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RESEARCH ARTICLE

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IMPROVING DIESEL ENGINE EFFICIENCY AND EMISSION CHARACTERISTICS USING CERIUM OXIDE NANOPARTICLE-BLENDED GREEN ALGAE BIODIESEL

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ABSTRACT

The current study compares the combustion, performance and emission properties of the compression ignition engine using Diesel, GABME B20 (Green Algae Biofuel Methyl Ester blend) as well as their corresponding mixtures with cerium oxide (CeO₂) nanoparticles at a concentration of 50 ppm. The experiment aims at the study of in-cylinder combustion behaviour, BTE, BSFC and controlled emissions (CO, HC, NO_x and smoke) under different brake power operation (0 -4.4 kW). The results of the combustion analysis showed that GABME/CeO₂ had the highest peak cylinder pressure (70 - 72 bar) and heat release rate maximum (68 - 72 J/ ° CA), which means that the oxidation rate and oxygen buffering capacity of CeO₂ nanoparticles were improved and the premixed combustion was enhanced. The performance outcomes indicated that Diesel/CeO₂ had the highest maximum BTE of 30.4% at full load and GABME/CeO₂ had 29.5% which is an improvement of 2 - 6% compared to the respective base fuels. At full load, GABME/CeO₂ (0.32 kg/kWh) had the lowest BSFC and was better fuel utilising. The analysis of emissions shown that CO, HC, smoke and smoke opacity decreased knowingly (up to 20%) with the addition of nanoparticles and NO_x increased somewhat (5 -15%) by the increase in combustion temperature. On the whole, the addition of 50 ppm of CeO₂ nanoparticles into the biodiesel blocks of algae led to a important increase in the combustion efficiency and the decrease of the unfinished combustion emissions, which is why its application is one of the promising ways of operating diesel engines in a sustainable and cleaner manner.



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I. INTRODUCTION

The high rate at which deposits of fossil fuel are being depleted as well as the increasing worry over emission of greenhouse gases has increased the scope of global research on the development of alternative fuel that can replace fossil fuel that is used in compression ignition (CI) engines, which is cleaner and more sustainable. Transportation, agricultural and industrial industries remain dominated by diesel engines because of the high thermal efficiency and longevity. The strong environmental policies require new methods to mitigate the emission of carbon monoxide (CO), unburnt hydrocarbons (HC), nitrogen oxides (NO_x) and PM. Biodiesel is one of the promising alternatives to replace the currently used diesel fuel due to its biodegradability, oxygenation and its ability to fit in the already developed diesel engine infrastructure [1]. Microalgae-produced 3rd -generation biodiesel has received important interest because it produces high lipid content, grows quickly and does not interfere with food crops. In comparison to the first- and second-generation biodiesel feed, microalgae can be cultivated in the non-arable land using wastewater or saline water, which is why it is a sustainable alternative in the long term. Algae based biodiesel especially Green Algae Biofuel Methyl Ester (GABME) has good combustion characteristics due to its natural oxygen content which improves oxidation during combustion.

However, its increased viscosity, reduced calorific value and possible rise in NO_x emissions are some of the constraints that limit its use in CI engines [2]. Consequently, the enhancement of physicochemical and combustion properties of the algae biodiesel is a field of research that is still active [3]. The recent developments in nanotechnology have also proposed the concept of nanoparticle additives that are effective to be used as combustion catalysts in biodiesel-diesel mixtures [4]. CeO₂, Al₂O₃, CuO and TiO₂ are metal oxide nanoparticles that have been confirmed to enhance fuel atomization, facilitate micro-explosion phenomena and enhance the oxidation kinetics [5]. Of them, cerium oxide nanoparticle is especially appealing because of the distinctive property of oxygen storage and release (Ce³⁺/Ce⁴⁺ redox cycle), which enables oxidation of precursors of CO and soot to continue throughout the combustion. This is an oxygen buffering process that enhances combustion efficiency and at the same time minimises incomplete combustion emissions [6]. A number of scientists have examined the role of CeO₂ nanoparticles on blends of biodiesel. Research indicates that nanoparticle fuels that are blended with fuels enhance BTE and low BSFC because of the increased heat release properties and a decreased ignition delay [7]. Experimental research on algae biodiesel additives of CeO₂ has shown a high peak CP and HRR, which show that there is more premixed combustion. Also, a decrease in CO, HC and smoke opacities has been extensively documented due to enhanced oxidation reactions and soot burnout mechanisms [8]. There is often a moderate level of increase in NO_x emissions and this is mainly explained by high in-cylinder temperature due to the increased combustion reactivity.

