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RESEARCH ARTICLE

Low heat rejection diesel engine performance, combustion, and emissions characteristics fuelled by diesel-vegetable oil blend

M. Mohamed Musthafa[1,*]

[1]School of Mechanical Engineering, SASTRA Deemed University, Thanjavur, 613401, India

Abstract

From environmental sustainability, energy security, and economic stability perspectives, transitioning from diesel engines to alternative fuels is significant. Alternative fuels are crucial in creating a sustainable and secure energy landscape. In this study, a 150 μm-thick Aluminium titanate coating was applied to the piston crown and cylinder liner, and blends of 10% raw vegetable oil (Pongamia and Neem) and 90% diesel by volume were tested to determine how these blends would affect the coated engines' characteristics. Using raw vegetable oil at up to 10% of the volume in the coated engine reduces the chemical processing required for biodiesel conversion and the associated cost. A distinguishing feature of this study is the direct incorporation of vegetable oils into diesel fuel at a 10% volumetric ratio for operation in a coated engine. Low heat rejection engines running on diesel-pongamia oil and diesel-neem oil blends of 10% by volume performed the best, with 4.9% and 3.4% higher brake thermal efficiency and 12.6% and 10.93% lower brake specific energy consumption, respectively, than uncoated engine diesel operations. Emission reductions (HC/CO/smoke) for coated engines were 33.3%/56.3%/45.7% with diesel–pongamia and 26.6%/51.5%/39.4% with diesel–neem. While the coated engine demonstrated a slight improvement in combustion behaviour, it was accompanied by an increase in NOx emissions of 25.9% and 19.3% for the diesel–pongamia and diesel–neem oil blends, respectively.

Keywords: Aluminium titanate, diesel, engine characteristics, neem oil, pongamia oil

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1. Introduction

The extensive use of diesel engines has driven the exploration of alternative fuels. A B10 blend (10% biodiesel, 90% diesel by volume) is a viable option, as its thermo-physical properties are comparable to those of diesel, enabling its use without engine modifications. [1]. But the vegetable oil-diesel blend showed lower engine performance and higher NOx emissions [2, 3]. One-third of the heat liberated during the burning of fuel is converted into useful work as brake power, and the remaining two-thirds is lost as waste heat via cooling water, exhaust gases, friction, and radiation. One-third of the heat liberated during the burning of fuel is converted into useful work as brake power, and the remaining two-thirds is lost as waste heat via cooling water, exhaust gases, friction, and radiation. Hence, the waste is converted into work as much as possible by coating the cylinder head, cylinder liner, piston crown, and valves with low-thermal-conductivity ceramic material to reduce heat loss to cooling water and exhaust gases. Theoretically, the engine's efficiency would increase. The literature indicates that various thermal barrier materials, such as zirconia, NiCrB, MgO–ZrO_2, YSZ, PSZ, and sintered silicon nitrate (SSN), have been used to coat engine combustion chamber components over the past two decades [4-7]. Mubarak (2019) reported a significant increase in engine efficiency and reduced HC, CO, and smoke emissions and also noted lower cylinder pressure rise and ignition delay of both coated and uncoated engines running on waste cooking oil-diesel blend. [8]. Selvam et al. (2018) studied a coated engine (the piston was coated with YSZ), powered with diesel and biodiesel, and showed increased performance and lower emissions, except for an increase in NOx [9]. Jena et al. (2018) observed a 3% increase in thermal efficiency and an 8% decrease in fuel consumption for $FeCl_3$-coated diesel engines compared to uncoated engines. But NOx and CO_2 were increased. [10]. Mohamed Musthafa (2017) reported a slight increase in efficiency and a decrease in NOx of a PSZ-coated

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*Corresponding Author
E-mail Adress: mmmusthafa71@gmail.com

