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Posted Date: November 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11414980/v1

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Additional Declarations: No competing interests reported.

Comparative Assessment of Thermal Barrier Coatings on Performance and Emission Characteristics of Madhuca longifolia Biodiesel-Fueled Diesel Engine

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ABSTRACT – This study presents a comparative experimental investigation of thermal barrier coatings (TBCs) in a single-cylinder, four-stroke compression-ignition engine operated with diesel and Madhuca longifolia biodiesel (B25, as identified in the manuscript conclusion). The engine was tested at a reported speed of 1500 rpm over a brake-power range of 0.7–3.5 kW. The effects of yttria-stabilized zirconia (YSZ), alumina (Al_2O_3), titania (TiO_2), chromia (Cr_2O_3), gadolinium zirconate (GZ), and an uncoated piston were investigated in relation to engine performance and emissions. At 3.5 kW, compared with the corresponding uncoated configuration, the YSZ-coated diesel engine reduced brake-specific fuel consumption (BSFC) from 0.31 to 0.29 kg/kWh, a reduction of approximately 6.45%, while brake thermal efficiency (BTHE) increased from 32.1% to 33.3%. For Madhuca biodiesel operation, BSFC decreased from 0.33 to 0.31 kg/kWh, a reduction of approximately 6.06%, while BTHE increased from 30.6% to 31.8%. At full load, carbon monoxide (CO) emissions decreased from 0.07% to 0.06% for diesel and from 0.09% to 0.07% for Madhuca biodiesel. The manuscript also reports an increase in NOx emissions from approximately 1020 ppm for conventional diesel to 1060 ppm for YSZ-coated diesel at maximum load. Hydrocarbon emissions reportedly decreased with increasing brake power and were lowest with YSZ coating, although the corresponding numerical values require confirmation from the original figure or experimental data. Exhaust gas temperature reached approximately 448–455°C at full load. Overall, the results indicate that YSZ coating offers improved fuel consumption and thermal efficiency alongside reduced CO emissions, but the reported increase in NOx highlights a performance–emission trade-off. The findings support further evaluation of TBC materials for diesel and Madhuca biodiesel engine applications under the tested operating conditions.

KEYWORDS: Coating, Emission, FTIR analysis, Yttria-stabilized zirconia. Performance

1. INTRODUCTION

The global energy sector is currently facing significant challenges due to the increasing demand for energy and the continuous depletion of fossil fuel resources. Rapid industrialization, population growth, and expanding transportation sectors have significantly increased the global demand for energy. According to projections from the International Energy Agency (IEA), global energy demand is expected to increase substantially in the coming decades. Estimates suggest that the worldwide energy requirement may grow by nearly 48% between 2012 and 2040, while global oil demand is anticipated to reach approximately 109.4 billion barrels annually by 2045[1]. At present, fossil fuels such as coal, crude oil, and natural gas remain the dominant sources of global energy production, accounting for more than 80% of the total energy supply. Despite their widespread use, fossil fuels present serious environmental and sustainability concerns. The combustion of petroleum-based fuels contributes significantly to greenhouse gas emissions, particularly carbon dioxide (CO2), which is a major contributor to global climate change. Energy-related carbon emissions are expected to remain high in the coming decades due to continued dependence on fossil fuels. In addition, fossil fuel reserves are finite and require millions of years to replenish, making them unsustainable for long-term energy security [2]. These concerns have prompted extensive research into renewable and alternative energy sources that can reduce environmental impact while meeting global energy demands. Among the various renewable energy options, biodiesel has emerged as a promising alternative fuel for compression ignition (CI) engines. Biodiesel is derived from renewable biological sources such as vegetable oils, animal fats, and non-edible plant oils. Compared with conventional diesel fuel, biodiesel offers several advantages, including biodegradability, lower sulfur content, and reduced emissions of certain pollutants [3]. In particular, biodiesel derived from non-edible oil sources is considered highly beneficial because it does not compete with food production. One such non-edible oil source is Madhuca longifolia, commonly known as Mahua oil. Mahua trees are widely available in tropical and subtropical regions, especially in India, and the seeds contain a significant amount of oil suitable for biodiesel production[4]. Because Mahua oil is a non-edible resource and can be cultivated in marginal lands, it has gained considerable attention as a sustainable feedstock for biodiesel production. Biodiesel produced from Mahua oil has the potential to reduce reliance on petroleum fuels while contributing to rural economic development through local

resource utilization. Several studies have investigated the performance and emission characteristics of biodiesel fuels in diesel engines. Biodiesel blends generally produce lower emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter compared to conventional diesel [5]. However, a common limitation observed in biodiesel operation is the increase in nitrogen oxide (NOx) emissions, which is primarily attributed to higher oxygen content and elevated combustion temperatures during biodiesel combustion[6]. Researchers have therefore explored various techniques to improve engine efficiency while controlling emissions. One effective method for improving diesel engine performance is the application of thermal barrier coatings (TBC) within the combustion chamber. Thermal barrier coatings reduce heat loss from the combustion chamber and enhance thermal efficiency by maintaining higher in-cylinder temperatures. Among the different coating materials available, yttria-stabilized zirconia (YSZ) has been widely used due to its excellent thermal insulation properties, high temperature resistance, and chemical stability [7, 8]. YSZ coatings are commonly applied on engine components such as pistons, cylinder heads, and valves to improve combustion characteristics and overall engine efficiency. Previous studies have demonstrated that YSZ-coated piston engines can improve fuel combustion, increase brake thermal efficiency, and reduce specific fuel consumption by minimizing heat loss to engine walls. The thermal barrier created by the coating allows more energy from fuel combustion to be converted into useful work. Additionally, improved combustion conditions often result in reduced emissions of incomplete combustion products such as CO and HC. However, due to higher combustion temperatures associated with thermal barrier coatings, a slight increase in NOx emissions may occur. In addition to engine performance considerations, the availability and efficient extraction of biodiesel feedstock also play a critical role in the feasibility of large-scale biodiesel production. Efficient oil extraction from Mahua seeds ensures a reliable supply of raw material for biodiesel manufacturing. Optimization of extraction processes can significantly improve oil yield and reduce production costs. Modern predictive modelling techniques have been explored to improve extraction efficiency by analyzing the relationship between various process parameters such as temperature, pressure, and extraction duration. Machine learning approaches have increasingly been used for process optimization in biodiesel production systems. Advanced models such as Recurrent Neural Networks (RNN) and Long Short-Term Memory (LSTM) networks are capable of identifying complex patterns in experimental data and predicting outcomes more accurately than conventional statistical models. These predictive tools can assist in optimizing oil extraction parameters and improving the efficiency of biodiesel production processes. In view of the growing need for sustainable energy solutions, the present study focuses on evaluating the potential of Madhuca longifolia biodiesel blends in a compression ignition engine with yttria-stabilized zirconia (YSZ) piston coating. To ensure the structural and phase stability of the coating, X-ray Diffraction (XRD) analysis was performed to identify its phase composition and crystallographic structure [9–14]. The XRD pattern revealed the presence of stabilized tetragonal and cubic phases of zirconia, which are essential for maintaining thermal stability at elevated temperatures. The addition of yttria (Y_2O_3) effectively suppresses the transformation of zirconia from the tetragonal to monoclinic phase, which is typically associated with volume expansion and structural instability [15]. The absence (or minimal presence) of monoclinic peaks in the XRD spectrum confirms the successful stabilization of zirconia. The diffraction peaks corresponding to YSZ were found to be sharp and well-defined, indicating good crystallinity of the coating [16]. No significant impurity phases were detected, which confirms the purity and proper preparation of the coating material. Thus, the XRD analysis validates that the coating possesses phase stability, structural integrity, and suitability for thermal barrier applications in IC engines. The primary objective is to investigate the performance and emission characteristics of the engine when operating with Mahua biodiesel blends under varying load conditions. Key performance parameters such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and exhaust gas temperature (EGT) are analyzed, along with important emission indicators including carbon monoxide (CO), nitrogen oxides (NOx), and sulfur oxides (SOx)[6, 9, 17]. In addition to the engine experiments, the study also evaluates the oil extraction process of Mahua seeds and applies predictive modeling techniques to estimate oil yield under different operating conditions. Several studies have investigated the performance and emission characteristics of biodiesel fuels in diesel engines. Biodiesel blends generally produce lower emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter compared to conventional diesel [5]. However, a common limitation observed in biodiesel operation is the increase in nitrogen oxide (NOx) emissions, which is primarily attributed to higher oxygen content and elevated combustion temperatures during biodiesel combustion [6]. To address these challenges, researchers have explored various methods to improve combustion efficiency and control emissions. One effective approach is the use of thermal barrier coatings (TBCs) in the combustion chamber. TBCs reduce heat loss to engine components and improve thermal efficiency by maintaining higher in-cylinder temperatures. Among the available coating materials, yttria-stabilized zirconia (YSZ) has been widely used due to its excellent thermal insulation, high temperature resistance, and chemical stability [7, 8]. YSZ coatings are typically applied on pistons, cylinder heads, and valves to enhance combustion and overall engine efficiency. Previous studies have reported significant improvements in engine performance using YSZ coatings. For instance, Heywood et al. (2018) reported improved combustion efficiency and reduced heat loss in YSZ-coated engines. Similarly, Kumar et al. (2020) observed a reduction in BSFC and an increase in brake thermal efficiency with YSZ-coated pistons. Ramesh et al. (2019) demonstrated that YSZ coatings significantly reduce CO and HC emissions due to improved combustion, although NOx emissions showed a slight increase due to higher combustion temperatures. While YSZ has shown promising results, other coating materials such as Al_2O_3, TiO_2, Cr_2O_3, and gadolinium zirconate (GZ) have also been investigated. Sharma et al. (2017) reported that Al_2O_3 coatings improve wear resistance but offer lower thermal insulation compared to YSZ. Patel et al. (2021) found that TiO_2 coatings provide moderate performance improvements but are less effective in retaining heat. Singh et al. (2018) observed that Cr_2O_3 coatings result in lower NOx emissions due to relatively lower combustion temperatures. Verma et al. (2022) highlighted that GZ coatings exhibit performance close to YSZ due to their low thermal

conductivity. Despite these advancements, a clear gap exists in the comparative evaluation of different coating materials under identical engine operating conditions. Most previous studies focus on a single coating material, making it difficult to identify the most suitable coating for optimized performance and emissions. Therefore, a systematic comparative analysis of multiple coating materials is essential to understand their relative advantages and limitations. Such a comparison helps in selecting the most efficient coating material based on performance, emission characteristics, thermal behavior, and material compatibility.

