Indian Journal of Chemical Technology
Vol. 32, March 2025, pp. 211-222
DOI: 10.56042/ijct.v32i2.13657

Improving the suitability of triple blend biodiesel in a low heat rejection diesel engine with the addition of nanoparticle through performance and emission characteristics analysis

M. Elango[1]*, C. Sowmya Dhanalakshmi[2], P. Madhu[3] & T. Vijay Muni

[1]Department of Mechanical Engineering, Erode Sengunthar Engineering College, Erode 638057, Tamil Nadu, India

[2]Department of Mechanical Engineering, SNS College of Technology, Coimbatore 641035, Tamil Nadu, India

[3]Department of Mechanical Engineering, Karpagam College of Engineering, Coimbatore 641032, Tamil Nadu, India

[4]Department of Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram 522302, Andhra Pradesh, India

*E-mail: elango3088@gmail.com

Received 10 September 2024; accepted 22 January 2025

The primary aim of this research is to efficiently utilize biodiesel and nanoparticles in thermal barrier-coated (TBC) engines. In view of this, a novel neem seed oil (NSO) and linseed oil (LSO) have been chosen for this work, and they are changed into neem seed oil methyl ester (NME) and linseed oil methyl ester (LME) through transesterification process. The blend B20 (10% NME + 10% LME + 80% diesel) and B20 with 50 ppm CeO_2 (B20C50) is prepared and used for that analysis in both conventional and coated engines. For the coated engine, the combustion chamber parts are coated with partially stabilized zirconia (PSZ) using the atmospheric plasma spray coating method. Initially, neat diesel, B20, and B20C50 are tested in a conventional engine, and later, B20C50 is tested in a TBC engine. Load tests are conducted on a direct injection (DI) diesel engine by changing the load from 0 to 100% to assess performance and emission characteristics. From the experimental work, it was noted that B20C50 in the TBC engine showed 3.3% higher brake thermal efficiency (BTE) and 26.92% lower brake specific fuel consumption (BSFC) than diesel fuel operated in a conventional engine. When associated with diesel, the emissions of carbon monoxide (CO) and hydrocarbons (HC) are lower by 30.77% and 24.32%, respectively. The emission of oxides of nitrogen (NOx) in the TBC engine is recorded as similar to diesel fuel.

Keywords: Cerium oxide, Coated engine, Engine analysis, Partially stabilized zirconia, Ternary blend biodiesel

Introduction

More reliance on energy conservation and alternative energy sources is anticipated in the upcoming century as fossil fuel supplies are predicted to become more limited, more costly, and the subject of growing environmental concern[1]. Renewable energy comes from natural resources that renew more quickly than they are used up. Solar, wind, hydroelectric, geothermal, and biomass are widely agreed to be the main types of renewable energy. Non-renewable resources known as fossil fuels take hundreds of millions of years to form and produce harmful greenhouse gases when they are used to generate energy. For a variety of uses, solar technologies can provide fuels, power, lighting, heating, and cooling[2]. Photovoltaic panels turn sunlight into electrical energy. Bioenergy is another type of renewable energy that includes a range of organic materials and other manures for power and heat generation[3].

The internal combustion engine, often known as an IC engine, is arguably the most graceful creation made by humans that has ever had a bigger impact on society and the economy. Vegetable oil or animal fats are the biological sources that can be used for the production of biofuel with low emission profiles[4]. Biodiesel is the best fuel to address upcoming energy-related concerns. There is currently an awful need to create an improved combustion engine that completely eliminates exhaust pollutants with improved efficiency[5]. In this way, IC engines with biodiesel would be a significant portion of future transport systems, due to their eco-friendly operation[6]. Currently, various researches have been done on the development of the performance of conventional IC engines without major changes[7]. Biodiesel for compression ignition (CI) engines has become more popular since it is widely used directly or blended with diesel[8]. A wide range of feedstock can be used for producing biodiesel. Biodiesels have more benefits such as renewable in nature, availability, and lubricity. Many of the literature reports that biodiesel emits less pollution, excluding NOx. The availability of excess oxygen is the cause for higher NOx emissions[9,10]. Numerous investigations into the improvement of biodiesel and its blend-operated engines have been conducted[11]. Advanced biofuels from non-edible feedstocks have emerged as a promising alternative in light of the difficulties associated with feedstock shortages. Ashok *et al*. used *Calophylluminophyllum* biodiesel for IC engine operation. The authors used B20, B40, B60, and B80 blends[12]. The study found that all blends consumed more fuel than diesel. However, CO emissions reduced for all blends. With the combination of linseed, rubber seed, and diesel, Sudalaiyandi *et al*. produced three different blends for IC engines[13]. The triple blend produced higher BTE with lower BSFC. In addition to that, the blended fuel generated fewer NO_2 and CO.

One of the most important strategies to increase the quality of biodiesel is the addition of additives[14]. Additives are substances that can be mixed into fuel to alter its properties and improve its performance. Previously, many literatures utilized various fuel additives with biodiesel and found improved performance in IC engines. Ramesh Babu *et al*. looked at the results of using ZnO with cotton seed methyl ester[15]. The authors showed increased BTE like diesel fuel at a blend of 25% biodiesel. They also showed reduced HC and CO production due to moderate oxygen levels. Rashedul *et al*. described the use of antioxidants to improve brake power, lower BSFC, and reduce NOx emissions[16]. Elahi *et al*. discovered that blending alumina with a 20% biodiesel blend led to considerable reductions in combustion time and ignition delay[17]. The study displayed greater peak pressure and an improved heat release rate. Hosseini *et al*. added carbon nanotubes to biofuel at the dosage levels of 30, 60, and 90 ppm[18]. Compared to diesel, the biodiesel with nano additives showed enhanced BTE with reduced BSFC. The above parameters were improved by up to 8.12% and 7.12%, respectively, but the NOx emission in this experiment was improved by 27.49%. Engine tests with different dosage levels from 20 ppm to 80 ppm of CeO_2 with biodiesel were performed by Sajith *et al*.[19]. The authors analyzed the emission and performance parameters. The addition of CeO_2 with biodiesel improved the BTE by 1.5%. In addition to that, the fuel additive increased HC oxidation, which caused 30% and 40% reduced NO and HC emissions, respectively. Similar to the above, the addition of Cu, Fe, Pt, and graphene nanoparticles with biodiesel blend showed the improvement in combustion with reduced emissions[20-23].

Improved engine performance can be attained by combining biodiesel with engine modification techniques such as TBC. TBCs have found widespread use in gas turbines and aircraft engines to enhance their efficiency and extend operation life[24]. TBCs consist of two coats: a ceramic coating and a metallic bond coating. The bond coat adheres the ceramic coat to a metal surface while the ceramic coat serves as thermal insulation. This section delivers a thorough discussion of the TBC and the performance of the TBC-coated engine. The TBC engine on the other side is called a low-heat-rejection engine. Low heat rejection was claimed for diesel engines with ceramic-layered components[25]. With coating, we can achieve a reduction in engine heat loss[26]. The coating on engine valves, piston crown and cylinder head can be achieved by applying a layer of material having very low thermal conductivity[27]. The value of thermal conductivity is extremely important since the layer has to minimize the heat rejection. However, it was noted that coatings on engine components are common. SiCa, SiN, Al, and $MgSiO_2$ are the commonly used ceramic materials for engine coating. TBC can be made with a bond coat (NiCrAl) that resists oxidation. The bond layer protects the substrate from corrosion and oxidation[28]. The total thickness of the layer might be from 150 µm to 500 µm whereas the bond coat takes up to 150 µm. Due to its increased porosity, the plasma spraying method is a widely adopted way for coating engine components[29].