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engine powered by DTBP-added biodiesel [11]. Li et al. (2016) also detected an increase in the efficiency of the coated engine [12]. Sivakumar and Senthil Kumar (2014) found that an increase in efficiency and greater HC and CO emissions for the YSZ-piston crown-coated engine [13]. Shrigiri (2020) tested a coated engine running on tobacco-seed biodiesel and reported enhanced performance and reduced emissions. [14]. Parthasarathy Murugesan et al. (2023) conducted a test on a coated engine fuelled by a B20 (waste plastic oil) blend with 20 ppm copper nanotubes, noting improved performance and reduced emissions. [15]. Vidyasagar Reddy et al. (2024) reported enhanced engine performance and reduced emissions (except NOx) for blended fuels comprising diesel, mahua, and jatropha [16]. Annamalai et al. (2024) investigated a PSZ-coated engine fuelled with B20 (tamanu biodiesel) and 15% exhaust gas recirculation and observed increased engine efficiency and reduced emissions [17]. Srinivas Reddy et al. (2022) observed reductions in PM, CO, and HC emissions from coated and uncoated engines fuelled with blends of diesel, algae oil, diethyl ether (DEE), and copper nanoparticles at advanced injection timing. [18]. Rabbani et al. (2023) reported significant reductions in PM, CO, NOx, and HC emissions in an LHR engine operating on a plastic oil–diesel blend with optimised injection timing at full load. [19]. Krishna et al. (2023) found that reduced PM, CO, and HC emissions from a coated engine running on a dual-fuel blend of cottonseed biodiesel and biogas. [20]. Several literature studies reported that uncoated engines fuelled with vegetable oil-diesel blends reduced engine efficiency, increased fuel consumption, and increased exhaust emissions. To address the existing research gap, a low heat rejection (LHR) diesel engine is employed to facilitate efficient combustion of highly viscous vegetable oil–diesel blends. Also, the literature indicates that aluminium titanate as a thermal barrier material has not been explored. Hence, this study intends to investigate the engine characteristics of low thermal conductivity (enabling effective thermal insulation). Aluminium titanate coated on the piston crown and liner when fuelled with two different vegetable oils and diesel. viz., Pongamia oil blend and neem oil blend.

2. Materials and methods

2.1. Vegetable oils

Pongamia oil and neem oil are superior to other non-edible oils due to their diverse applications, environmental benefits, and unique properties. These two oils were obtained from their seeds using the Soxhlet extraction method. Raw oils are heated to remove hexane and water. [21]. B10 blends were prepared by mixing diesel and raw oil at a 90:10 ratio. The properties of blends are tested and listed in Table 1.

Table 1. Key physicochemical properties of diesel, vegetable oils, and diesel–vegetable oil blends [22]

Properties	Method of measurement	Diesel	Raw Pongamia oil	Raw Neem oil	Diesel -Pongamia oil (B10)	Diesel- Neem oil(B10)	ASTM standards
Density kg.m-3	Digital density meter	0.86	0.924	0.96	0.884	0.892	D4052
Viscosity at 40 °C (cSt)	Kinematic viscometer	2.5	19.5.	21.4	4.2	4.62	D445
Heating Value (kJ/kg)	Bomb calorimeter	43500	40240	40570	42340	41270	D240
Flashpoint(°C)	Pensky–Martens Closed Cup Tester	47	194	152	65	66	D93
Fire point(°C)		55	212	167	72	74	D92
Cetane Number	Ignition Quality Tester	47	49	51	50	49	D613

2.2. Thermal barrier coating

Detonation gun (d-gun) coating, as shown in Figure 1, is often considered superior to other thermal spray techniques due to its high particle velocity and temperature, superior coating quality, versatility in material application, cost-effectiveness, and low substrate temperature. It contains a water-cooled barrel for supplying nitrogen, oxygen, fuel gas, and aluminium titanate powder and a spark plug to ignite the mixture of fuel gas and oxygen. Once the fuel gas is burnt, aluminium titanate powder is propelled at high velocity through the barrel, resulting in the formation of a dense 150 µm thick coating on the piston crown and cylinder. Table 2 outlines the methods adopted for coating thickness measurement, whereas Table 3 presents the physicochemical properties of aluminium titanate (Al_2TiO_5).

In the methods mentioned above, cross-sectional scanning electron microscopy (SEM) is highly accurate, direct, and suitable for micron- to sub-micron coatings.

Principle: A coated sample is sectioned, polished, and imaged using SEM. The coating–substrate interface and surface are visible, allowing direct thickness measurement.

Table 2. Recommended approaches for aluminium titanate coating measurements.