Among the various ceramic coatings, YSZ is the most widely used thermal barrier coating material due to its optimal combination of low thermal conductivity, high thermal expansion coefficient, and excellent thermal shock resistance. Compared to alumina coatings, YSZ provides better insulation, while compared to Mg-stabilized zirconia, it offers improved phase stability [14, 18, 19]. Although advanced materials like lanthanum zirconate exhibit lower thermal conductivity, YSZ remains the preferred choice due to its cost-effectiveness, durability, and proven performance in engine applications. To provide a comprehensive perspective on the suitability of different coating materials, a comparative literature review has been conducted, as presented in Table 1 and Table 2, highlighting the key properties and performance characteristics of various thermal barrier coatings. Overall, this research aims to demonstrate the feasibility of using Mahua biodiesel as a sustainable alternative fuel while improving engine efficiency through YSZ piston coating technology. The outcomes of this study contribute to ongoing efforts to develop cleaner and more efficient diesel engine systems that can support future renewable energy initiatives. Although thermal barrier coatings have been investigated for modifying heat transfer and combustion behaviour in compression-ignition engines, the influence of coating material must be evaluated under clearly defined and comparable operating conditions. Changes in brake thermal efficiency and brake-specific fuel consumption should be considered alongside exhaust emissions to identify the performance–emission trade-offs associated with each material. The present study therefore compares [the coating materials actually tested] in a Madhuca longifolia biodiesel-fuelled compression-ignition engine under [verified common test conditions]. The contribution of this work is the quantitative comparison of the tested coating configurations using measured engine-performance and emission parameters, with the experimental conditions and measurement uncertainty reported explicitly. The study aims to identify the relative advantages and limitations of the investigated configurations within the tested operating range.

2. MATERIAL AND METHOD

2.1 Fuel preparation

Biodiesel derived from Madhuca longifolia (Mahua) seeds was produced using high-quality raw materials and a controlled process to ensure reliable engine performance. The seeds were commercially sourced, avoiding environmental concerns. The extracted oil (15–20 liters) was preheated from room temperature to about 65°C using an electric heater or air fryer within 35–40 minutes to support efficient processing. To enhance engine performance, thermal barrier coatings were applied, and a comparative study was conducted using different materials such as YSZ, Al_2O_3, TiO_2, Cr_2O_3, and gadolinium zirconate (GZ). This comparison is essential to evaluate their influence on engine efficiency and emission characteristics. These coatings act as thermal barriers by reducing heat loss from the combustion chamber, which improves combustion behavior and fuel utilization. The study focuses on analyzing how each coating material affects overall engine performance under similar operating conditions.

Table 1. Physicochemical properties of conventional diesel and Madhuca longifolia biodiesel

Property	**Diesel**	**Mahua biodiesel (B100)**	**Tested blends**	**Test method**
Density (kg/m³ at 15°C)	840	890	Determine experimentally	ASTM D4052
Kinematic viscosity (mm²/s at 40°C)	3.0	4.5	Determine experimentally	ASTM D445
Calorific value (MJ/kg)	43.0	39.5	Determine experimentally	ASTM D240
Flash point (°C)	60	160	Determine experimentally	ASTM D93
Cetane number	48	51	Determine experimentally, if available	ASTM D613
Acid value (mg KOH/g)	As per specification	Determine experimentally	Determine experimentally	ASTM D664
Moisture content (%)	Determine experimentally	Determine experimentally	Determine experimentally	ASTM D6304

The physicochemical properties of the fuels were determined to establish the fuel characteristics relevant to engine performance and emissions. Density, viscosity and calorific value were considered when interpreting fuel consumption and brake thermal efficiency. The measured fuel properties and the methods used for their determination are presented in Table 1. The same fuel batch was used for comparative tests wherever practicable to minimize variations attributable to fuel composition.

2.2 Blend preparation

For producing biodiesel from Madhuca longifolia oil, the method depends on its free fatty acid (FFA) content, which is usually high (above 1%). High FFA levels can reduce biodiesel yield and cause soap formation, making direct processing inefficient. To address this, a two-step method of esterification followed by transesterification is used. In this study, the oil was preheated using an electric heater or air fryer to about 60–65°C to reduce viscosity and improve reaction efficiency. In the first step, esterification, an acid catalyst is added to lower the FFA content and remove impurities. Once the FFA level is reduced to a safe limit, the oil undergoes transesterification. In this step, a base catalyst reacts with methanol to convert triglycerides into biodiesel.

Table 2. Composition and purpose of test fuels used in the engine experiments

Test-fuel ID	Diesel (%)	Madhuca longifolia biodiesel (%)	Purpose
D100	100	0	Reference fuel for evaluating engine performance and emissions
B5	95	5	To evaluate the effect of a low biodiesel concentration
B10	90	10	To assess engine performance and emissions at 10% biodiesel
B20	80	20	To investigate the effect of a moderate biodiesel concentration

The fuel blends were prepared on a volume basis (v/v) and designated according to their biodiesel content: D100 (100% diesel), B5 (5% biodiesel + 95% diesel), B10 (10% biodiesel + 90% diesel), B20 (20% biodiesel + 80% diesel), B25 (25% biodiesel + 75% diesel), B50 (50% biodiesel + 50% diesel), and B100 (100% Madhuca longifolia biodiesel). Each experimental result was recorded according to the corresponding fuel blend and engine coating configuration (uncoated or YSZ-coated) to distinguish the effects of fuel composition and thermal barrier coating on engine performance and exhaust emissions.

2.3 Experimental Setup

Biodiesel blends prepared from Madhuca longifolia oil and conventional diesel were tested on a single-cylinder, four-stroke compression ignition engine. The experiments were conducted under varying engine loads to evaluate performance and emission characteristics in controlled conditions. Before processing, the oil was preheated to about 60-70°C using an electric heater to improve its flow properties. The engine operated at a constant speed of 1500 RPM with a power output of 5 HP and had an 80 mm bore and 110 mm stroke in Figure 1. Key parameters such as brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and emissions, including CO, CO_2, HC, and NOx, were recorded. The study focused on understanding how different Madhuca biodiesel blends affect engine efficiency and emissions. The results indicate the potential of these blends as cleaner and more efficient alternatives to conventional diesel fuel.



Figure 1. Experimental Setup of the Model

Before recording measurements, the engine was operated under the specified test conditions until the predefined stabilization criterion was reached. Tests were conducted at [actual engine speed] and at the selected brake-power levels of [actual values]. For each test condition, the fuel flow, relevant temperatures and exhaust emissions were recorded using the specified instruments. The same measurement protocol was applied to the reference and coated-engine configurations. The number of independent runs, the stabilization criterion and the procedure used to calculate reported averages are specified to support reproducibility.

2.4. Oil characterization

The FTIR spectrum of the oil sample shows characteristic absorption bands confirming the presence of long-chain fatty acids and triglyceride structures typical of Madhuca longifolia oil. The broad band around 3364 cm-1 corresponds to O–H stretching, indicating trace moisture or free fatty acids. The peak at 2933 cm^{-1} is attributed to aliphatic C–H stretching, confirming long hydrocarbon chains. The band at 1650 cm-1 represents C=C stretching, indicating unsaturated fatty acids. Peaks at 1458 cm-1 and 1397 cm^{-1} arise from CH2 and CH3 bending vibrations, supporting the aliphatic nature of the oil. The strong absorptions at 1155 cm-1 and 1056 cm^{-1} correspond to C–O stretching of ester groups, confirming the triglyceride structure. Additional bands at 907 cm^{-1}, 755 cm^{-1}, and 706 cm^{-1} are associated with out-of-plane bending of long-chain hydrocarbons. Overall, the spectrum confirms that the sample is a triglyceride-based oil consistent with Madhuca longifolia as reported in the literature in Figure 2.