Taymaz used the plasma-spray approach to provide a 0.35 mm-thin coating of $CaZrO_3$ to engine components like the valves and cylinder head. The authors tested the impact of coating on efficiency and fuel consumption. In comparison to a conventionally cooled engine, the well-insulated $CaZrO_3$ engine exhibits a notable improvement in fuel efficiency[30]. Uzun and Akçil carried out atrial study to analyze the impact of ceramic coatings on diesel engine operating performance using NiCrAl- $CaZrO_3$ /$MgZrO_3$. The result of the study showed lower CO, NOx, smoke, and particle emissions with improved combustion efficiency[31]. According to Morel *et al*. the application of TBC effectively resisted the flow of heat and highlighted the prevalence of high in-cylinder temperatures due to complete combustion[32]. Using ethanol, Lawrence *et al*. examined an IC engine coated with PSZ[33]. According to this study, ethanol with coating increased BTE by up to 1.64% with a significant reduction of BSFC. Karthickeyan *et al*. mixed pyrogallol with biodiesel blend and analyzed the combination in a TBC engine coating with yitria stabilized zirconia (YSZ) to boost the engine performance[34]. The coated engine showed higher BTE with good combustion properties. In addition to that, the blended fuel showed lower emission characteristics with a coated engine. Engine efficiency for various biodiesels under ceramic-coated conditions was found to be higher and fuel consumption was found to be lower. Linseed oil biodiesel was subjected to an investigation on a Cr_3C_2 coated engine[35]. In this study, the author preheated the biodiesel and utilized it for engine analysis. The preheated biodiesel in a coated engine showed increased NOx emissions. Using sunflower oil biodiesel, Haşimoğlu conducted experimental work on a turbocharged $CaZrO_3$ coated engine. The results displayed increased BTE by up to 6.5% in a coated engine compared to a standard engine[36].

The thorough literature study revealed a large number of studies using different non-edible biodiesels on the TBC engine. However, very little research has been done on using biodiesel diesel blends with various nanoparticles in ceramic-coated engines. However, no research was found in the literature regarding the usage of ternary blends of diesel, NME, and LME dosed with CeO_2 nanoparticles and performance assessment in NiCrAl-PSZ-coated engine. In this study, neem seed oil and linseed oil were transformed into the corresponding biodiesel through a transesterification reaction. The usage of biodiesel for IC engine is beneficial for the environmental sustainability and society. The feedstock used for this study is a renewable, biodegradable fuel that can reduce greenhouse gas emissions, improve air quality, and reduce smog. Biodiesel also can promote rural and agricultural economic development. The prepared blended fuel was tested in a PSZ-coated engine. Various engine operating characteristics, such as BTE, BSFC, CO, HC, and NOx were measured and compared with diesel.

Experimental Section

Biodiesel preparation

In this study, both Neem Seed Oil (NSO) and Linseed Oil (LSO) were obtained through mechanical processing of the required quantity of neem seeds and linseeds. Around 35 wt% of the oil was extracted from both the seeds. The biodiesels were prepared through the transesterification process. 500 mL of raw NSO was taken, and the process was conducted using a stirrer maintained at 60°C with an agitation speed of 400 rpm for an oil-to-methanol ratio of 1:5. The solution was heated, and the preheated oil was dissolved in a 1% methanol/NaOH solution at room temperature. A reaction was continued for up to 90 min by keeping it at 60°C. The mixture was cooled to atmospheric temperature and allowed to settle for more than 24 h and after that the settled catalyst was separated. Glycerin and biodiesel are the two different products obtained at the end of the process. The glycerin was removed carefully, and the Neem Methyl Ester (NME) was separated and stored for engine analysis. The same method was used for the production of Linseed Methyl Ester (LME). The NME and LME characteristics are displayed in Table 1.

Test fuel preparation

Two types of test fuels, such as ternary blend and ternary blend with CeO_2 were prepared and utilized for the analysis. Initially, B20 blended fuel was prepared by direct mixing. In order to prepare nano biodiesel, an ultrasonicator operated at 50 kHz was employed as designated by Elumalai *et al.*[37]. The CeO_2 with a particle size of 50–100 nm and a 50 ppm concentration are mixed into the B20 biodiesel blend to make B20C50. The fuel characteristics for both biodiesel and standard fuel were represented in Table 2.

Table 1 — Characteristics of raw oil and biodiesel

Properties	NSO	LSO	NME	LME	Unit	ASTM test protocol
Viscosity	17.2	24.1	6.2	2.4	cSt	445
Density	920	895	905	875	kg/m^3	D1798
Flash point	260	245	165	65	°C	D93
Fire point	272	255	181	80	°C	D93
Cetane number	32.3	35.4	54.1	52.0	-	D613-84
Calorific value	38.1	39.4	38.6	39.3	MJ/kg	D240

Test bench and procedure

A single-cylinder CI engine of rated power of 5.2 kW at 1500 rpm coupled to an electrical dynamometer was used for this study. Table 3 represents its specifications. The cylinder pressure is found using a pressure transducer. Encoders are installed on the crankshaft to track its location. Measurements of various gas emissions from exhaust ports are made using an AVL 444 exhaust gas analyzer. First, the engine was functioned with diesel, and the various operating parameters were noted for reference. The readings in each stage were recorded after 15 min or after steady-state conditions. After that, it is switched to biofuel operating mode. For that, a tank was cleaned using the respective fuel, and then it was filled with the B20 and B20C50 ppm. After completing the experiments with the conventional diesel engine with diesel and nanofuel, the engine components were replaced with ceramic-coated pistons and valves. The TBC engine was further utilized for analysis with B20 + 50 ppm fuel. For all fuels, the load is changed from 0 to 100% at 20% intervals. At each loading condition, all the parameters were noted and recorded. Fig. 1 shows the graphical representation of the test bench.