Method	Accuracy	Suitable Coating Thickness
Cross-sectional SEM	High	1–300 µm
Optical Microscopy	Moderate	>10 µm
Eddy Current Gauge	Moderate	5–200 µm
Ultrasonic	Low–Moderate	>20 µm
FIB-SEM	Very High	<5 µm

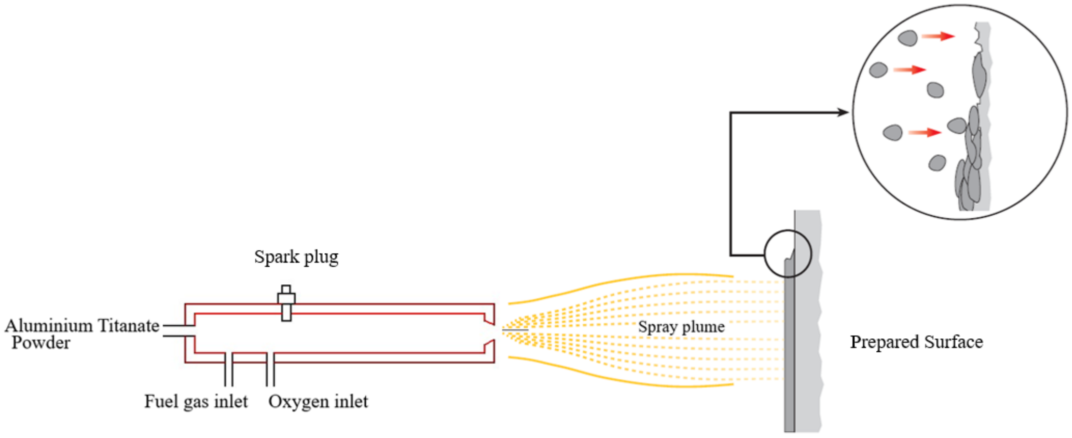

Figure 1. Detonation gun coating

Table 3. The key properties of Aluminium titanate [20]

Property	Value/Characteristic
Chemical Formula	Al_2TiO_5
Crystal Structure	Orthorhombic
Appearance	Gray or bluish ceramic
Melting Point	1860 °C
Heat conductivity	1–2 W/m °C
Operating Temperature	Up to 1400–1500 °C
Compressive Strength	100–200 MPa
Young's Modulus	100–130 GPa
Porosity	Often 10–30%

2.3. Experimental setup

Figure 2 illustrates the experimental engine test rig, and Table 3 summarizes the engine specifications. The engine test rig is fitted with a data acquisition system and an engine software tool to measure the pressure rise during combustion as a function of crank angle. A Delta 1600L exhaust gas analyser was used to measure exhaust emissions. Its specifications are listed in Table 4. The diesel-vegetable oil blend was prepared by adding 900 ml of diesel and 100 ml of Pongamia/neem raw oil to a beaker and stirring with a magnetic stirrer at room temperature for approximately 10–15 minutes. Check for phase stability and absence of separation. The blend was stored in airtight, labelled containers before engine testing. The blend was designated as B10. The coated and uncoated engine characteristic test was conducted for the test fuels under the same load spectrum for analysis.

Figure 2. Experimental setup (photographic view)

Table 4. Test engine specifications

Engine rated power	5.7 kW
Engine rated speed	1500 rpm
Cylinder diameter	88.6 mm
Cylinder stroke length	112 mm
Swept volume	662.45 cc
Compression ratio	17
Loading device	Eddy current dynamometer
Fuel Injection pressure	210 bar
Fuel injection timing	22 degree CA

Table 5. Gas analyser specifications and measurement parameters

Exhaust gas	Range	Precision	Resolution
HC	0-10000	± 1ppm	10 ppm
CO	0-10%	±0.05%	0.01% volume
CO_2	0-20%	±0.05%	0.001% by volume
O_2	0-20%	± 0.01%	0.01% by volume
NOx	0-5000ppm	± 50 ppm	1ppm

Uncertainty about this experimental setup

$$= \sqrt{\begin{matrix}(\text{Apply load})^2 + (\text{rated speed})^2 + (\text{pressure})^2 + \\ (\text{temperature})^2 + (\text{fuel consumption})^2\end{matrix}}$$

$$= \sqrt{[(0.22)^2 + (0.22)^2 + (0.41)^2 + (0.26)^2 + (0.22)^2]}$$

$$= \pm 0.6292\$$$

3. Results and discussion

The examination of engine characteristics of aluminium titanate-coated diesel engines running on diesel and B10 blends at different loads for result analysis.

3.1. Brake thermal efficiency

From Graph 3, it was observed that coated engines running on diesel-pongamia oil and diesel-neem oil blends performed the best, with a 4.9% & 3.4% higher engine thermal efficiency at maximum load due to reducing heat losses, improving the combustion of higher-viscosity fuels, and leveraging the oxygen content of vegetable oils for complete combustion [23]. The diesel-Pongamia oil blend used in the coated engine showed a 1.5% increase in brake power efficiency. It is closer to diesel fuel in uncoated engine operation than the diesel-neem oil blend due to its lower viscosity, higher calorific value, and cetane number. Similar results were noted in other studies [24, 25].