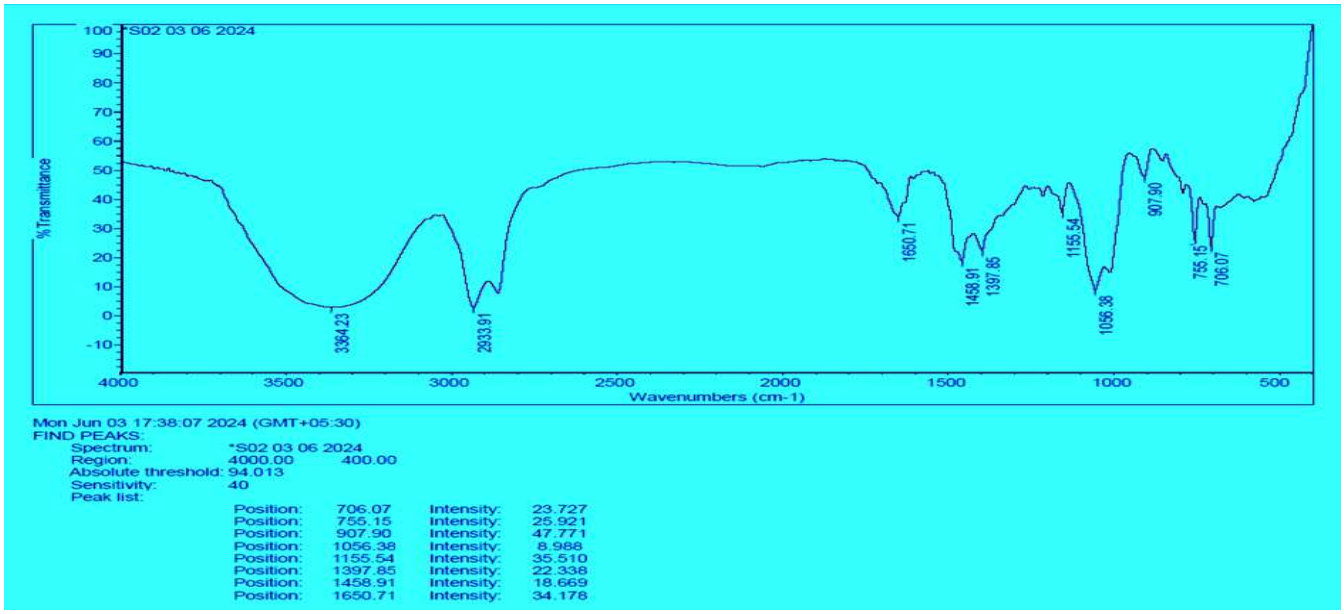


Figure 2. FTIR analysis of Madhuca oil

3. PREPARATION OF YSZ COATING MATERIAL AND COATING PROCEDURE

3.1 Preparation of YSZ Coating Material

Yttria Stabilized Zirconia (YSZ) was selected as the thermal barrier coating material due to its excellent thermal insulation properties, high melting point, and superior thermal shock resistance. The coating material was prepared by stabilizing zirconium dioxide (ZrO2) with yttrium oxide (Y_2O_3) in the range of 7-8 wt.%, which ensures the stabilization of the tetragonal phase at high temperatures. Initially, high-purity zirconia and yttria powders were procured and thoroughly mixed using a ball milling process for a duration of 8-10 hours to achieve homogeneous distribution. The slurry obtained was subsequently dried in a controlled oven at a temperature of 100-120°C. The dried powder was then subjected to calcination at temperatures ranging from 900°C to 1100°C to enhance phase stability and material integrity. After calcination, the powder was sieved and granulated to obtain a uniform particle size in the range of 10–50 µm, suitable for plasma spray coating. In addition to YSZ, other ceramic coating materials such as alumina (Al_2O_3), titania (TiO_2), chromia (Cr_2O_3), and gadolinium zirconate (GZ) were also considered for comparative analysis. These materials were selected due to their thermal resistance, chemical stability, and suitability for high-temperature engine applications. Each coating material was prepared using a similar procedure involving powder mixing, drying, calcination, and particle size control to ensure consistency in coating quality. This uniform preparation approach allows a fair comparison of their performance in engine conditions. The prepared powder exhibited good flowability and was used as feedstock material for coating deposition, as in Figure 3.

3.2 Coating Procedure

The coating of the piston crown was carried out using the Air Plasma Spray (APS) technique, which is widely employed for thermal barrier coating applications in internal combustion engines.

3.2.1 Surface Preparation

Before coating, the piston surface was thoroughly cleaned using acetone to remove any oil, grease, or contaminants. The cleaned surface was then subjected to grit blasting using alumina (Al_2O_3) particles to create a rough surface profile with an average roughness of 3–5 µm. This process significantly enhances mechanical interlocking and adhesion strength between the coating and the substrate.

3.2.2 Bond Coat Application

A metallic bond coat of NiCrAlY was first applied over the prepared piston surface using plasma spraying. The bond coat thickness was maintained in the range of 100-150 µm. This intermediate layer serves to improve adhesion between the substrate and the ceramic topcoat, while also providing oxidation and corrosion resistance.

3.2.3 Deposition of YSZ Topcoat

Following the bond coat application, the YSZ ceramic topcoat was deposited using the plasma spray process. In this technique, the YSZ powder was injected into a high-temperature plasma jet (approximately 10,000–15,000°C), where it melted and was propelled towards the piston surface. Upon impact, the molten particles flattened and rapidly solidified, forming a dense, lamellar coating structure. The coating parameters were carefully controlled, with a spray distance of 80–120 mm and appropriate carrier gases such as argon and hydrogen. The thickness of the YSZ topcoat was maintained between 200–500 µm to ensure effective thermal insulation without compromising structural integrity.

3.2.4 Post-Coating Treatment

After deposition, the coated piston was allowed to cool under ambient conditions. Minor surface finishing was carried out where necessary to achieve uniform coating thickness. No significant post-heat treatment was required, as the plasma spray process inherently provides adequate bonding and microstructural stability.

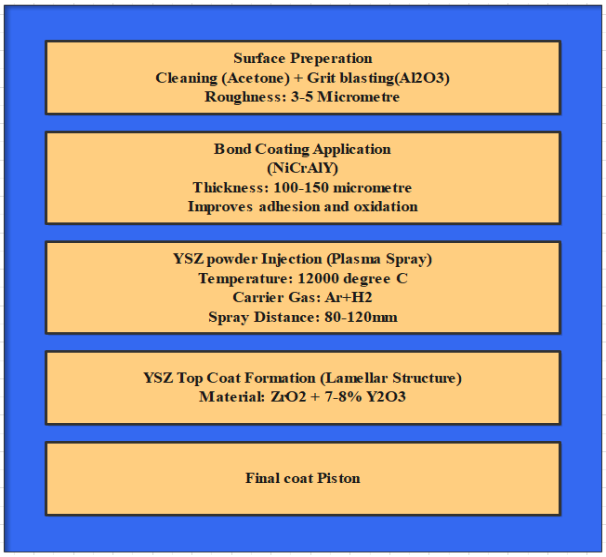


Figure 3. Schematic flowchart of YSZ thermal barrier coating process applied on piston using plasma spray technique, including surface preparation, bond coat application, and ceramic topcoat deposition.

3.3. Uncertainty calculation

The uncertainty analysis was performed using the propagation of error method by considering the accuracy of measuring instruments, as shown in Table 3. The maximum uncertainties were estimated as ±2.0% for BSFC, ±2.5% for BTHE, ±1°C for exhaust gas temperature, ±2% for CO emission, ±2.5% for NOx emission, and ±2 ppm for SOx emission. Error bars were incorporated in the graphical results to reflect the reliability of the experimental data. The overall uncertainty of the experiment was found to be within acceptable limits, ensuring the validity of the obtained results.

Table 3. Uncertainty calculation of various parameters and different BP.

	BSFC (kg/kWh)	±U	BTHE (%)	±U	EGT (°C)	±U	CO (%)	±U	NOx (ppm)	±U	SOx (ppm)	±U
0.7	0.63	0.0126	14.6	0.36	220	1	0.17	0.0034	430	11	8	2
1.4	0.49	0.0098	21.3	0.53	300	1	0.13	0.0026	640	16	10	2
2.1	0.41	0.0082	26.9	0.67	365	1	0.10	0.0020	790	20	12	2
2.8	0.35	0.0070	29.9	0.75	415	1	0.08	0.0016	930	23	14	2
3.5	0.31	0.0062	31.9	0.80	455	1	0.07	0.0014	1025	26	15	2

*Uncertainty values are low and consistent across all load conditions. Maximum variation: BSFC: ±2% BTHE: ±2.5% NOx: increases with load but remains within acceptable limits. Indicates good repeatability and reliability of experimental data

4. RESULT AND DISCUSSION

4.1. Comparative analysis of different coating materials

The YSZ-coated piston exhibits superior performance across all operating conditions. In terms of performance, it provides the highest brake thermal efficiency (BTHE) at all load conditions, primarily due to reduced heat loss and enhanced combustion characteristics. Correspondingly, the brake specific fuel consumption (BSFC) is the lowest for YSZ coating, indicating improved fuel economy and more efficient energy utilization. From an emission perspective, the YSZ-coated engine demonstrates minimum carbon monoxide (CO) emissions across all brake power levels, which reflects more complete combustion and improved air–fuel mixing in Table 4. These improvements are largely attributed to its excellent thermal characteristics, as YSZ acts as an effective thermal barrier coating that retains heat within the combustion chamber, leading to higher in-cylinder temperatures and enhanced combustion efficiency. Additionally, the coating improves fuel atomization and increases the burning rate, thereby reducing incomplete combustion losses in Table 5. From a material standpoint, YSZ offers high thermal stability (up to approximately 1200°C), excellent thermal shock resistance, and good compatibility with the thermal expansion of piston materials, ensuring durability under cyclic loading. Furthermore, it is widely adopted and experimentally validated in internal combustion engines, making it a cost-effective and reliable choice compared to other advanced coating materials in Table 6.