The source also emphasises the effect of the size of nanoparticles, concentration, injection pressure, compression ratio and hydrogen enrichment on combustion and emission properties in recent literature [9]. Specifically, the Variable Compression Ratio (VCR) engines offer a flexible platform to study combustion behaviour under different conditions of thermodynamic conditions. Compression ratio adjustment has a direct impact on peak pressure, temperature, ignition delay and heat release dynamics in general [10], [11]. Although a lot of research has been done on nanoparticle-blended biodiesel in conventional CI engines, there has been limited research on thoroughly examining the combustion parameters, including CP and HRR and performance and emission characteristics in a VCR engine using algae biodiesel of the third generation [12-14]. In addition, the vast majority of available studies concern binary fuel mix (diesel-biodiesel or biodiesel-nanoparticle systems). It is necessary to have more understanding regarding the thermochemical interactions in tertiary blends of diesel, third-generation biodiesel and metal oxide nanoparticles under different load conditions [15], [16]. The synergies of the innate oxygen concentration of algae biodiesel and the catalytic oxygen buffering ability of CeO₂ nanoparticles have the potential to induce a profound change in combustion phasing and emission patterns.

The literature on the systematic experimental confirmation of such collective effects is not adequately covered [17], [18]. The other point of weaknesses in previous research is the lack of sufficient correlation between combustion features and emission formation processes [19-21]. Although results of BTE betterment and cuts in CO and smoke are well known, little effort has been made to identify the relationship between peak CP, HRR and the generation of pollutants under different loads. In the case of high-impact journal articles, a combined combustion-performance-emission strategy is necessary towards explaining the underlying mechanisms in the nanoparticle-aided biodiesel combustion [22], [23]. In that regard, the current research project examines the combustion, performance and emission of a VCR diesel engine using a ternary blend of Diesel, GABME B20 and CeO₂ nanoparticles at the concentration of 50 ppm. Under different brake power conditions, detailed study of CP, HRR, and controlled emissions (CO, HC, NO_x and smoke opacity) are scrutinised [24-26]. The innovation of the present study is the assessment of the third-generation algae biodiesel and CeO₂ nanoparticles synergistic combustion enhancement in a VCR engine context, which offers more findings on the aspects of combustion phasing and trade-offs between emissions.

Even though the possibility of nanoparticle-blended bio-diesel fuels is confirmed by the previous studies, there is still a distinct research gap in correlating combustion intensity parameters (CP and HRR) to efficiency and formation of emissions in algae-based ternary fuel under controlled conditions of compression [27], [28]. Further, there is a paucity of research on the use of third-generation biodiesel with cerium oxide nanoparticles in VCR engines [29]. Accordingly, the study at present is going to fill the gap in the experimental quantification of the mechanism that increases the combustion and its overall effect on the engine efficiency and environmental performance. Cerium oxide nanoparticles have been chosen because of their excellent redox performance, catalytic efficacy in oxidation of soot, thermal stability and compatibility with biodiesel fuels. Similarly, algae biodiesel of the third generation is selected because of its sustainability benefits and the high level of oxygen content that supplements the oxygen release catalytic process of CeO₂. Through the combination of these two new and improved fuel technologies, the study aims at offering a viable way forward towards enhancing the efficiency of diesel engines and reducing the effects of incomplete combustion as a remedy to sustainable production of energy and cleaner operation of CI engines.

II. MATERIALS AND METHODS

II.1 PREPARATION OF GREEN ALGAE BIOFUEL METHYL ESTER (GABME20)

Microalgae ability to absorb nutrients and sunlight to create biomass that is high in lipids has led to their current popularity as a feedstock for renewable energy. Because of its rapid growth, ecological tolerance and oil-enhanced production, *Chlorella vulgaris* is the most researched microalgae [23]. These characteristics make *C. vulgaris* a feasible feedstock for the commercialisation of biofuel, both as a replacement for conventional fossil fuels and in terms of environmental factors like carbon capture and waste management. In order to create GABME20, a 20% biodiesel blend composed of *Chlorella vulgaris*, this study will examine the use of a base-catalyzed transesterification technique. In order to achieve a rapid pace of transformation while meeting quality standards for the biodiesel fuel category used in engines, the transesterification process was optimised. The established applications of *C. vulgaris* in nutrition and medicine provide further financial advantages for employing it as feedstock, bolstering the viability of an integrated algal biorefinery.

II.2 PHYSICOCHEMICAL CHARACTERIZATION

In accordance with ASTM standards, the physicochemical properties of the produced GABME20 product were carefully examined to ensure that the fuel fulfilled predetermined quality criteria.

Spec. gravity, viscosity, boiling range, cetane number, flash point and energy content were among the characteristics that were investigated. For precision, every physicochemical characteristic was measured three times and the average results were published. Table 2 summarises the features of generated GABME20 that were contrasted with ASTM limits and neat diesel fuel. Added GABME20 + CeO₂ the powder and sem image is shown in Figure 1.

Table 1: Fuel Properties of Diesel, GABME20 and GABME20 + CeO₂ Nanoparticles.

Property	Diesel	GABME20	GABME20 + CeO ₂
Physical state	Liquid	Liquid	Liquid
Specific gravity @ 16 °C	0.86	0.90	0.848
Stoichiometric air–fuel ratio	14.5	13.2	13.8
Kinematic viscosity @ 40 °C (mm ² /s)	2.42	4.1	3.9
Boiling range (°C)	160–366	185–365	180–340
Cetane number	51	55	53
Flash point (°C)	59	162	73
Calorific value (kJ/kg)	44,000	39,700	40,250

Source: Authors, (2026).



