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Research article

Investigation on effect of cerium oxide additive in waste plastic oil fueled CI engine

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ABSTRACT

In this study, the effects of incorporating cerium oxide into diesel and WPO blends were investigated to determine the potential of the blend as a fuel additive. The study aimed to assess engine-performance, emission, and combustion properties of the blend. The experiments utilized a single-cylinder diesel engine, and researchers prepared two different blends of WPO with 25% WPO in diesel and 50% WPO in diesel. Cerium oxide was added to these blends at concentrations of 25 ppm and 50 ppm using an ultrasonicator. The results demonstrated that increasing cerium oxide content in the blend (50 ppm) led to reduced CO, HC, and NOx emissions at higher loads. For instance, B50 + 50 ppm exhibited lower CO and NOx emissions, while B25 + 50 ppm demonstrated lower HC and smoke emissions. Furthermore, raising the CeO_2 content from 25 ppm to 50 ppm resulted in a 3% increase in brake thermal efficiency. Moreover, cerium oxide positively impacted combustion and performance properties of the blends. Among the tested blends, the B50 + 50 ppm combination showcased the highest brake thermal efficiency, optimal air-fuel ratio, and the lowest specific fuel consumption. In conclusion, employing cerium oxide as a fuel additive in diesel-WPO blends offers a promising approach for realizing a sustainable and environmentally friendly future.

1. Introduction

In the recent years, mankind has been witnessing significant changes in the climate conditions. Many countries are struggling to ensure their energy security due to the escalating population count and the high energy demand required to sustain economic growth. Globally, over 3.9 billion tons of oil equivalent were produced annually, with an average rate of 85 million barrels per day since 2010. Additionally, 3700 million tons of coal and 2900 million tons of natural gas are also produced [1]. In further, the rapid phase of industrial growth inherently contributes to the depletion of fossil fuels, such as coal and oil reservoirs that are being used in day-to-day human activities.

Petroleum fuels are of hydrocarbons, which, upon combustion would release harmful gases like Nitrous oxides (NO_x), Methane (CH_4), Carbon Monoxide (CO). This emissions coming out as a result of fossil fuel combustion lead to detrimental effects such as glacier

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melting, heatwaves, and floods [2]. adopting alternative fuels to cater the internal combustion engines would appear as a potential solution to address this alarming environmental issuesAlternative fuel that mimics the properties of petroleum-based fuels started utilizing plastics highly, owing to the huge availability of plastics produced to accompany the expanding population. Khan et al. [3] reported that the viscosity of waste plastic pyrolysis oil (WPPO) obtained at 425 °C was 1.98 cSt, lower than that of diesel. The densities of waste plastic pyrolysis oil and WPPO50 were found to be 0.7477 g/cc and 0.7943 g/cc, respectively, which closely resemble diesel. The calorific value was found to be 9829.3515 kcal/kg. Thus, the authors suggested to utilize waste plastic oil derived through pyrolysis as an alternative fuel,

Nanofluids are characterized as two-phase fluid mediums containing both solid and liquid components, creating a heterogeneous mixture or colloidal suspension of condensed nanomaterials [4]. The solids can be metals, metal oxides, carbons, while liquids include water, oil, and energy fuels. Buonomo et al. [5] highlighted that nanofluids find applications in various industries like electronics and automobiles due to their superior heat transfer properties when compared to traditional cooling fluids. Researchers mostly recommend the two-step method for nanofluid preparation due to its efficiency, cost-effectiveness, and time-saving benefits [6,7]. The study in this work investigated the potential of incorporating cerium oxide nanoparticles into diesel and waste plastic oil (WPO) blends as a fuel additive. This research was motivated by the growing concern for environmental sustainability and the need to find innovative solutions for recycling plastic waste while simultaneously improving fuel properties. Diesel-WPO blends have emerged as a promising alternative fuel source, and cerium oxide, known for its catalytic properties, was considered for its potential to enhance combustion efficiency and reduce emissions in such blends. The study aimed to provide insights into the practical implications of using cerium oxide in diesel-WPO blends by assessing engine performance, emissions, and combustion properties.

2. Literature review

Through pyrolysis, plastic materials transform into useful functional products such as plastic oil fuels. Su et al. [8] introduced the application of $AlCl_3$–NaCl eutectic as a catalyst in the pyrolysis of waste plastic elements (WPE). This catalyst demonstrated benefits such as decreased initial pyrolysis temperatures, accelerated reaction rates, leading to reduced energy consumption and shorter pyrolysis duration. Furthermore, the use of $AlCl_3$–NaCl eutectic resulted in the breakdown of larger oil components and lowered the primary cracking temperature of WPE, discouraging olefin formation and favoring the production of simpler liquid products. The research team also explored alternative catalysts like natural and synthetic zeolites, fly ash, and kaolin for pyrolysis. Miandad et al. [9] conducted investigations into the catalytic pyrolysis of plastic waste to liquid oil using both natural and synthetic zeolite catalysts. Their findings highlighted the enhanced yield of liquid oil, particularly from polystyrene (PS), utilizing 50% synthetic zeolite catalyst and 54% natural zeolite. However, oil production yields decreased when PS was mixed with other plastics such as polypropylene (PP) and polyethylene (PE). Pyrolysis oils primarily consist of aromatics such as styrene and benzene, alongside aliphatic hydrocarbons. The heating values of plastic oil closely resemble those of regular diesel fuel. Utilizing natural zeolite catalysts offers cost-effective advantages in the pyrolysis process. Waste plastic oil (WPO) stands out as a promising alternative to diesel fuel. Catalytic pyrolysis emerges as the preferred method for converting waste plastics into oil, as well as other byproducts like char, which can be employed as cooking fuel and in related applications. Luo et al. [10] delved into the reusability of catalysts, specifically Kaolin, for low-density polyethylene (LDPE) catalytic pyrolysis. Prolonged usage of K1250 catalyst led to an increase in aromatic content and particle size and it is found to exhibit higher aliphatic hydrocarbon as well as H_2 content. The growing aromatic content contributed to particle size expansion. Carbon deposition presence resulted in minor choking, closing micropores upon catalyst application, and consequentially reducing acidity and catalyst surface area. K1250 proved to be the optimal catalyst, delivering high-quality plastic oil and generating substantial yield during initial stages. The catalyst's effectiveness extended to pyrolysis gas production with commendable standards and outputs. For LDPE plastic waste conversion into oil via catalytic pyrolysis at 600°C, K1250 emerged as the preferred choice. Importantly, the composition and structure of K1250 remained consistent even after pyrolysis that ensures its reusability. Its cost-effectiveness, reliability as a catalyst, and reusability further solidified its appeal as a suitable catalyst.