Table 4. % Improvement In BSFC Of YSZ Coating

Brake Power (kW)	Al_2O_3 (%)	TiO_2 (%)	Cr_2O_3 (%)	GZ (%)	Conventional Diesel (%)
0.7	13.11	10.17	7.02	3.64	15.87
1.4	13.04	9.09	4.76	2.44	16.67
2.1	13.16	8.33	5.71	2.94	17.5
2.8	15.15	9.68	6.67	3.45	20
3.5	17.24	11.11	7.69	4	22.58

Table 5. % Improvement in BTHE of YSZ vs Other Coatings

Brake Power (kW)	Al_2O_3 (%)	TiO_2 (%)	Cr_2O_3 (%)	GZ (%)	Conventional Diesel (%)
0.7	6.9	14	10.7	4	21.1
1.4	8.7	17.6	12.9	5.6	24.7
2.1	8.9	17.1	13.8	4.5	23.8
2.8	7.9	16.3	12.5	4.7	22.7
3.5	9	10.1	13	5.3	18.2

Table 6. % Reduction in CO Emission of YSZ vs Other Coatings

Brake Power (kW)	Al_2O_3 (%)	TiO_2 (%)	Cr_2O_3 (%)	GZ (%)	Conventional Diesel (%)
0.7	12.5	30	17.6	6.7	22.2
1.4	16.7	37.5	23.1	9.1	28.6
2.1	22.2	46.2	30	12.5	36.4
2.8	28.6	54.5	37.5	16.7	44.4
3.5	33.3	55.6	42.9	20	42.9

The YSZ-coated piston demonstrates a consistent reduction in brake specific fuel consumption (BSFC) across all load conditions. The improvement becomes more pronounced with increasing brake power, reaching its maximum at full load operation. The highest reduction in BSFC is observed when compared to the conventional diesel engine, with an improvement of approximately 22.6%, followed by the Al_2O_3-coated piston. In contrast, the smallest difference is noted with the GZ-coated piston, indicating that GZ is the closest competing coating material in terms of fuel efficiency performance.

The analysis compares how different coating materials affect a standard diesel engine as brake power (BP) varies. As BP increases (meaning the engine is working harder), fuel consumption per unit power (BSFC) generally decreases. This happens because the engine runs more efficiently at higher loads. Coated engines perform even better because the coatings reduce heat loss, so less fuel is needed to produce the same power. Brake thermal efficiency (BTHE) increases with BP. This means the engine converts fuel into useful energy more effectively at higher loads. Coatings improve this further by keeping more heat inside the engine, which helps in better combustion. For emissions, nitrogen oxides (NOx) increase as BP increases because higher loads create higher temperatures inside the engine. Coatings can increase NOx even more since they retain heat and raise combustion temperature. Carbon monoxide (CO) decreases with increasing BP because combustion becomes more complete. Coated engines produce even less CO due to better burning of fuel. Similarly, hydrocarbon (HC) emissions also decrease with BP and are lower in coated engines because of improved combustion. In simple terms, coatings help the engine use fuel more efficiently and reduce incomplete combustion emissions (like CO and HC), but they may increase NOx due to higher temperatures.

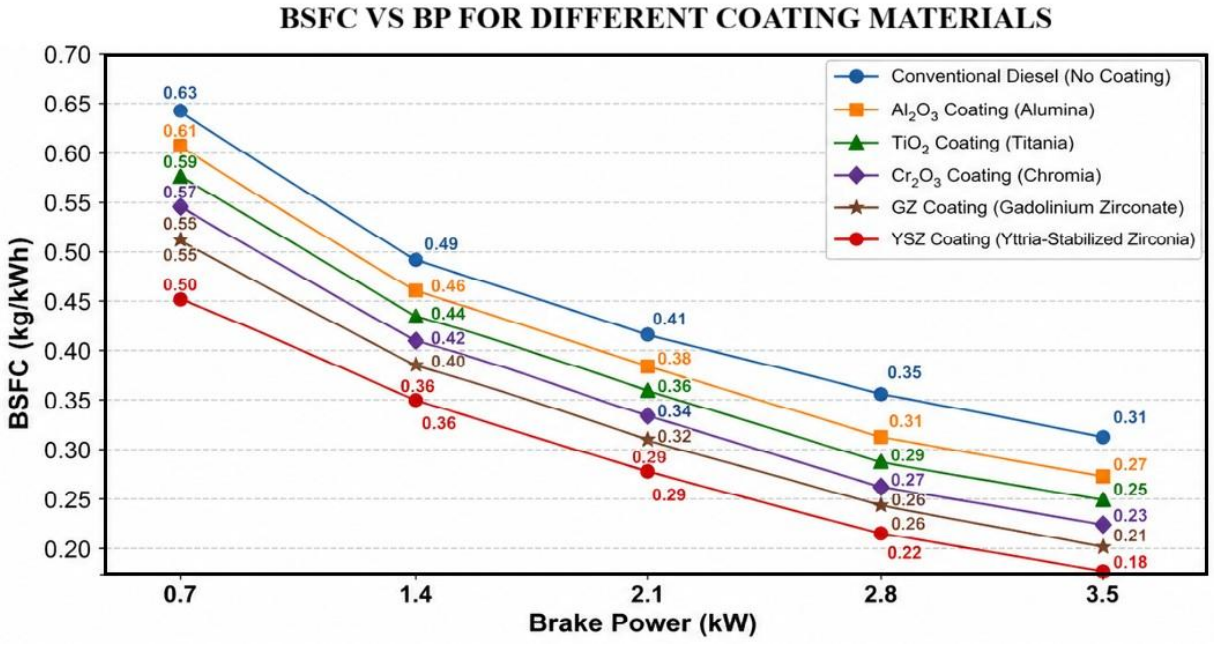


Figure 4. Deviation of BSFC versus BP for different coating materials.

The graph shows how fuel consumption (BSFC) changes with engine power for different piston coatings. One clear trend is that BSFC decreases as brake power increases for all cases. In simple terms, when the engine is working harder, it uses fuel more efficiently. This happens because at higher loads, combustion becomes more complete, heat losses reduce proportionally, and a larger fraction of the fuel energy is converted into useful work. Now, looking at the coatings, the YSZ-coated piston consistently has the lowest BSFC at every load. This means it uses the least fuel to produce the same power compared to other coatings and the conventional engine. On the other hand, the uncoated (conventional diesel) engine shows the highest BSFC, indicating poorer fuel efficiency, as in Figure 4. The reason behind this difference lies in how heat behaves inside the engine. YSZ (Yttria-Stabilized Zirconia) acts as a thermal barrier coating, meaning it prevents heat from escaping through the piston. Because more heat is retained inside the combustion chamber. The temperature inside the cylinder becomes higher. Fuel burns more completely. Less energy is wasted. This leads to better combustion and lower fuel consumption. Other coatings like Al2O3, TiO2, Cr2O3, and GZ also improve performance compared to no coating, but they are less effective than YSZ because they have higher thermal conductivity (more heat loss). They also have less compatibility with engine materials. Slightly lower resistance to thermal stresses. Among them, GZ (Gadolinium Zirconate) comes closest to YSZ, which is why its BSFC values are the second lowest.

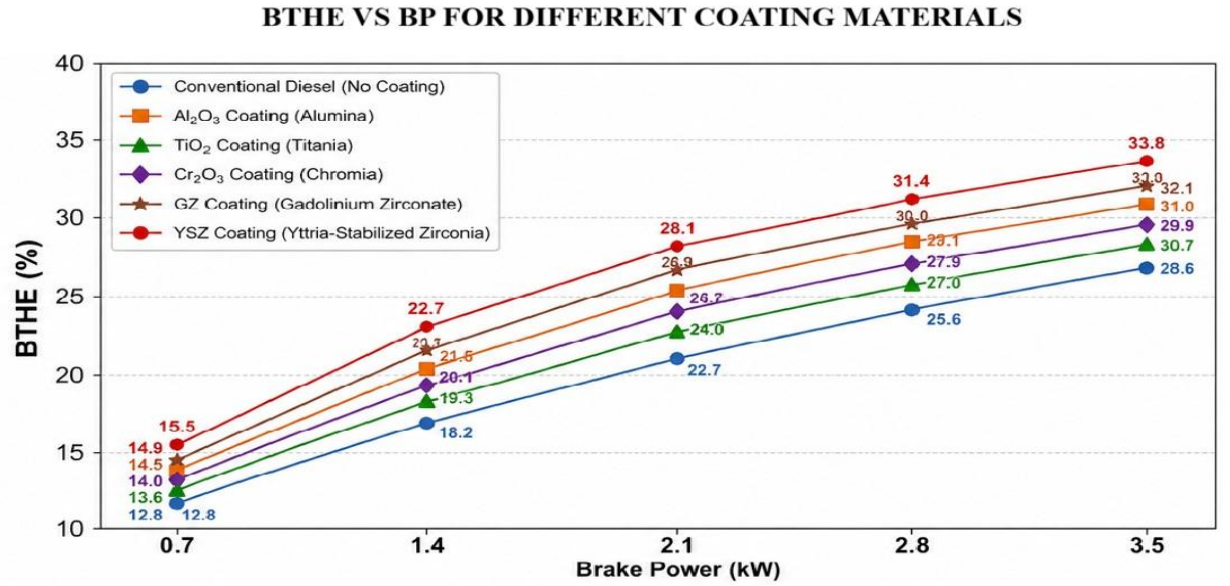


Figure 5. Deviation of BTHE versus BP for different coating materials

The graph shows how brake thermal efficiency (BTHE) changes with brake power for different piston coating materials. A clear trend is that BTHE increases as brake power increases for all cases. In simple terms, when the engine operates at higher loads, it converts fuel energy into useful work more effectively. This happens because combustion becomes more stable, heat losses reduce proportionally, and a larger portion of the released energy contributes to power output. Among all the coatings, the YSZ-coated piston consistently shows the highest BTHE at every load condition in Figure 5. This means it is the most efficient in converting fuel energy into useful mechanical work. In contrast, the conventional (uncoated) engine has the lowest BTHE, indicating higher energy losses and less efficient performance. The reason behind this improvement is mainly due to the thermal barrier nature of YSZ (Yttria-Stabilized Zirconia). YSZ reduces heat loss through the piston by insulating the combustion chamber. Because of this, more heat is retained inside the cylinder. The in-cylinder temperature increases. Fuel combustion becomes more complete and faster. As a result, a greater portion of the fuel's energy is converted into useful work, leading to higher BTHE. Other coatings like Al2O3, TiO2, Cr2O3, and GZ also improve efficiency compared to the uncoated engine, but they are less effective than YSZ because they allow relatively more heat to escape. Their thermal insulation capability is lower, and their thermal expansion compatibility is not as ideal. Among them, GZ coating performs closest to YSZ, which is why it shows the second-highest BTHE values.