Table 2 — Properties of test fuel and diesel

Properties	B20	B20C50	Diesel	Unit
Viscosity	2.9	2.9	2.8	cSt
Density	836	838	832	kg/m^3
Flash point	58	60	56	°C
Fire point	65	66	64	°C
Cetane number	51.2	51.6	51.0	-
Calorific value	42.8	42.95	43.16	MJ/kg

Table 3 — Engine specification

Engine type	Kirloskar TV1, power 5.2 kW, 1500 rpm, water cooling
Ignition type	Compression
Compression ratio	17.5:1
Loading	Eddy current, water cooled
Number of cylinder	1
Number of stroke	4
Stroke and stroke	110 mm and 87.5 mm
Orifice diameter	20 mm
Injection timing	23 °BTDC
Gas analyzer	AVL DiGas
Fuel	Diesel, B20 and B20+50 ppm
Injection pressure	210 bar

Thermal barrier coating

The PSZ coating process was carried out utilizing an automatic power unit and atmospheric plasma spray (APS) process. The APS approach is employed since it is the most appropriate[38]. Melted metal is sprayed onto a metal surface to create a coating. The coating was performed with the tungsten cathode and copper anode with high voltage. At first, the bond coat NiCrAl was applied on the substrate, and then PSZ was applied onto the same surface. The direct application of the coating material was not advised due to fixed combustion unit specifications[39,40]. To create a coarse layer, a low amount

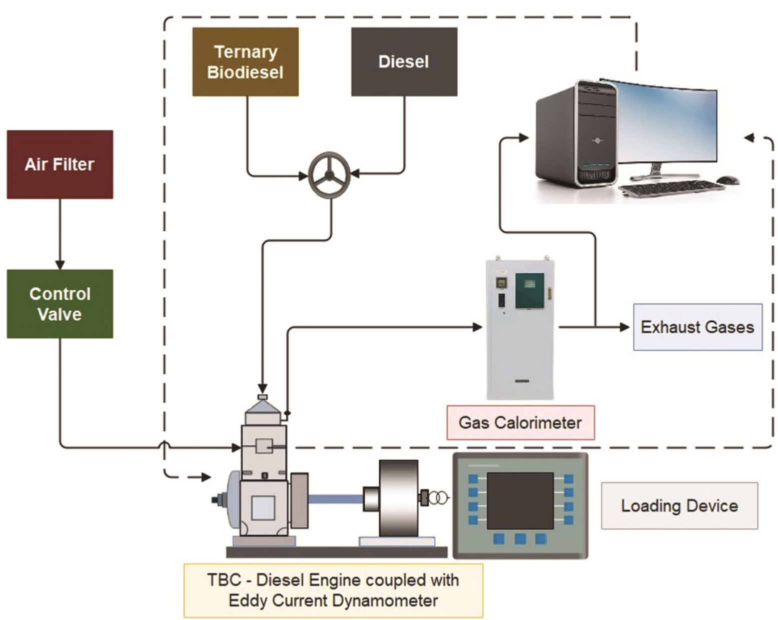

Fig. 1 — Schematic of the test bench

Table 4 — Uncertainty value of the instruments

Instruments		Range	Accuracy	Uncertainty
Exhaust Gas Analyzer	CO	0–10% vol.	± 0.1%	0.07%
	HC	0-30000 ppm	± 1 ppm	0.60%
	NO_x	0–5000 ppm	± 1 ppm	0.59%
Viscometer (Redwood)		20 °C to 99 °C	± 1 °C	0.56%
Flash Point Apparatus		20 °C to 370 °C	± 1 °C	0.40%
Bomb Calorimeter		15 °C to 35 °C	± 0.01 °C	0.02%

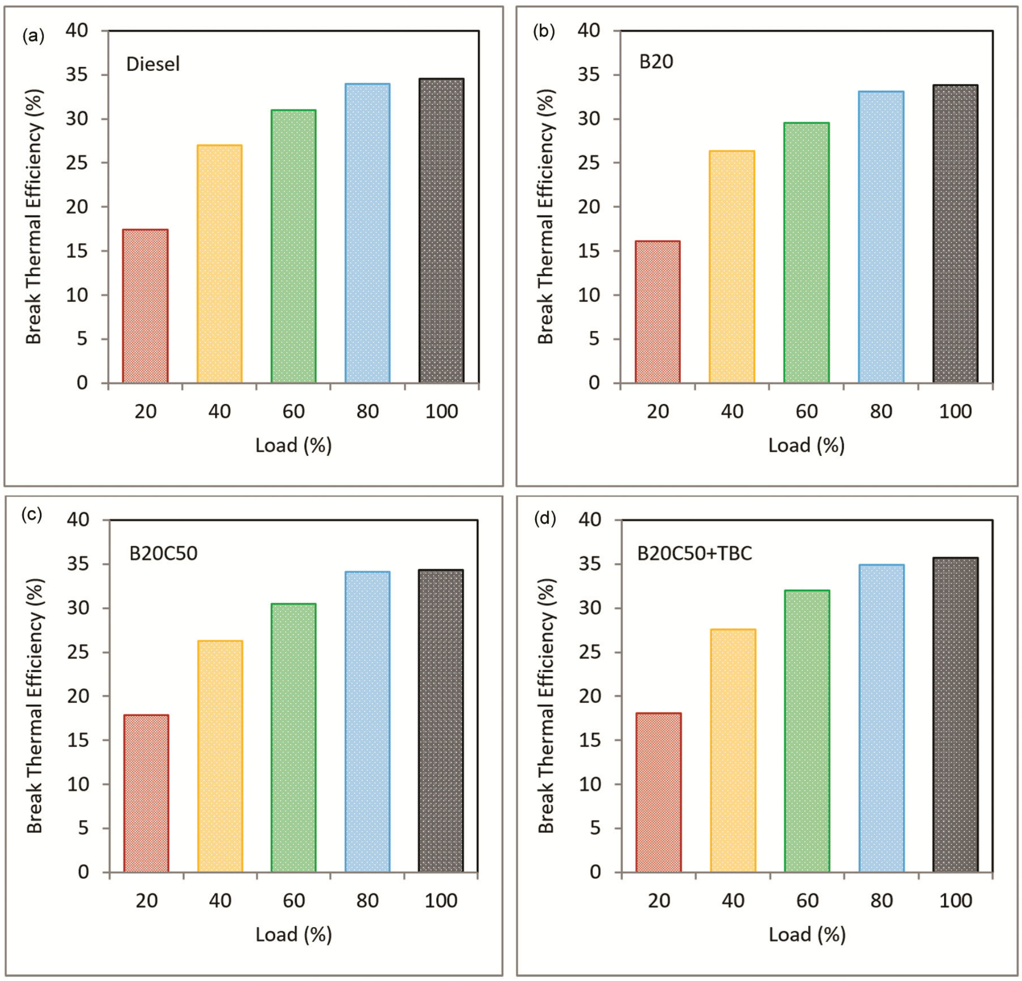

Fig. 2 — Change in BTE

of sandblasting was used, and ethanol was used to clean the components. The two coating layers consist of a bond coat made of NiCrAl on the first layer, which is 150 µm thick and PSZ on the second layer, which is 200 µm thick. PSZ was chosen for this study because of its decreased thermal conductivity and enhanced coefficient of thermal expansion.

Analysis of experimental uncertainty

The accuracy of experimental results should be addressed and validated through uncertainty calculations and analysis. Every individual element is dispersed equally, and measurements were made using the equipment's accuracy and calibration functions. Table 4 represents the uncertainty of each instrument.