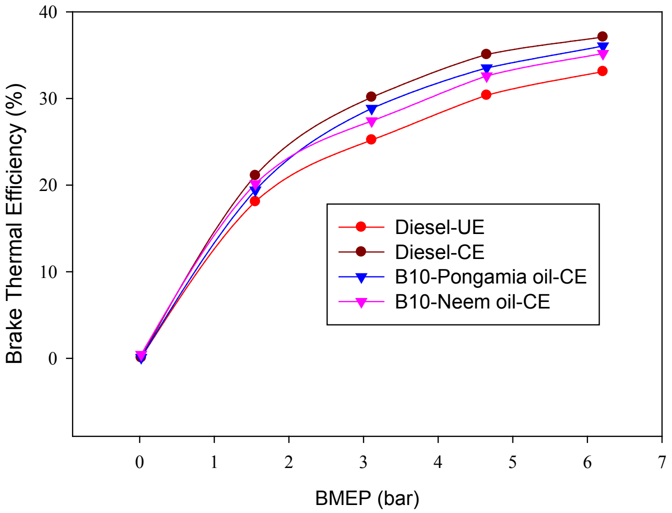

Figure 3. Variation of brake thermal efficiency with brake mean effective pressure for the test fuels

3.2. Brake-specific energy consumption

Figure 4 illustrates the variation of BSEC with load for the test fuels. At maximum load, reductions of 12.6% and 10.93% were observed for diesel-pongamia and diesel-neem blends, respectively, relative to uncoated engine diesel operation. The decrease is attributed to improved thermal insulation and enhanced combustion efficiency (25). The diesel-Pongamia oil blend gives a 1.7% greater reduction of energy consumption than the diesel-neem oil blend, owing to its superior thermal properties.

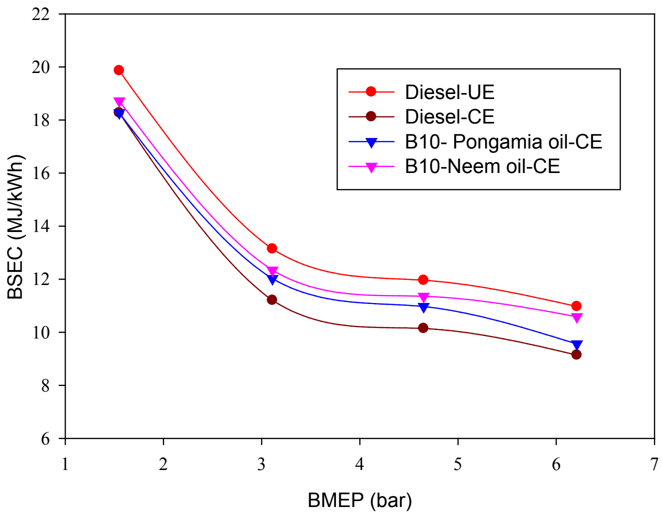

Figure 4. Brake-specific energy consumption vs. brake means effective pressure for the test fuels

3.3. Exhaust gas temperature

Figure 5 illustrates the variation of EGT with load for coated and uncoated engines using diesel and B10 blends. EGT increases with load because of increased fuel consumption. However, the coated engine operating on diesel–pongamia and diesel–neem blends exhibited lower EGT by 15% and 9%, respectively, compared to uncoated diesel operation, indicating improved combustion efficiency and reduced exhaust heat losses (10). A coated engine significantly reduces heat loss to the exhaust gas, resulting in a higher in-cylinder temperature.