Figure 1: CeO₂ Nanoparticles – Powder & SEM Morphology.

Source: Authors, (2026).

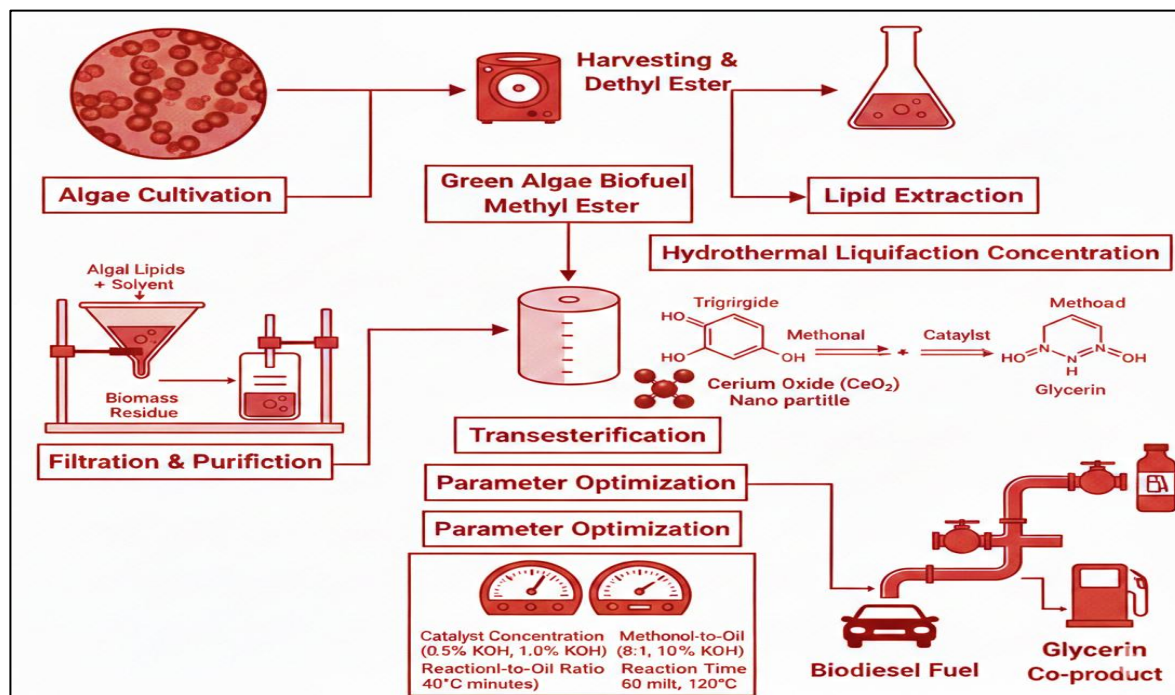


Figure 2: Preparation of biodiesel.

Source: Authors, (2026).

III. EXPERIMENTAL SETUP



Figure 3: Experimental set up.

Source: Authors, (2026).

The experiment examined the effects of adding (CeO_2) nanoparticles to green algae-based biodiesel (GABME20) on emissions and engine performance using a basic diesel engine shown in Figure 3. Current information from sensors installed to measure an engine's crankshaft angle, chamber temperature, and piston pressure was collected using a data gathering system. The internal airflow was assessed using a laser-based method. Pure diesel, GABME20, and GABME20 mixed with 50 ppm of CeO_2 nanoparticles uniformly distributed in the fuel by ultrasonication were among the many fuel mixes assessed for the engine study. The engine was continually operated with variable loads and at a constant speed of 1800 rpm.

IV. RESULT AND DISCUSSION

IV.1 CYLINDER PRESSURE (CP)

Figure 4 shows cylinder pressure with crank angle at full load which is compared to that of Diesel, Diesel/ CeO_2 (50 ppm), GABME and GABME/ CeO_2 (50 ppm). The highest pressure of the pure Diesel was noted 67 - 68 bar that was reached at 8 -10° ATDC. Induced of 50 ppm CeO_2 nanoparticles to Diesel slightly decreased the peak pressure to approximately 65 - 66 bar, which can be explained by enhanced control of premixed combustion and decreased ignition delay. The peak pressure of GABME was a at 68 -69 bar and this can be attributed to the fact that it contains some natural oxygen content that facilitates better combustion. It is worth that GABME/ CeO_2 (50 ppm) had the highest peak cylinder pressure of 70 -72 bar which shows it has a better combustion intensity because of the catalytic properties of the cerium oxide nanoparticles. The enhanced oxygen buffering property of CeO_2 increases the reaction of oxidation in the premixed step resulting in increased combustion pressure. It was confirmed that the nanoparticle blended biodiesel had a 3 - 5% higher peak pressure than pure Diesel and this value increased the combustion properties without causing the unusual pressure change.

