Thermal Barrier Coating (TBC) onto the Piston Crown and Valves for Improving Engine Performance and Emission Characteristics by Using Diesel And Mahua Methyl Ester (MME) as a Fuel

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Abstract:
The present research aims to enhance engine performance and emission characteristics by applying Thermal Barrier Coating (TBC) to the piston crown and valves, using diesel and Mahua Methyl Ester (MME) as fuels. A conventional Direct Injection (DI) diesel engine was converted into a Low Heat Rejection (LHR) engine by applying a 0.5 mm thickness of $3Al_2O_3$-$2SiO_2$ (as TBC) onto the piston crown and valves, with MME used as fuel in the LHR engine. Fuel injector pressure was maintained at 200 bar for investigation. Results indicate that the application of TBC increases brake thermal efficiency to 13.65% at 25% load with diesel compared to a conventional DI diesel engine. Significant improvements in specific fuel consumption and brake thermal efficiency of the LHR engine with MME fuel were observed at full load. Using MME and diesel fuels with TBC resulted in lower exhaust gas temperatures. Additionally, smoke density of MME with and without TBC was significantly reduced, while carbon monoxide emissions were moderately reduced under all loads with MME fuel and TBC. Furthermore, MME with TBC significantly reduced hydrocarbon emissions at all loads.
Keywords: Mahua methyl ester biodiesel, Diesel fuel, Thermal barrier coating, Low heat rejection engine.

Introduction:

Biodiesel is one of the most prominent renewable fuels, being non-toxic and biodegradable. It is an oxygenated ester-based fuel derived from first-generation, second-generation, and third-generation oils. Biodiesel, with its inherent oxygen content ranging from 9% to 12% by weight, exhibits favorable properties such as good lubricity, low sulfur content, and compatibility with various blends of petro-diesel fuel, making it a more impactful alternative compared to traditional diesel fuels (Sudheer, 1). In India, the production of non-edible oils is limited, prompting government initiatives to explore biodiesel production from sources like Mahua, Jatropha, Karanja, Linseed, Cotton, Mustard, and Neem (Padhi et al., 2). Mahua seeds are abundant in many tribal regions of India, with trees capable of yielding seeds as early as the 7th year of growth. Mahua seed oil, commonly used in Indian cuisine, is semi-solid at room temperature and contains high levels of viscous components, with free acid content ranging from 30% to 40%. During biodiesel production, glycerin and various by-products can be obtained from the processing of Mahua oil (Agarwal et al., 3; Padhi et al., 4).

The high percentage of Free Fatty Acids (FFA) in raw Mahua oil necessitates their conversion to biodiesel through processes like transesterification or esterification (Vijay et al., 5; Azam et al., 6). While Mahua oil shares similarities in properties and chemical composition with other non-edible oils like Cotton, Neem, and Karanja, it stands out for its higher viscosity and FFA content. Various processes, including transesterification, esterification, dilution, micro-emulsion, and pyrolysis, are employed to reduce viscosity and produce biodiesel, with transesterification being favored for its efficiency and yield (Chauhan et al., 7; Sirurmath et al., 8).

In this study, experimental investigations were conducted using Mahua Methyl Ester (MME) biodiesel and diesel, with properties of both fuels determined. Heat loss during combustion in internal combustion engines (IC engines) poses a significant challenge, impacting engine efficiency, fuel consumption, and emissions. Thermal barrier coatings (TBC), applied to the piston crown and valves, transform conventional diesel engines into Low Heat Rejection (LHR) engines, thereby reducing heat loss and improving performance (Karaoglanli et al., 9). Effective TBC application promises reduced fuel consumption, higher thermal efficiency, emission reduction, and elimination of the cooling system in LHR engines (Buyukkaya et al., 10).