Nalluri et al. [11] conducted research on the experimental investigation of an economical catalyst for plastic waste conversion through catalytic pyrolysis. Inexpensive catalysts, such as fly ash, were employed in the pyrolysis process for both HDPE & LDPE plastics. The study revealed that employing 5% catalyst concentration could result better yields compared to 10% and 15% of catalyst concentration. An examination of the catalyst mass fraction concerning reaction temperature revealed a decrease in reaction temperature with an increase in catalyst percentage, leading to a reduced energy input. Correspondingly, reaction time decreased as catalyst percentage increased, with C15% exhibiting a shorter reaction time than C5% and C10%. The produced oil from HDPE displayed properties akin to diesel fuel, while the oil from LDPE resembled gasoline properties. Aisien et al. [12] explored the use of FCC catalyst in both thermal and catalytic pyrolysis of waste polypropylene plastic. Thermal pyrolysis yielded significant liquid oil and other products, though a 0.1 catalyst ratio led to decreased liquid oil yield. The properties of the liquid oil closely resembled those of diesel fuel, demonstrating good quality. Al-Salem et al. [13] highlighted the limitations of batch reactors due to their unreliability and inefficiency stemming from the need for frequent feedstock replenishment, resulting in increased labor costs. They suggested Microwave Aided Reactors (MAR) as an effective alternative to Conical Spouted Bed Reactors (CSPR), particularly for handling large particles of varying densities, thereby reducing operational costs and degradation time. Catalytic pyrolysis offers advantages over the thermal process, including improved efficiency due to reduced residence time and enhanced product selectivity. The use of catalysts like zeolites in catalytic cracking produces high-quality motor engine fuels, minimizing the need for post-pyrolysis upgrades.

Das et al. [14] successfully employed blends of waste plastic oil and diesel in an unmodified engine. The authors reported that the brake thermal efficiency at full load was 25.08% for diesel and 25.91% for waste plastic oil, but increasing WPO composition in the blend adversely affected efficiency due to reduced heat release resulting from increased blend fuel viscosity. Panda et al. [15] reported to observe higher exhaust gas temperatures for blended WPO-diesel fuels compared to neat diesel due to incomplete combustion during the initial expansion stroke. At high loads, brake specific fuel consumption (BSFC) for diesel, 40% WPO blend, and 50% WPO blend were 0.385 kg/kWh, 0.387 kg/kWh, and 0.388 kg/kWh, respectively, reflecting the higher calorific value of WPO [14,15]. Chockalingam et al. [16] analyzed plastic oil usage and found slightly higher total fuel consumption for WPO-diesel blends under higher loads, correlating fuel consumption with the amount of plastic oil added. Kumar et al. [17] analyzed a diesel engine's performance fueled by distilled waste plastic oil, noting emissions properties like CO, HC, and Carbon di-oxide (CO_2). CO emissions were found to be 0.08 ppm for diesel and 0.03 ppm for the WPO blend due to lower air-fuel ratios at maximum loads. unburned hydrocarbon emissions from WPO were consistently higher compared to diesel fuel due to the incomplete combustion and the presence of unsaturated (organic compound) hydrocarbons in WPO [14,17]. Wathakit et al. [18] investigated the impact of WPO in a diesel engine with variable compression catio (CR) and found that smoke emissions were lower for WPO than for diesel due to its lower distillation temperature and viscosity.

Karthikeyan et al. [19] investigated the use of titanium oxide nanoparticle-infused biodiesel-diesel blends for their research. When employing B30 + 100 ppm of titanium oxide nanoparticles, CO and smoke emissions decreased at both minimum and maximum loads. CO_2 emissions decreased at minimum loads with B30 + 100 ppm and at maximum loads with B30 + 50 ppm. HC emissions decreased at minimum loads with B30 + 25 ppm and at maximum loads with B30 + 100 ppm. NOx emissions decreased at minimum loads with B30 + 100 ppm and at maximum loads with B30 + 50 ppm. Similar study was performed by Jayaraman et al. [20] and Sunil et al. [21] to explore the performance, combustion and emission characteristics of TiO_2 infused biodiesel. The research studies reported that increasing TiO_2 nanoparticles reduced the emissions while enhancing the sfc due to its decreased calorific value and increased viscosity. The studies also revealed that the high activation energy of the nanoparticles promoted complete combustion. However, increasing combustion temperatures in case of TiO_2 infusions caused increase in NOx emissions. Inclusion of TiO_2 in biodiesel-diesel combination facilitates increasing interaction with air, evaporation rate, thereby reducing the ignition delay [22].

In the similar fashion, addition of TiO_2 nanoparticles in plastic pyrolysis oil (PPO) shortened the ignition delay period [23]. Also, adding TiO_2 to PPO reduced BSFC due to decreased delay time, as PPO has a lower heating value than diesel fuel.

In a different work, Sachuthananthan et al. [23] examined diesel and plastic oil blends with magnesium oxide (MgO) nanoparticles infusion. The authors reported that the optimum volume of MgO in the bio-diesel blends would be of 100 ppm to provide improvement in BTE and addition of any further amount of nanoparticles could result in more NO_x emissions. Similar observations were reported by Arunprasad et al. [24].

Chinnasamy et al. [25] studied the influence of aluminum oxide (Al_2O_3) nanoparticles on the combustion, emissions, and performance of the CI engine run with blends of WPO in diesel. Particles of smaller in size are found to improve the BTE, since small particles could enhance the heat transfer rate and atomization. Al_2O_3 particles of 20 nm average diameter are found to reduce the CO and NOx emissions when compared to the pure WPO case. However, the particles at 100 nm in size could adversely produce higher emissions which could be due to high viscosity of the fuel with large size nanoparticles, improper air-fuel mixing, and reduction of oxygen contribution.

Shaisundaram et al. [26] explored the performance and emission characteristics of Momordica charantia seed biodiesel blended with cerium oxide nanoparticles. In the absence of cerium oxide as a nano additive, the blend exhibited higher BSFC and lower BTE due to lower oxygen content in the fuel. The addition of cerium oxide reduced BSFC and increased BTE by enhancing oxygen content, leading to reduced emissions of carbon monoxide, hydrocarbons, nitrogen oxides, and carbon dioxide. Sree Harsha et al. [27] conducted experiments using biodiesel produced from calophyllum - inophyllum seed oil blended with cerium oxide and multi-walled carbon nanotubes as additives. Blends without nano additives exhibited higher BSFC and NO_x emissions compared to diesel due to lower calorific value. The inclusion of nano additives improved BTE, decreased BSFC, and reduced emissions of NO_x, CO, smoke, and HCs.

Earnest et al. [28] analyzed the effects of orange-peel oil methyl ester blended with cerium oxide (CeO_2) on performance and emissions. Cerium oxide presence increased BTE and decreased BSFC compared to diesel, attributed to reduced ignition delay, improved fuel-air mixing, increased fuel exposure surface area, and carbon deposit oxidation. These properties contributed to lowered emissions of NO_x, CO and smoke.

According to Kumaravel et al. [29], adding cerium as a nano additive improved fuel properties compared to diesel. The addition of CeO_2 increased BTE relative to diesel, attributed to enhanced atomization, reduced viscosity, and increased surface-to-volume ratio of the nano additive. These properties improved performance and decreased HC, CO, and smoke emissions. However, NO_x emissions were higher than diesel due to complete combustion and higher temperatures. The B5D85 CeO2 100 ppm blend demonstrated excellent results with increased performance and reduced emissions.

Lokesh et al. [30] noted that diesel fuel exhibited lower brake thermal efficiency (BTE), higher exhaust gas temperature (EGT), and increased CO emissions due to higher viscosity. The addition of CeO_2 to diesel shows increased BTE, EGT, and reduced CO and HC emissions. However, using CeO_2 in diesel raised NO_x and BSFC compared to normal diesel.