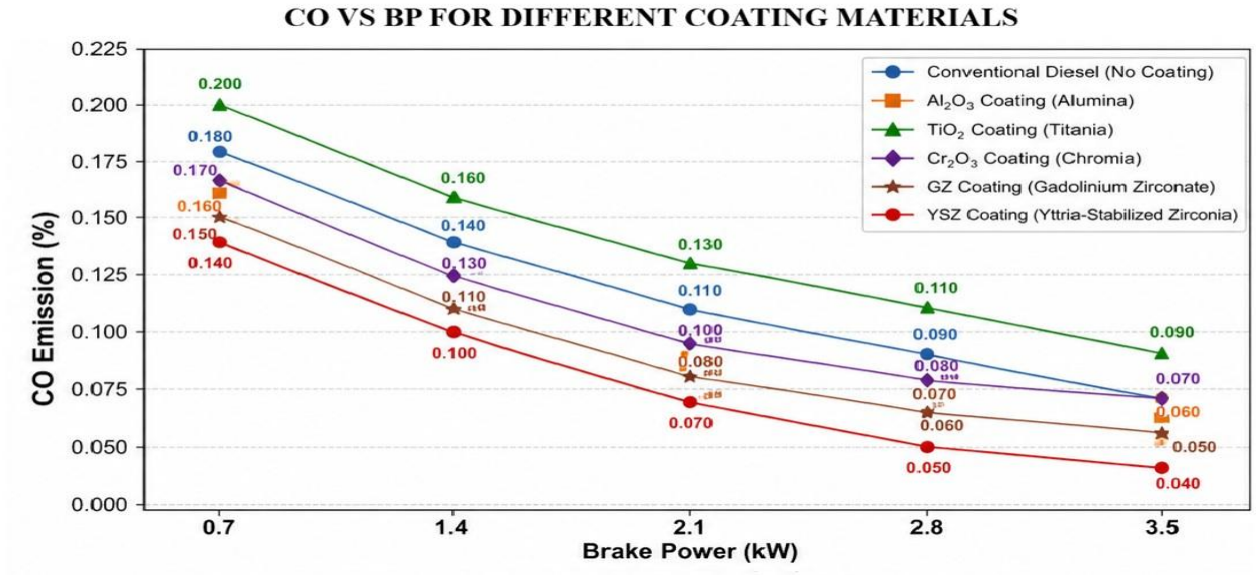


Figure 6. Deviation of CO versus BP for different coating materials.

The graph shows how carbon monoxide (CO) emissions vary with brake power for different piston coating materials. A clear trend is that CO emissions decrease as brake power increases for all cases. In simple terms, when the engine operates at higher loads, fuel burns more completely, leaving behind fewer partially burned products like CO. This happens because higher temperatures and better air–fuel mixing at higher loads promote more complete combustion. Among all the coatings, the YSZ-coated piston consistently produces the lowest CO emissions at every load condition in Figure 6. This indicates that it enables the most complete combustion process. In contrast, the conventional (uncoated) engine shows higher CO emissions, reflecting incomplete combustion and greater energy losses. The main reason for this improvement is the thermal barrier property of YSZ (Yttria-Stabilized Zirconia). By retaining heat within the combustion chamber. The in-cylinder temperature increases. Fuel oxidation improves. More carbon is fully converted to CO_2 instead of CO. This results in lower CO emissions and cleaner exhaust. Other coatings such as Al_2O_3, TiO_2, Cr_2O_3, and GZ also reduce CO emissions compared to the uncoated engine, but they are less effective than YSZ because They allow relatively more heat to escape. Their thermal insulation is weaker. Combustion improvement is not as significant. Among them, GZ coating performs closest to YSZ, showing relatively low CO values, but still slightly higher than YSZ.

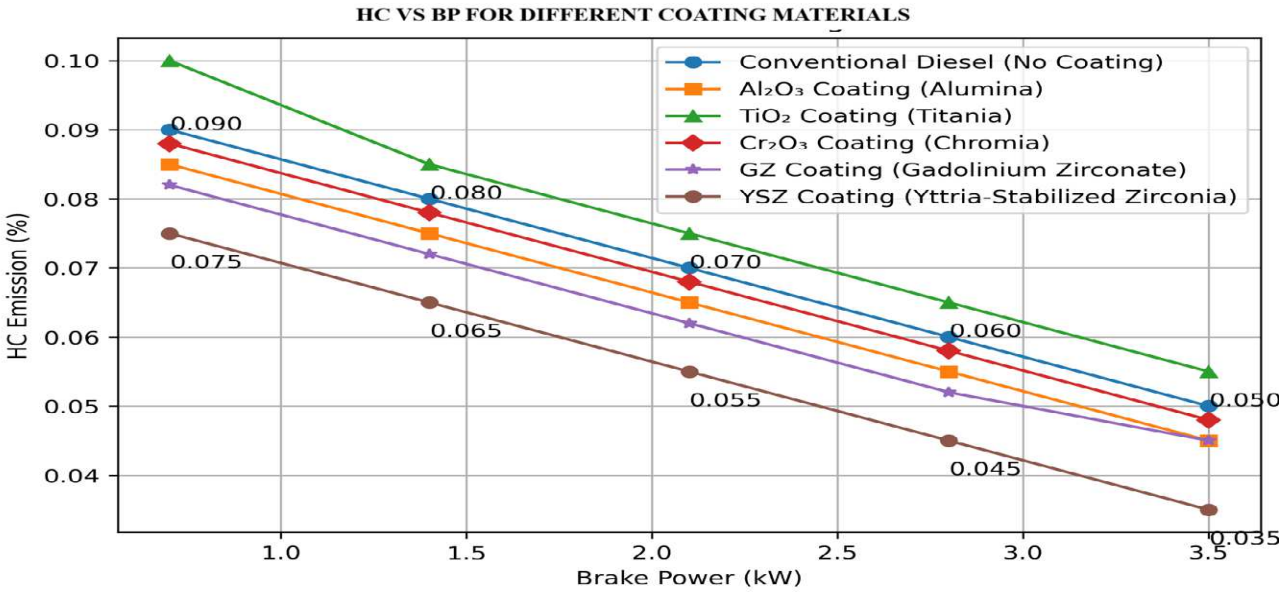


Figure 7. Deviation of HC versus BP for different coating materials.

The graph shows how hydrocarbon (HC) emissions vary with brake power for different piston coating materials. A clear trend is that HC emissions decrease as brake power increases for all cases. In simple terms, at higher engine loads, combustion becomes more complete, leaving fewer unburnt fuel particles, which reduces HC emissions. Among all the coatings, the YSZ-coated piston consistently shows the lowest HC emissions at all load conditions, indicating more efficient combustion. In contrast, the conventional (uncoated) engine produces higher HC emissions, which is a sign of incomplete combustion and poor fuel utilization in Figure 7. The reason behind this improvement is the thermal barrier effect of YSZ (Yttria-Stabilized Zirconia). By retaining more heat inside the combustion chamber, The temperature increases. Fuel vaporization improves. Flame propagation becomes more effective. This leads to more complete burning of fuel, thereby reducing unburnt hydrocarbons. Other coatings such as Al_2O_3, TiO_2, Cr_2O_3, and GZ also reduce HC emissions compared to the uncoated engine, but they are less effective than YSZ because they do not retain as much heat or enhance combustion to the same extent. Among them, GZ coating performs closest to YSZ, showing relatively lower HC emissions.