Various ceramic coatings, including Mullite, AL2O3, TiO2, CaO/MgO–ZrO2, and Yttria-stabilized Zirconia (YSZ), have been explored for engine applications due to their suitable properties (Cao et al., 11; Mohamed et al., 12; Lima et al., 13). TBC options like Al2O3, Ca/Mg-PSZ, Mullite, and TiO2 present viable alternatives to YSZ, offering appropriate properties for engine applications.

2. LOW HEAT REJECTION ENGINE

For many years, ceramics have been utilized in the development of Low Heat Rejection (LHR) engines. Ceramic materials offer a lower heat conduction coefficient and weight compared to conventional engine materials, contributing to improved engine performance (Gatowski et al., 14; Kamo et al., 15).

Selection of TBC Material for IC Engines

To meet the requirements of an effective Thermal Barrier Coating (TBC) for internal combustion engines, it is essential to identify suitable materials with robust bond coating properties capable of withstanding the harsh conditions within the engine combustion chamber. The key requirements for a high-quality TBC include:

- Chemical inertness.
- Strong adherence to metallic substrates.
- High melting point.
- Low thermal conductivity.
- No phase change within the room temperature range.
- Matching thermal expansion coefficient with the metallic substrate (Kam et al., 15; Abedin et al., 16).

While several ceramic materials have been employed as TBCs in diesel engines, Mullite stands out for its favorable physical properties such as thermal conductivity, corrosion resistance, hardness, and thermal shock resistance below 1273 K. The physical properties of Mullite as a TBC are summarized in Table 1 below, indicating its suitability for IC engine applications.

Table 1: Properties of Mullite

Property	**Value**
Melting Point	2123 K
Poisson's Ratio	0.25
Thermal Conductivity (λ)	3.3 W/mK
Young's Modulus (E)	127 GPa
Thermal Expansion Coefficient (α)	5.3 x 10^-6 (1400 K), (293 K - 1273 K)

These properties highlight Mullite as a promising candidate for use as a Thermal Barrier Coating in IC engine applications, offering the necessary durability and performance characteristics required for efficient engine operation.