Hoang [31] found that introducing CeO_2 to blended fuels improved engine performance, reduced heat emission rate, and in-cylinder pressure. This led to increased brake thermal efficiency and brake power (BP), while BSFC decreased. Cerium oxide facilitated micro-explosions, improved atomization, increased oxygen content, and catalytic oxidation, contributing to these positive outcomes. Using cerium oxide in nanofluid or biodiesel-water emulsion form enhanced the heat-absorbing capability of CeO_2 nanoparticles, leading to greater reduction in NOx emissions. Cerium oxide also acted as an oxidation agent, accelerating fuel oxidation and significantly decreasing CO, HC, and smoke emissions.

Padmanabhan et al. [32] studied blends of biodiesel (Aloe Vera)-diesel with cerium oxide nanoparticle and found that cerium oxide addition improved oxygen content, combustion temperature, complete combustion and increased BTE, yet it reduced BSFC. While CO

Fig. 1. Probe sonicator.

& HC emissions increased with rising cerium oxide concentration, they remained lower than diesel emissions. Cerium oxide nanoparticles also lowered CO_2 and NO_x levels.

Kalaimurugan et al. [33] examined the performance and emissions of Neochloris oleoabundans algal oil (B20) blended with cerium oxide nanoparticle and diesel fuel. CeO_2blending is found to improv the BTE and lowered BSFC which could be due to its enhanced combustion, atomization, improved air-fuel mixing, and increased fuel-oxygen interaction on a larger surface area. Improved fuel injection and oxygen utilization by CeO_2 led to enhanced peak pressure, exhaust gas temperature (EGT), and a higher rate of pressure rise due to improved HRR during the premixed combustion stage.

Waste plastic oil-fueled engines offer several advantages, including waste plastic recycling, energy recovery, and a reduction in landfill waste, potentially leading to a lower carbon footprint and energy independence in specific contexts. However, these engines also face limitations, primarily related to emissions and air quality concerns, variability in fuel quality, potential engine modifications, energy-intensive processing methods, competition with other recycling efforts, and regulatory and safety considerations. Balancing these advantages with the associated limitations requires careful evaluation and mitigation strategies to ensure both environmental benefits and safe, efficient operation.

In recent years, the increasing environmental concerns and the need for sustainable energy sources have prompted researchers to explore alternative fuels and additives to improve combustion efficiency and reduce emissions in internal combustion engines. One of the significant challenges in this regard is finding an effective and environmentally friendly fuel additive that can enhance engine performance while mitigating harmful emissions. This study addresses this challenge by investigating the potential of cerium oxide as a fuel additive in diesel-waste plastic oil blends. The primary problem is to assess whether the incorporation of cerium oxide into these blends can lead to improved engine performance, reduced emissions, and enhanced combustion properties, thereby offering a sustainable and environmentally friendly solution for the future of transportation and power generation.

3. Methodology

Various blends of fuel were prepared for the study, including pure diesel as well as blends denoted as B25, B50, B25 + CeO_2 25 ppm, B25 + CeO_2 50 ppm, B50 + CeO_2 25 ppm, and B50 + CeO_2 50 ppm. To measure the cerium oxide nanoparticles accurately, 25 and 50 mg portions were weighed using an electrical weighing machine. The nanoparticles weighed with the aid of an electronic weighing machine of ±0.001 mg accuracy were introduced into the blended fuels at different proportions within a 1-liter beaker. To ensure uniform dispersion of the particles in the fuel, the blended fuels with cerium oxide particles were subjected to thorough mixing for a

Table 1
Input variables.

Parameter/Material	Values/Name
Load (N-m)	5, 10, 15, 20
Nanoparticle	Cerium Oxide
Concentration (ppm)	25, 50

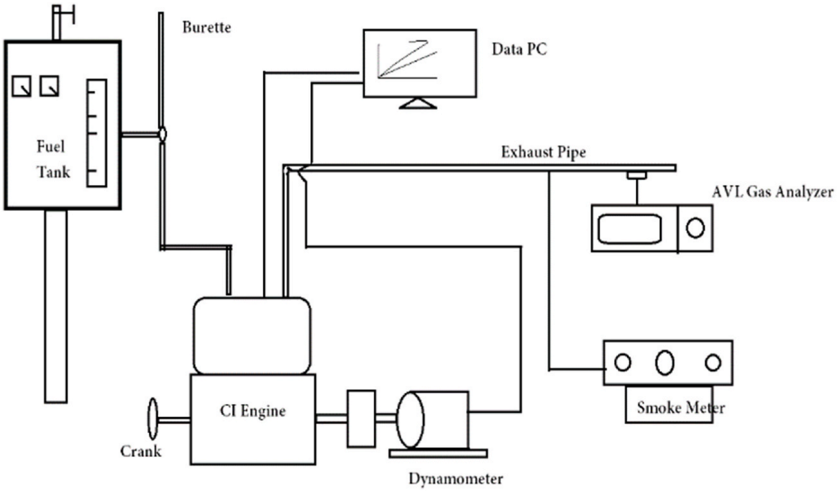

Fig. 2. Schematic diagram of experimental setup.

Fig. 3. Experimental setup used for the present work.

duration of 75 minutes. For this process an ultrasonicator as shown in Fig. 1 is used in this work. All the prepared combination of fuels are subjected to evaluation in a compression ignition (CI) engine. Table 1 gives the details of nanoparticle variants and the different load conditions adopted in the present study. At first, the engine was loaded at 20 N-m for aperiod of 20 min, The load was then reduced to 0 N-m gradually and allowed to attain the steady state. During the engine tests, parameters such as the time taken for 10 ml of fuel consumption, temperatures, and gauge differentials were meticulously recorded. Subsequently, an analysis was performed

Table 2
Engine specifications.

SI.No.	Parameters	Specifications
1	No of Cylinder	1
2	Stroke	4 Stroke
3	Compression Ratio	16.5 : 1
4	Fuel Tank Capacity	6.5 L
5	Cubic Capacity	0.553 L
6	Bore*Stroke	80*110 mm
7	Speed	1500 rpm
8	Torque at Full Load	2.387 Kg-m
9	Crank Shaft Center Height	203 mm
10	Lub Oil Sump Capacity	3.7 L
11	Size of Bare Engine	617*504*843 mm
12	Dry Engine Weight	130 kg
13	SFC	195 + 5% g/kWh

Table 3
Properties of fuel.

Fuel	Density (kg/m^3)	Specific Gravity	Calorific Value (kJ/kg)	Viscosity (mm^2/s @ 40 °C)	Carbon Residue (%)	Flash Point (°C)	Fire Point (°C)	Cloud Point (°C)	Pour Point (°C)
Diesel	839	0.839	43000	2.44	0.18	55	51	17	−11
B25	804.16	0.80416	40526.224	2.68	0.25	61	59	4.8	−4.6
B50	804	0.804	40743.792	2.89	0.38	50	43	15.8	−1.5
B25 + 25 ppm	812.4	0.812	42664.248	2.70	0.25	60	58	7.6	1
B25 + 50 ppm	810.41	0.810	42911.104	2.72	0.25	59	51	7.5	1.1
B50 + 25 ppm	829.16	0.829	43086.832	2.88	0.35	58	46	13	−1.1
B50 + 50 ppm	822.19	0.822	42710.272	2.89	0.34	58	50	14	−0.6

Table 4
Details of the measuring instruments.

