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TECHNICAL PAPER

Comparative studies on emission reduction in thermal barrier coated engine using single blend ratio of various non-edible oils

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Abstract An increase in energy consumption, fluctuation in oil prices, depletion of fossil fuels, demolition of natural resources and need for less carbon content in fuel induces the way to find an alternative fuel. Biodiesel is the most promising and environment-friendly alternative to the conventional fuel. This paper presents the comparative studies of various non-edible oils in single cylinder, four-stroke diesel engine with eddy current dynamometer. In the present study, cashewnut shell liquid methyl ester, orange methyl ester and neem oil methyl ester were obtained from its respective non-edible oils via transesterification process. Diesel engine was coated with partially stabilized zirconia (PSZ) as thermal barrier coating. Biodiesel samples were blended with diesel in 20:80 ratios. In this work, the following engine characteristics such as brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), CO, HC, NOx, smoke emissions for both coated and uncoated engine conditions were measured. From the experimentation, it was concluded that orange methyl ester with diesel and neem oil methyl ester with diesel when used as an alternative to the conventional fuel showed higher BTE, lower BSFC along with lower emissions of CO, HC, NOx, and smoke in engine coated with PSZ. This substantiates the dual benefits of PSZ coating with the new alternative fuels on emission reduction.

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1 Introduction

In the recent decades, energy crisis was created across the world due to faster depletion of fossil and non-renewable fuel resources. Consequently, this has paved the way for global warming which was caused mainly by exhaust emission from vehicles. All these have motivated many researchers to explore solutions for depletion of fossil fuel and to find an alternative fuel from renewable resources with lower exhaust emission. To overcome the challenges, governments revise the norms regularly to check the exhaust emission from automobiles.

The degradation of natural resources, dependency on fossil fuel and hike in oil prices lead to the thirst for finding an alternative. Burning of fossil fuel causes emission of greenhouse gases like carbon monoxide, hydrocarbon, nitrous oxide, etc., which leads to global warming. To reduce the effects of green house gases and prevent global warming, an alternative is essential. Biodiesel is the most promising and eco-friendly alternative to the fossil fuel, because it is non-toxic, renewable and biodegradable resource [1–4]. Biodiesel consists of 12 % of oxygen which enables complete combustion and produces less emission.

From the recent researches, it has been observed that biodiesels have been identified as promising alternative fuels for engines. Biodiesel have been produced by the traditional method called Transesterification process from various non-edible seeds like *Manketti* seed [5], Australian beauty leaf [6], *Calophyllum inophyllum* [7, 8], *Moringa oleifera* [9], *Putranjiva roxburghii* [10], *Thevetia peruviana* [11], *Yucca aloifolia* [12], *Annona* seed [13], linseed [14] and so on. The biodiesel fuels were blended with diesel fuel and used in diesel engine after undergoing transesterification process [15, 16]. Biodiesels exhibit better performance than the conventional fuels, which also depend on fuel property and in-cylinder pressures, whereas lower emission can be achieved with biodiesels. The factors like high combustion temperature, fuel quenching and fuel injection pressure [17] play an important role in biodiesel. Ashraful et al. [18] investigated the physiochemical properties of palm and *C. inophyllum* biodiesel. They observed better engine performance with lower percentage of biodiesel blends and better emission characteristics with higher percentage of biodiesel blends. The lowest smoke intensity was found at 27.5 % for PB10 and CI10 biodiesel blends compared with diesel fuel. Gorgi et al. [19] investigated the effect of weather conditions on the engine performance. They developed two mathematical models using artificial neural network (ANN) and regression technique for predicting the power and brake-specific fuel consumption (BSFC) of the IC engine. The neural network model with hidden layer of 5 and 10 neurons showed better result for power and BSFC. This model helps the researchers to evaluate the engine performance parameters at variable climatic operating conditions.

Many researchers, on the other hand, have also attempted with thermal barrier coating as better technique to reduce exhaust emission. Thermal barrier coating was provided in cylinder head, piston crown, inlet and exhaust values using plasma spray technique. Musthafa et al. [20] used fly ash as coating material with rice bran and *Pongamia* methyl ester with diesel as fuels in conventional engine. The results showed that the performance was improved with reduction in emission. Also, 20 percent ratio of fuel sample with above coating showed a better result than other fuel samples. Biodiesel was prepared from *Pongamia pinnata* and neem oil by transesterification with aluminium titanate [21] as a coating material in diesel engine. This combination was noticed with lower emission than other fuel samples in same engine operating condition. Also, performance was found to increase with coated engine due to high combustion temperature by thermal barrier coating.

Aydin [22] used Rainbow-186 single cylinder diesel engine with cotton seed oil and sunflower oil in uncoated and coated (Zirconium oxide) engine at full load by varying the engine speed. It was concluded that performance was improved and emissions marginally decreased with prepared sample in coated engine condition. *Kapok* oil methyl ester [23] was attempted in partially stabilized zirconia engine and observed a better improvement in performance and reduction in emission (except NOx) for coated condition than in uncoated engine condition. Biodiesel 50 % blend sample showed the better results than other fuels in coated engine operation. The use of thermal barrier coating was found to show better result than uncoated engine in all aspects. Also it was a promising method for emission reduction in diesel engine. Mosarof et al. [24] observed the friction and wear characteristics of palm and *C. inophyllum* biodiesel blends at a fully loaded diesel engine in the speed range of 1000–2400 rpm with 40 and 80 kg load. They conducted friction and wear tests using four-ball tester with constant speed of 1800 rpm. They observed that palm oil (PB-20) has good lubrication performance in terms of friction and wear and produced relatively lower CO and HC emissions than the diesel and biodiesel blends in engine.