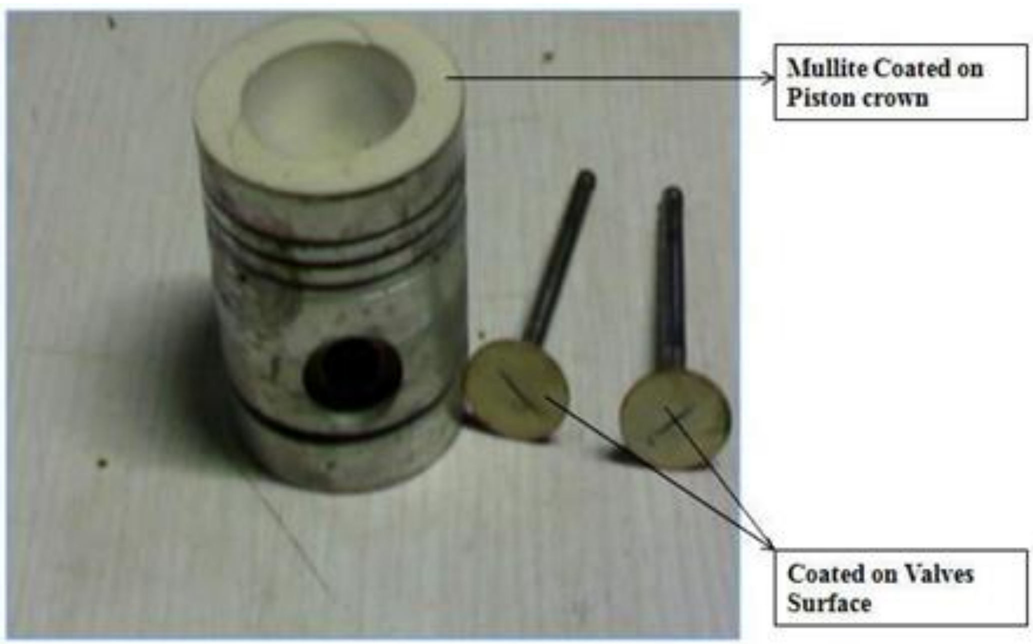

Figure 1: Mullite Coated Piston Crown and Valves Surface

The objective of this research is to enhance the performance of Low Heat Rejection (LHR) engines using diesel and biodiesel fuels while maintaining a constant fuel injection pressure. To achieve this, a single-cylinder diesel engine is converted into an LHR engine by applying a 0.5mm thick coating of Mullite onto the valves and piston crown, as depicted in Figure 1. The experiment involves the use of standard diesel and biodiesel fuels, both with and without Thermal Barrier Coating (TBC), to evaluate their impact on engine performance and emissions.

3. TRANSESTERIFICATION PROCESS

The transesterification process begins with preheating Mahua oil at temperatures ranging from 65°C to 70°C for 30 minutes to eliminate moisture content. Subsequently, 1000ml of Mahua oil is mixed with 14 grams of potassium hydroxide and 300ml of methanol. This mixture is then heated to 55°C while being stirred for 60 minutes, facilitating the chemical reaction between the Mahua oil and the additives to produce Mahua Methyl Ester (MME). After completion, the mixture is allowed to settle in a separating flask for 24 hours, separating the glycerin from the MME. The MME is then washed with warm distilled water to remove residual catalyst or soap content. Following this, the MME is heated at 100°C for 30 minutes to eliminate any remaining water traces, resulting in the production of Mahua Biodiesel, as illustrated in Figure 2.

4. FUEL PROPERTIES

Various physical properties of diesel and MME fuels are outlined in Table 2 below. These properties have been tested in the laboratory of Malla Reddy Engineering College (A), Secunderabad, Telangana, India. It is noted that the properties of MME fuel comply with the standards of ASTM D 6751 and EN 14214.

Figure 2: Final Product of Pure Mahua Biodiesel

Table 2 presents the physical properties of diesel and Mahua Methyl Ester (MME) fuels. These properties were tested at the laboratory of Malla Reddy Engineering College (A), Secunderabad, Telangana, India. It is noteworthy that the properties of MME fuel adhere to the standards of ASTM D 6751 and EN 14214.

Table 2: Properties of the Fuels

Properties	Diesel	MME
Density (15°C), kg/m^3	835	872
Specific gravity	0.850	0.916
Kinematic viscosity at 40°C, mm^2/s	2.4	4.0
Calorific Value (KJ/kg)	42930	39400
Flash Point °C	70	127
Fire Point °C	76	136
Cloud point °C	-10 to -15	6
Pour point °C	-35 to -15	1
Colour	Light brown	Dark yellow
Cetane number	51	46
Aniline point °C	69	63
Iodine value	NM	60
Diesel index	150	145

5. EXPERIMENTAL SETUP

Engine Test: A 3.5 kW single-bore diesel engine with fixed speed of 1500 rpm, water-cooled, is utilized for investigating performance enhancements and emission reductions. The schematic of the experimental setup is depicted in Figure 3, with a hydraulic dynamometer employed for loading the engine.

Table 3: Engine Specifications

Name of Specifications	Values
Name of Engine	Kirloskar
Stroke	4
Type of Cooling	Water Cooled
B.H.P.	5
Stroke Length	110mm
Bore	80mm
No. of Cylinder	1
Compression Ratio	16.5:1
Speed	1500rpm

Specification	Values
Fuel Injection Pressure	200 Bar
Rated Output	3.68kw (5.0 hp)
Connecting Rod Length	230.0mm
Exhaust Valve Open	340°
Exhaust Valve Closes	554°
Inlet Valve Open	527°
Inlet Valve Close	750°
Injection Advance	27° BTDC
Loading Type	Hydraulic