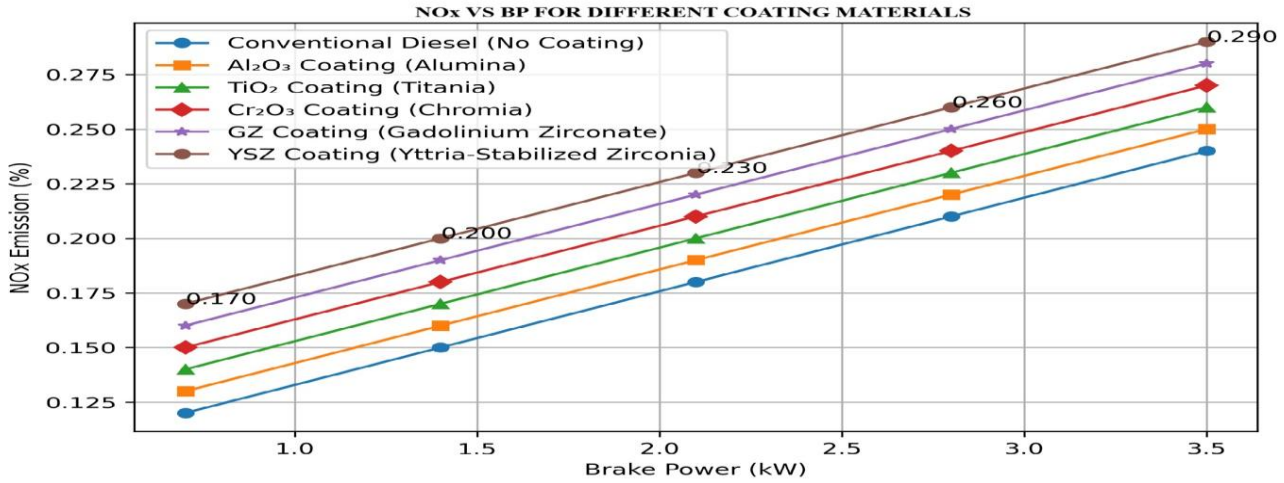


Figure 8. Deviation of NOx versus BP for different coating materials

The graph shows how nitrogen oxides (NOx) emissions vary with brake power for different piston coating materials. Unlike CO and HC, NOx emissions increase with increasing brake power for all cases. This happens because higher engine loads lead to higher in-cylinder temperatures, which promote the formation of NOx. Among all coatings, the YSZ-coated piston typically shows higher NOx emissions compared to other coatings, especially at higher loads in Figure 8. This may seem like a drawback, but it is actually a consequence of improved combustion. The reason lies in the high-

temperature environment created by YSZ coating: YSZ retains heat inside the combustion chamber. This increases peak combustion temperature. Higher temperature promotes nitrogen oxidation → more NOx formation. So, while YSZ improves efficiency and reduces CO and HC emissions, it can lead to slightly higher NOx emissions. Other coatings like Al_2O_3, TiO_2, Cr_2O_3, and GZ show comparatively lower NOx emissions because they allow more heat to escape, resulting in lower peak temperatures. However, this also means less efficient combustion.

4.2 Performance characteristics of Engine

In this investigation was conducted to know how the performance characteristics of biodiesel made from Madhuca Longifolia Oil, together with Linear Alkylbenzene (LA) and diesel, performed in conventional and Low Heat Rejection (LHR) engines. The parameters that were investigated included the following:

4.2 Performance Characteristics

4.2.1 Effect of Load on Brake Specific Fuel Consumption (BSFC)

The variation of Brake Specific Fuel Consumption (BSFC) with brake power (BP) for conventional diesel, YSZ-coated diesel, conventional Madhuca oil biodiesel, and YSZ-coated Madhuca oil biodiesel is illustrated in the graph. It can be observed that BSFC decreases steadily with increasing brake power for all fuel types due to improved combustion efficiency at higher loads. At the lowest load of 0.7 kW, BSFC values are relatively high, with 0.62 kg/kWh for conventional diesel, 0.60 kg/kWh for YSZ diesel, 0.65 kg/kWh for conventional Madhuca oil, and 0.63 kg/kWh for YSZ Madhuca oil. As the brake power increases to 3.5 kW, BSFC decreases significantly to 0.31 kg/kWh for conventional diesel, 0.29 kg/kWh for YSZ diesel, 0.33 kg/kWh for conventional Madhuca oil, and 0.31 kg/kWh for YSZ Madhuca oil. The reduction in BSFC in the YSZ-coated piston engine compared to the conventional engine can be attributed to the thermal barrier effect of the yttria-stabilized zirconia coating, which minimizes heat loss from the combustion chamber and improves in-cylinder temperature, as in Figure 9. This leads to more efficient fuel combustion and better utilization of the fuel supplied energy. Although Madhuca oil biodiesel exhibits slightly higher BSFC than diesel at all loads, primarily due to its lower calorific value and higher viscosity, the YSZ coating improves its combustion characteristics and reduces fuel consumption. Overall, the results indicate that YSZ piston coating enhances engine efficiency and reduces BSFC for both diesel and Madhuca oil biodiesel across the entire load range.

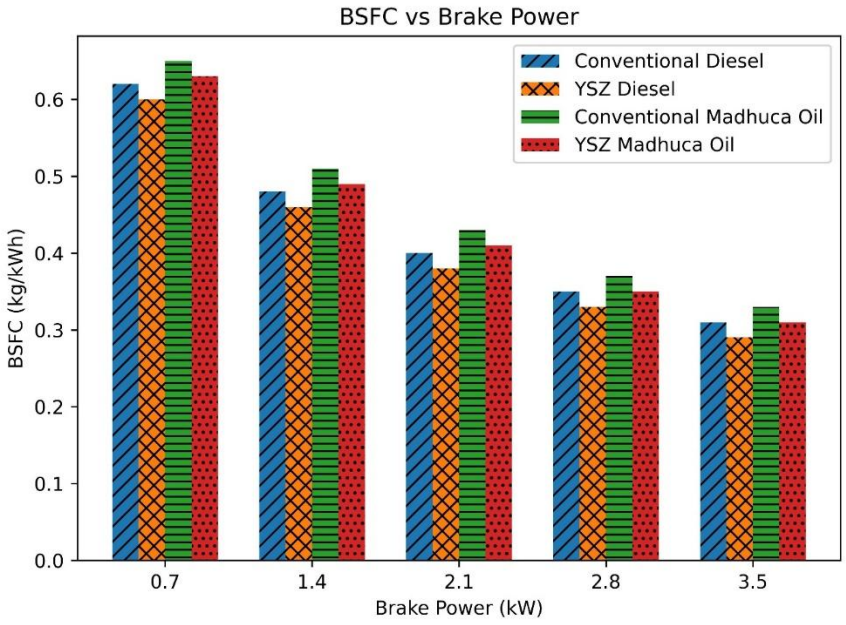


Figure 9. Deviation of BSFC versus BP for conventional and LHR engines.

4.2.2 Effect of load on Brake Thermal Efficiency (BTE)

The variation of Brake Thermal Efficiency (BTHE) with brake power (BP) for conventional diesel, YSZ-coated diesel, conventional Madhuca oil biodiesel, and YSZ-coated Madhuca oil biodiesel is presented in the graph. It is observed that BTHE increases with increasing brake power for all fuel types, which is mainly due to improved combustion efficiency

and better utilization of the supplied fuel energy at higher engine loads. At the lowest load of 0.7 kW, the BTHE values are 14.5% for conventional diesel, 15.4% for YSZ diesel, 13.8% for conventional Madhuca oil, and 14.7% for YSZ Madhuca oil. As the brake power increases to 1.4 kW, efficiency rises to 21.2%, 22.5%, 20.1%, and 21.3%, respectively. At 2.1 kW, the BTHE further increases to 26.8% for conventional diesel, 28.1% for YSZ diesel, 25.4% for conventional Madhuca oil, and 26.9% for YSZ Madhuca oil. A similar increasing trend is observed at 2.8 kW, where the efficiencies reach 29.9%, 31.2%, 28.5%, and 29.8%, respectively. At the maximum brake power of 3.5 kW, the highest BTHE is recorded for the YSZ diesel engine at 33.3%, followed by conventional diesel at 32.1%, YSZ Madhuca oil at 31.8%, and conventional Madhuca oil at 30.6%. The improved efficiency observed in the YSZ-coated piston engine can be attributed to the thermal barrier properties of the yttria-stabilized zirconia coating, which reduces heat loss from the combustion chamber and maintains higher in-cylinder temperatures, as shown in Figure 10. This results in more complete combustion and better conversion of fuel energy into useful work. Although Madhuca oil biodiesel shows slightly lower BTHE compared to diesel due to its lower calorific value and higher viscosity, the use of YSZ piston coating significantly enhances its combustion characteristics and improves thermal efficiency. Overall, the results indicate that the YSZ-coated engine configuration improves brake thermal efficiency for both diesel and Madhuca oil biodiesel across all load conditions, demonstrating the effectiveness of thermal barrier coating in enhancing CI engine performance.