Exhaust emission from engine leads to respiratory issues in human beings. Some of the researchers developed a model of respiratory unit and analysed their characteristics using computational fluid dynamics (CFD). Gorgi et al. [25] investigated the detailed two-phase flow modelling of airflow, transport and deposition of micro-particles (1–10 mm) in a realistic tracheobronchial airway geometry based on CT scan images under various breathing conditions (i.e. 10–60 L/min). Gorgi et al. [26] investigated the airflow behaviour and particle transport and deposition in different breathing conditions such as light breathing condition (15 L/min), normal breathing condition (30 L/min) and heavy breathing condition (60 L/min). The realistic geometry data were reconstructed from CT scan images of the human airways with 0.5 mm thickness of slices. Computational fluid dynamics (CFD) was applied to characterize the fluid flow in human airway models.

In the present study, non-edible oils like cashew nut shell liquid oil, orange oil and neem oil were converted into methyl ester components using transesterification process. Each individual methyl ester was blended with conventional diesel fuel in 20:80 ratios, respectively. Also, partially stabilized zirconia was used as insulating material to provide thermal barrier coating to engine. Investigation on emission analysis was carried out for diesel and blended fuel samples in coated and uncoated engines and the results were compared and analysed. Similar studies were found in the literature, but comparative study on fixed blend ratio for different oils with partially stabilized zirconia thermal barrier coating is scanty.

2 Materials and methods

2.1 Non-edible oil selection and biodiesel production

There were many non-edible oils available in the market. In the present study, three non-edible oils were selected and purchased from local market located in Coimbatore, Tamilnadu. The oils used in the study were (1) Cashew nut shell liquid oil, (2) Raw orange oil and (3) Raw neem oil.

Table 1 Acid value of non-edible oils

Non-edible oils	Acid Value (mg KOH/g)
Cashew nut shell liquid oil	15.2
Orange oil	3.8
Neem oil	31.6

Table 1 shows the acid value of non-edible oils. 'Transesterification' was carried out for separation of esters from non-edible oils. Figure 1 shows the block diagram for the production of biodiesel.

2.1.1 Cashew nut shell liquid biodiesel

Raw cashew nut shell liquid oil was preheated for few minutes about 65 °C. The known quantity of sodium hydroxide was mixed with methanol, and then preheated cashew nut shell liquid oil was introduced. The process was carried out at 60–65 °C for 90 min with the help of soxhlet condenser to minimize methanol vapourization. After the stipulated time, solution was transferred to separation funnel and allowed to settle for 1 day without any disturbance. It was found that no separation in layers of prepared sample was identified and no trace of glycerine was found.

2.1.2 Orange oil biodiesel

The purchased raw orange oil was filtered and heated to about 60 °C which removes the moisture content. For transesterification process, sodium methoxide was prepared from a known quantity of sodium hydroxide and methanol which was a homogeneous mixture. Sodium methoxide was mixed with pre-heated raw orange oil and heated to about 80 °C for a period of 60 min. The chemically treated raw orange oil was transferred to separation funnel and allowed to settle for 8 h. After the stipulated time, two distinct layers were observed, where upper layer was occupied with crude glycerine and lower layer with orange oil methyl ester. The lower layer was separated and allowed to react thrice with warm distilled water to remove excess catalyst and alcohol. Ultimately, the final ester was heated to about 80 °C to remove the water molecules and increase the purity of obtained sample.

2.1.3 Neem oil biodiesel

A known quantity of neem oil was heated to about 60 °C for few minutes followed by addition of methanol to the solution for 5 min continuously. A small quantity of sulphuric acid was admitted to the prepared sample and heated to 65 °C for more than 60 min in soxhlet condenser. The solution was transferred to separation funnel and remains undisturbed for 1 day. Thus, two layers were identified. The upper layer consists of impurities, excess alcohol and sulphuric acid. The lower layer was again heated to about 55 °C and mixed with sodium methoxide solution (mixture of sodium hydroxide and methanol) for about 60 min at 55 °C. The solution was transferred to a separation funnel and allowed to settle for 24 h. The lower layer consists of crude glycerine whereas the upper layer contains the esters of neem oil. Esters of neem oil were purified by triple washing with warm distilled water. To remove the water molecules and to obtain neem oil methyl ester, the purified solution was heated to about 60 °C.

2.2 Fuel samples

In biodiesel samples, 20 % biodiesel blend produced better results than other blending ratios [23]. Thus, 20 % prepared biodiesel samples were blended with 80 % neat diesel fuel under volumetric condition. The samples attempted in the present study were 1. B1 (20 % cashew nut shell liquid methyl ester with 80 % diesel fuel) 2. B2 (20 % orange oil methyl ester with 80 % diesel fuel), 3. B3 (20 % neem oil methyl ester with 80 % diesel fuel). The above-mentioned