Quantity measured	Least count	Measuring device
Torque	0.1 Nm	Eddy current dynamometer
Temperature	0.1 °C	Thermocouples
Flow rate of diesel blend	0.2 ml	Burette
Crank angle	1°CA	Angle encoder
Air flow rate	0.00006 m^3/s	Orifice meter
Smoke emissions	0.1%	AVL 437C smoke meter
CO emission	0.01%	AVL DiGas 444 N gas analyser
HC emissions	1 ppm	
NOx emissions	10 ppm	
In-cylinder pressure	33 pC/bar	Pressure sensor

using a 5-gas emission analyser and a smoke meter to measure NO_x, HC, CO, CO_2, O_2, and smoke emissions. Additionally, the peak pressure and heat release rate (HRR) were quantified using combustion analyzer software. This comprehensive process was systematically repeated for different load conditions, specifically 5, 10, 15, and 20 N-m, with corresponding readings documented.

4. Experimental setup

The schematic diagram of the experimental setup is provided in Fig. 2 and experimental setup utilized a single-cylinder, 4-stroke diesel engine, is depicted in Fig. 3. The specifications of the engine are detailed in Table 2. Fuel for the engine is drawn from the fuel reservoir within the fuel tank, passing through a filter and subsequently a pressurized pump. Employing an eddy current dynamometer device, load is applied to the engine, with the device connected to the flywheel through a coupling shaft. As digital increments of load are introduced within the fuel tank, fuel consumption can be quantified using a pitot tube within the tank. The exhaust gases are released along with a portion of the heat through the exhaust valve. The measurement of emission parameters is facilitated by employing a smoke meter and an AVL gas analyzer, while a computer system captures all performance parameters. Table 3 outlines the essential fuel properties pertinent to the diverse fuels utilized in the experimental study. Table 4 shows details of measuring instruments and Table 5 provides uncertainty estimates of output indices.

Table 5
Uncertainty estimates of the output parameters.

Output parameter	Uncertainty (±)
CO emission	2.74%
HC emissions	2.7%
NOx emissions	2.2%
Brake thermal efficiency	2.46%
Cylinder pressure	2%
Brake Specific Fuel Consumption	2.46%

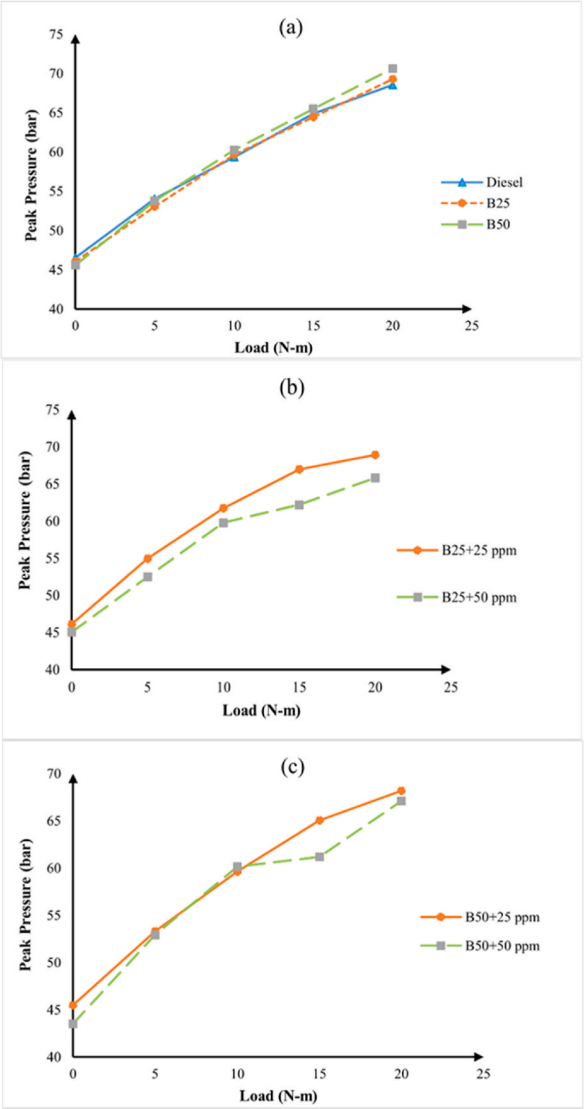

Fig. 4. Variation of Cylinder Peak Pressure with load while the engine is fueled with (a) Diesel and WPO without nanoparticles (b) 25% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles (c) 50% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles.

5. Results and discussion

5.1. Combustion characteristics

5.1.1. Cylinder pressure

Fig. 4(a–c) shows variations of peak cylinder pressure for various fuel input combinations. Combustion characteristics play a

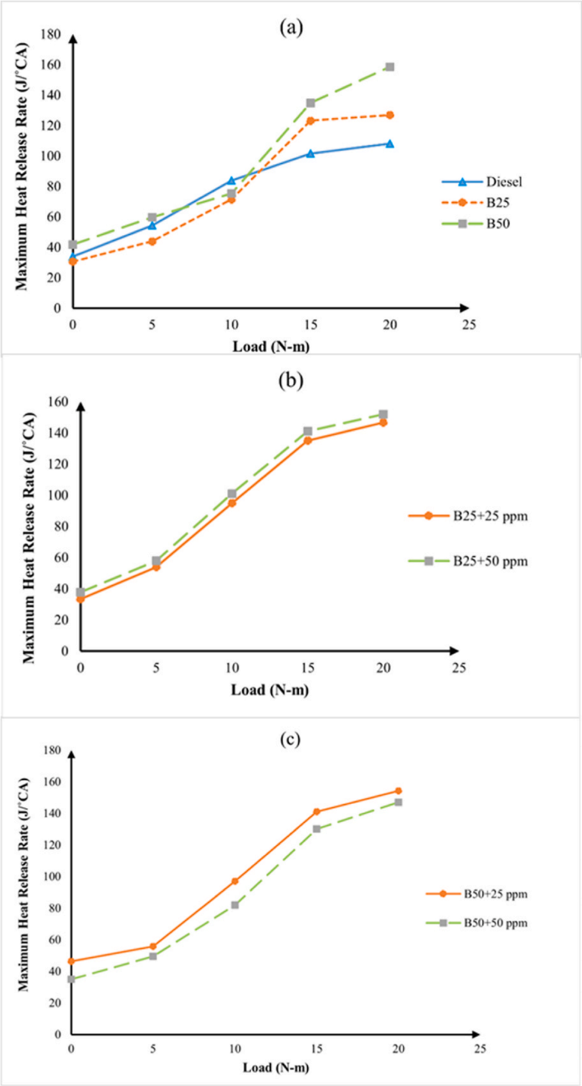

Fig. 5. Variation of Maximum heat release rate with load while the engine is fueled with (a) Diesel and WPO without nanoparticles (b) 25% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles (c) 50% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles.

pivotal role in influencing engine performance, combustion efficiency, and emissions. These characteristics encompass parameters such as HRR, Cylinder Pressure, and in cylinder peak pressure. The results of cylinder peak pressure for diesel, B25, B50, B25+CeO2 25 ppm, B25+CeO2 50 ppm, B50+CeO2 25 ppm, and B50+CeO2 50 ppm blends at different load conditions are depicted in Fig. 4.