Results and Discussion

Effect on BTE

The change in BTE in relation to various consignments for different operating fuels is illustrated in Fig. 2. At 100% load, the respective BTE for diesel, B20, B20C50, and B20C50+TBC were 34.54%, 33.8%, 34.35%, and 35.72%, respectively. The thermal efficiency is commonly represents the conversion of fuel into usable piston work[41]. Compared to diesel fuel operated in a conventional engine, the B20 blend mixed with CeO_2 operated in a TBC engine showed 3.3% higher BTE. Compared to all fuels, the B20 biodiesel operated in a diesel engine showed lower BTE because of its greater viscosity and lower energy value. The greater oxygen percentage in CeO_2 participated much in combustion and hence it boosts combustion, leading to higher BTE[42]. According to nano-structural investigation, the presence of several oxygenated groups on the biodiesel was the cause of sufficient oxygen. Consistently, biodiesel with nanoparticles, has a higher surface-area-to-volume ratio. The distribution of CeO_2 in the fuel can also improve chemical reactivity during combustion[43]. In the TBC engine, B20C50 showed improved BTE due to higher combustion temperature. In a coated engine, fuel consumption was lower for the same amount of power output, which helped to improve the BTE. The ceramic layer in the engine had the effect of improving the pressure ratio. Based on the diesel cycle, the brake power (BP) will increase when the pressure ratio is slightly raised.

Effect on BSFC

Utilization of fuel supplied to the engine for the development of BP is measured by BSFC. Fig. 3 illustrates variation in BSFC for different load. According to Sajith *et al*. adding CeO_2 lowers the amount of gasoline used for producing unit BP since it oxidizes carbon buildup in the engine, resulting in

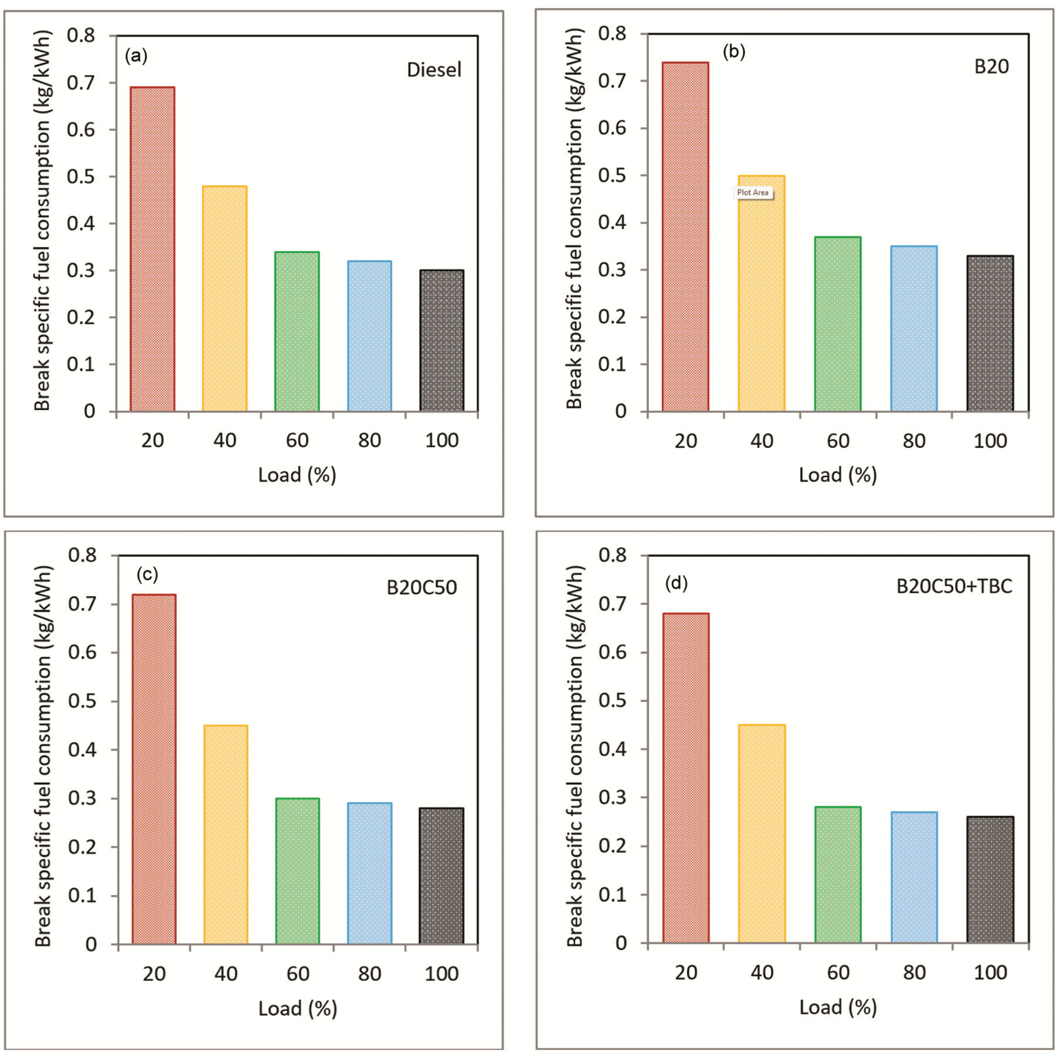

Fig. 3 — Change in BSFC

efficient and smooth operation[19]. At 100% load, BSFC for diesel, B20, B20C50, and B20C50+TBC is recorded as 0.3 kg/kWh, 0.33 kg/kWh, 0.28 kg/kWh, and 0.26 kg/kWh, respectively. B20 fuel has a lower heating value than all other blends, so to deliver the same power at 1500 rpm, the conventional engine consumed more fuel. However, due to the oxidation, the addition of CeO_2 with B20-blended fuel was demonstrated to reduce BSFC by 7.14% related to diesel, which enhances the combustion rate at full load[44]. It is also clear from the previous studies that in comparison to fuel without metallic base additives, the fuel with additives burned better in the cylinders[45]. The BSFC for B20C50 in the TBC engine is 0.26 kg/kWh, which is 15.38% and 26.92% lower compared to diesel and B20 operated in a conventional engine. Better oxidation and micro-explosion may be the main reasons for the reduced BSFC in the TBC engine[46]. According to Ramasamy *et al*. the BSFC and combustion chamber temperature were significantly correlated. This result demonstrated that the coating on the engine components had a considerable influence on the rise in combustion chamber temperature[47]. A higher combustion chamber temperature aided in decreasing ignition delay period and improved burning.