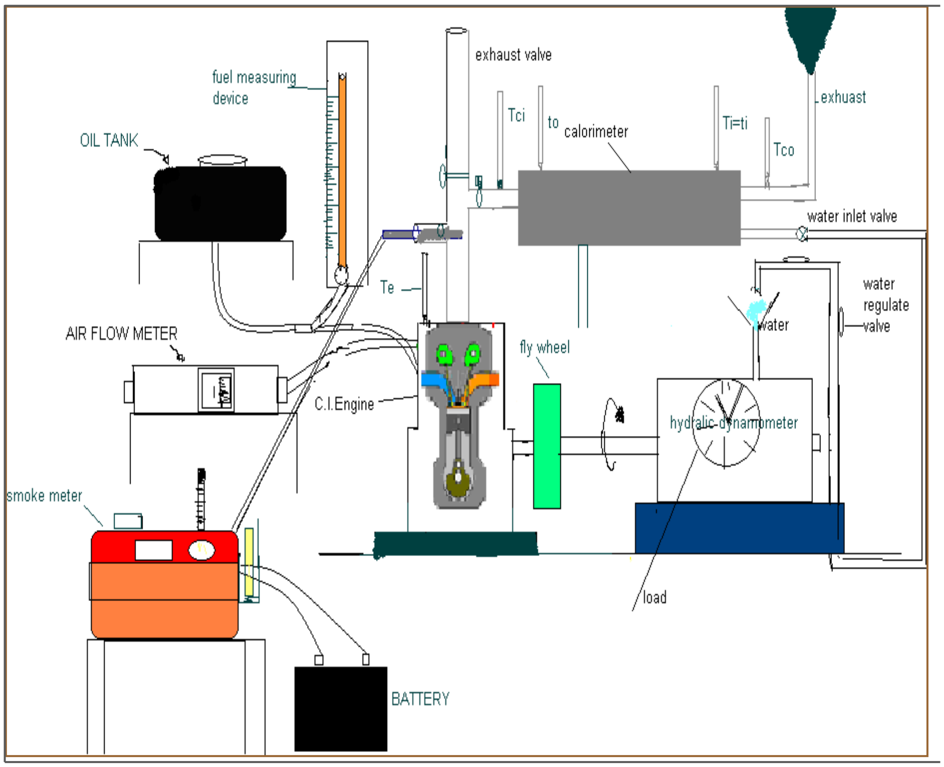

Figure 3: Schematic Plan of Experimental Setup

1. RESULTS AND DISCUSSION

The Low Heat Rejection (LHR) engine was evaluated under various load conditions using different diesel and biodiesel fuels, both with and without Thermal Barrier Coating (TBC). The findings are analyzed and presented in the subsequent sections.

Performance and Emission Parameters

6.1.1 Brake Specific Fuel Consumption

The variation in brake specific fuel consumption (BSFC) with load at a fuel injection pressure of 200 bar, demonstrating the effects of using TBC and not using TBC with different fuels, is presented in Figure 4. Here, the fuel consumption of diesel is less compared to MME oil. The BSFC of diesel without TBC at full load is 0.40 kg/kW-hr, and for biodiesel, it is 0.44 kg/kW-hr. In comparison, with TBC, diesel at full load shows a BSFC of 0.37 kg/kW-hr, and biodiesel shows [missing value] kg/kW-hr. At 25% load, the fuel consumption of diesel with TBC was found to be lower. The use of TBC, whether present or absent, increases the fuel consumption of biodiesel due to its lower calorific value.