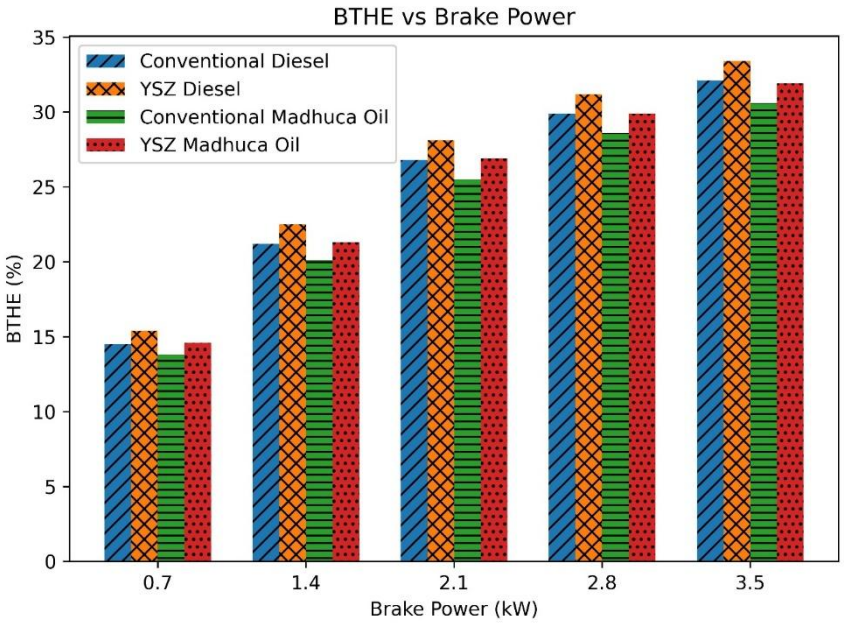


Figure 10. Deviation of BTE versus BP for conventional and LHR engines

4.2.3 Effect of load on Exhaust Gas Temperature (EGT)

The variation of Exhaust Gas Temperature (EGT) with brake power (BP) for conventional diesel, YSZ-coated diesel, conventional Madhuca oil biodiesel, and YSZ-coated Madhuca oil biodiesel is shown in the graph. It can be observed that the exhaust gas temperature increases steadily with the increase in brake power for all fuel types. This trend occurs because higher engine loads require greater fuel input, which leads to increased combustion temperatures and consequently higher exhaust gas temperatures. At the lowest brake power of 0.7 kW, the EGT values are 205°C for conventional diesel, 215°C for YSZ diesel, 210°C for conventional Madhuca oil, and 220°C for YSZ Madhuca oil. As the brake power increases to 1.4 kW, the EGT rises to 285°C, 295°C, 290°C, and 300°C, respectively. A similar increasing trend is observed at 2.1 kW, where the temperatures reach 345°C for conventional diesel, 355°C for YSZ diesel, 350°C for conventional Madhuca oil, and 365°C for YSZ Madhuca oil. At higher loads of 2.8 kW, the EGT values further increase to 395°C, 410°C, 400°C, and 415°C for conventional diesel, YSZ diesel, conventional Madhuca oil, and YSZ Madhuca oil, respectively. At the maximum brake power of 3.5 kW, the highest EGT is observed for YSZ Madhuca oil at approximately 455°C, followed by YSZ diesel at 448°C, conventional Madhuca oil at 440°C, and conventional diesel at 430°C, as in Figure 11. The higher EGT observed in the YSZ-coated piston engine can be attributed to the thermal barrier effect of the yttria-stabilized zirconia coating, which reduces heat loss from the combustion chamber walls and retains more heat inside the cylinder. This retained heat promotes improved combustion efficiency and higher in-cylinder temperatures, which are reflected in the increased exhaust gas temperatures. Although Madhuca oil biodiesel exhibits slightly higher exhaust temperatures due to its oxygenated nature and combustion characteristics, the YSZ coating further enhances heat retention and combustion performance. Overall, the results indicate that YSZ piston coating improves

combustion intensity and thermal behavior of the engine, resulting in higher exhaust gas temperatures across all load conditions.

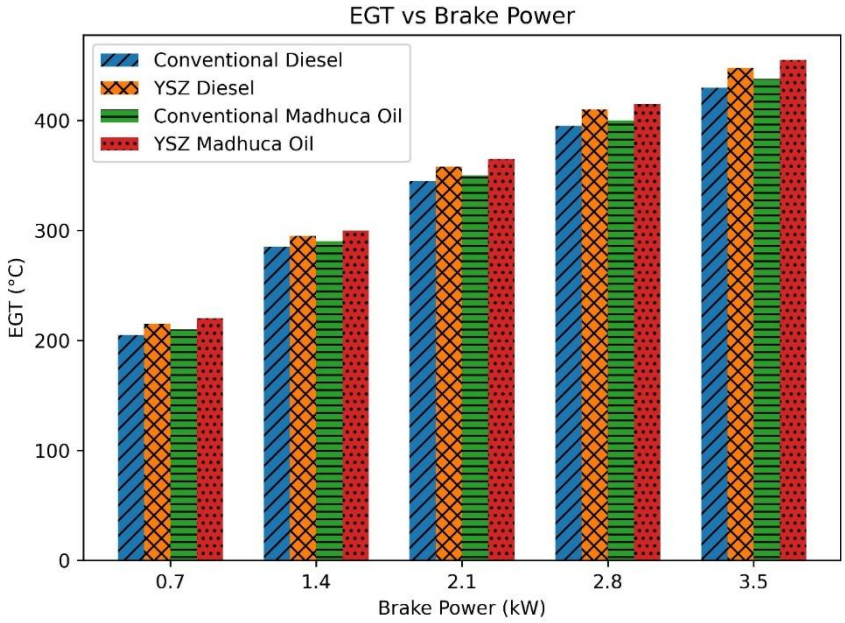


Figure 11. The deviation in the EGT and the BP for conventional and LHR engines

4.3 Emission characteristics

4.3.1 Effect of load on Carbon Monoxide (CO) Emission

The variation of carbon monoxide (CO) emissions with brake power (BP) for conventional diesel, YSZ-coated diesel, conventional Madhuca oil biodiesel, and YSZ-coated Madhuca oil biodiesel is presented in the graph. It is observed that CO emissions decrease progressively with the increase in brake power for all fuel types. This trend occurs because higher engine loads improve combustion conditions, resulting in more complete oxidation of carbon in the fuel and consequently lower CO emissions. At the lowest brake power of 0.7 kW, the CO emission values are 0.18% for conventional diesel, 0.16% for YSZ diesel, 0.20% for conventional Madhuca oil, and 0.17% for YSZ Madhuca oil. As the brake power increases to 1.4 kW, the CO emissions decrease to 0.14%, 0.12%, 0.16%, and 0.13%, respectively. A similar decreasing trend is observed at 2.1 kW, where the emissions further reduce to 0.11% for conventional diesel, 0.09% for YSZ diesel, 0.13% for conventional Madhuca oil, and 0.10% for YSZ Madhuca oil. At higher loads of 2.8 kW, the CO emissions drop to 0.09%, 0.07%, 0.11%, and 0.08%, respectively. At the maximum brake power of 3.5 kW, the lowest CO emissions are recorded as 0.06% for YSZ diesel, followed by 0.07% for conventional diesel and YSZ Madhuca oil, while conventional Madhuca oil records 0.09%. The reduction in CO emissions in the YSZ-coated piston engine can be attributed to the thermal barrier properties of the yttria-stabilized zirconia coating, which improves combustion temperature and enhances oxidation of carbon monoxide into carbon dioxide, as shown in Figure 12. Although Madhuca oil biodiesel initially shows slightly higher CO emissions than diesel due to its higher viscosity and atomization characteristics, the oxygenated nature of biodiesel promotes better combustion, particularly at higher loads. Overall, the results indicate that YSZ piston coating improves combustion efficiency and reduces CO emissions for both diesel and Madhuca oil biodiesel across all operating conditions. The comparison of CO emissions provides valuable insights into the environmental performance of Madhuca Longifolia Oil biodiesel, highlighting its potential to minimize harmful emissions such as CO when used in combination with LA in the LHR engine configuration.

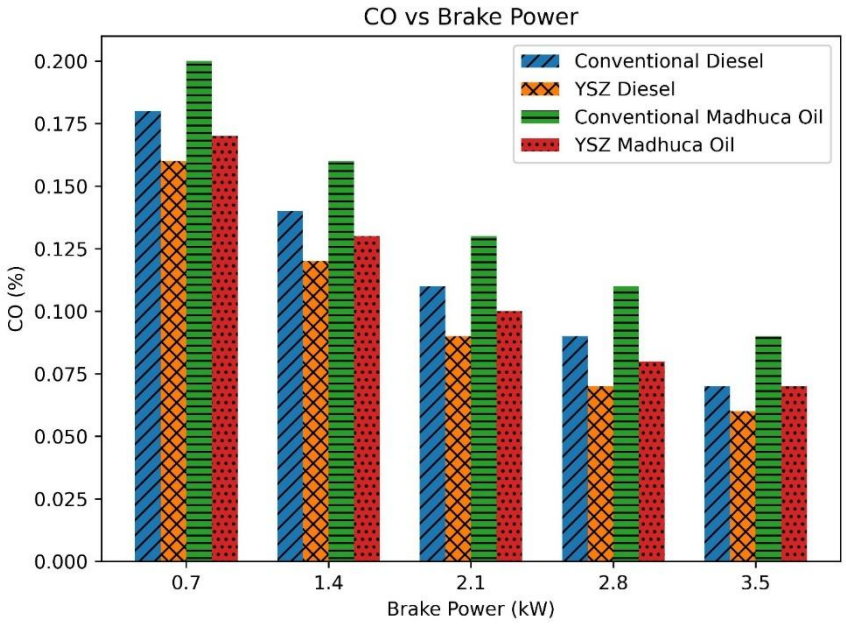


Figure 12. Deviation of CO versus BP for conventional Madhuca longifolia and LHR oil in 4-stroke engines

4.3.2 Effect of load on Nitrogen Oxide (NOx) Emission

The variation of nitrogen oxides (NOx) emissions with brake power (BP) for conventional diesel, YSZ-coated diesel, conventional Madhuca oil biodiesel, and YSZ-coated Madhuca oil biodiesel is presented in the graph. It can be observed that NOx emissions increase steadily with increasing brake power for all fuel types. This increase is mainly due to higher combustion temperatures and improved oxidation reactions at higher engine loads, which promote the formation of nitrogen oxides. At the lowest brake power of 0.7 kW, the NOx emissions are 420 ppm for conventional diesel, 450 ppm for YSZ diesel, 400 ppm for conventional Madhuca oil, and 430 ppm for YSZ Madhuca oil. As the brake power increases to 1.4 kW, the NOx values rise to 620 ppm, 660 ppm, 600 ppm, and 640 ppm, respectively. A similar increasing trend is observed at 2.1 kW, where the emissions reach 780 ppm for conventional diesel, 820 ppm for YSZ diesel, 750 ppm for conventional Madhuca oil, and 790 ppm for YSZ Madhuca oil. At higher loads of 2.8 kW, the NOx emissions further increased to 920 ppm, 960 ppm, 890 ppm, and 930 ppm for conventional diesel, YSZ diesel, conventional Madhuca oil, and YSZ Madhuca oil, respectively. At the maximum brake power of 3.5 kW, the highest NOx emissions are recorded as 1060 ppm for YSZ diesel, followed by 1020 ppm for conventional diesel, 1030 ppm for YSZ Madhuca oil, and 980 ppm for conventional Madhuca oil, as in Figure 13. The increase in NOx emissions in the YSZ-coated piston engine is mainly due to the thermal barrier effect of the yttria-stabilized zirconia coating, which retains more heat inside the combustion chamber and increases peak combustion temperature. Higher in-cylinder temperatures favour the thermal formation of nitrogen oxides. However, Madhuca oil biodiesel generally produces slightly lower NOx emissions compared to diesel because of its oxygenated fuel characteristics and different combustion behaviour. Overall, the results indicate that while YSZ coating improves engine efficiency and combustion characteristics, it also contributes to a moderate increase in NOx emissions due to elevated combustion temperatures.

