catalytic additives.

In addition to the fuel composition, metal-oxide nanoparticles have shown potential in aiding combustion by catalyzing oxidation and leading to better atomization of the fuel. Cerium oxide nanoparticles are the most explored among these. CeO_2 is considered an oxygen buffer based on the reversible redox mechanism between Ce^{4+} and Ce^{3+}, allowing the oxidation of CO, HC, and soot (Yusuf *et al.* 2022). It has been observed (Dinesha *et al.* 2021) that the use of CeO_2 nanoparticles in biodiesel blends enhanced thermal efficiency, and reduced carbon monoxide and hydrocarbon emissions due to higher surface area activity and higher oxygen availability. (Muniyappan and Krishnaiah 2024) observed the same effect for CuO and CeO_2 nanoparticles in Mahua biodiesel, where the improvement in combustion efficiency and reduction in BSFC were attributed to shorter oxidation time for intermediate species.

Biodiesel-fueled RCCI engines can take synergistic advantages of the coupled effects of alcohols and nanoparticles. Alcohols facilitate the preparation of the mixture and lower the soot emission, while CeO_2 nanoparticles govern the catalytic oxidation of the unburnt species, increasing the oxidation reaction rate and thus stabilize the combustion. It has been shown that low concentrations of nanoparticles (5 – 15 ppm) are generally sufficient for positive changes in combustion and emission characteristics (Tamrat *et al.* 2024). These concentrations further minimize nanoparticle aggregation, while the oxygen buffering effect supports increased oxidation without compromising fuel stability. CeO_2-doped biodiesel–alcohol blends have shown significant reductions in soot opacity (≈10–12 %), CO and HC emissions and BTE over base biodiesel blends (Hameed and Muralidharan, 2023). Nonetheless, at high nanoparticle concentrations, viscosity rises, spray behavior is impaired, and injector deposits can form, illustrating an optimal dosage and dispersion approach.

Table 1. Engine operation nomenclature

Constraints	Primary	Secondary
Inj. time	23° CA	10° CA - 13° CA
Blends of fuel used	70%	30%
Inj. Pressure	220 bar	220 bar

The combined effects of these factors on engine emissions are not simple. Better combustion, however, usually results in less soot and unburned hydrocarbons, but complete oxidation leads to a higher in-cylinder temperature which increases the amount of NO_x. This balance can be alleviated *via* EGR, pilot injection tuning and indirect control of the fuel reactivity ratio. While EGR lowers in-cylinder O_2 concentration and peak flame temperature, catalytic nanoparticles favor oxidation of intermediate species under mildly O_2-deficient conditions to maintain efficient oxidation. In this way, it becomes possible to move the NO_x –soot trade-off in the direction of lower soot without a significant NO_x penalty.

While plenty of work has been done on biodiesel-based RCCI engines, to the best of our knowledge, a systematic study comparing lower-chain alcohols (butanol) and higher-chain alcohols (hexanol) in RCCI using the same operating conditions has not been

reported previously, while also evaluating the synergetic effect of CeO_2 nanoparticles with sapota biodiesel.

Table 2. Engine specification

Parameter	Specification
Type of Engine	Single-cylinder, four-stroke, water-cooled, direct injection diesel engine
Make/Model	Kirloskar TV1 (or equivalent research engine)
Dimensions of bore and stroke	80 mm × 110 mm
Length of connecting rod	300 mm
Ratio of compression	17:01
Power	3.5 kW at 1500 rpm
Cylinder count	1
System of Injection	Common rail direct injection (CRDI) with dual injectors
Timing of primary Inj.	23° CA bTDC
Timing of secondary Inj.	10°–13° CA bTDC
Pressure if Inj.	220 bar (both injectors)
Fuel Injection Split	70% primary – 30% secondary
Cooling System	Water-cooled
Ignition Type	Compression ignition
Dynamometer	Eddy current dynamometer (for load control)
ECU	Electronic Control Unit for injection and timing control
Emission Measurement	AVL DiGas 444 N and AVL 437C (Gas and smoke analyzer)
Combustion Analyzer	Piezoelectric pressure transducer with crank angle encoder
Test Fuels	Diesel + SOME + But. /Hex. with CeO_2 nano-additive

The objective of this work is to experimentally study the effects of the alcohol chain length (butanol and hexanol) and concentration of CeO_2 nanoparticles (5–15 ppm) on the performance, combustion and emission characteristics of a sapota oil methyl ester-fueled RCCI engine. The results may therefore guide HRF–LRF chemistry and nanoparticle catalysis optimization for clean and efficient RCCI performance.

2. MATERIALS AND METHODS

2.1 Materials

Three different types of fuels (hexanol, butanol and SOME) were used in the work. The higher alcohols were obtained from a local chemical supplier. Sapota oil methyl ester was locally made starting with the mechanical grinding step (the first) followed by the transesterification step that produces the methyl ester and lowers the viscosity of the fuel.