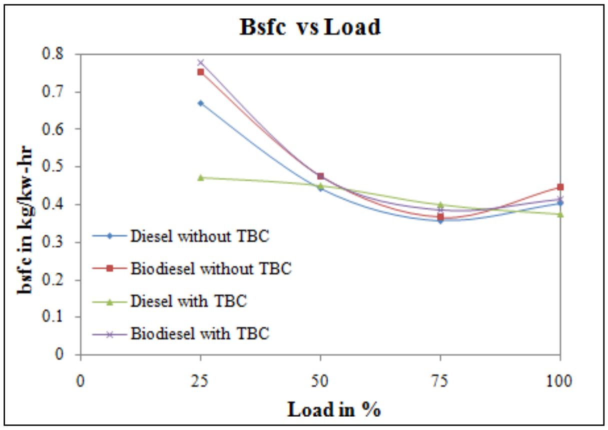

Figure 4: BSFC vs Load

6.1.2 Brake thermal efficiency

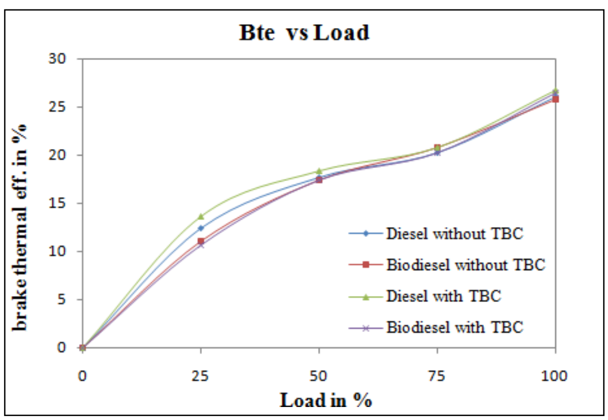

Figure 5: BTE vs. Load

Figure 5 illustrates the variation of brake thermal efficiency (BTE) with load at a fuel injection pressure of 200 bar. The experiment was conducted with and without Thermal Barrier Coating (TBC) for different fuels. At a 25% load condition, diesel with TBC showed improvement. However, at full load, no significant improvement was observed. This lack of improvement at full load is attributed to the higher viscosity of the fuels, which leads to poor atomization, fuel vaporization, and combustion, thereby not enhancing thermal efficiency significantly.
Exhaust Gas Temperature

Figure 6 demonstrates the variation of exhaust gas temperature with load at 200 bar injection pressure. The results indicate that, across all cases, the exhaust gas temperature increased with an increase in load. For fuels without TBC, MME oil exhibited the highest exhaust gas temperature at 265°C, while diesel showed a temperature of 255°C. Conversely, with TBC, MME oil reached the highest exhaust gas temperature of 427°C, compared to diesel's 337°C. The higher exhaust temperatures observed for MME oil, especially with TBC, can be attributed to the higher combustion temperatures achieved with TBC, which absorbs more heat during the combustion process. Additionally, the presence of more oxygen in biodiesel contributes to a higher peak combustion temperature, thus increasing the exhaust gas temperature for MME at full load.