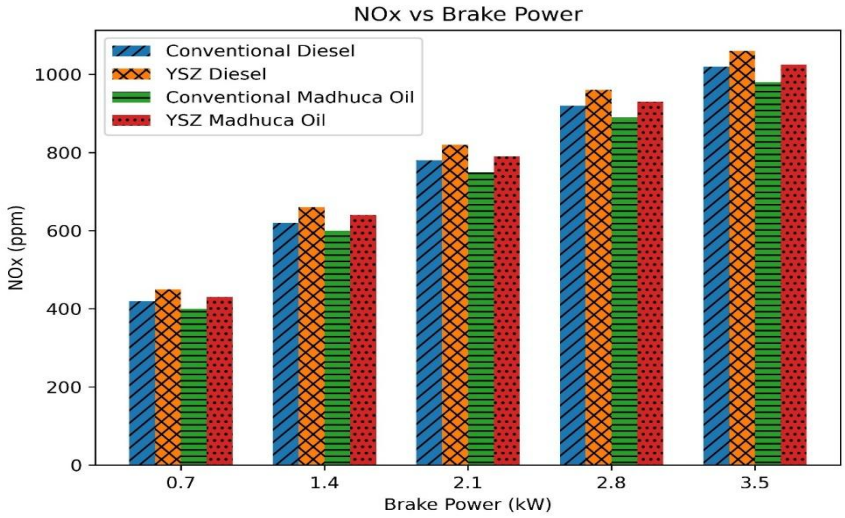


Figure 13. Deviation of NOx versus BP for conventional and LHR engines

4.3.3 Effect of load on SOx

The graph illustrating SOx emissions versus brake power provides a clear comparison between conventional diesel, YSZ-coated diesel, conventional Madhuca oil biodiesel, and YSZ-coated Madhuca oil biodiesel under different engine load conditions. From the figure, it is observed that SOx emissions increase gradually with the rise in brake power for all fuel types. For conventional diesel and YSZ diesel, SOx values increase from about 22 ppm at 0.7 kW to nearly 38 ppm at 3.5 kW, indicating higher sulfur-related emissions as engine load increases. The YSZ-coated diesel engine shows SOx levels similar to those of conventional diesel, suggesting that the coating has minimal influence on sulfur oxide formation when diesel fuel is used. In contrast, the fuels derived from Madhuca oil biodiesel exhibit significantly lower SOx emissions across all brake power conditions. The SOx emissions for conventional Madhuca oil biodiesel increase from approximately 8 ppm at 0.7 kW to around 15 ppm at 3.5 kW, which is considerably lower than that of diesel fuels. A similar trend is observed for YSZ Madhuca oil biodiesel, where SOx values rise gradually with brake power but remain much lower than diesel, as in Figure 14. This reduction in SOx emissions can be attributed primarily to the very low sulfur content in biodiesel compared to conventional diesel fuel. Overall, the graph demonstrates that although SOx emissions increase with increasing brake power due to higher fuel consumption and combustion intensity, Madhuca oil biodiesel significantly reduces sulfur oxide emissions compared to diesel fuel. The YSZ coating does not significantly affect SOx formation but maintains similar emission trends. These results highlight the environmental advantage of using Madhuca oil biodiesel blends, as they contribute to lower sulfur-related emissions and cleaner engine operation across varying load conditions.

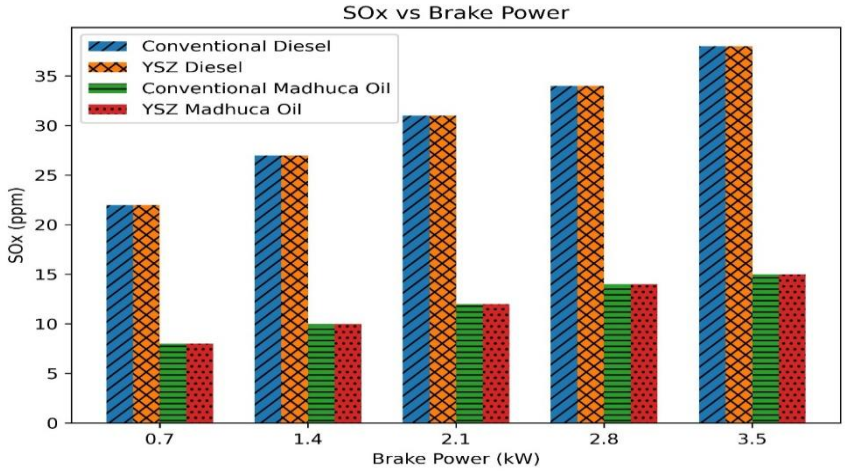


Figure 14. Deviation of smoke opacity versus BP for conventional and LHR engines.

The findings of this investigation should be interpreted within the limits of the tested engine configuration, fuel composition, coating specifications and operating conditions. The results obtained from a single-cylinder compression-ignition engine may not be directly generalizable to engines with different geometries, injection systems or operating regimes. The long-term durability of the coatings under thermal cycling, including their resistance to cracking and delamination, also requires evaluation if extended-duration testing was not performed. Further work should investigate coating durability, material-specific thermal properties and a broader range of operating conditions to establish the long-term performance and practical applicability of the investigated configurations.

5. CONCLUSION

The present study investigated the performance and emission characteristics of a single-cylinder compression ignition engine fueled with B25 biodiesel derived from Madhuca longifolia and equipped with different thermal barrier coatings (TBCs), including YSZ, Al_2O_3, TiO_2, Cr_2O_3, and gadolinium zirconate (GZ). The results demonstrated that increasing engine load improved brake thermal efficiency (BTE) and reduced brake-specific fuel consumption (BSFC). At maximum load, BSFC decreased from 0.62 to 0.31 kg/kWh for the conventional engine and further to 0.29 kg/kWh with coated configurations. BTE increased from 32.1% for the uncoated piston to 33.4% with coating. Exhaust gas temperatures reached approximately 448–455°C, indicating enhanced heat retention within the combustion chamber. The coated configurations also reduced incomplete combustion emissions. CO emissions decreased from 0.07% to 0.06% for diesel and from 0.09% to 0.07% for biodiesel operation, while HC emissions also declined. However, NOx emissions increased slightly, reaching approximately 1060 ppm compared with 1020 ppm for the conventional engine, owing to higher combustion temperatures. Differences among the coating materials were attributed to their thermal conductivity, thermal stability, and heat-retention characteristics. Uncertainty analysis indicated acceptable experimental reliability, with uncertainties of ±2–2.5% for performance parameters. Overall, combining Mahua biodiesel with suitable thermal barrier coatings offers potential for improving engine efficiency and reducing CO and HC emissions, although NOx control remains necessary. Future studies should optimize coating properties and investigate exhaust gas recirculation and after-treatment techniques to minimize NOx emissions.

ACKNOWLEDGEMENTS

No agency funding was received.

Funding Declaration: The funding has not been taken from any agency the corresponding author is to be merely responsible for the same.

CONFLICT OF INTEREST

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

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests.

DATA AVAILABILITY STATEMENT

All the data have been associated with the manuscript only; further data required will be available from the corresponding author on reasonable request.

AUTHORS CONTRIBUTION

Authors are encouraged to provide an author statement file describing their specific contributions to the article using the appropriate author contribution roles to increase transparency. The corresponding author is responsible for ensuring that all authors agree on the accuracy of the descriptions. All authors' roles should be mentioned, using the appropriate categories underneath. Authors may have played a variety of roles in their contributions. Contributions from authors do not affect the criteria for authorship established by the journal. The following are the words used to describe author contributions.

Conceptualisation; Methodology; Validation; Formal analysis; Data curation; Formal analysis; Investigation; Resources; Software; Visualisation; Writing - original draft; Writing - review & editing; Funding acquisition; Project administration; Supervision.

Authorship statements should be formatted with the names of authors first and the author contribution role(s) following, such as

Rakesh Dubey (Conceptualization; Methodology; Formal analysis; Visualisation; Supervision)

R. Meenakshi Reddy (Methodology; Data curation; Writing - original draft; Resources)

Ch. Sreenivasa Rao (Writing - original draft; Writing - review & editing)

P. Vijaya Kumar (Data curation; Formal analysis; Investigation; Resources)

Hariprasad Tarigonda (Software, Visualisation, Funding acquisition)

Ajeet Kumar Prajapati (Data curation; Writing - review & editing ; Writing - original draft; Resources)

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