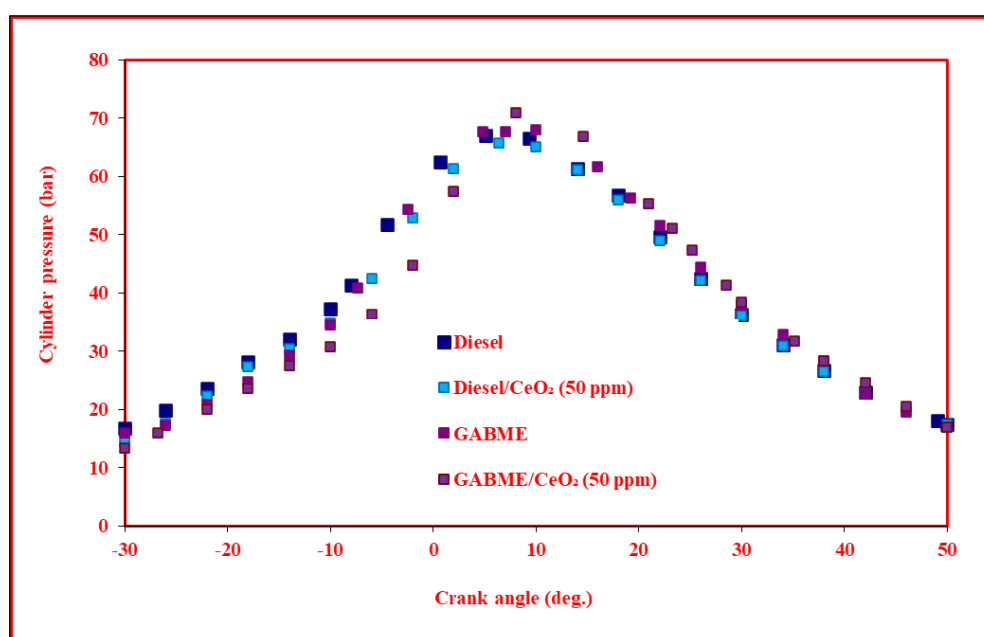


Figure 4: CP Characteristics of Diesel/GABME/ CeO_2 .

Source: Authors, (2026).

IV.2 HEAT RELEASE RATE (HRR)

The tested fuels have notice in their properties of heat release rate that shows the existence of premixed and diffusion combustion stages shown in Figure 5. Pure Diesel had a peak HRR of $62 - 65 \text{ J/}^\circ \text{CA}$, which slightly before TDC (62° to 70°CA), which a strong premixed burning phase. The highest HRR of $60 - 63 \text{ J/}^\circ \text{CA}$ with Diesel/ CeO_2 (50 ppm) was similar but slightly reduced indicating that the combustion was controlled through catalytic oxidation. GABME exhibited a peak HRR of almost $58 - 60 \text{ J/}^\circ \text{CA}$ which is slightly lower than the values of Diesel which the concept by the higher viscosity and shorter ignition delay of GABME. GABME/ CeO_2 (50 ppm) shows the peak of the HRR of around $68 - 72 \text{ J/}^\circ \text{CA}$, which is nearly 10 -15 per cent higher than that of pure Diesel. The high HRR is explained by the better atomization, decreased ignition delay and the better micro-explosion phenomena promoted by CeO_2 nanoparticles. The diffusion combustion stage of nanoparticle blends was more gradual and sustained which means that the heat was well dispersed and the combustion was level.

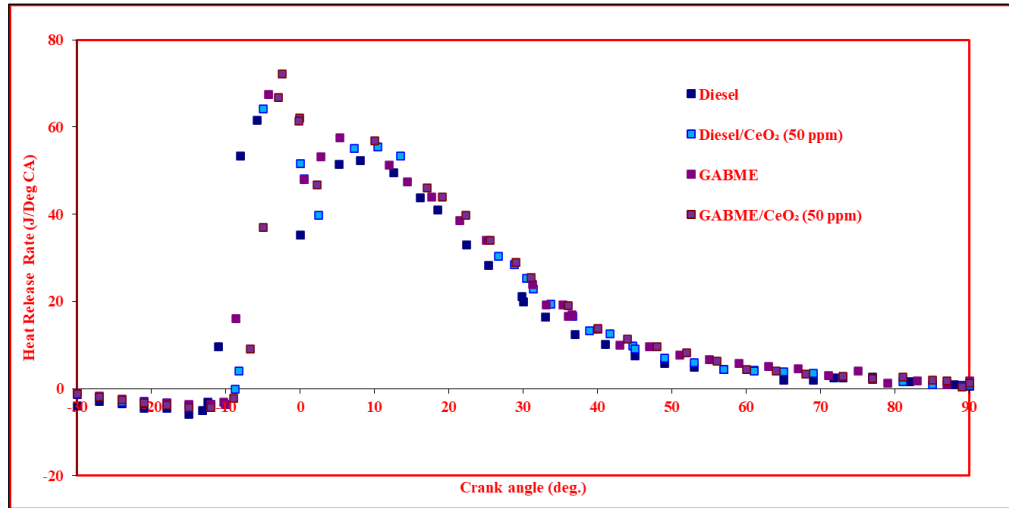


Figure 5: HRR Characteristics of Diesel/GABME/ CeO_2 .

Source: Authors, (2026).