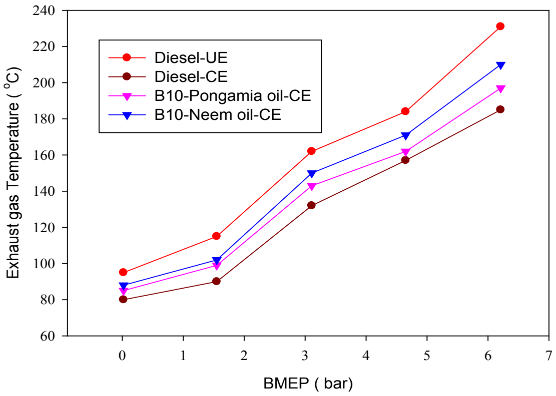

Figure 5. Influence of brake mean effective pressure on exhaust gas temperature for the tested fuels

3.4. The heat losses to engine cooling water and exhaust gas

Conducting a heat balance test on a diesel engine in both coated and uncoated states reveals a significant reduction in heat to the cooling water and exhaust gas. Applying thermal barrier coatings (TBCs) in engine components reduces heat loss to the cooling system and alters the distribution of exhaust energy. Figures 6 and 7 show the percentage heat loss to cooling water and to exhaust gas, respectively, as a function of engine load. In uncoated engines (UE), approximately 30% of the fuel's energy is lost to the cooling system. The implementation of TBCs in coated engines reduces this heat loss. Studies have reported that coated engines exhibit a significant reduction in cooling-water temperature, leading to improved thermal efficiency (15). It was noted that the cooling water temperature was higher. Hence, the diesel-Pongamia oil blend enhanced engine efficiency in the coated engine, reduced by 4% and 2% for the diesel-Pongamia and diesel-neem oil blends, respectively.

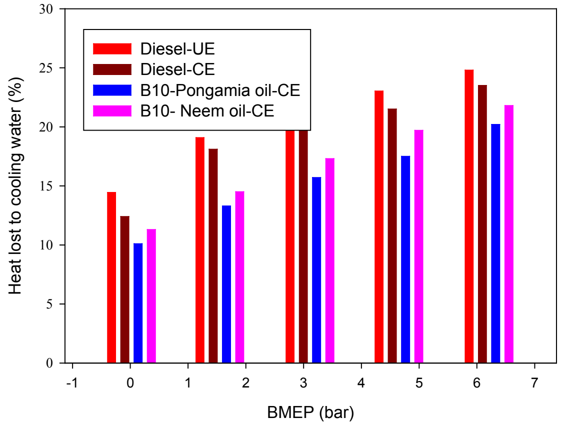

Figure 6. Percentage of heat lost to the cooling water for the test fuels

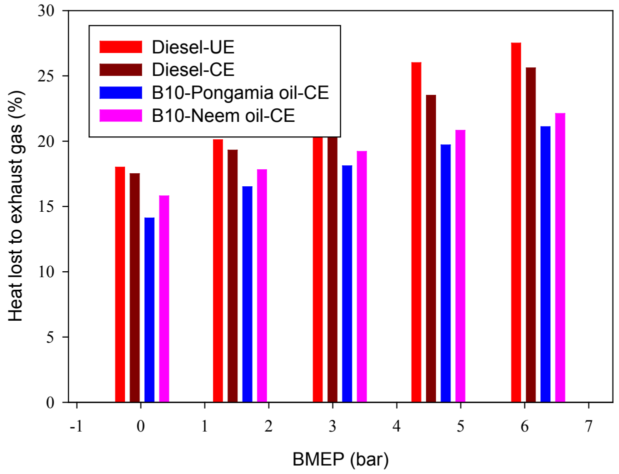

Figure 7. Percentage of heat lost to the exhaust gas for the test fuels

3.5. Maximum cylinder pressure

Figure 8 presents the maximum cylinder pressure versus crank angle for the test engines. The pressure rise is mainly dictated by premixed combustion characteristics [22]. The coated engine showed consistently higher in-cylinder pressures than the uncoated engine, with peak pressure increments of 4 bar and 4.5 bar for diesel–neem and diesel–pongamia blends, respectively. The reason might be the low-thermal-conductivity coating material, which reduces heat loss to the cooling fluid and exhaust gas, leading to higher in-cylinder temperatures and pressures.