2.1.1. Oil Extraction and Characterization

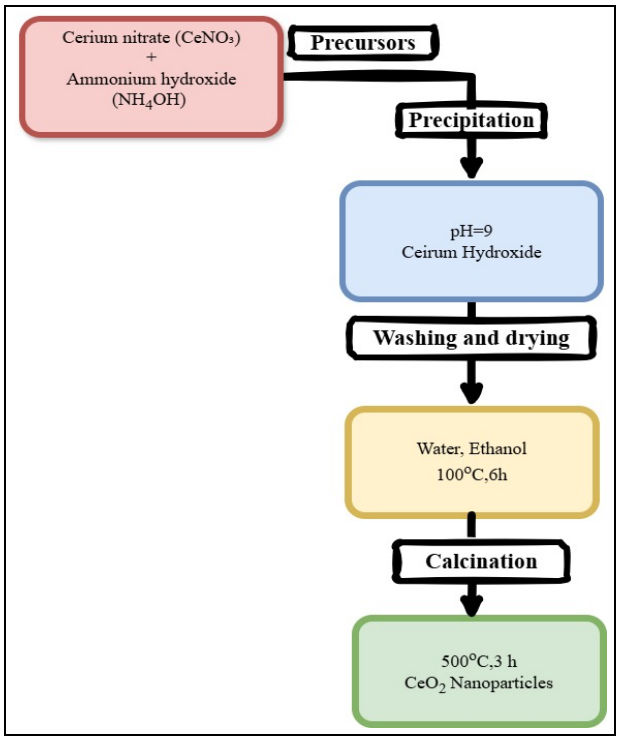


Fig. 1: Schematic representation of CeO_2 nanoparticle synthesis *via* precipitation method

Sapota seeds were collected from a local source in Andhra Pradesh and Tamil Nadu and, naturally dried in a seed drier at 60°C, followed by dehulling of outer skin of the kernels manually. The dried seeds were subsequently ground mechanically to extract the oil. Transesterification was done in one step with 50 g of sapota oil in an Erlenmeyer flask together with KOH and methanol. Glycerin and SOME were extracted by phase separation and distillation after stirring the mixture for 90 minutes at 500 rpm using a mechanical stirrer in a hot plate heater. The percentage of free fatty component state in the oil was found to be 1.79% (Mylavarapu *et al.* 2025).

2.2. Synthesis of Nano Additive

Fig. 1 shows the synthesis process of CeO_2 additive. Cerium oxide nanoparticles were developed by precipitation process because it is a simple, low cost, and high yield process capable of producing fine and well-distributed particles. $Ce(NO_3)_3 \cdot 6H_2O$ was employed as precursor salt and NH_4OH was used as a precipitating agent in the procedure. To 0.1 M cerium nitrate solution, drops of aqueous ammonium hydroxide were added at 200 rev/min under stirring until the pH of the solution reached approximately 9 and a pale-yellow cerium hydroxide precipitate was formed. The suspension was allowed to age for about 12 hours to ensure full precipitation and particle growth. The precipitate was

filtered and washed a few times with distilled water and ethanol to remove the excess nitrates and byproducts, after ageing. The final precipitate solution was subsequently amply rinsed and dried up in the presence of the fresh air at 100 ℃ for 6 hours in order to take away the residual water content. Thereafter, the dry powder was calcined in muffle furnace at 500 ℃ for 3 hours to enhance the crystallization during transformation of cerium hydroxide to cerium oxide nanoparticles. The calcined powder was ground into a fine powder and stored in desiccators to prevent moisture absorption.

2.3. Experimental Engine and Set Up

Fig. 2 presents the basic configuration of the test engine. The fuel injected in the air intake manifold is less reactive, and the other through the engine's primary injection is more reactive. The two fuels coupled access to the flow meter which in turn connected to the electronic control unit (ECU) of the test engine. An eddy current dynamometer is controlled using a dynamic controller, and an emission and combustion analyzer is used to measure the emissions and combustion.

2.4. Fuel Taxonomy

Table 3 shows the nomenclature of fuel blends used in the study. The following base fuel: B20D70BU10 (20% SOME + 70% diesel + 10% n-butanol, based on volume) was considered the benchmark dual-fuel blend for comparison purposes. To investigate the catalytic impacts of nanoparticles, CeO_2 was also incorporated into the same base blend at three concentrations (5 ppm, 10 ppm, and 15 ppm). These are described below as B20D70BU10C5, B20D70BU10C10, and B20D70BU10C15, respectively (Zheng *et al.* 2018).