Fig. 1 Block diagram for production of biodiesel

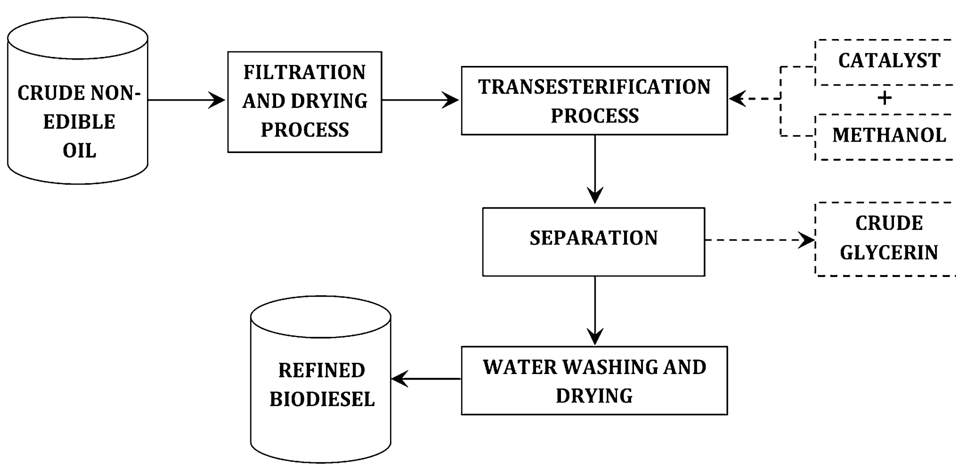

Table 2 Thermal and physical properties of diesel fuel, prepared methyl esters and blended fuel samples

Property	Density (kg/m^3)[a]	Kinematic viscosity @ 40 °C (cSt)[a]	Flash point (°C)[a]	Gross calorific value (MJ/kg)[a]	Calculated cetane index
Diesel	823.1	3.90	56	43.2	47
CNSLME	902.4	4.21	162	33.8	40
B1	830.9	3.20	55	40.1	–
OME	811.2	3.48	161	34.4	46
B2	855.6	3.53	66	40.0	–
NOME	862.3	4.40	167	41.0	52
B3	836.4	4.03	73	43.0	–

[a] All properties were identified based on ASTM standards under laboratory condition

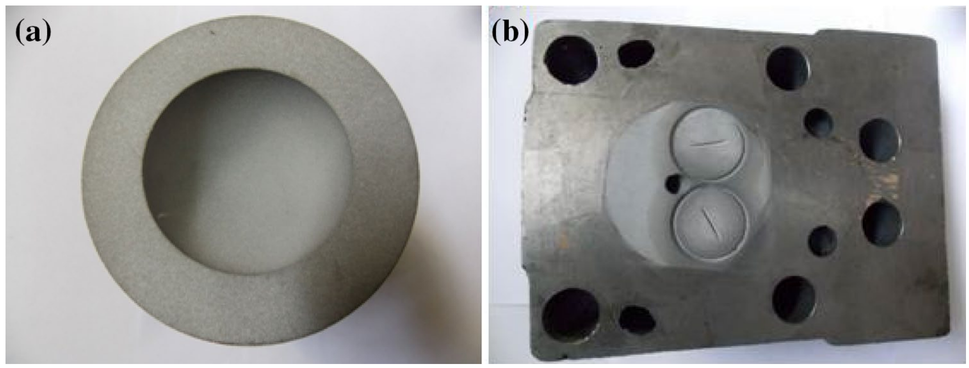

Fig. 2 **a** PSZ-coated piston crown **b** PSZ-coated cylinder head, intake and exhaust valve

fuels were benchmarked with neat diesel fuel under same operating condition. Table 2 shows the various thermal and physical properties of neat diesel fuel, prepared esters and blended fuel samples.

2.3 Thermal barrier coating for engine combustion chamber components

Figure 2a, b shows the parts of the combustion chamber with thermal barrier coating. Partially stabilized zirconia (PSZ) was used as the thermal barrier coating material and applied using plasma spray technique. The engine selected for experiment has a compression ratio of 18. To maintain the same compression ratio during experimentation, micromachining was carried out in piston crown area. After micromachining, surface was cleaned with ethylene glycol to provide better bond coat between piston and ceramic coating material [23].

2.4 Experimental setup and procedure

Table 3 shows the specifications of experimental setup. Kirloskar TV1 model engine was used for experimentation. Eddy current dynamometer was used to produce brake power to engine. Figure 3 shows the single cylinder four-stroke direct injection diesel engine with eddy current dynamometer and data acquisition system. AVL 444 di-gas analyser was used for measuring CO (in % volume), HC (ppm) and NOx (ppm) emission using NDIR (non-dispersive infra-red) technique. A cold trap and filter element was used to prevent the entry of water vapour in the exhaust sample into the analyser. AVL 437 C free accelerator smokemeter was used to measure smoke density in HSU (Hartridge smoke unit).

Initially, engine was started with diesel fuel in uncoated engine and allowed to run for more than 30 min to attain steady-state condition. The steady-state condition was analysed by measuring the rise in engine outlet water temperature to 50–55 °C. It was ensured that there is no leakage of fuel and lubrication oil before starting the experiment. Loads were given to engine gradually starting from no load condition to full load condition. For each load condition, engine was allowed to run for 10 min and the last 3 min was used for result recording purpose. After completing the experiment, fuel was drained out completely from fuel tank and fuel line. Then, the same procedure was carried out using biodiesel blends with diesel in both coated and uncoated engines.

2.5 Error analysis

An uncertainty analysis has been carried out to check the correctness of the results obtained from the experiment conducted in the engine. Uncertainty and error analysis highly depend on the instruments used, working environment, operating conditions, observations made from the experiment, etc.

Table 3 Specification of experimental setup

Equipment name: Engine	
Make and model	Kirloskar TV1
No. of cylinders	One
Type	Four-stroke, direct injection, diesel engine
Bore × Stroke	87.5 mm × 110 mm
Rated power	5.2 kW at 1500 rpm
Compression ratio	18
Injection pressure	210 bar
Injector nozzle	3 hole type
Dynamometer	Eddy current
Equipment name: gas analyser	
Make and model	AVL 444 di- gas analyser
Measures	CO, HC, NOx
Range	CO: 0–10 (% volume), HC: 0–2000 (ppm), NOx: 0–5000 (ppm)
Equipment name: Smokemeter	
Make and model	AVL 437C free accelerator smokemeter
Measures	Smoke density
Range	0–100 (HSU)

Table 4 shows the experimental uncertainty in the measurement of various performance parameters such as load, speed, fuel flow, temperature, crank angle, and emissions. The total uncertainty during experimentation was calculated using propagation of error technique proposed by Holman [27].