IV.3 BRAKE THERMAL EFFICIENCY

The BTE improved gradually with brake power of all the tested fuels and followed the same trend as the combustion improvement of CP and HRR characteristics shown in Figure 6. Diesel had 13.9% BTE at 1.1 kW, Diesel/ CeO_2 (50 ppm) increased to 14.6 and GABME B20 had 13.5 and GABME/ CeO_2 had 14.1. At 2.2 kW the efficiencies rose to 22.5% with Diesel, 24% with Diesel/ CeO_2 , 22% with GABME B20 and 23.3% with GABME/ CeO_2 . Another increase was noted at 3.3 kW with 26.9% and 28.5% and 26.4 and 27.8 respectively. At 4.4 kW, Diesel/ CeO_2 reached 30.4% and GABME/ CeO_2 reached 29.5%, pure Diesel reached 28.6 and GABME B20 reached 27.9. The steady increase of around 2 -6% with the addition of CeO_2 is explained by the increased combustion reactivity, the increased oxidation reactivity and the increased use of heat, which resulted in the high energy conversion efficiency in comparison to the corresponding base fuels.

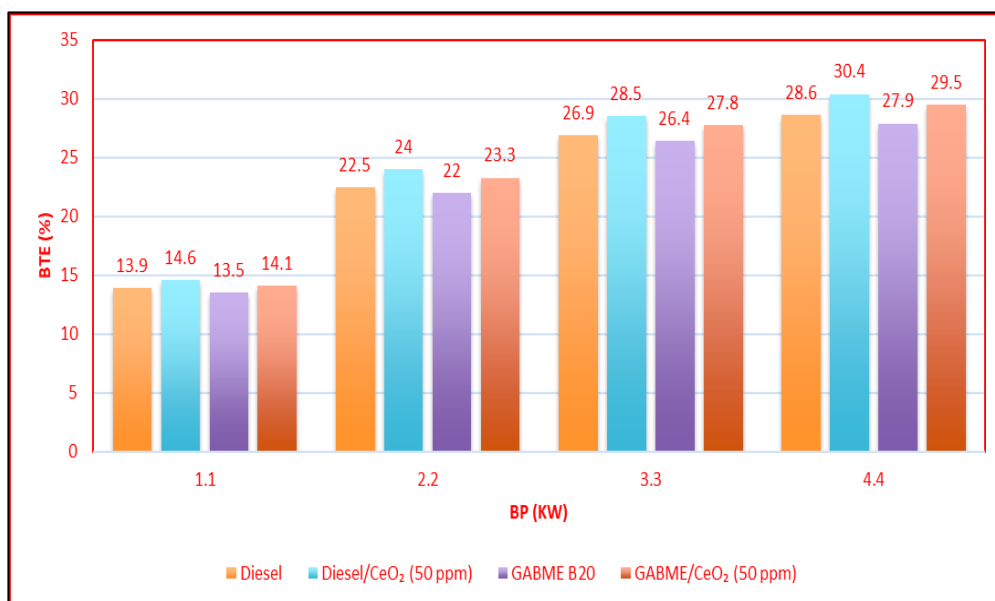


Figure 6: BTE of Diesel/GABME/ CeO_2 .

Source: Authors, (2026).

IV.4 BRAKE SPECIFIC FUEL CONSUMPTION

The BSFC also declined with the brake power of all the tested fuels, which implies the enhanced fuel usage at higher loads shown in Figure 7. Diesel had a BSFC of 0.792 kg/kWh at 1.1 kW, Diesel/CeO₂ (50 ppm) had 0.762 kg/kWh and GABME B20 was 0.81 kg/kWh and GABME/CeO₂ was 0.776 kg/kWh. When the BSFC values dropped further to 0.497, 0.472, 0.51 and 0.486 kg/kWh respectively at 2.2 kW. At 3.3 kW, Diesel and Diesel/CeO₂ had 0.375 and 0.353 kg/kWh, respectively and GABME B20 and GABME/CeO₂ had 0.34 and 0.365 kg/kWh, respectively. Diesel was found to have 0.374 kg/kWh at full load (4.4 kW), Diesel/CeO₂ was lower at 0.353 kg/kWh, GABME B20 was found to be 0.38 kg/kWh and lowest BSFC was realised with GABME/CeO₂ at 0.32 kg/kWh. The steady decrease in BSFC by addition of CeO₂ (around 4 - 8% when compared to the base fuels) can be linked to the increase in combustion efficiency, oxidation kinetics and fuel - air mixing leading to more efficient conversion of energy and the consumption of less fuel per unit brake power.