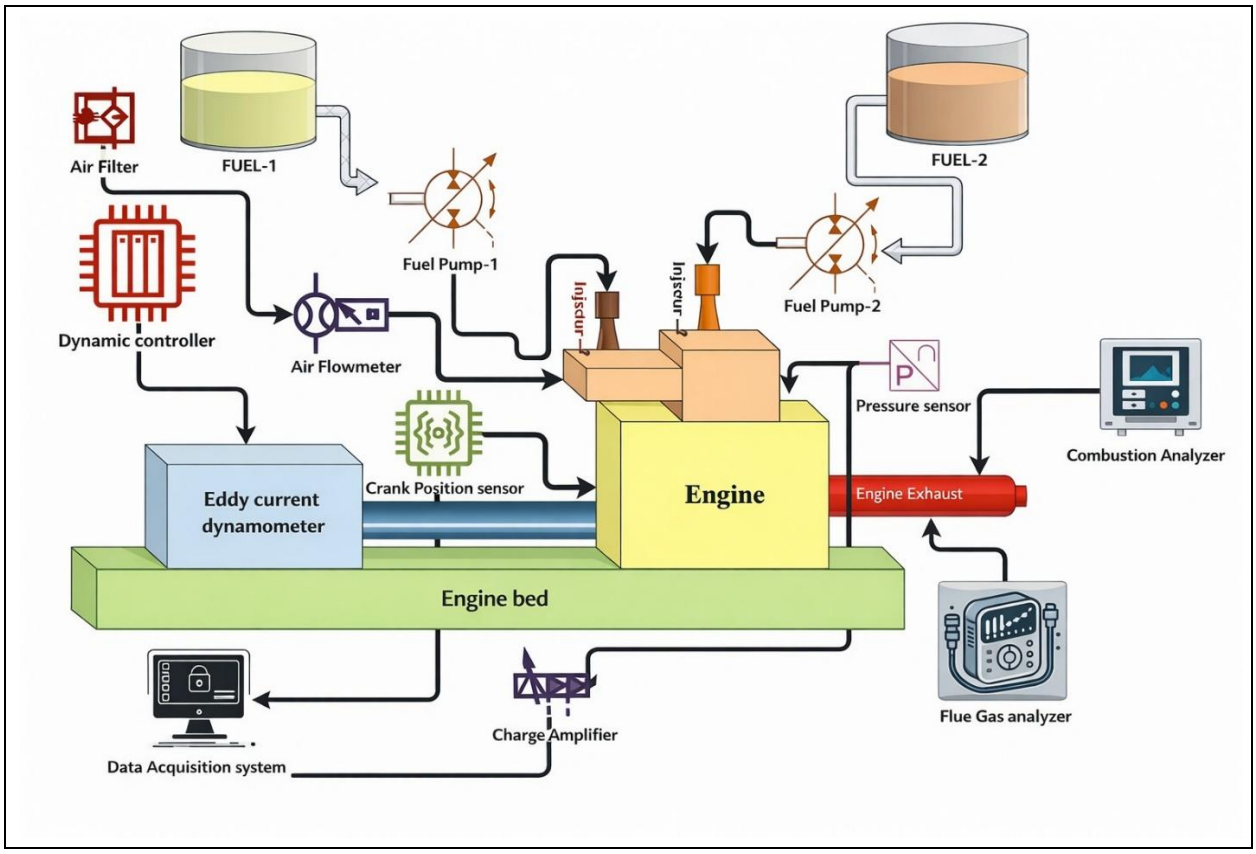


Fig. 2: Schematic experimental set up (Mylavarapu *et al.* 2025).

A parallel series of blends was prepared with 1-hexanol instead of butanol to quantitatively evaluate the effects of higher-chain alcohols on fuel reactivity and combustion characteristics. The hexanol blend was then named B20D70HEX10 which consisted of 20% SOME, 70% diesel and 10% 1-hexanol. Correspondingly, the nano-additive concentrations of 5 ppm, 10 ppm and 15 ppm were mixed with this combination to produce B20D70HEX10C5, B20D70HEX10C10 and B20D70HEX10C15, respectively (Yusuf *et al.* 2022).

This naming pattern BD for the percentage of biodiesel (SOME), D for the percentage of diesel, BU for the percentage of butanol addition which contributed 10% by volume fraction surfactant-free hexanol input fraction by 10% vol–1. The letter C with a number indicates the concentration of CeO_2 nanoparticles in ppm.

Specifically, a blend of 20% biodiesel, 70% diesel, 10% butanol, and 10 ppm of CeO_2 nanoparticles would be identified as B20D70BU10C10, while the same blend composition with a hexanol based blend would be identified as B20D70HEX10C15, with the corresponding ppm of CeO_2.

Table 3. Shows the fuel and Nanoparticle nomenclature

Fuel Symbols	SOME (%)	But. (%)	Hex. (%)	Diesel (%)	CeO_2 Nano additive (ppm)
B20D70BU10	20	10	–	70	-
B20D70BU10C5	20	10	–	70	5
B20D70BU10C10	20	10	–	70	10
B20D70BU10C15	20	10	–	70	15
B20D70HEX10	20	–	10	70	-
B20D70HEX10C5	20	–	10	70	5
B20D70HEX10C10	20	–	10	70	10
B20D70HEX10C15	20	–	10	70	15

Butanol and hexanol were added to improve volatility, oxygen content, and pre-mixing of the base biodiesel-diesel blend, and CeO_2 nanoparticles were added as catalytic combustion promoters to facilitate oxidation of unburnt hydrocarbons and soot precursors. The systematic variation in composition permitted an extensive investigation of the effects of alcohol chain length and nano-additive concentration on ignition delay, heat release rate, BTE, and the key exhaust emissions of NO_x, CO, and HC and smoke opacity at RCCI operating conditions (Dwarshala *et al.* 2023).