Total uncertainty = square root of [(uncertainty of total fuel consumption)^2 + (uncertainty of brake power)^2 + (uncertainty of brake-specific fuel consumption)^2 + (uncertainty of brake thermal efficiency)^2 + (uncertainty of CO)^2 + (uncertainty of HC)^2 + (uncertainty of NOx)^2 + (uncertainty of smoke)^2 + (uncertainty of exhaust gas indicator temperature)^2 + (uncertainty of pressure pick up)^2] = square root of $[(1)^2 + (0.2)^2 + (1)^2 + (1)^2 + (0.2)^2 + (0.1)^2 + (0.2)^2 + (1)^2 + (0.15)^2 + (1)^2] = \pm 2.27$ %.

The total uncertainty was found to be ±2.27 % for entire test.

3 Results and discussion

3.1 Influence of thermal barrier coating on engine performance characteristics

3.1.1 Brake thermal efficiency

Figure 4 shows the variation of BTE for diesel and other prepared samples with different engine load conditions for coated and uncoated engines. At full load uncoated engine, BTE was observed as 31.8, 31.6, 31.2 and 31 % for diesel, B3, B2 and B1, respectively. Under same operating condition with coated engine, BTE was noticed as 32.9, 32.8, 32.5 and 32.4 % for diesel, B2, B3 and B1, respectively. From the figure, it was found that the BTE for diesel and biodiesel samples increases with the increase in load condition for both coated and uncoated engines. BTE was observed as low at the initial load condition and gradually increasing as the load increases for both engine conditions. In coated engine, a marginal increase in BTE was observed. Increase in efficiency was due to the thermal barrier coating in engine, as the temperature within the combustion chamber was maintained for definite time. Vedharaj et al. [29] used partially stabilized zirconia as coating material in diesel engine with cashewnut shell liquid oil methyl ester to investigate the engine characteristics. They observed increase in brake thermal efficiency with increase in load condition.

3.1.2 Brake-specific fuel consumption

Figure 5 shows the variation of brake-specific fuel consumption with different engine load conditions for coated and uncoated engines. BSFC observed for uncoated engine was 0.33, 0.31, 0.30 and 0.29 kg/kWh for B1, B2, B3 and diesel fuel, respectively. In coated engine, BSFC observed was 0.38, 0.36, 0.35 and 0.34 kg/kWh for B1, B2, B3 and diesel fuel, respectively. From Fig. 5, it was found that the BSFC for diesel and biodiesel samples decreases with the increase in load condition for both coated and uncoated engines. BSFC was found to be high at the initial load condition and declining as the load increases for both engines. In coated engine, decrease in BSFC was due to the thermal barrier coating as the heat was absorbed by the coating in the combustion chamber of the engine. In uncoated engine, decrease in BSFC was due to low calorific value and density of the fuel. Similar results were observed by Musthafa et al. [28] using *Pongamia* methyl ester with Al_2O_3-coated diesel engine.

3.2 Influence of thermal barrier coating on engine emission characteristics

3.2.1 Carbon monoxide

Figure 6 shows the variation of CO emission for diesel and other prepared samples for coated and uncoated engines at different engine load conditions. There were many factors contributing to CO emission like combustion temperature, combustion pressure, air fuel mixture ratio and oxygen content in fuel [21]. In uncoated engine with high load condition, the diesel produces 0.15 %vol., and the biodiesel samples such as B1, B2 and B3 produce 0.13, 0.05 and 0.06 %vol. of CO emission, respectively. In coated engine with high load condition, diesel produces 0.16 %vol., and