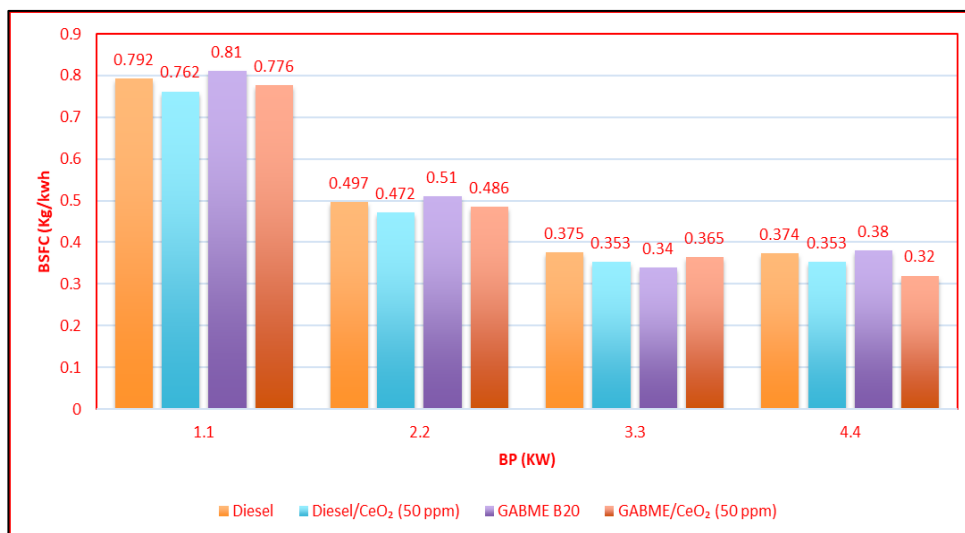


Figure 7: BSFC of Diesel/GABME/CeO₂.

Source: Authors, (2026).

IV.5 CARBON MONOXIDE (CO)

CO emissions rose to full load with all the fuel mixtures because the richer the mixture the higher the brake power, but addition of nanoparticles caused a substantial lowering of CO formation shown in Figure 8. Diesel produced 0.129% at no load and Diesel/CeO₂ produced 0.1145% and GABME B20 produced 0.114 and GABME/CeO₂ produced the lowest of that was 0.1012%. CO was reduced at 1.1 kW as 0.124% (Diesel) to 0.1092% (Diesel/CeO₂) and GABME B20 and GABME/CeO₂ produced 0.1078% and 0.096, respectively. Diesel produced more at full load (4.4 kW) of 0.211%, but Diesel/CeO₂ decreased it to 0.1796; GABME B20 produced 0.19 and GABME/CeO₂ further lowered the figure to 0.162. This is because the decrease of 10 -20 percent by addition of CeO₂ is attributed to the enhanced oxidation of CO into CO₂ owing to the ability of the cerium oxide nanoparticles to buffer oxygen.

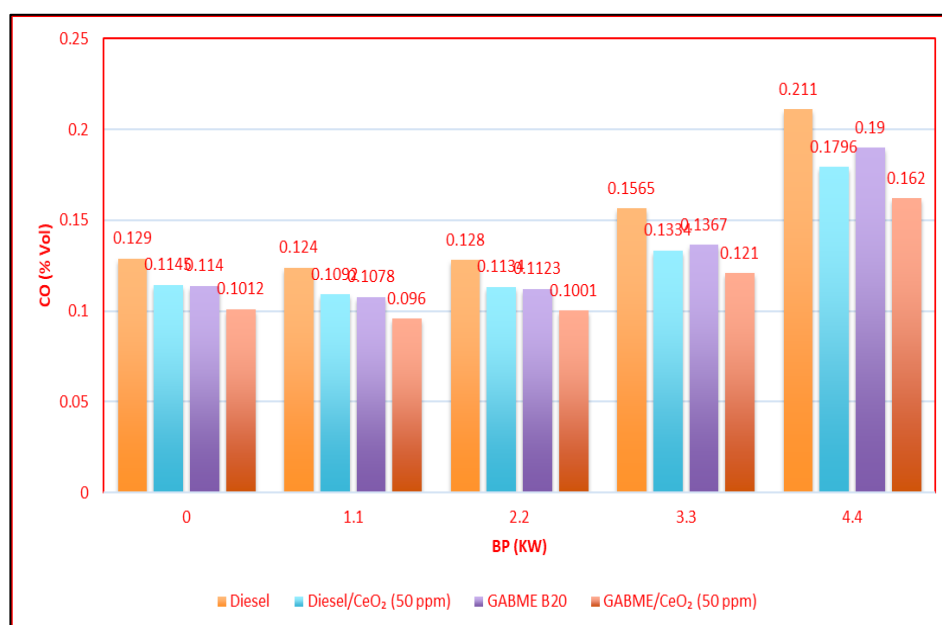


Figure 8: CO of Diesel/GABME/CeO₂.

Source: Authors, (2026).

IV.6 HYDROCARBON (HC)

The emission of unburned hydrocarbons rose with the load with all fuels mainly because the combustion in high fuel injection rates was incomplete shown in Figure 9. Diesel produced 38 ppm at no load, Diesel/CeO₂ produced 33 ppm, GABME B20 produced 38 ppm and GABME/CeO₂ produced 34 ppm. HC emissions at 2.2 kW were 45, 42, 48 and 43 ppm (Diesel, Diesel/CeO₂, GABME B20 and GABME/CeO₂) respectively. Diesel gave a high figure of 53 ppm at full load (4.4 kW), followed by 48 ppm with Diesel/CeO₂, 58 ppm with GABME B20 and 50 ppm with GABME/CeO₂. The uniform reduction of almost 8-12 per cent by the addition of nanoparticle is evidence of increased completeness of combustion and better flame propagation behaviour.