Effect on CO emission

CO is considered the most significant air pollutant that can prevent the flow of oxygen to the organs, and it is exceedingly dangerous to the living organisms. High CO concentrations in the air limit the quantity of oxygen that can reach vital organs like the heart and brain through the bloodstream. CO takes part in atmospheric chemical reactions that result in the production of ozone, a climate change gas. Additionally, CO has a negligible direct impact on the climate. Because of these factors, CO is categorized as a short-lived climate forcing agent, which is why lowering CO emissions is being explored as a potential tactic to lessen the effects of global warming. In IC engines, incomplete fuel combustion contributes to the production of CO[48]. The changes in CO production for diesel, B20, B20C50, and B20C50+TBC are revealed in Fig. 4. It can be

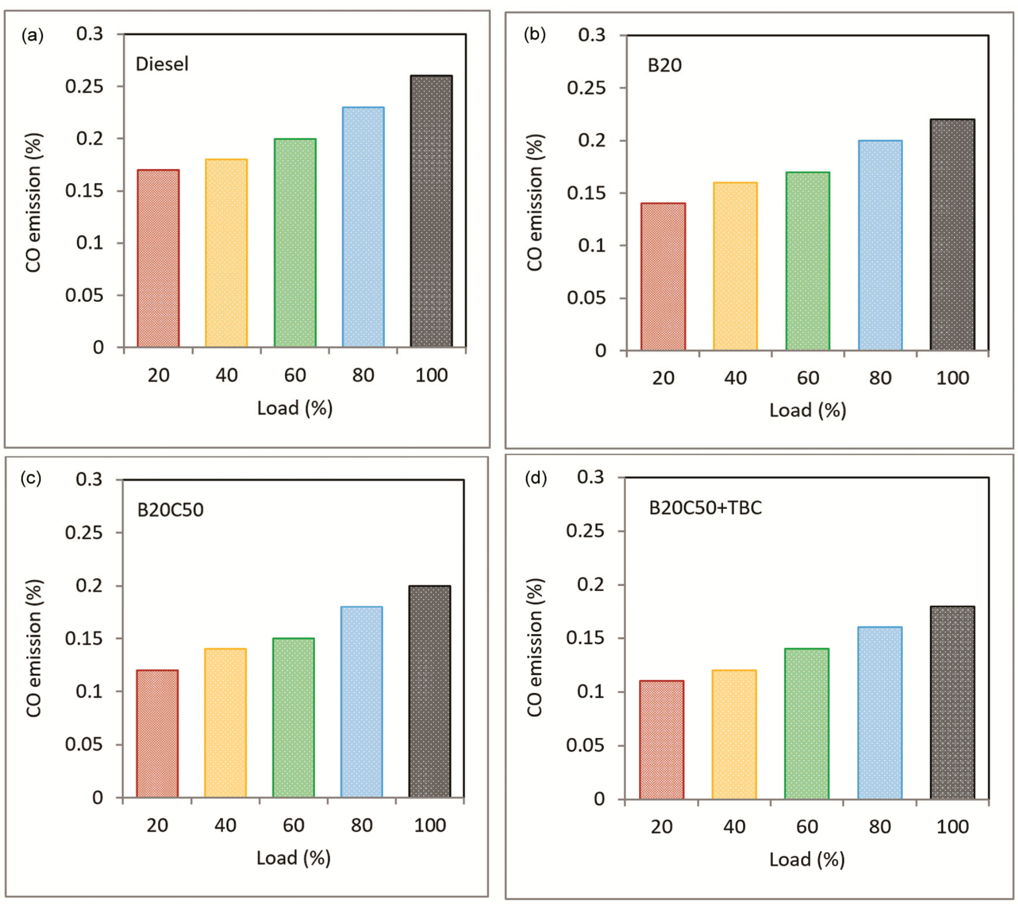

Fig. 4 — Change in CO emission

implicit that the diesel in the conventional engine produced more CO than other fuels. The emission rates of B20, B20C50, and B20C50+TBC in this study were 0.26%, 0.22%, 0.20%, and 0.18%, respectively. The reduced CO emission for the biodiesel blend in the engine is due to the occurrence of oxygen. The higher oxygen in biodiesel fuel assist them to burn rapidly and completely lowers the production of CO. Compared to diesel, B20 and B20C50 in the conventional engine emit 15.38% and 23.08% lower CO, respectively. The TBC engine operated with B20C50 fuel showed 30.77%, 18.18%, and 10.0% reduced CO than diesel, B20, and B20C50 operated in a conventional engine. Because in the TBC engine, the oxidation is complete and the ignition delay is reduced[49].

Effect on HC emission

Fig. 5 displays the impact on HC emissions at different loads for diesel and other blended fuels. For all fuels, reduced engine load results in lower HC emissions, while full engine load results in higher HC formation. This is associated with insufficient oxygen when a higher amount of fuel is supplied at higher loads[50]. Generally, the increased HC emissions are caused by increased viscosity and decreased volatility of the fuel. The peak in-cylinder pressures and heat release rates (HRR) with higher biodiesel blends may result in somewhat higher HC emissions. Increased HC emissions at higher brake power are most likely caused by the greater acid values of the fuels[51]. In this phase, diesel fuel in the conventional engine produced more HC than other fuels. At 100% load, the HC