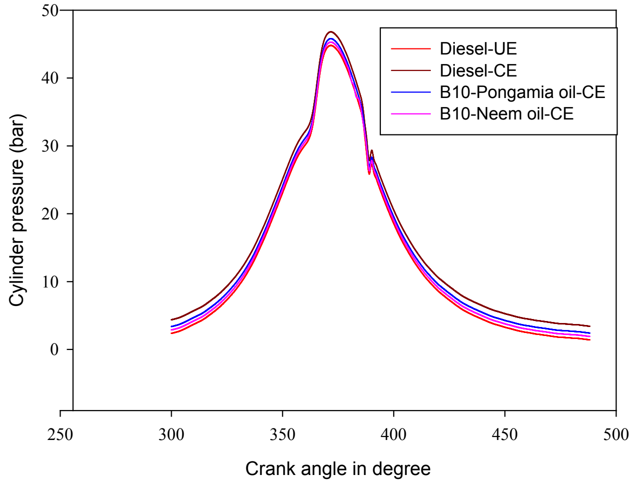

Figure 8. Variation of cylinder pressure versus crank angle in degree

3.6. Cumulative heat release rate

Figure 9 illustrates the cumulative heat release rate versus crank angle at maximum engine load for coated and uncoated engines. The literature indicates that the accumulated heat release rate in the premixed combustion phase depends on delayed ignition and the burning rate [9, 11]. The maximum heat release rate for diesel and B10 fuels under coated conditions was higher than that observed in a conventional diesel engine. It was noted that 0.95 kJ/cycle and 0.82 kJ/cycle were for diesel-pongamia oil and diesel-neem oil, respectively. The reason might be that elevated temperatures in coated engines improve combustion, leading to a more rapid and complete release of energy from the fuel-air mixture. This result in a steeper CHR curve compared to uncoated engines. Higher in-cylinder temperatures facilitate better atomization and vaporization of the fuel, especially for biodiesel blends. This improved fuel-air mixing contributes to more efficient combustion and increased CHR. Cumulative heat release rate disturbance between 380° and 400° crank angle, due to residual fuel burning after the main combustion event, leading to fluctuations in heat release, and inhomogeneous mixing of fuel and air can result in pockets of rich or lean mixtures.

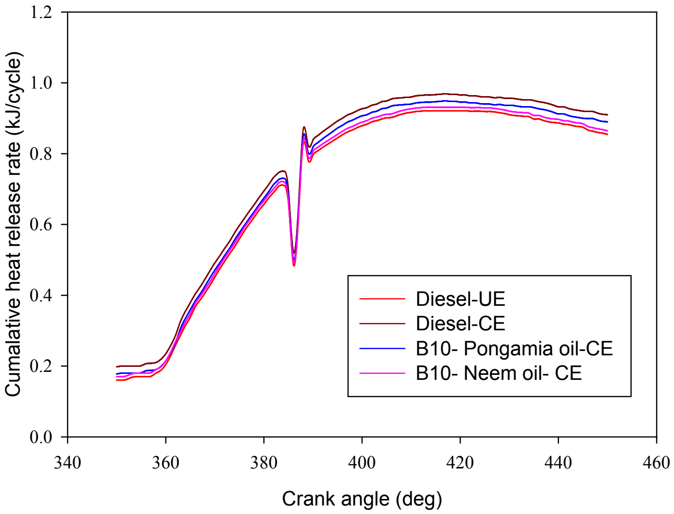

Figure 9. Variation of cumulative heat release rate versus crank angle in degree

4. Emission characteristics

The exhaust emissions have been discussed in the section. The literature has reported significant reductions in HC, CO, and CO_2 emissions but a substantial decrease in diesel engine efficiency when fuelled with biodiesel [24-27].

4.1. Hydrocarbon emission

Figure 10 illustrates HC emissions as a function of load. HC emissions decreased with increasing load due to improved combustion conditions. Compared to uncoated diesel operation, the coated engine achieved reductions of 33.3% and 26.6% for diesel–pongamia and diesel–neem blends, respectively. HC emissions decreased in the coated engine compared with the uncoated engine during diesel operation. Coated engine reported lower HC emissions for both fuel blends due to enhanced heat retention in the combustion chamber, leading to more efficient fuel combustion. The pongamia oil blend was also noted to have lower emissions than the neem oil blend due to its higher oxygen content, which promotes complete combustion [26].