3. RESULTS AND DISCUSSION

3.1 Characterization of Nanoparticles

The crystalline structure of the synthesized sample was analyzed through X-Ray Diffraction (XRD) with the corresponding diffraction pattern shown in Fig. 3. The XRD pattern exhibits sharp diffraction peaks at 2θ values of approximately 28°, 32°, 47°, 55°, 59°, 69°, 73°, and 77°, which correspond to the (111), (200), (220), (311), (222), (400), (331), and (420) crystallographic planes, respectively (JCPDS Card No.: 34-0394). These reflections are in good agreement with the characteristic peaks of a face-centered cubic (FCC) crystal structure, confirmng the formation of a highly crystalline phase.

The intense and narrow diffraction peaks indicate excellent crystallinity of the material, suggesting that the synthesized particles possess a well-ordered atomic arrangement with minimal structural defects. The absence of any secondary or impurity peaks further confirms that the sample is single-phase and highly pure. The crystallite size can be further estimated using the Debye–Scherrer equation provided the full width at half maximum (FWHM) of the major peaks. The average crystalline size was 10.4 nm.

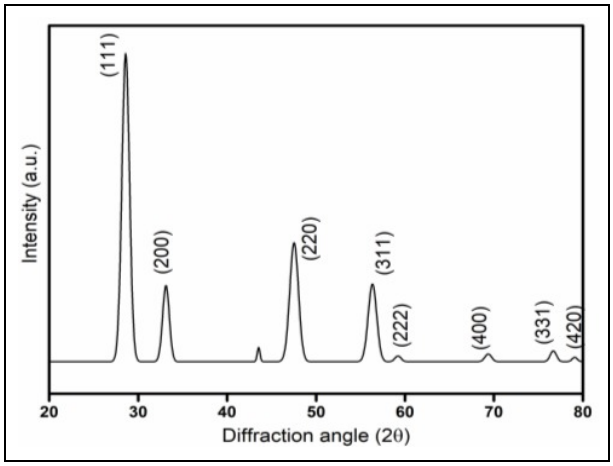


Fig. 3 XRD pattern of synthesized CeO_2 nanoparticles

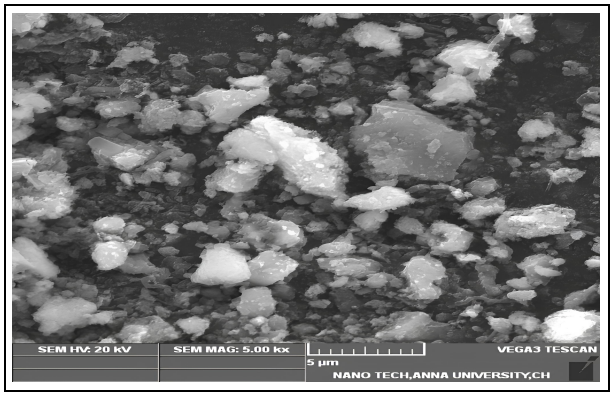


Fig. 4: SEM image of CeO_2 nanoparticles

The nanoparticles were dispersed in the fuel blends using ultrasonication for 30 minutes prior to experimentation. No surfactant was used. The prepared blends remained visually stable without observable sedimentation for the duration of the experimental trials

The surface morphology of the synthesized sample was examined using Scanning Electron Microscopy (SEM), and the corresponding micrograph is shown in Fig. 4. This image clearly reveals a nanostructured, porous and highly agglomerated morphology.

3.2 Performance Parameters

The engine performances are indicated by two parameters called BTE and brake specific energy consumption (BSEC) (Yusuf *et al.* 2022). The former is a measure of the engine's ability to convert the chemical energy in fuel to usable mechanical energy. A high BTE is a measure of the efficacy of the fuel used and of the engine itself. On the other hand, BSEC indicates the

energy consumption to generate one unit of brake power. It also provides allowances for fuel property variations, especially during alternative fuel investigations.