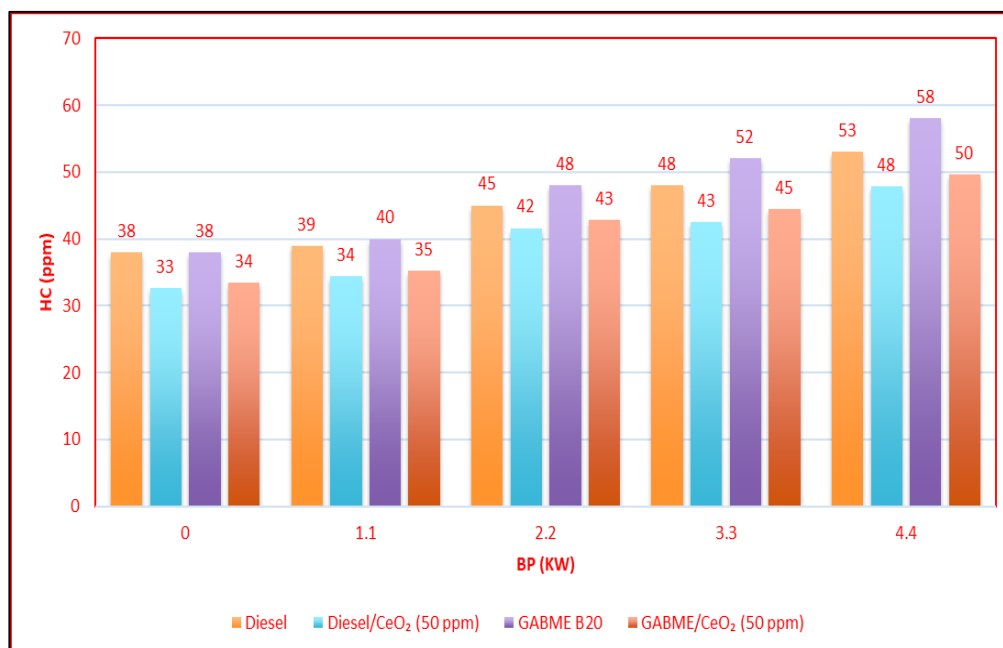


Figure 9: HC of Diesel/GABME/CeO₂.

Source: Authors, (2026).

IV.7 NITROGEN OXIDES (NOx)

Emissions of NO_x were increasing with the load because of an increase in combustion temperature and the availability of oxygen shown in Figure 10. At zero load, both Diesel and Diesel/CeO₂ gave 295 ppm and GABME B20 and GABME/CeO₂ gave 310 ppm and 317 ppm, respectively. At 2.2 kW, the levels of NO_x went to 429 ppm (Diesel), 456 ppm (Diesel/CeO₂), 463 ppm (GABME B20) and 488 ppm (GABME/CeO₂). Diesel produced maximum NO_x of 4.4 kW, i.e., 574ppm, Diesel/CeO₂ was 605ppm, GABME B20 was 670ppm and GABME/CeO₂ was highest of 710ppm. The rise of 5 -15 percent on the addition of nanoparticles is attributed to the increase in the combustion temperature and the kinetics of oxidation favouring the formation of thermal NO_x.

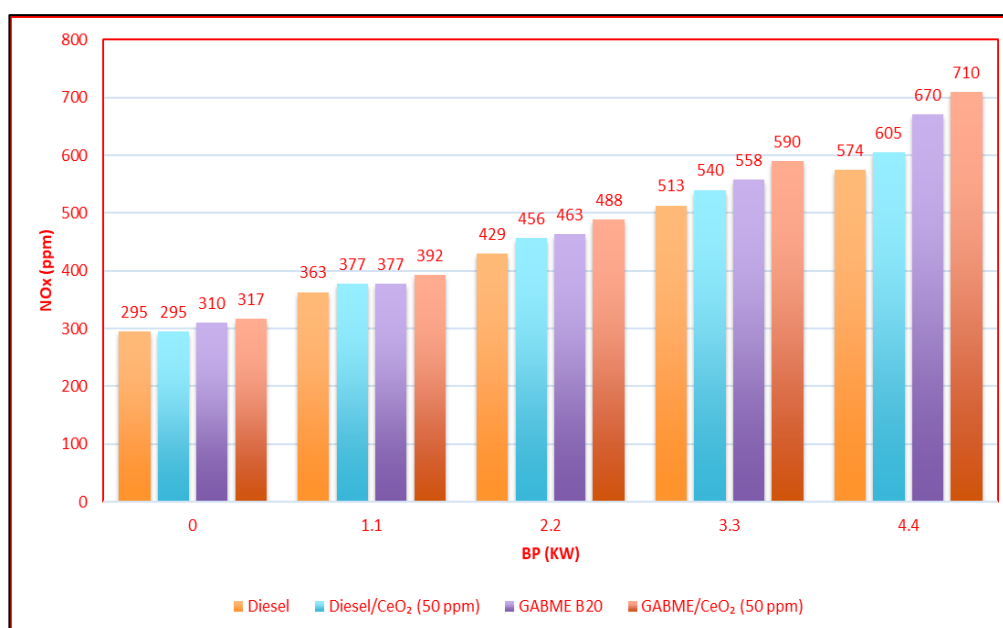


Figure 10: NO_x of Diesel/GABME/CeO₂.