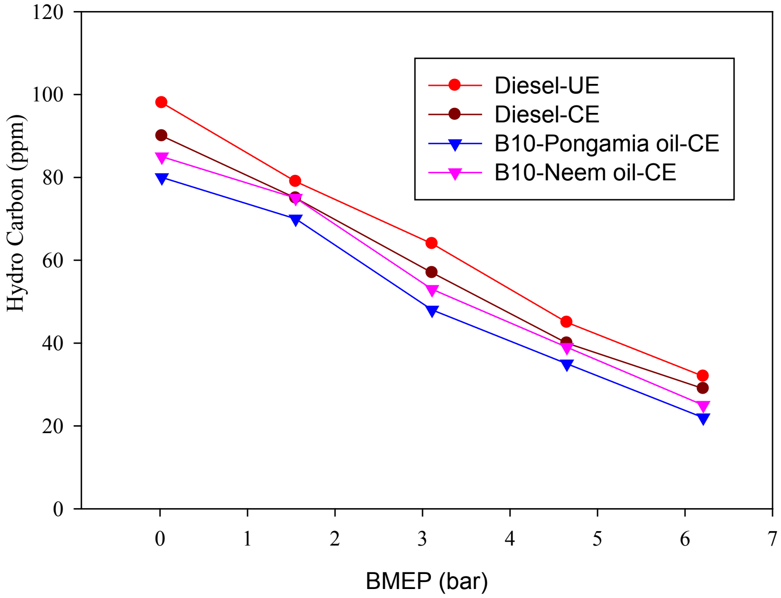

Figure 10. Hydrocarbon emissions vs. brake mean effective pressure for the test fuels

4.2. Carbon monoxide emission

Figure 11 reveals the variations of carbon monoxide emission for both coated and uncoated engines against BMEP. It was noted that there was a drastic reduction in CO emissions at higher loads in the coated engine with B10 fuels compared with the uncoated engine during diesel operation. It was perceived that a percentage decrease in CO emission by 56.3% and 36.9%, respectively, for diesel-pongamia oil and diesel-neem oil used in coated engines is greater than that of uncoated diesel operation. The diesel-Pongamia oil blend shows lower CO emissions than the B10-neem oil blend due to the higher oxygen content in the blend. The significant reduction in carbon monoxide (CO) emissions at higher loads in coated diesel engines is due to a higher thermal environment facilitated by thermal barrier coatings, which enables finer atomization and rapid vaporization of fuel and enhanced combustion efficiency [15, 24].

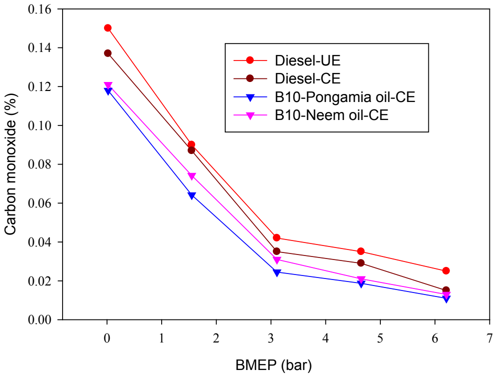

Figure 11. Carbon monoxide emissions vs. brake mean effective pressure for the test fuels

4.3. NO$_x$ emission

Literature reported an increase in NOx emissions for biodiesel used in uncoated and coated engines [9]. Figure 12 also shows higher NOx emissions from the coated engine than from the uncoated engine, especially at peak loads. A percentage increase in NOx emission was perceived by 25.9% and 19.3%, respectively, for diesel-pongamia oil and diesel-neem oil used in coated engines compared to uncoated diesel operation. The diesel-neem oil blend produces lower NOx emissions than the diesel-Pongamia oil blend due to its lower oxygen content. Thermal NOx is formed due to the higher combustion temperature of the coated engine [12, 21]. Optimising exhaust gas recirculation, advanced injection timing, and ethanol-biodiesel blending are effective methods for reducing NOx emissions from coated engines.