3.2.1 BTE

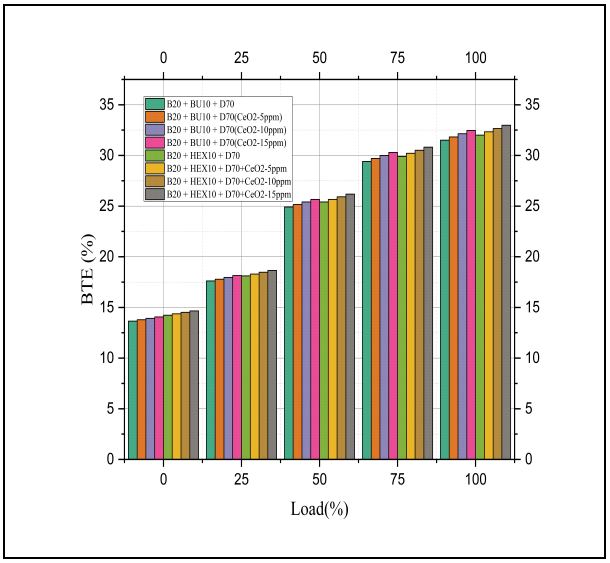


Fig. 5: Variation of BTE with engine load

Fig. 5 shows the value of BTE with load. In the separate comparison of both butanol and hexanol blends with CeO_2, an apparent improvement in BTE was observed. At full load, the peak BTE values were nearly identical for butanol- and hexanol-based blends, but the hexanol blends with CeO_2 showed slightly better engine efficiency at full load, likely because of superior premixing and combustion phasing. While both datasets indicate similar levels of improvement, the hexanol blends demonstrate modestly greater maximum efficiency. Such improvement is attributed to the higher oxygen content and volatility of hexanol which has better fuel–air mixing characteristics. CeO_2 nanoparticles additionally increase the combustion *via* oxygen donation and complete burning. Overall, hexanol–CeO_2 has the most reasonable balance between performance and efficiency for all loads.

3.2.2 BSEC

Fig. 6 indicates the change in BSEC with load. Decrease in BSEC with increasing load corroborates better combustion at the higher engine load for all fuel blends. The butanol blends, B20 + BU10 + D70 (CeO_2–15 ppm) has the lowest BSEC, which is about 6% lower than its corresponding base fuel. Equally in the case of hexanol blends, B20 + HEX10 + D70 (CeO_2–15 ppm) shows the lowest BSEC with a deterioration of around 6% as compared with its base. In agreement with the better combustion performance, hexanol blends exhibit consistently better BSEC than butanol ones. The reason for this enhancement was attributed to volatility of hexanol which allows for better combustion (Padmanaban *et al.* 2024). The presence of CeO_2 nanoparticles promotes oxidation and creates additional heat, leading to a reduction in energy loss. Hence, the B20 + HEX10 + D70 (CeO_2–15 ppm) blend provides the highest energy conversion efficiency and the lowest fuel energy requirement at all loads.

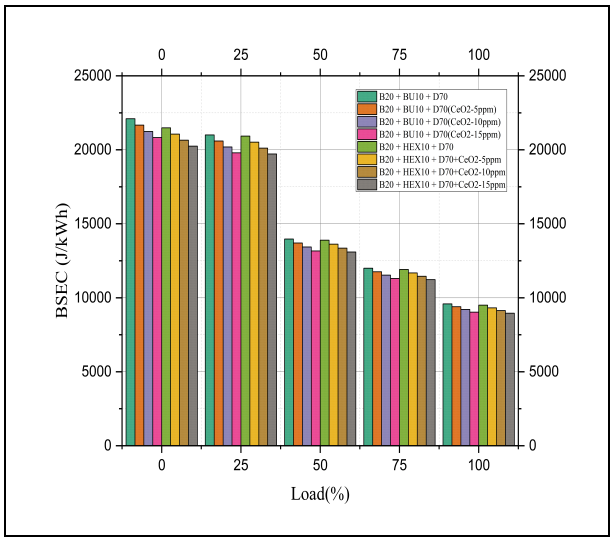


Fig. 6: Variation of BSEC with engine load

3.3 Emission Parameters

Emission parameters are of vital importance for evaluating the impact of engine operation on the environment. Hydrocarbon, CO and NO_x are produced by the reaction of nitrogen gas and oxygen in the high-temperature combustion engine environment. These are correlated to combustion temperature and air–fuel ratio. Collectively, these emissions determine combustion efficiency and environmental performance of the engine (Ramalingam *et al.* 2018).

3.3.1 HC

Fig. 7 shows the variation on emission of HC with Load. The addition of CeO_2 nanoparticles to all of the blends and loads leads to a slight reduction in hydrocarbon emissions. At all loads, the base butanol blend (B20 + BU10 + D70) produces the maximum HC, and the minimum was associated with the CeO_2–15 ppm form.

Although hexanol has a lower oxygen weight fraction than butanol, its longer carbon chain and improved miscibility promote extended premixing and more homogeneous combustion, resulting in reduced HC emissions. Likewise, within the hexanol series the least amount of HC emissions (approx. 9% lower than its base) was obtained with B20 + HEX10 + D70 (CeO_2–15 ppm), Due to enhanced oxidation and higher oxygen content by themselves, hexanol blends typically produce lower HC than butanol blends. The decrease with the supplementary CeO_2 is ascribed to the catalytic oxygen

buffering function of CeO_2 favoring the full combustion. This results in the reduction of unburnt hydrocarbons, which lead to overall improved combustion efficiency and enhanced emission quality (Ramachandran *et al.* 2023).