Comparing the peak pressure of WPO fuel with the blended fuels containing CeO_2 nanoparticles, it becomes evident from Fig. 4(a) that the peak pressure for WPO fuel is higher. This phenomenon can be attributed to the presence of CeO_2 nanoparticles, which possess a larger surface-to-volume ratio. This unique property of nanoparticles contributes to improved ignition characteristics and enhanced combustion efficiency. The introduction of CeO_2 nanoparticles into the blends results in a modified combustion process that affects the peak pressure which can be witnessed for both the cases of blended fuels from Fig. 4(b) and Fig. 4(c)

5.1.2. Heat release rate (HRR)

HRR is primarily influenced by factors such as the fuel source, air-fuel ratio, turbulence, and temperature. As depicted in Fig. 5 (a–c), it is evident that the load is directly proportional to HRR for all fuel combinations of with and without nanoparticles. Among the baseline fuels, B50 exhibits a higher HRR of 158.41 J/°CA, while diesel shows a lower HRR of 108.81 J/°CA as witnessed from Fig. 5 (a). This trend can be attributed to the prolonged ignition delay of WPO which could have improved the air-fuel mixing [34]. Additionally, WPO contains more oxygen content compared to pure diesel, contributing to efficient combustion and a higher HRR.

In the case of cerium-added blend fuels, it is observed from Fig. 5(b) and Fig. (c) that increasing the cerium content leads to a rise in the HRR. Specifically, the heat release rate is higher in B50 + 25 ppm and lower in B25 + 25 ppm, with values of 154.23 J/°CA and 146.53 J/°CA, respectively. This phenomenon can be attributed to the enhanced fuel injection and the oxidation-enhancing properties

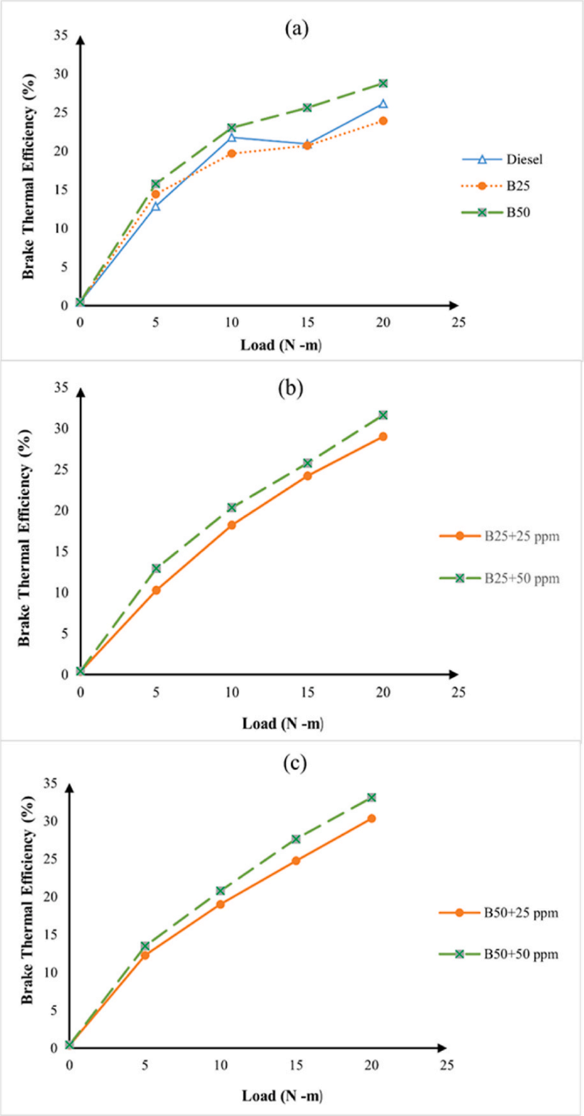

Fig. 6. Variation of Brake thermal efficiency with load while the engine is fueled with (a) Diesel and WPO without nanoparticles (b) 25% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles (c) 50% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles.

of cerium oxide. The presence of cerium oxide nanoparticles promotes more efficient fuel oxidation, which in turn contributes to the observed increase in heat release rate.

5.2. Performance characteristics

5.2.1. Brake thermal efficiency (BTE)

The brake thermal efficiency for diesel, B25, B50, B25+CeO_2 25 ppm, B25+CeO_2 50 ppm, B50+CeO_2 25 ppm, and B50+CeO_2 50 ppm fuels at various loads is depicted in Fig. 6. The brake thermal efficiency values for diesel, B25, B50, B25 + 25 ppm, B25 + 50 ppm, B50+CeO_2 25 ppm, and B50+CeO_2 50 ppm are 26.12, 23.89, 28.77, 29, 31.62, 30.34, and 33.07%, respectively. Analyzing the graphs, particularly in Fig. 6(a)–a consistent increasing trend in brake thermal efficiency can be observed across all loads for B50. Turning to Fig. 6(b) and (c), the behavior of blends involving B25 with an additional 25 ppm and 50 ppm of CeO_2, and B50 with an additional 25 ppm and 50 ppm of CeO_2 is depicted. Both graphs indicate an upward trend in Brake Thermal Efficiency (BTE) as the loads increase. Notably, in Fig. 6(b) and .(c), higher BTE values are evident when 50 ppm of CeO_2 is added to the blend. Cerium oxide nanoparticles, with their significant surface-to-volume ratio, offer enhanced thermal stability and improved catalytic activity. The distinct properties of CeO_2, such as thermal transmissibility and oxygen storage and release capabilities, contribute to improved combustion and complete combustion processes. This in turn leads to higher BTE values, especially evident in the B50+CeO_2 50 ppm blend. The presence of CeO_2

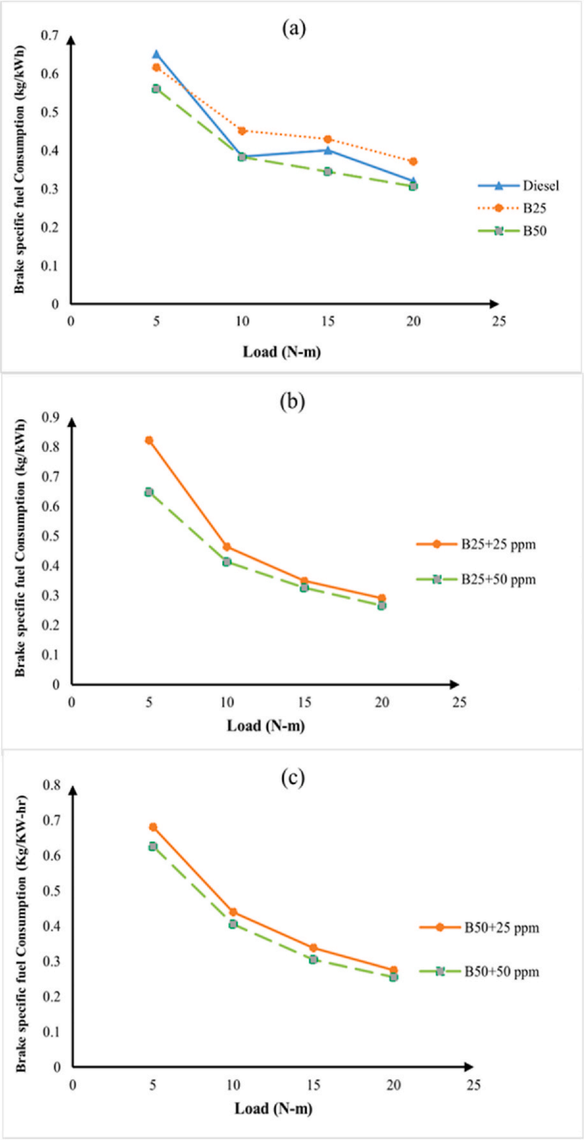

Fig. 7. Variation of brake specific fuel consumption with load while the engine is fueled with (a) Diesel and WPO without nanoparticles (b) 25% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles (c) 50% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles.