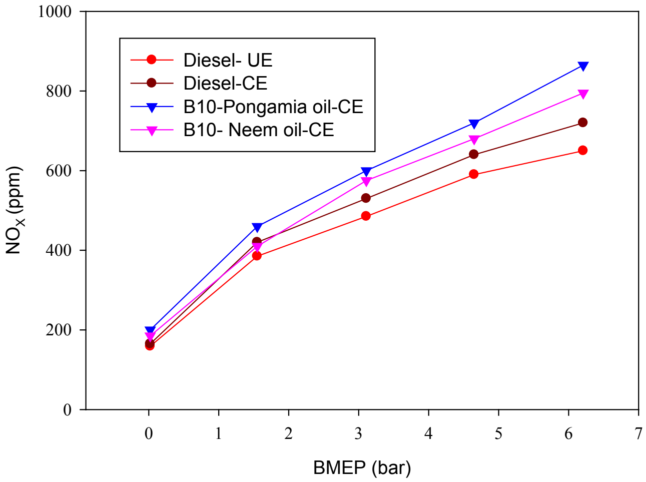

Figure 12. NOx emissions vs. brake mean effective pressure for the test fuels

4.4. Smoke opacity

Figure 13 shows the changes in smoke opacity against BMEP, indicating the soot content in the exhaust gases. The trend of increasing smoke opacity with increasing load is due to more fuel being burnt. The smoke opacity for both blended fuels in the coated engine is lower than that of diesel fuel operation in a conventional engine. The percentage decrease in smoke emission was 45.7% and 39.4%, respectively, for diesel-pongamia oil and diesel-neem oil used in coated engines rather than in uncoated diesel operation. Smoke opacity is generally lower in coated diesel engines running on blends than in conventional engines operating on pure diesel. This reduction is primarily due to the combined effects of thermal barrier coatings (TBCs) and biodiesel's inherent properties (20). Thermal retention promotes more complete combustion, thereby reducing soot particle formation and contributing to smoke opacity. In addition, vegetable oil contains higher levels of oxygen than conventional diesel. This additional oxygen facilitates more complete fuel oxidation during combustion, leading to lower smoke emissions.

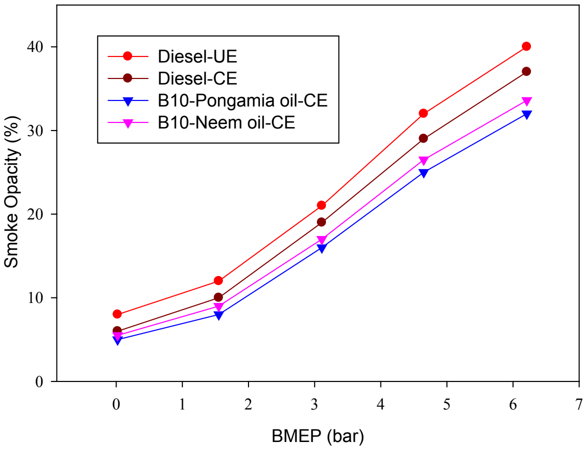

Figure 13. Smoke opacity vs. brake means effective pressure for the test fuels

5. Conclusion

The experimental study was carried out to evaluate the outcome of an Aluminium titanate-coated diesel engine on its performance, combustion, and emissions when running on pongamia oil-diesel blend and neem oil-diesel blend. Based on the investigational results, it was concluded that an Aluminium titanate diesel engine running with the Pongamia-diesel blend is, to some extent, the most competent blend, performing as well as the neem-diesel blend in a coated engine and in diesel operation in an uncoated engine. Coated engines operating on pongamia oil–diesel blends can improve performance metrics, resulting in a 4.9% increase in BTE and a 12.6% decrease in BSEC. In coated engines, both pongamia and neem oil–diesel blends showed decreased CO, HC, and smoke emissions by up to 56.3% 33.3%, and 45.9%, respectively. However, a 25.9% increase in NOx emissions was observed due to higher cylinder temperatures. The coating's thermal insulation increases cylinder pressure and cumulative heat release.

Suggestions for future studies

- LHR engine running on either adding an optimized percentage of antioxidants (BHT and TBHQ) or oxygenated additives such as ethanol or diethyl ether to biodiesel blends to suppress NOx emissions and promote improved combustion, thereby increasing engine efficiency.
- To optimize the fuel injection pressure and timing for a biodiesel blend used in the LHR engine to enhance efficiency and reduce NOx using artificial neural networks (ANN) and machine learning (ML) techniques.
- The approach of using catalytic reduction with exhaust gas recirculation can control NOx emissions without compromising performance.

Nomenclature

kW	kilowatt
LHR	Low heat rejection
YSZ	Yttria-stabilized zirconia
PSZ	partially stabilized zirconia
SSN	sintered silicon nitrate
NiCrB	nickel-chromium-boron alloy
MgO–ZrO_2	magnesium oxide-stabilized zirconia
FeCl_3	Ferric chloride,
EGR	Exhaust gas recirculation
ASTM	American Society for Testing and Materials
BMEP	Brake mean effective pressure
BSEC	Brake specific energy consumption
BTE	Brake Thermal Efficiency
EGT	Exhaust gas temperature
CHR	Cumulative heat release
BHT	Butylated hydroxytoluene
TBHQ	Tertiary butylhydroquinone
HC	Hydrocarbon
CO	Carbon monoxide
CO_2	Carbon dioxide
PM	Particulate matter
NOx	Nitrogen oxide

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Authorship contributions

The corresponding author contributed to the study's design and implementation, results analysis, and manuscript writing.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Ethics

There are no ethical issues with the publication of this manuscript.

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