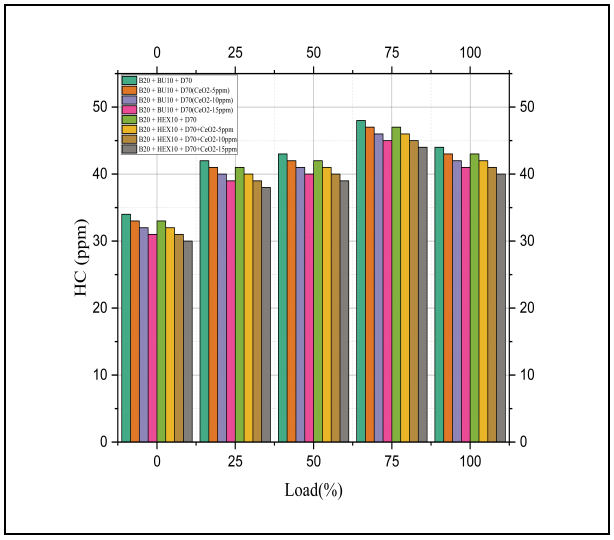


Fig. 7: Variation of HC emissions with engine load

3.3.2 CO

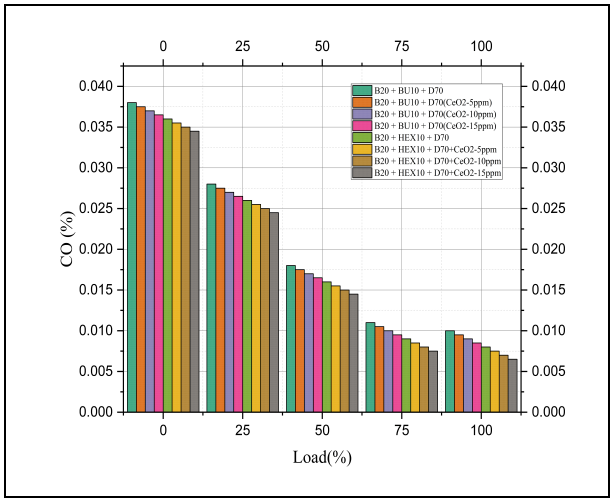


Fig. 8: Variation of CO emissions with engine load

Fig. 8 indicates the variation in CO with load for all fuel blends, the consistency of decreased CO emissions with load indicates that the combustion was complete at higher temperatures. B20 + BU10 + D70 (CeO_2–15 ppm) is the best CO reducer (almost 15% lower than its base blend) of all the butanol blends. Similar trends were observed in the hexanol series, where B20 + HEX10 + D70 (CeO_2–15 ppm) yields the minimum CO (0.006%) under full load. Overall, this is attributed to hexanol blends having a higher average oxygen content, thus facilitating complete oxidation of carbon to CO_2. CeO_2 nanoparticles support this effect further as they donate lattice oxygen when combusted. This, in turn, minimizes incomplete oxidation and is responsible for reduced CO formation. The statements imply lesser amount of CeO_2 contaminating the exhaust with greater combustion efficiency using hexanol blends containing CeO_2 (Joshua *et al.* 2023).

3.3.3 CO_2

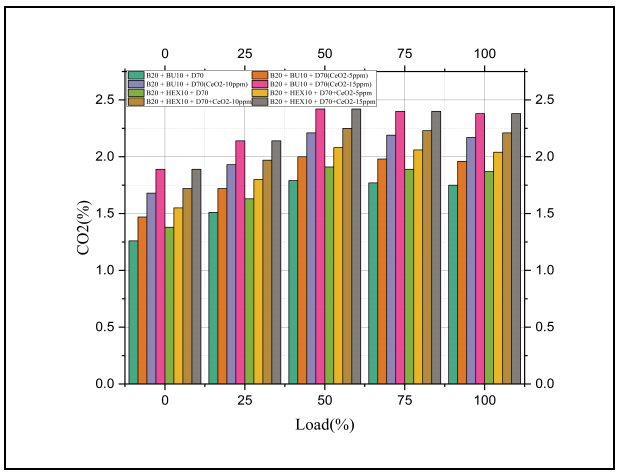


Fig. 9: Variation of CO_2 emissions with engine load

For all blends, CO_2 emissions increase with load, suggesting relatively more complete combustion along with the increase in temperature and pressure in the engine (Fig. 9). The butanol blends, B20 + BU10 + D70 (CeO_2–15 ppm) achieved the greatest CO_2 value (2.38%), indicating enhanced carbon oxidation. Likewise, with hexanol series, it is shown that the B20 + HEX10 + D70 (CeO_2–15 ppm.) reached 2.38%, which indicates that the combustion is more efficient. CeO_2 functions as a catalytic oxygen carrier facilitating full carbon species oxidation. So, there are higher levels of CO_2 here represents more efficient and cleaner combustion (Padmanaban *et al.* 2024).