nanoparticles not only reduces ignition delay and fuel evaporation time but also enhances fuel atomization, thanks to the improved micro-explosion effects facilitated by CeO_2 nanoparticles [29,31].

5.2.2. Brake specific fuel consumption (BSFC)

The brake specific fuel consumption values for diesel, B25, B50, B25+CeO_2 25 ppm, B25+CeO_2 50 ppm, B50+CeO2 25 ppm, and B50+CeO2 50 ppm blends at different loads are presented in Fig. 8, with the values being 0.32, 0.37, 0.30, 0.29, 0.26, 0.27, and 0.25 (kg/kWh), respectively. With the help of Fig. 7 it is witnessed that the BSFC decreases for all blends with increase in the load values. In Fig. 7(a), the decreasing order of BSFC is B25, diesel, and B50. In Fig. 7 (b&c), the BSFC consistently decreases from 0.8 to 0.3 across all cases, with the addition of 50 ppm of cerium oxide resulting in lower BSFC values. This can be attributed to CeO_2 enhancing the dispersion and propagation of fuel droplets, thereby improving air/fuel blending and combustion characteristics. The inclusion of CeO_2 in blended fuels contributes to the oxidation of carbon deposits, preventing fuel and air system clogging, and ultimately enhancing engine efficiency. In comparison to other blended fuels, B50+CeO_2 50 ppm exhibits lower fuel consumption at higher loads.

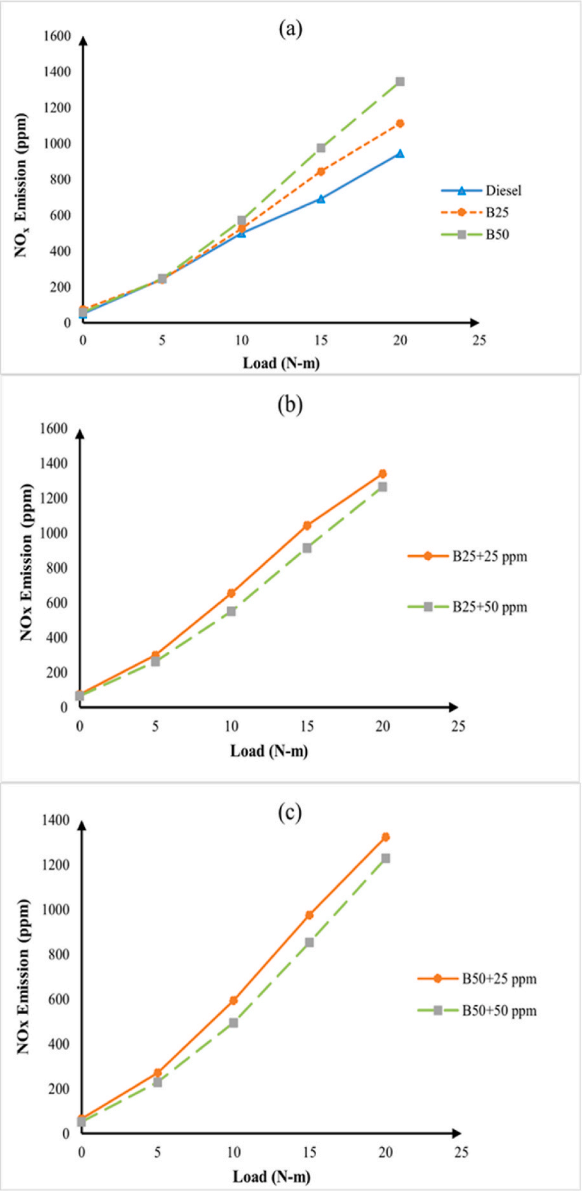

Fig. 8. Variation of NO_x emission with load while the engine is fueled with (a) Diesel and WPO without nanoparticles (b) 25% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles (c) 50% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles.

5.3. *Emission characteristics*

5.3.1. *Oxides of nitrogen (NO_x) emissions*

Nitrogen oxides emissions are generated when fuel burns at high temperatures in the presence of both nitrogen and oxygen. These emissions consist of a mixture of NO and NO_2, formed through the reaction of the nitrogen in the fuel with the oxygen in the air [35]. Upon analyzing Fig. 8(a), it is evident that initially, all blends exhibited similar emissions up to a load of 5 N-m. However, beyond that point, variations in emissions became noticeable, with B50 demonstrating higher emission levels compared to B25 and diesel. In Fig. 8 (b) and (c), emissions showed an exponential increase with load for all blends. Notably, B50 + 50 ppm displayed the lowest emissions among the investigated cases. Moreover, the addition of 50 ppm of cerium oxide to both B50 and B25 resulted in a gradual reduction in emissions compared to the addition of 25 ppm of cerium oxide.

Among the baseline fuels, blends containing waste plastic oil (B25 and B50) exhibited higher emissions than diesel. This can be attributed to the longer combustion delay and the presence of longer hydrocarbon chains in waste plastic oil [36]. In blends with cerium oxide, NO_x emissions were higher for B25 + 25 ppm (74 ppm) and lower for B50 + 50 ppm (53 ppm). The additional oxygen content in the cerium oxide-added blends increased the combustion temperature in the cylinder, subsequently leading to higher