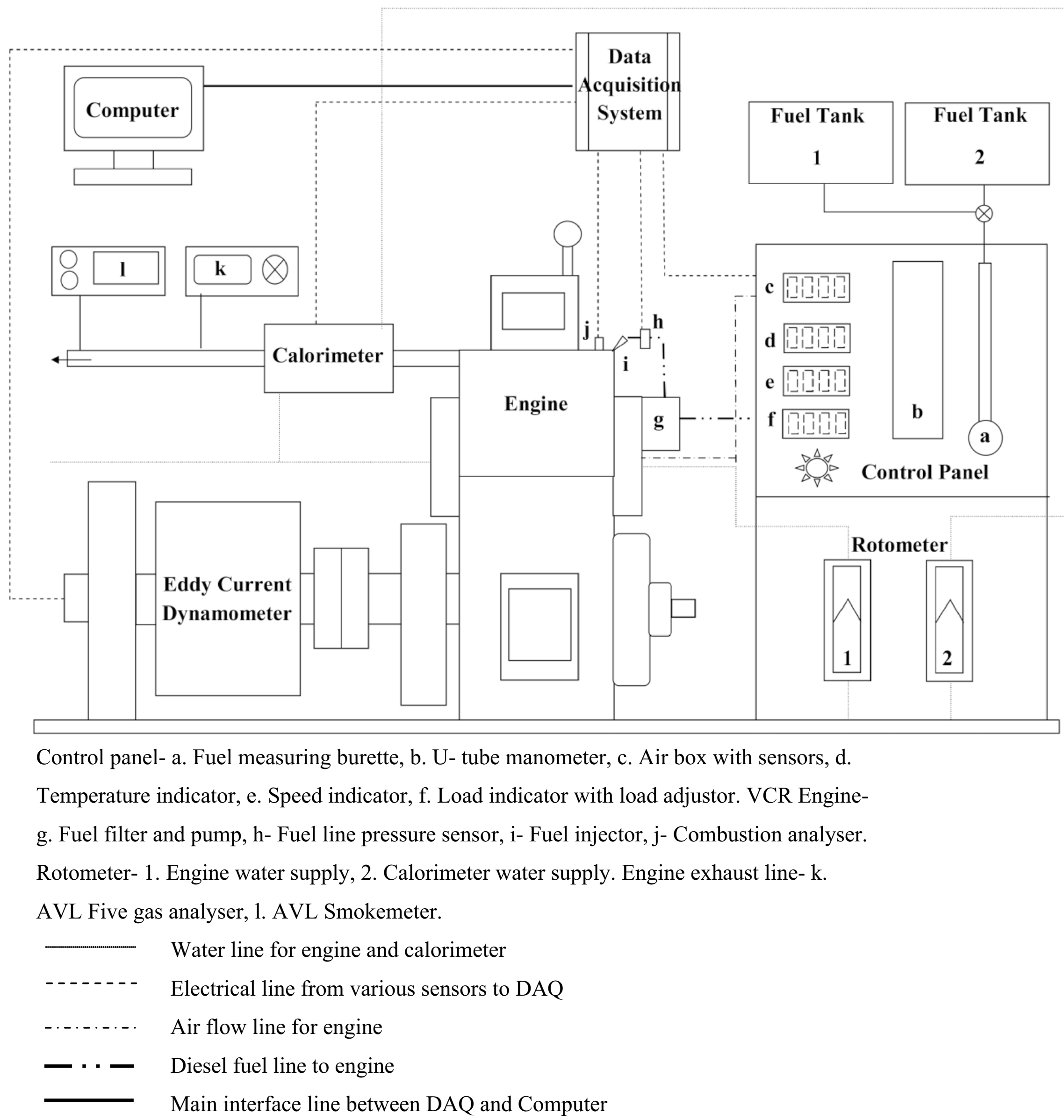

Fig. 3 Schematic diagram of experimental setup [36]

the biodiesel samples such as B1, B2 and B3 produce 0.15, 0.08 and 0.07 %vol. of CO emission, respectively. It was found that diesel produces higher CO emission than prepared fuel samples in both coated and uncoated engines. This increase in CO emission was due to unavailability of oxygen in diesel fuel. Due to lower calorific value and kinematic viscosity, B1 exhibits higher CO emission than other fuel samples. B1 consists of lower spray quality than B2 and B3 [30]. The thermal barrier coating increases the combustion temperature for all fuel blends to achieve complete combustion.

3.2.2 Hydrocarbon

Figure 7 shows the variation of HC emission for diesel and other prepared samples at different load conditions for both coated and uncoated engines. Incomplete combustion and flame quenching were the main reasons for HC emission [31]. The properties of fuel play a vital role in HC emission. Rashedul et al. [32] reported that high cetane index helps in reducing the ignition delay that leads to reduction in HC emission. Diesel possesses cetane index of 47 and biodiesel samples such as B1, B2 and B3 possess the cetane

Table 4 Experimental uncertainty

Parameters	Measuring technique	Accuracy	Errors (±)
Load	Strain gauge type load cell	± 10 N	± 0.2
Speed	Magnetic pickup principle	± 10 rpm	± 0.1
Fuel flow measurement	Volumetric measurement	± 0.1 cc	± 1
Temperature	Thermocouple	± 1 °C	± 0.15
Crank angle encoder	Magnetic pickup principle	±1 deg	± 0.2
Pressure	Magnetic pickup principle	± 0.1 kg	± 0.1
Time	Stop watch (Manual)	± 0.1 s	± 0.2
Manometer deflection	Balancing of column of liquid	± 1 mm	± 1
CO	NDIR technique	± 0.02 % volume	± 0.2
HC	NDIR technique	± 10 ppm	± 0.1
NOx	NDIR technique	± 12 ppm	± 0.2
Smoke	Opacimeter	± 1 HSU	± 1