3.3.4 SMOKE

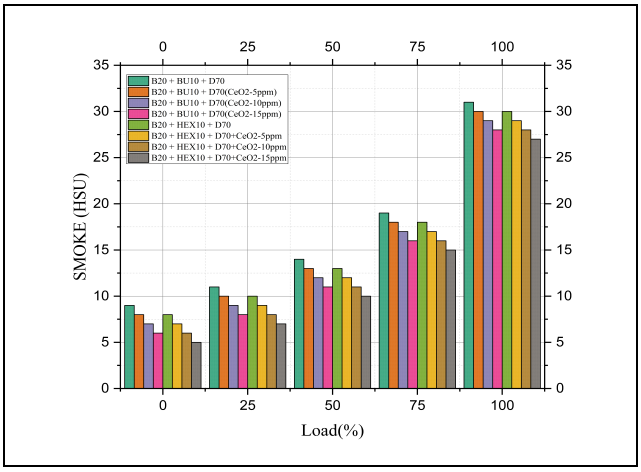


Fig. 10: Variation of smoke emissions with engine load

Fig. 10 shows the variation of SMOKE with load. Smoke opacity was measured in Hartridge Smoke Units (HSU). At higher engine loads, smoke emissions increase due to fuel-rich mixtures and incomplete oxidation at the higher fuel flow rates. At all the loads, highest smoke intensity is seen for the base butanol blend (B20 + BU10 + D70) and lowest for the blend with CeO_2–15 ppm. Hexanol blends also follow a similar decreasing trend in smoke point with B20 + HEX10 + D70 (CeO_2–15 ppm) having lowest smoke value of 27 at peak load. Due to the inherent higher oxygen content and higher volatility of hexanol blends, they ignite more readily and burn cleaner, resulting in consistently lower smoke, compared to those with butanol. The CeO_2 nanoparticles also provide active oxygen and promote soot oxidation. This results in a more complete combustion and less soot. Combining these trends with the exhaust results shows that the hexanol–CeO_2 combinations represent the cleanest of all fuels tested (Dinesha *et al.* 2021; Joshua *et al.* 2023; Ramalingam *et al.* 2018)

3.3.5 NO_x

Fig. 11 illustrates the deviation of NO_x with load. The rise in NO_x emissions with cumulative engine capacity for each fuel blends is attributed to increased temperature and availability of oxygen for combustion. Again, the NO_x was found to rise from 209 ppm at no load to 1645 ppm at full load with CeO_2–15 ppm for the butanol-based blend (B20 + BU10 + D70) and up to 1695 ppm for the hexanol-based blend (B20 + HEX10 + D70) One important observation is that since hexanol blends have higher oxygen content than butanol ones, it has shown that they consistently lead to a small quantity of NO_x emissions of up to 4% higher than that for butanol blends due to their higher combustion temperature. The observed NO_x levels (up to 1695 ppm at full load) are attributed to elevated in-cylinder temperatures and advanced combustion phasing under RCCI operation without EGR, which is consistent with previously reported RCCI studies. The increase with CeO_2 concentration results due to higher in-cylinder temperature by nanocatalyst for better oxidation (Dwarshala *et al.* 2023).

3.4 Combustion Parameters

In-Cylinder Pressure (ICP) and Heat release rate (HRR) are combustion parameters that demonstrate how effectively the mechanical work from the fuel energy released inside the cylinder is converted into useful work. It reflects the combustion intensity and timing because ICP is the fluctuation of pressure in combustion chamber during engine cycle.

Heat release rate indicates the heat released during combustion, describing how fast the chemical energy in the fuel is released. It is derived from the pressure–crank angle dataset and characterizes the phases of ignition delay, premixed combustion, and diffusion burning phases. Greater HRRs at the proper crank angle indicate more complete combustion and combustion efficiency. In most cases, the use of oxygenated fuels and CeO_2 nanoparticle increases peak HRR and it is also noted that the increases of peak HRR appeared earlier in the oxidation process by the influences of fuel oxidation and lower ignition delay.