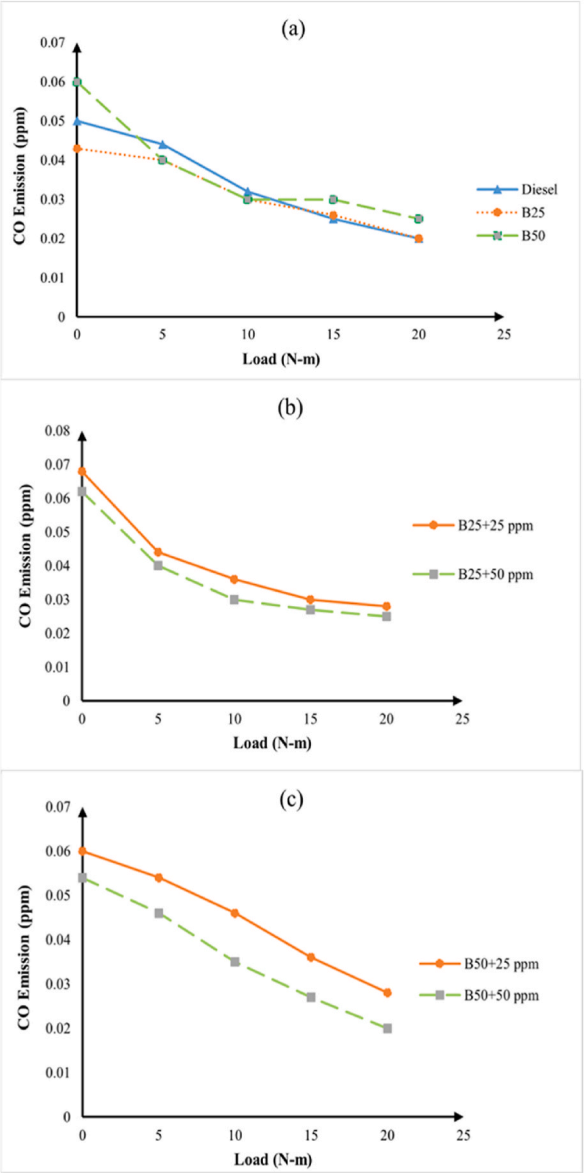

Fig. 9. Variation of CO emission with load while the engine is fueled with (a) Diesel and WPO without nanoparticles (b) 25% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles (c) 50% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles.

nitrogen oxide emissions [37]. Cerium oxide aids in breaking down the fuel during combustion, resulting in an increased formation of nitrogen oxide. Additionally, the addition of 50 ppm of cerium oxide demonstrated potential for emission reduction, particularly in B50 and B25 blends.

5.3.2. Carbon monoxide (CO) emissions

Carbon monoxide is produced when combustion is incomplete due to insufficient oxygen content inside the combustion chamber. Interestingly, CO emissions are found to be reduced at higher loads and that can be attributed to the impact of CeO_2 nanoparticles. These nanoparticles enhance oxygen content, facilitating complete combustion, and in further, the reduction in fuel viscosity promotes effective fuel atomization, thereby leading to decreased CO emissions. The recorded CO emissions for diesel, B25, B50, B25 + 25PPM, B25 + 50PPM, B50 + 25PPM, and B50 + 50PPM are 0.01, 0.02, 0.025, 0.028, 0.025, 0.028, and 0.02 ppm, respectively. When analyzing Fig. 9(a), it becomes apparent that B50 displays higher CO emissions at higher loads, while B25 and diesel exhibit similar trends. Upon inspecting Fig. 9(b) and (c), it is evident that CO emissions gradually decline with increasing load for both blends. Interestingly, all blends showcase lower CO emissions at higher loads. Furthermore, the addition of 50 ppm to both B25 and B50 blends results in diminished CO emissions compared to B50 alone.

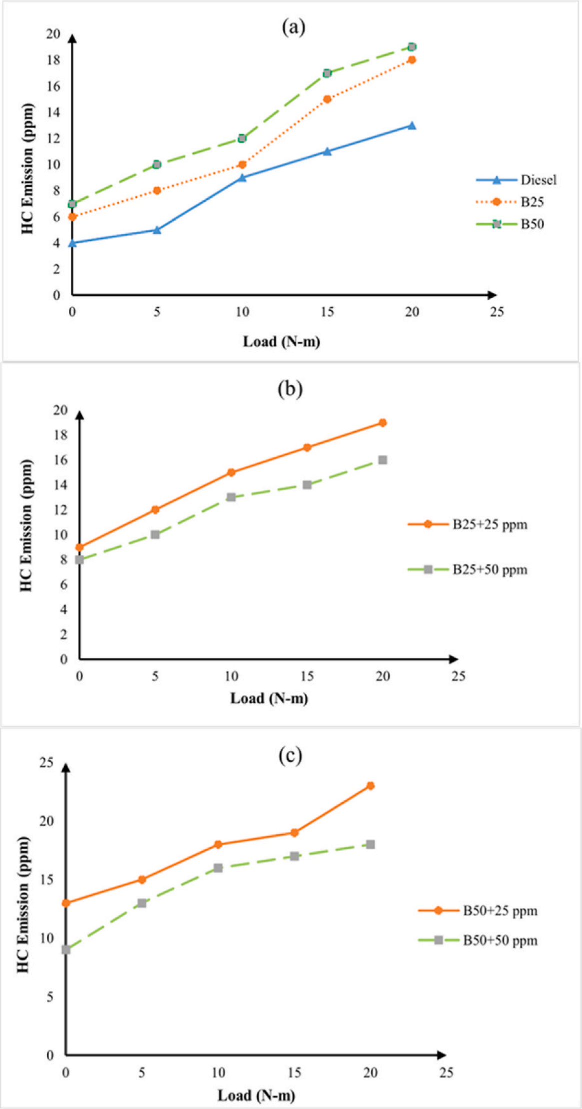

Fig. 10. Variation of HC emission with load while the engine is fueled with (a) Diesel and WPO without nanoparticles (b) 25% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles (c) 50% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles.

5.3.3. Hydrocarbons (HC) emissions

Fig. 10(a–c) shows variations of HC emissions for various input parameters. HC emissions arise due to insufficient oxygen content and a higher ignition temperature. Hence, WPO blends result higher HC emissions compared to the diesel fuel owing to its high heat releasing tendency, which can be obtained in Fig. 10(a). At maximum loads, HC emissions are diminished because CeO_2 nanoparticles can enhance oxygen content and facilitate effective atomization, thereby reducing HC emissions. Typically, higher HC emissions are seen due to the presence of unsaturated hydrocarbons that disrupt the combustion process. Therefore, the addition of CeO_2 can mitigate HC emissions at high loads as witnessed from Fig. 10(b) and Fig.(c). Based on Fig. 11, it can be concluded that B25 + 50PPM and B50 + 50PPM outperform all other blended fuels in terms of HC emissions. Specifically, the emissions for Diesel, B25, B50, B25 + 25PPM, B25 + 50PPM, B50 + 25PPM, and B50 + 50PPM are measured at 13, 18, 19, 19, 23, 18, and 19 ppm, respectively. The trends observed in HC emissions closely resemble those observed in NO_x emissions, demonstrating consistent patterns and behaviors across the experimental measurements.