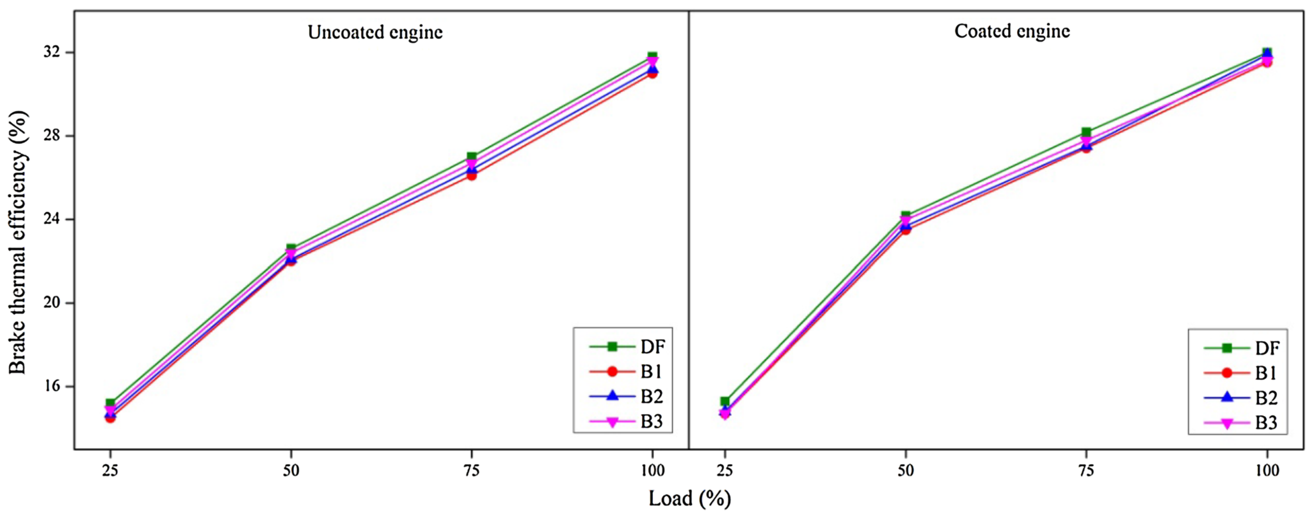

Fig. 4 BTE with various fuels and loads in coated and uncoated engines

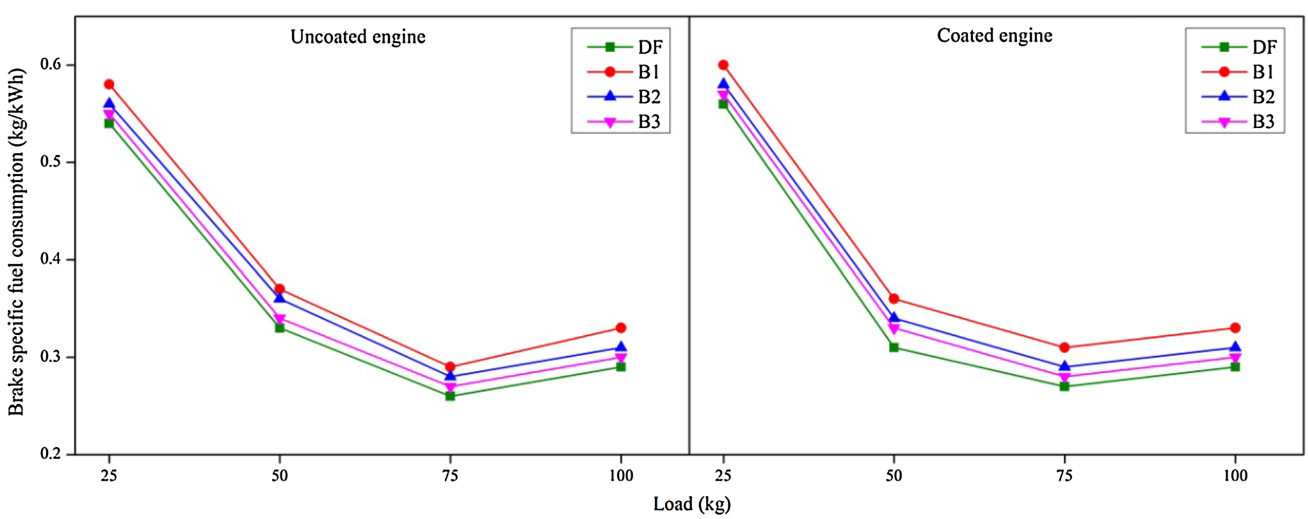

Fig. 5 BSFC with various fuels and loads in coated and uncoated engines

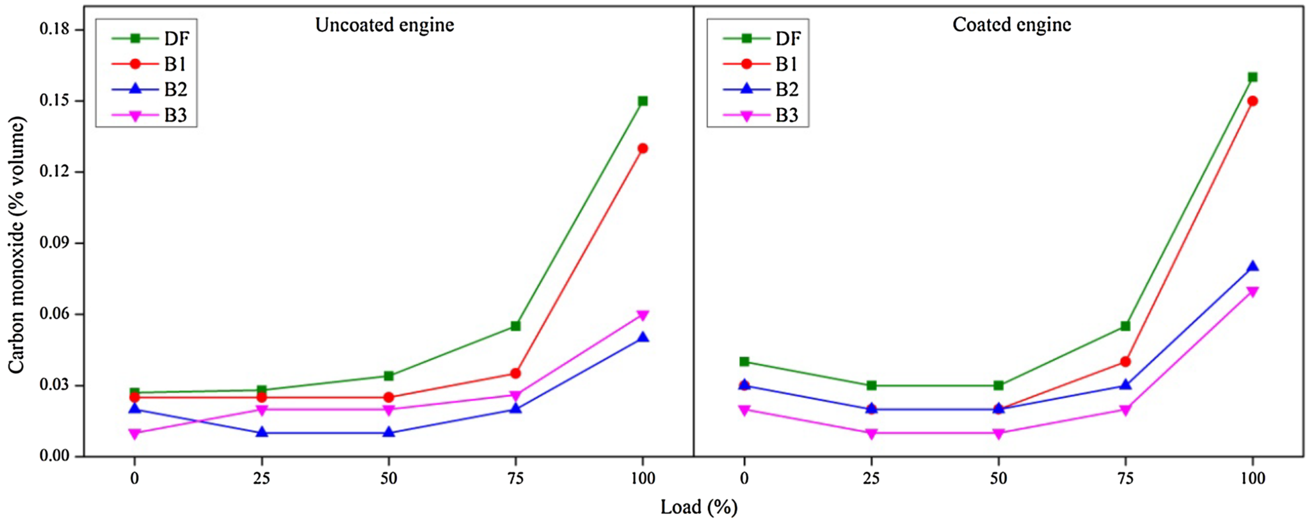

Fig. 6 CO emission with various fuels and loads in coated and uncoated engines

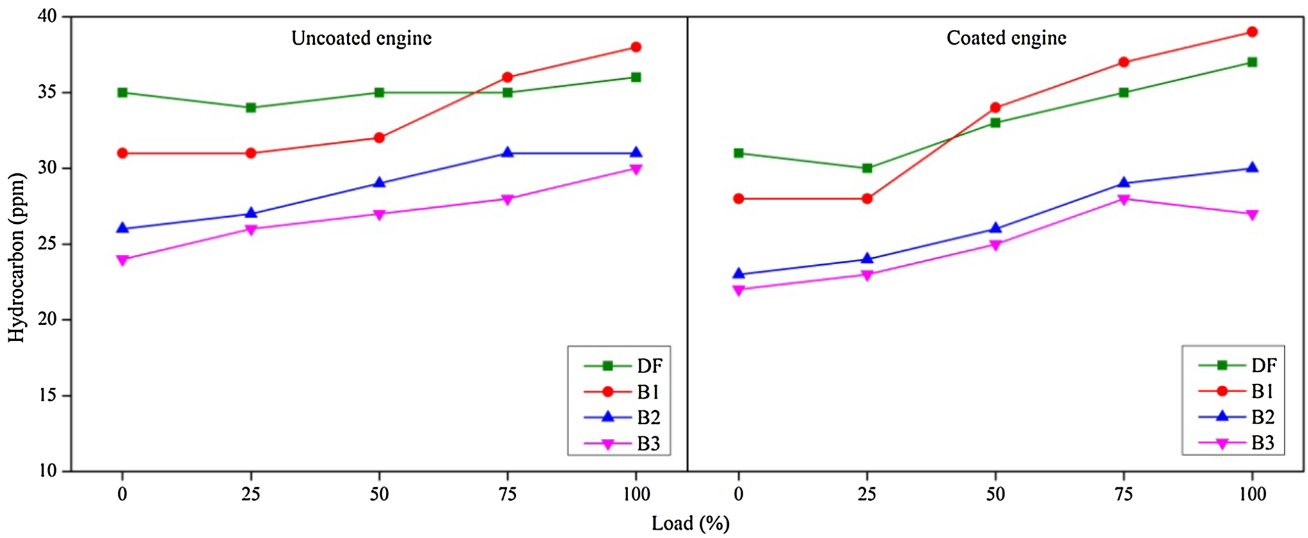

Fig. 7 HC emission with various fuels and loads in coated and uncoated engines

index of 40, 46 and 52, respectively. It was noticed that B1 showed lower cetane number than the other prepared fuel samples, due to the high density and calorific value of the fuel. Consequently, it was found that B1 and diesel show higher HC emission than B2 and B3 in both coated and uncoated engines.

In uncoated engine with high load, HC emission was found as 36 ppm, 38 ppm, 31 ppm and 30 ppm for diesel, B1, B2 and B3, respectively. In coated engine with high load, HC emission was found as 37, 39, 30 and 27 ppm for diesel, B1, B2 and B3 samples, respectively. The fuel samples B2 and B3 show lower HC emission than diesel and B1 in both coated and uncoated engines. This lower emission was achieved due to its higher cetane value than the other fuel samples.

3.2.3 *Oxides of nitrogen*

Variation of NOx emission for diesel and other prepared samples at different engine load conditions for coated and uncoated engines have been shown in Fig. 8. Due to high oxygen content, biodiesel shows higher NOx emission than diesel [33, 34]. The increase in combustion temperature raises NOx emission, especially in coated engine condition [20, 28]. From the present study, in uncoated engine, NOx emission was observed as 451, 562, 496 and 480 ppm for