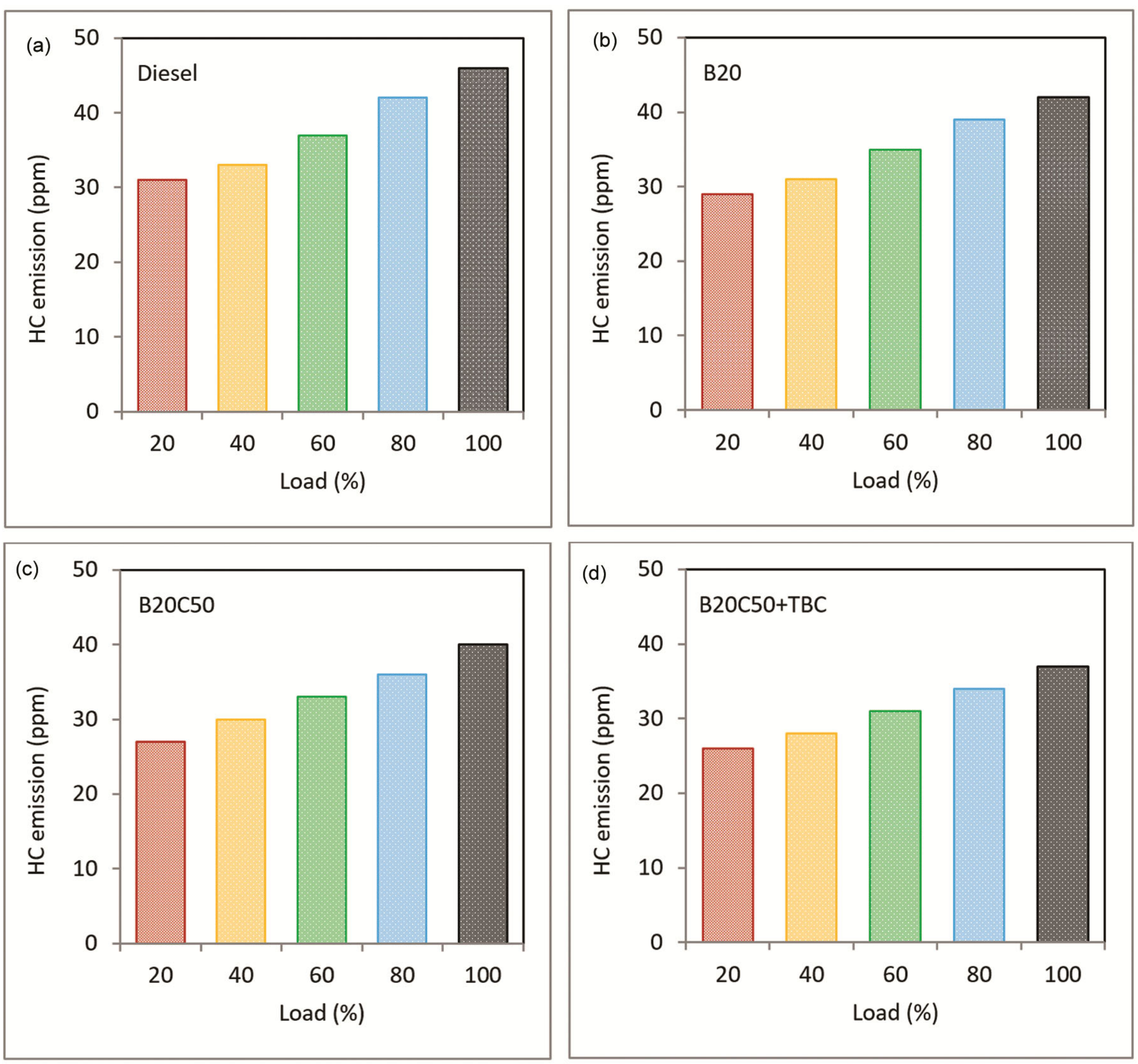

Fig. 5 — Change in HC emission

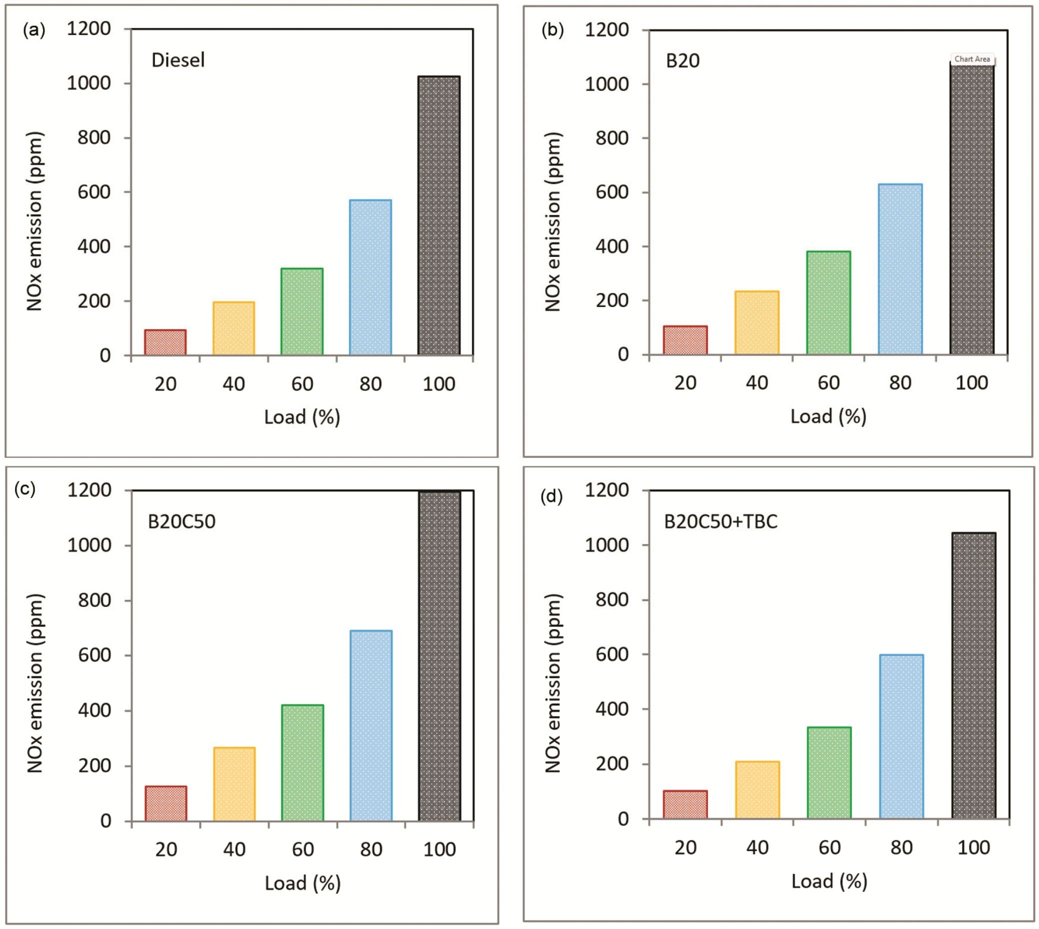

Fig. 6 — Change in NOx emission

emissions for B20, B20C50, and B20C50+TBC are 46 ppm, 42 ppm, and 40 ppm, and 37 ppm, respectively. Adding CeO_2 to B20 fuel increases vaporization[52]. Further, the fuel atomization was enhanced with CeO_2, leading to decreased HC emissions. The chemically bonded oxygen in fuel improved the rate of combustion. Compared to diesel, B20 and B20C50 in the conventional engine emit 9.52% and 15% lower HC, respectively, due to catalytic reaction inside the combustion chamber. B20 with nanoparticles in the TBC engine emits less HC emissions than all other tested fuels. The TBC engine significantly increased the local heat temperature and contributed to the breakdown of the primary fuel molecules. In this case, the B20C50 in the TBC engine emits 24.32% lower HC than diesel operated in a conventional engine.

Effect on NOx emission

NOx emissions of diesel, B20, and B20C50 in a conventional engine and B20C50 in a TBC engine are represented in Fig. 6. In a conventional engine, diesel has lower NOx emissions than biodiesel and biodiesel with nano-additives. Diesel, B20, and B20C50 in a conventional engine emit 1026 ppm, 1082 ppm, and 1195 ppm at 100% load. The improved NOx emission in a engine is due to greater oxygen level. The existence of oxygen in biodiesel and nanoparticles increases the rate of burning; hence the temperature of the combustion process increases[53]. It also shows that the emission of NOx from the engine is a function of combustion chamber temperature. This result is consistent with other literature[54,55] that indicates decreased NOx emissions from the engine running on diesel without any additives. On the other hand, B20C50 running on the TBC engine showed reduced NOx production of 1045 ppm, which is 3.42% and 12.55% less than B20 and B20C50 operated on a conventional engine. The emission of NOx is much like diesel fuel. Generally, in TBC engines, the NOx is increased due to higher chamber temperature. But the addition of CeO_2 significantly decreases the generation of NOx.

Conclusion

The distinct effects of CeO_2 nanoparticles on a ternary blend of NME, LME, and diesel on the performance and emission characteristics of conventional and PSZ-coated engines have been tested experimentally. For the analysis, a Kirloskar TV1 model DI diesel engine with an eddy current dynamometer was utilized successfully. In all aspects, biodiesel with nanoparticles in the TBC engine at 100% load showed improved performance and emission characteristics, except NOx. It showed 3.3% higher BTE and 26.92% lower BSFC than diesel. While considering the emissions, it showed 30.77% and 24.32% reduced CO and HC emissions, respectively. The NOx emission in the TBC engine was recorded as being similar to diesel fuel. The improved performance with reduced BSFC is due to better pressure ratio and complete combustion. The TBC engine expressively increased the local heat temperature and contributed to the breakdown of the primary fuel molecules.