5.3.4. Smoke emission

Smoke is generated during combustion when the combustion process remains incomplete. This can occur due to insufficient fuel combustion, presence of unburned combustible materials, or interactions among gases and particles within the combustion zone. Notably, smoke emissions increase as the load rises across all fuels. Analyzing Fig. 11(a), it becomes apparent that both B50 and B25 display similar smoke emissions during the initial load phases. However, as the loads exceed 5 Nm, a descending trend emerges, with

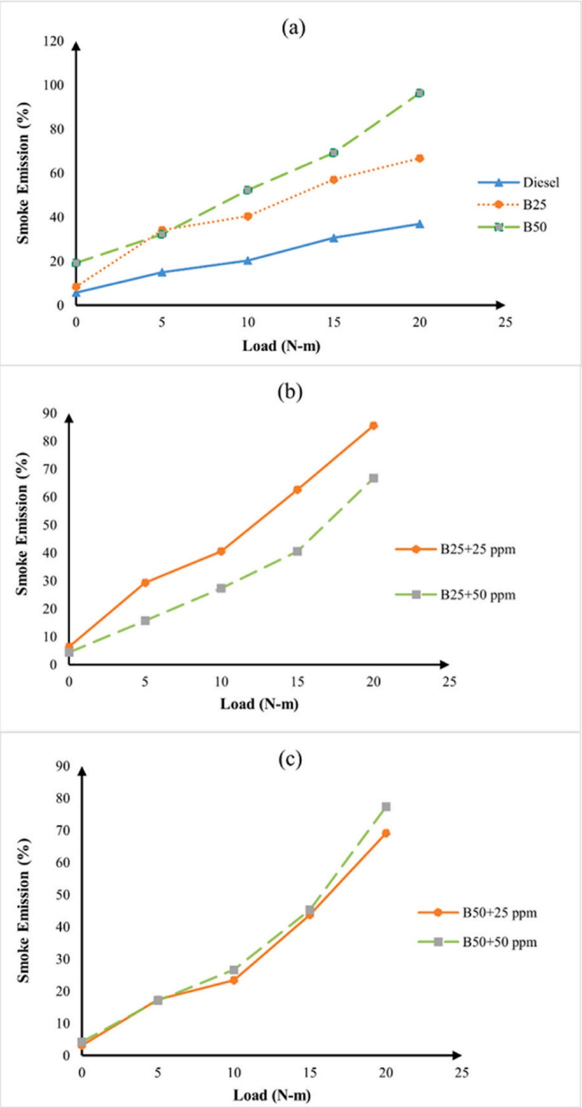

Fig. 11. Variation of smoke emission with load while the engine is fueled with (a) Diesel and WPO without nanoparticles (b) 25% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles (c) 50% WPO in diesel with 25 and 50 ppm CeO_2 nanoparticles.

smoke emissions ranking in the order: B50, B25, and Diesel. Turning to Fig. 11(b), it is evident that the B25 + 25 ppm blend exhibits higher emission levels compared to the B25 + 50 ppm blend across all loads, with a significant 10% difference. While examining Fig. 11(c)–a marginal disparity can be observed between the B50 + 25 ppm and B50 + 50 ppm blends at all loads. Nevertheless, the B50 + 50 ppm blend outperforms the B50 + 25 ppm blend at higher loads, presenting a 5% increase in emissions. Among the baseline fuels, B50 displays elevated smoke emissions (96.2%), whereas diesel exhibits the least (37%) under maximum load conditions. This discrepancy arises from WPO-diesel blends possessing higher viscosity than diesel, potentially hindering fuel atomization and resulting in heightened smoke formation [34]. Smoke varies from 6.4% at zero load to 85.6% at maximum load for B25 + 25, whereas for B25 + 50, it ranges from 4.4% at zero load to 66.7% at maximum load. Similarly, for B50 + 25, the variation is from 3.1% at zero load to 61.2% at maximum load, and for B50 + 50, it fluctuates from 4.2% at zero load to 77.3% at maximum load. Notably, an increase in cerium oxide content in the blends is found to result decrease in smoke emissions for the respective blend. This trend is attributed to the enhanced combustion properties and shorter ignition delay introduced by the blends incorporating cerium oxide [38].

6. Conclusion

In summary, the experimental investigation involving varying concentrations of cerium oxide nanoparticles in diesel-waste plastic oil blended fuels has yielded valuable insights with direct relevance to real-world applications.

- **Enhanced Efficiency and Economy:** The application of cerium oxide, particularly at a 50 ppm concentration, resulted in a notable 2–3% increase in brake thermal efficiency. This enhancement holds the potential to significantly improve fuel economy and reduce energy consumption in practical applications, such as automotive and industrial sectors.
- **Cost Reduction:** Higher cerium oxide concentrations contributed to a substantial 7% reduction in brake specific fuel consumption, especially under higher engine loads. This reduction not only promises cost savings but also efficient resource utilization in a variety of industrial settings.
- **Emission Mitigation:** A significant decrease in both NOx and smoke emissions was observed, with a 7.5% reduction in NO_x emissions and an 11% decrease in smoke emissions when compared to the 25 ppm configuration. This finding underscores the environmental benefits of cerium oxide as an effective strategy for emissions reduction, aligning with the imperative of environmental protection and compliance with emission standards.
- **Carbon Footprint Reduction:** Notably, there was a 33% reduction in CO emissions in the B50 + 50 ppm configuration, accompanied by a 24% decline in brake specific fuel consumption. These reductions signify a potential reduction in the carbon footprint associated with applications employing cerium oxide-blended fuels.
- **Improved Combustion Dynamics:** The observed correlation between increased cerium oxide concentration and decreased peak pressure and heat release rate during the combustion process highlights the potential for improved combustion efficiency and smoother engine operation. This aspect is critical for optimizing engine performance and durability in various industries.

In conclusion, the results of this study emphasize the multifaceted benefits of cerium oxide as a fuel additive in diesel-waste plastic oil blends, making it a compelling choice for practical applications. From enhanced efficiency and cost savings to emissions reduction and improved combustion processes, cerium oxide presents a viable path toward creating sustainable and environmentally friendly energy solutions across diverse industrial sectors.

Data availability statement

Data included in article. No other data available for this research.

CRediT authorship contribution statement

U. Ulagarjun: Writing – original draft, Methodology, Investigation. **Varun V. Varma:** Writing – original draft, Methodology, Investigation. **Abhijith K. Menon:** Writing – original draft, Methodology, Investigation. **N. Gobinath:** Writing – review & editing, Writing – original draft, Formal analysis. **A.R. Palanivelrajan:** Project administration, Methodology. **T.M. Yunus Khan:** Writing – review & editing, Validation, Funding acquisition. **Rahmath Ulla Baig:** Writing – review & editing, Project administration, Funding acquisition, Formal analysis. **Naif Almakayeel:** Writing – original draft, Investigation. **Feroskhan M:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

B25 - Diesel-25%, Waste plastic oil-75%
B50 - Diesel-50%, Waste plastic oil-50%
B25 + 25 ppm - Diesel-25%, Waste plastic oil-75%, Cerium oxide nanoparticles-25 ppm
B25 + 50 ppm - Diesel-25%, Waste plastic oil-75%, Cerium oxide nanoparticles-50 ppm
B50 + 25 ppm - Diesel-50%, Waste plastic oil-50%, Cerium oxide nanoparticles-25 ppm
B50 + 50 ppm - Diesel-50%, Waste plastic oil-50%, Cerium oxide nanoparticles-50 ppm
B30 + TiO_2 25 ppm - Biodiesel-30%, Diesel-70%, Titanium Oxide nanoparticles-25 ppm
B30 + TiO_2 50 ppm - Biodiesel-30%, Diesel-70%, Titanium Oxide nanoparticles-50 ppm
B30 + TiO_2 100 ppm - Biodiesel-30%, Diesel-70%, Titanium Oxide nanoparticles-100 ppm
C5%, C10%, C15% - Catalyst concentration of 5, 10, 15%
B5D85 CeO2 100 ppm - Pyrolysis oil-5%, Diesel-85%, Cerium Oxide nano additives −100 ppm
WPPO50 - Waste plastic pyrolysis oil-50%, Diesel-50%

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