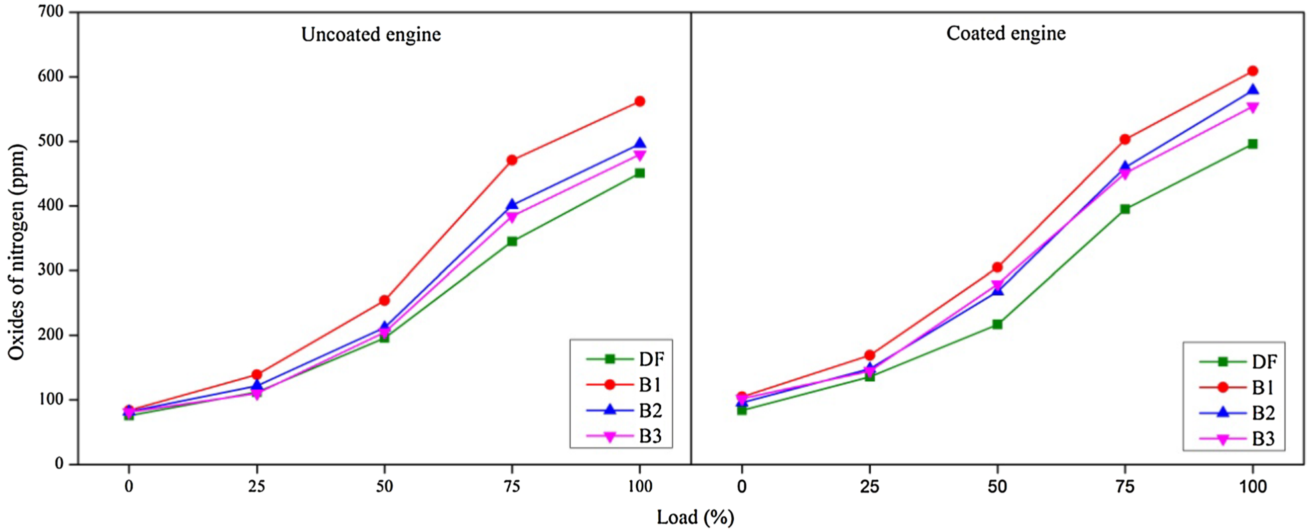

Fig. 8 NOx emission with various fuels and loads in coated and uncoated engines

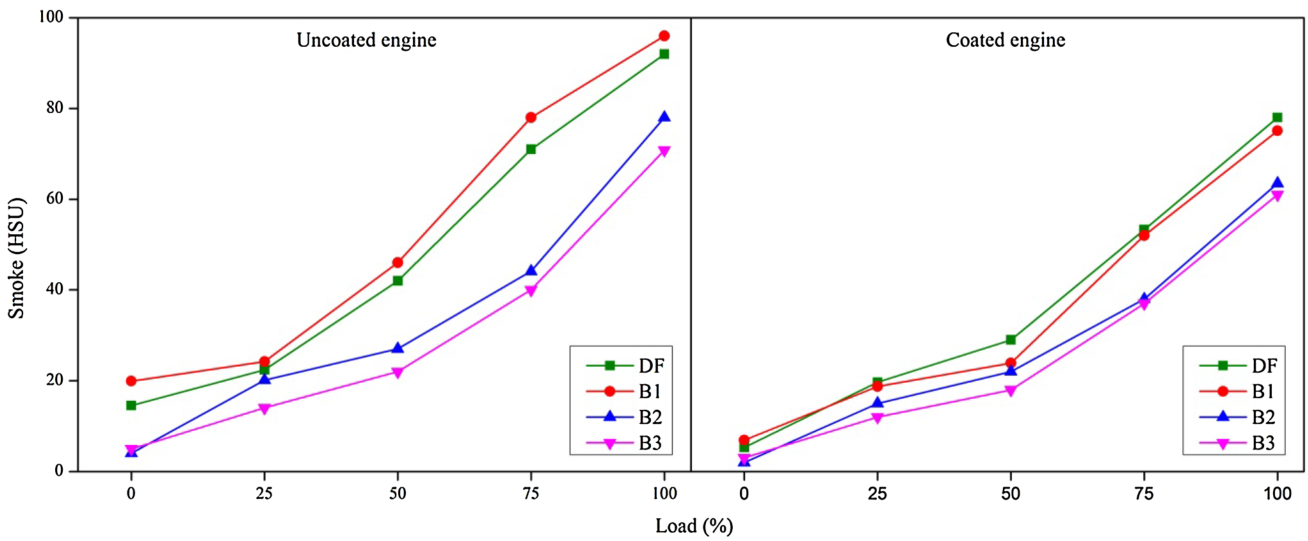

Fig. 9 Smoke emission with various fuels and loads in coated and uncoated engines

diesel fuel, B1, B2 and B3 at full load condition, respectively. In coated engine condition, NOx emission was observed as 496, 609, 579 and 554 ppm for diesel fuel, B1, B2 and B3 at full load condition, respectively. It was found that the coated engine with biodiesel shows higher NOx emission than diesel fuel due to the thermal barrier coating. These types of similar trends were also observed [22, 29, 35] and concluded that high oxygen content and coating were the causes for higher NOx emission.

3.2.4 Smoke

Figure 9 shows the variation of smoke emission for diesel and other prepared samples at different engine load condition for coated and uncoated engines. The engine operated in uncoated condition at full load emits 92 HSU, 96 HSU, 78 HSU and 70.8 HSU of smoke for diesel, B1, B2 and B3 fuels, respectively. In coated engine at full load, results were 78 HSU, 75.1 HSU, 63.5 HSU and 61 HSU for diesel, B1, B2 and B3 samples, respectively. A drastic reduction in the emission was observed in coated engine than uncoated engine at all load condition. The reduction in smoke emission was noticed due to high oxygen content in fuel and high combustion temperature which was achieved due to thermal barrier coating. Similar results were observed [22, 29, 35] using different thermal barrier coatings and biodiesel samples.

4 Conclusion

An investigation on performance and emission was carried out on single cylinder, four-stroke, water cooled, direct injection, diesel engine with eddy current dynamometer. Studies were made in uncoated engine followed by coated engine using partially stabilized zirconia (PSZ) as thermal barrier coating material. In both engines, three samples of biodiesel prepared have been experimented. The following results were obtained from experimentation:

- BTE for diesel, B1, B2 and B3 was observed as low at the initial load condition and gradually increasing as the load increases for both coated and uncoated engines.
- BSFC for diesel, B1, B2 and B3 was observed as high at the initial load condition and declining as the load increases for both coated and uncoated engines.
- CO emission for B2 and B3 was lower compared to diesel and B1 fuel in both coated and uncoated engines due to calorific value and kinematic viscosity.
- B1 and diesel fuel were found to produce higher HC emission than B2 and B3 samples as it has higher cetane value.
- Due to thermal barrier coating, NOx emission was found higher for coated engine than uncoated engine for all fuel samples. However, B2 and B3 prepared samples were found to produce lower NOx emission than other fuels in both conditions.
- Diesel, B1, B2 and B3 were found to produce lower smoke emission in coated engine than in engine without coating, as it has high oxygen content and combustion temperature.

From the experimentation, it can be concluded that B2 (20 % orange oil methyl ester with 80 % diesel) and B3 (20 % neem oil methyl ester and 80 % diesel) might be considered as promising alternative fuels with partially stabilized zirconia (PSZ) coating in diesel engine.

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