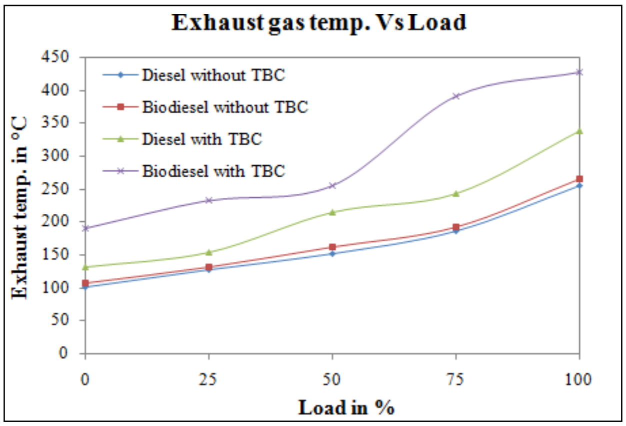

Figure 6: Exhaust Gas Temperature vs Load

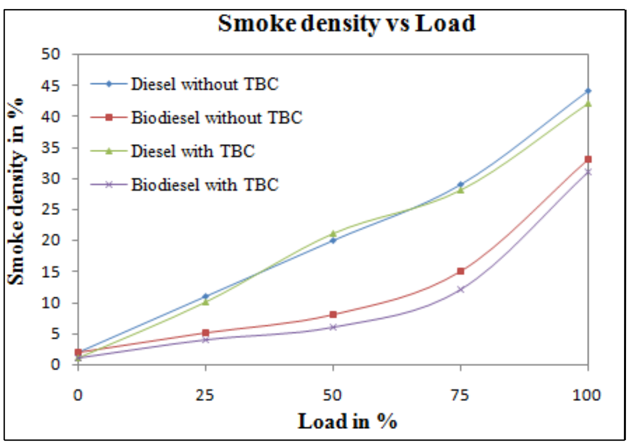

Figure 7: Smoke Density vs Load

Smoke Density Variation with Load

Figure 7 illustrates the variation of smoke density with load. The smoke density for MME, both with and without TBC, was found to be significantly reduced compared to diesel, with or without TBC. This reduction in smoke density for biodiesel is attributed to its better vaporization properties at higher combustion temperatures and the higher oxygen content in biodiesel.

CO Emissions

Figure 8 depicts the variation of carbon monoxide (CO) emissions with load at a 200 bar injection pressure. The results, which compare the emissions with and without TBC for both diesel and biodiesel fuels, show an increase in CO emissions at a 100% load condition compared to lower loads (0%, 25%, 50%, and 75%). From 1% to 75% load, CO emissions were found to be lower, indicating improved combustion efficiency and the beneficial effect of the higher oxygen molecule content in biodiesel.

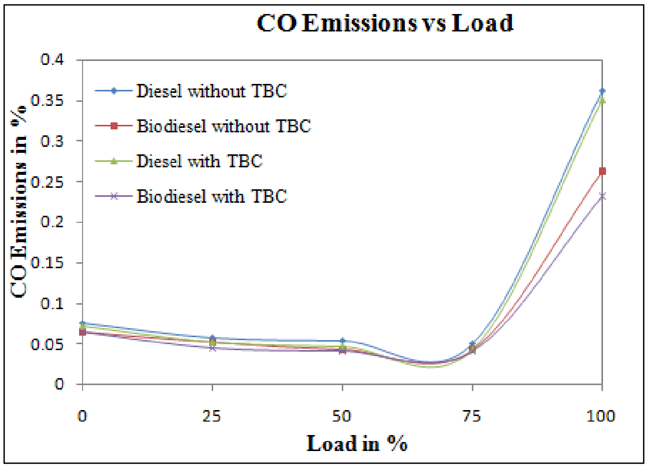

Figure 8: CO Emissions vs Load

HC Emissions

Figure 9 presents the comparison of hydrocarbon (HC) emissions for diesel and biodiesel at a 200 bar injection pressure, with and without TBC. Biodiesel exhibited significantly lower HC emissions compared to diesel. Without TBC at maximum load, HC emissions were 90 PPM for diesel and 47 PPM for MME. At 100% load with TBC, a remarkable reduction in HC emissions was observed: 63 PPM for diesel and 45 PPM for biodiesel. This reduction is likely due to an increase in combustion temperature, resulting in decreased heat losses and the presence of more oxygen in biodiesel.