Nomenclature

IC	Internal combustion
CI	Compression ignition
DI	Direct injection
TBC	Thermal barrier coating
NSO	Neem seed oil
LSO	Linseed oil
NME	Neem seed oil methyl ester
LME	Linseed oil methyl ester
PSZ	Partially stabilized zirconia
D	Diesel
B20	10% NME + 10% LME + 80% diesel
B20C50	B20 with 50 ppm CeO_2
CeO_2	Cerium oxide
ppm	Parts per million
BP	Brake power
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
CO	Carbon monoxide
HC	Hydrocarbon
NOx	Oxides of nitrogen

References

1 Pandey A K, Kalidasan B, Reji K R, Rahman S, Tyagi V V, Krismadinata & Tyagi S K, Solar energy utilization techniques, policies, potentials, progresses, challenges and recommendations in ASEAN countries, *Sustainability*, 14 (2022) 11193.

2 Pathak S K, Tyagi V V, Chopra K, Rejikumar R & Pandey A K, Integration of emerging PCMs and nano-enhanced PCMs with different solar water heating systems for sustainable energy future: A systematic review, *Solar Energy Mater Solar Cells*, 254 (2023) 112237.

3 Sowmya D C & Madhu P, Utilization possibilities of Albiziaamara as a source of biomass energy for bio-oil in pyrolysis process, *Energy Sources Part A: Recovery Util Environ Eff*, 41 (2019) 1908.

4 Dhanalakshmi C S & Madhu P, Recycling of wood bark of Azadirachtaindica for bio-oil and chemicals by flash pyrolysis, *Indian J Ecol*, 46 (2019) 347.

5 Shivaprasad K V, Rajesh R, Wogasso W A, Nigatu B & Addisu F, Usage of hydrogen as a fuel in spark ignition engine, *IOP Conf Ser: Mater Sci Eng*, 376 (2018) 012037.

6 Ravi R & Pachamuthu S, Design and development of innovative protracted-finned counter flow heat exchanger (PFCHE) for an engine WHR and its impact on exhaust emissions, *Energies*, 11 (2018) 2717.

7 Ravi R, Pachamuthu S & Kasinathan P, Computational and experimental investigation on effective utilization of waste heat from diesel engine exhaust using a fin protracted heat exchanger, *Energy*, 200 (2020) 117489.

8 Saravanakumar K, Robinson Y, Dhanalakshmi C S & Madhu P, Improving the poor properties of methyl ester with pyrolysis oil and fossil diesel-An experimental investigation on PSZ ceramic coated engine with the addition of GO nanoparticles, *Indian J Chem Technol*, 31 (2024) 553.

9 Senthilkumar S, Karthick A, Madavan R, Moshi A A M, Bharathi S S, Saroja S & Dhanalakshmi C S, Optimization of transformer oil blended with natural ester oils using Taguchi-based grey relational analysis, *Fuel*, 288 (2021) 119629.

10 Parthasarathy M, Ramkumar S, Lalvani J I J, Elumalai P V, Dhinesh B, Krishnamoorthy R & Thiyagarajan S, Performance analysis of HCCI engine powered by tamanu methyl ester with various inlet air temperature and exhaust gas recirculation ratios, *Fuel*, 282 (2020) 118833.

11 Anand K, Bhardwaj A, Vinod D, Ashwinbhai P K, John K V & Dhanalakshmi C S, Utilization of triple blend biodiesel towards performance and emission characteristics of diesel engine, *AIP Conf Proc*, 2800 (2023) 020141.

12 Ashok B, Nanthagopal K, Saravanan B, Azad K, Patel D, Sudarshan B & Ramasamy R A, Study on isobutanol and Calophylluminophyllum biodiesel as a partial replacement in CI engine applications, *Fuel*, 235 (2019) 984.

13 Sudalaiyandi K, Alagar K, Kumar R V & Madhu P, Performance and emission characteristics of diesel engine fueled with ternary blends of linseed and rubber seed oil biodiesel, *Fuel*, 285 (2021) 119255.

14 Stephen L T, Madhu P, Dhanalakshmi C S & Kumar R V, An experimental investigation on performance, emission and combustion characteristics of IC engine using liquid fuel produced through catalytic Co-pyrolysis of pressed oil cake and mixed plastics with the addition of nanoparticles, *Fuel*, 379 (2025) 133092.

15 Babu A R, Jeyandan A, Kumar K M, Logesh K, Rayudu J V & Manikanta G S D, Experimental investigation on the

performance and emission characteristics of CI engine using waste cotton seed biodiesel with ZNO as a fuel additive, *Int J Ambient Energy*, 41 (2020) 669.

16 Rashedul H K, Masjuki H H, Kalam M A & Ashraful A M, Performance and emission of a CI engine using antioxidant treated biodiesel, *J Clean Energy Technol*, 5 (2017) 7.

17 Soudagar M E M, Nik-Ghazali N N, Kalam M A, Badruddin I A, Banapurmath N R, Ali M A B, & Akram N, An investigation on the influence of aluminium oxide nano-additive and honge oil methyl ester on engine performance, combustion and emission characteristics, *Renew Energy*, 146 (2020) 2291.

18 Hosseini S H, Taghizadeh-Alisaraei A, Ghobadian B & Abbaszadeh-Mayvan A, Performance and emission characteristics of a CI engine fuelled with carbon nanotubes and diesel-biodiesel blends, *Renew Energy*, 111 (2017) 201.

19 Sajith V, Sobhan C B & Peterson G P, Experimental investigations on the effects of cerium oxide nanoparticle fuel additives on biodiesel, *Adv Mech Eng*, 2 (2010) 581407.

20 Heidari-Maleni A, Gundoshmian T M, Karimi B, Jahanbakhshi A & Ghobadian B, A novel fuel based on biocompatible nanoparticles and ethanol-biodiesel blends to improve diesel engines performance and reduce exhaust emissions, *Fuel*, 276 (2020) 118079.

21 Hosseinzadeh-Bandbafha H, Tabatabaei M, Aghbashlo M, Khanali M, Khalife E, Shojaei T R & Mohammadi P, Consolidating emission indices of a diesel engine powered by carbon nanoparticle-doped diesel/biodiesel emulsion fuels using life cycle assessment framework, *Fuel*, 267 (2020) 117296.

22 Ayyakkannu V & Vinoth R, Effect of CuO nano additive with novel punnai methyl ester in a TBC CI engine, *Indian J Chem Technol*, 30 (2023) 765.

23 Lv J, Wang S & Meng B, The effects of nano-additives added to diesel-biodiesel fuel blends on combustion and emission characteristics of diesel engine: A review, *Energies*, 15 (2022) 1032.

24 Godiganur V S, Nayaka S & Kumar G N, Thermal barrier coating for diesel engine application-A review, *Mater Today: Proc*, 45 (2021) 133.

25 Abbas S M & Elayaperumal A, Experimental investigation on the effect of ceramic coating on engine performance and emission characteristics for cleaner production, *J Clean Prod*, 214 (2019) 506.