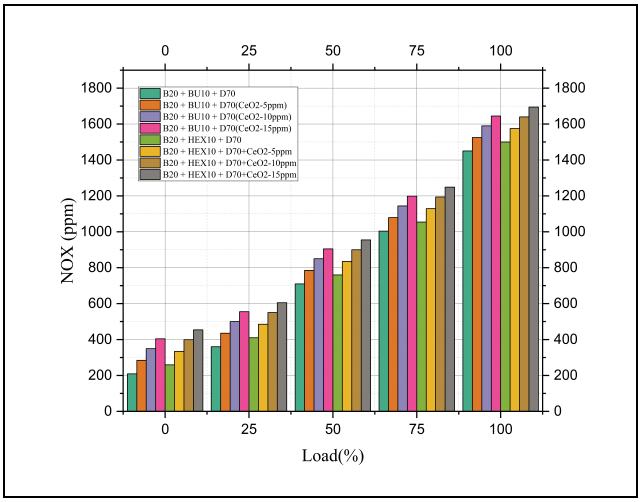


Fig. 11: Variation of NO_x emissions with engine load

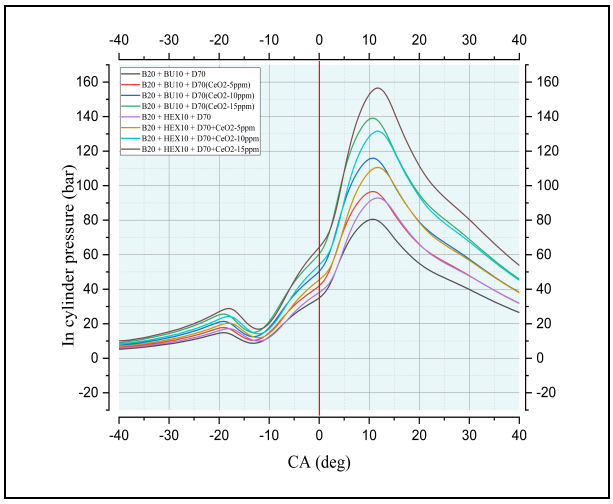


Fig. 12: Crank angle vs in cylinder pressure

3.4.1 In-cylinder Pressure

Fig. 12 indicates the change in in-cylinder pressure with respect to crank angle. After ignition, the in-cylinder pressure quickly rises and then peaks slightly past Top Dead Centre (TDC). Rate of rise of peak pressure is maximum for B20 + HEX10 + D70 (CeO_2–15 ppm) compared to the base butanol blend (35 bar vs. ~64 bar peak pressure). More ICP with higher CeO_2 contents confirm better combustion, owing to better atomization and oxidation rate. The more rapid and

complete combustion is attributed to the higher miscibility and higher volatilities of the hexanol blends, resulting in higher pressures than for the butanol blends. The addition of CeO_2 nanoparticles helps as a combustion catalyst by providing oxygen to further reduce ignition delay (Gharehghani *et al.* 2021). This results in a higher flame speed and improved heat release close to TDC. In general, the hexanol– CeO_2 combination shows better combustion characteristics along with an elongated in-cylinder pressure profile.

Fig. 13 shows the variation of heat release rate through crank angle. The HRR curve has a peak value right before TDC due to the fast combustion of premixed air–fuel mixture. The top values of HRR show that the combustion of B20 + HEX10 + D70 (CeO_2–15 ppm) is fastest and most complete, approximately 30 J/°CA.

The bottom butanol mixture gives the lower HRR, which confirms fuel oxidation to be slower. Higher butanol and hexanol blends ignite earlier and show higher HRR peaks with increasing CeO_2concentration due to better atomization and subsequent catalytic reactions. Since butanol blends are unstable and behave differently compared to hexanol-based fuels, the HRR is relatively higher for hexanol-based fuels owing to better volatility and higher oxygen content. CeO_2 nanoparticles are oxygen donors, boosting oxidation, and heat release (Dwarshala *et al.* 2023). In summary, the hexanol–CeO_2 (15 ppm) combination led to the fastest combustion characterized by an ideal HRR contour near TDC to enable maximum energy conversion and minimum unburnt emissions.

3.4.2 Heat release rate

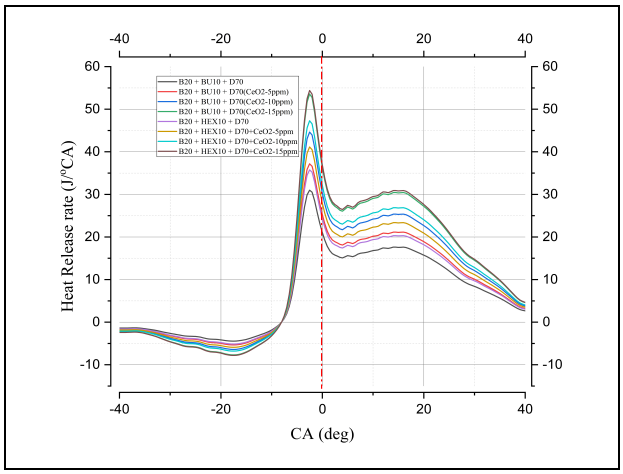


Fig. 13: Crank Angle *vs* Heat release rate

4. CONCLUSION

The experimental results show that the use of oxygenated alcohols in conjunction with CeO_2 nanoparticles has a significant role in enhancing the RCCI engine performance with sapota biodiesel. CeO_2 addition improved brake thermal efficiency and reduced brake specific energy consumption by up to 3% and ~6%, respectively. Compared to butanol blends, hexanol-based blends had better combustion features, lower emissions of HC, CO, and smoke. High nanoparticle concentrations can lead to slight rise in combustion temperature which can increase NO_x emissions. B20D70HEX10C15 yielded the best compromise between improvements in efficiency and reductions in emissions over all fuels tested. Nanoparticle dispersion stability, injector durability, and NO_x mitigation strategies, such as EGR, must be analyzed in future work.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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