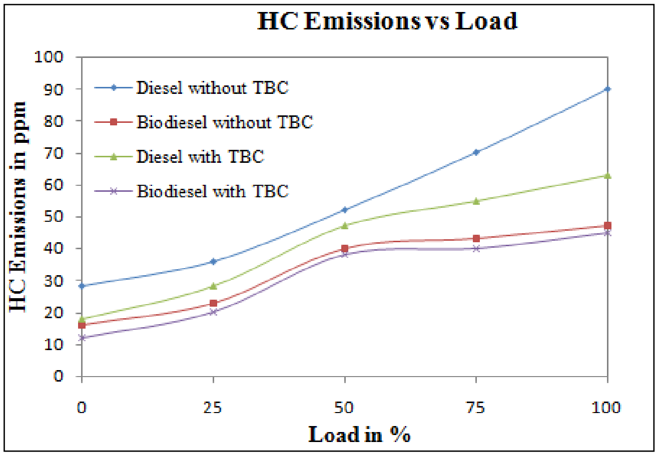

Figure 9: HC Emissions vs Load

NOx Emissions

The variation of nitrogen oxides (NOx) emissions with load at a 200 bar pressure is shown in Figure 10, for both diesel and MME fuels, with and without TBC. NOx emissions are generated by the oxidation of nitrogen in the air at high temperatures. It was noted that biodiesel, regardless of TBC use, tends to produce higher NOx emissions due to the higher oxygen levels in MME biodiesel, which facilitate better combustion and result in higher temperatures. Conversely, diesel without TBC exhibited lower NOx emissions.

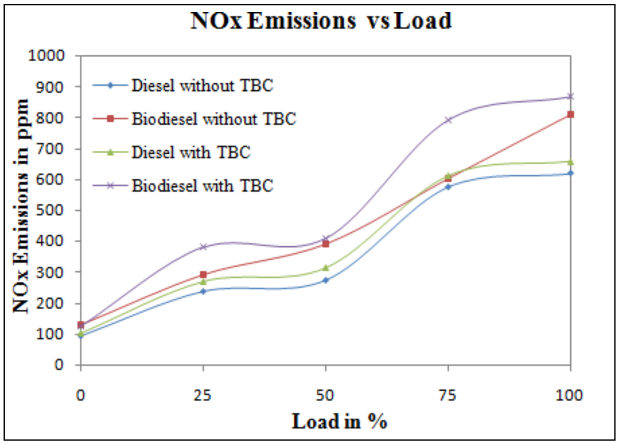

Figure 10: NOx vs Load

7. CONCLUSIONS

In this study, efforts to enhance engine performance using Mahua biodiesel in compression ignition (C.I) engines were undertaken, employing various technologies both with and without Thermal Barrier Coating (TBC), and compared against traditional diesel fuel. Experiments were conducted using MME (Mahua Methyl Ester) fuel and TBC technologies, exploring performance and emissions extensively. These experiments maintained a constant fuel injector pressure of 200 bar and operated at a steady speed of 1500 rpm. Following thorough investigation and analysis of the Low Heat Rejection (LHR) engine, key conclusions were drawn:

- The properties of Mahua methyl ester, including Density, Fire point, Flash point, and Kinematic viscosity, were observed to meet the ASTM D 6751 and EN 14214 standards. The values of these properties were found to be very close to, and in some cases higher than, those of diesel, except for the calorific value (CV), which was lower. This lower CV contributes to an increased Ignition Delay during the combustion process in the LHR Engine.
- The DI diesel engine was converted into an LHR engine by applying a 0.5 mm thickness of 3Al2O3-2SiO2 as TBC onto the piston crown and valves. Subsequent investigations into performance and emission characteristics were conducted and analyzed.
- Fuel consumption for diesel was lower compared to MME biodiesel. The lower calorific value of biodiesel means that both using and not using TBC increases its fuel consumption.
- A significant increase in brake thermal efficiency at a 25% load condition was observed with TBC-enhanced diesel, attributable to the insulating effects of TBC.

- Lower exhaust gas temperatures were achieved with TBC for both MME and diesel, due to more efficient heat retention during combustion. Additionally, smoke density for MME, with and without TBC, was significantly reduced, benefiting from the higher oxygen content in biodiesel.
- CO emissions across all load conditions were moderately decreased with biodiesel using TBC. Remarkable reductions in HC emissions were noted for MME biodiesel with TBC, a result of the oxygen molecules present in the MME oil.
- Biodiesel, regardless of TBC application, resulted in higher NOx emissions due to the oxidation of atmospheric nitrogen at high temperatures. Diesel without TBC exhibited lower NOx emissions.
- MME biodiesel presents a viable alternative fuel for diesel engines, whether modified with TBC or unmodified, offering a sustainable option over traditional diesel fuel.

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