26 Işcan B, Application of ceramic coating for improving the usage of cottonseed oil in a diesel engine, *J Energy Inst*, 89 (2016) 150.

27 Viswanathan K, Wu W, Taipabu M I & Chandra-Ambhorn W, Effects of antioxidant and ceramic coating on performance enhancement and emission reduction of a diesel engine fueled by Annona oil biodiesel, *J Taiwan Inst Chem Eng*, 125 (2021) 243.

28 Masera K & Hossain A K, Biofuels and thermal barrier: A review on compression ignition engine performance, combustion and exhaust gas emission, *J Energy Inst*, 92 (2019) 783.

29 Thirunavukkarasu R & Periyasamy S, Enhancing diesel engine performance and balancing emissions with effect and contribution of MgO-ZrO_2 and AT13 layered piston, *Arab J Sci Eng*, 45 (2020) 9699.

30 Taymaz I, The effect of thermal barrier coatings on diesel engine performance, *Surface Coat Technol*, 201 (2007) 5249.

31 Uzun A & Akçil M, Effects of thermal barrier coating on a turbocharged diesel engine performance, *Surface Coat Technol*, 116 (1999) 505.

32 Morel T, Wahiduzzaman S, Fort E F, Tree D R, De-Witt D P & Kreider K G, Heat transfer in a cooled and an insulated diesel engine, *SAE Trans*, (1989) 1052

33 Lawrence P, Mathewsz P K & Deepanraj B, Experimental investigation on performance and emission characteristics of low heat rejection diesel engine with ethanol as fuel, *Am J Appl Sci*, 8 (2011) 348.

34 Karthickeyan V, Effect of cetane enhancer on Moringaoleifera biodiesel in a thermal coated direct injection diesel engine, *Fuel*, 235 (2019) 538.

35 Hazar H & Sevinc H, Investigation of the effects of pre-heated linseed oil on performance and exhaust emission at a coated diesel engine, *Renew Energy*, 130 (2019) 961.

36 Haşimoğlu C, The effects of biodiesel on performance and exhaust emissions of a low heat rejection diesel engine, *Energy Sources Part A: Recovery Util Environ Eff*, 34 (2012) 570.

37 Elumalai P V, Balasubramanian D, Parthasarathy M, Pradeep kumar A R, Iqbal S M, Jayakar J & Nambiraj M, An experimental study on harmful pollution reduction technique in low heat rejection engine fuelled with blends of pre-heated linseed oil and nano additive, *J Clean Prod*, 283 (2021) 124617.

38 Kumar P M, Uvaraja V C & Madhu P, Effect of Al_2O_3/PSZ and Al_2O_3/YSZ ceramic coating in CI engine fueled with ternary blends of castor seed oil and jatropha oil biodiesel dosed with diesel, *J Ceram Process Res*, 23 (2022) 647.

39 Ramakrishnan C, Devan P K & Karthikeyan R, Experimental study on the performance and emission characteristics of Jojoba oil fueled DICI engine, *Environ Prog Sustain Energy*, 36 (2017) 248.

40 Sevinc H & Hazar H, Investigation of performance and exhaust emissions of a chromium oxide coated diesel engine fueled with dibutyl maleate mixtures by experimental and ANN technique, *Fuel*, 278 (2020) 118338.

41 Raja T, Rathinasamy T, Ayyakannu V & Setiyo M, Experimental optimization of injection parameters to enhance combustion characteristics of engine on using CE40 fuel, *Indian J Chem Technol*, 31 (2024) 383.

42 Raguraman D, Kumar A, Prasanna R Y S, Patil P Y, Samson I J, Dhanalakshmi C S, Madhu P & Lalvani J I J R, Performance and emission characteristics of pyrolysis oil obtained from neem de oiled cake and waste polystyrene in a compression ignition engine, *Adv Mater Sci Eng*, 2021 (2021) 3728852.

43 Shaafi T, Sairam K, Gopinath A, Kumaresan G & Velraj R, Effect of dispersion of various nanoadditives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blend-A review, *Renew Sustain Energy Rev*, 49 (2015) 563.

44 Mehanathan S, Madhu P, Dhanalakshmi C S & Vijayakumar R, Synergistic recovery of renewable hydrocarbon resources via Co-pyrolysis of non-edible linseed and waste polypropylene: A study on influence of plastic on oil production and their utilization as a fuel for IC engine, *J Energy Inst*, 118 (2025) 101905.

45 Keskin A, Gürü M & Altıparmak D, Influence of metallic based fuel additives on performance and exhaust emissions of diesel engine, *Energy Convers Manage*, 52 (2011) 60.
46 Elumalai P V, Nambiraj M, Parthasarathy M, Balasubramanian D, Hariharan V & Jayakar J, Experimental investigation to reduce environmental pollutants using biofuel nano-water emulsion in thermal barrier coated engine, *Fuel*, 285 (2021) 119200.
47 Ramasamy N, Kalam M A, Varman M & Teoh Y H, Effect of thermal barrier coating on the performance and emissions of diesel engine operated with conventional diesel and palm oil biodiesel, *Coatings*, 11 (2021) 692.
48 Kivevele T T, Kristóf L, Bereczky Á & Mbarawa M M, Engine performance, exhaust emissions and combustion characteristics of a CI engine fuelled with croton megalocarpus methyl ester with antioxidant, *Fuel*, 90 (2011) 2782.
49 Ashok B, Nanthagopal K, Mohan A, Johny A & Tamilarasu A, Comparative analysis on the effect of zinc oxide and ethanox as additives with biodiesel in CI engine, *Energy*, 140 (2017) 352.
50 Murugesan E & Kannan G R, An experimental study on synthesis of ternary biodiesel through potassium hydroxide catalyst transesterification, *Environ Prog Sustain Energy*, 42 (2023) e13958.
51 Doppalapudi A T, Azad A K & Khan M M K, Experimental investigation on diesel engine performance, combustion, and emissions characteristics with Tucuma and Ungurahui biodiesel blends, *Fuel*, 371 (2024) 132161.
52 Gangula V R, Nandhana G G R & Tarigonda H, Investigation on different thermal barrier-coated piston engines using Mahua biodiesel, *J Inst Eng Ser C*, 102 (2021) 131.
53 Devarajan Y, Munuswamy D B & Mahalingam A, Investigation on behavior of diesel engine performance, emission, and combustion characteristics using nano-additive in neat biodiesel, *Heat Mass Transf*, 55 (2019) 1641.
54 Shukla P C, Gupta T, Labhasetwar N K, Khobaragade R, Gupta N K & Agarwal A K, Effectiveness of non-noble metal based diesel oxidation catalysts on particle number emissions from diesel and biodiesel exhaust, *Sci Total Environ*, 574 (2017) 1512.
55 Dhinesh B, Bharathi R N, Lalvani J I J, Parthasarathy M & Annamalai K, An experimental analysis on the influence of fuel borne additives on the single cylinder diesel engine powered by Cymbopogonflexuosus biofuel, *J Energy Inst*, 90 (2017) 634.