Source: Authors, (2026).

IV.8 SMOKE OPACITY

All fuels showed an increment of smoke emissions with load because of increased fuel accumulation during the diffusion combustion stage shown in Figure 11. Diesel produced 11% at no load, Diesel/CeO₂ reflected 10%, GABME B20 reflected 8% and GABME/CeO₂ reflected 8%. Smoke opacity was 25% (Diesel), 22% (Diesel/CeO₂), 21% (GABME B20) and 19% (GABME/CeO₂) at 3.3 kW. Diesel produced 35 percent at full load (4.4 kW), Diesel/CeO₂ produced 30 percent, GABME B20 produced 27 percent and GABME/CeO₂ was the lowest with 24 percent. This cutting down by almost 10 -20 percent of addition of CeO₂ is attributed to the presence of better oxidation of the soot and an increase in the air-fuel mixing, leading to cleaner burning than the base fuels.

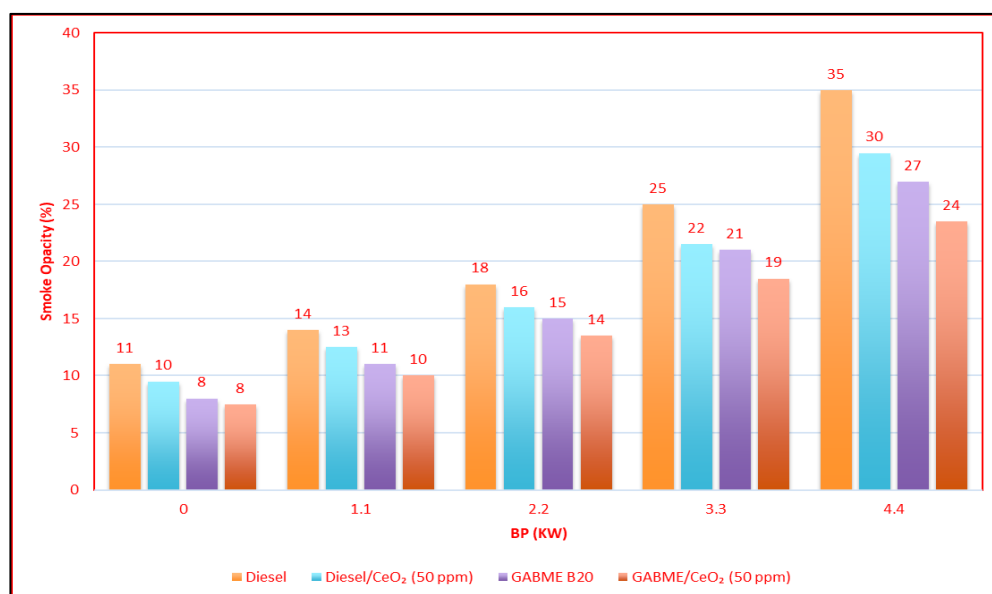


Figure 11: Smoke opacity of Diesel/GABME/CeO₂.

Source: Authors, (2026).

V. CONCLUSION

This paper has shown that addition of cerium oxide (CeO₂) nanoparticles of concentration of 50 ppm concentration have a substantial effect on the combustion and performance properties of GABME B20 and Diesel fuels in a compression ignition engine. Improved reactivity of combustion and reduction of the ignition delay of nanoparticle-blended fuels are verified by the increased peak cylinder pressure and high rate of heat release. Thermal efficiency with the brakes increased steadily in all loading conditions but Diesel/CeO₂ attained 30.4% and GABME/CeO₂ at full load reached 29.5%. It was found that a important decrease in the BSFC was achieved, especially with GABME/CeO₂ (0.32 kg/kWh) with regard to improved energy conversion efficiency. Emissions properties showed large reductions in CO, HC and smoke opacities because of enhanced oxidation and soot removal processes, but there were small increases in NO_x emissions because of elevated in-cylinder temperature. In general, the outcomes establish that the enriched algae biodiesel blends with CeO₂ nanoparticles can be a valid route to improve engine efficiency and reduce unfinished combustion emissions. Such nanoparticle-enhanced biofuels with optimised NO_x control measures can be an efficient and viable substitute to regular diesel fuel in the future low-emission diesel engine use.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: C.S. Abdul Favas, Ramarao Madhialagan, Prakash Sekar and P. Kumaran.

Methodology: Prakash Sekar and P. Kumaran.

Investigation: C.S. Abdul Favas.

Discussion of results: C.S. Abdul Favas, Ramarao Madhialagan, Prakash Sekar and P. Kumaran.

Writing – Original Draft: C.S. Abdul Favas.

Writing – Review and Editing: Ramarao Madhialagan, Prakash Sekar and P. Kumaran.

Resources: C.S. Abdul Favas.

Supervision: C.S. Abdul Favas.

Approval of the final text: C.S. Abdul Favas, Ramarao Madhialagan, Prakash Sekar and P. Kumaran.

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