Influence of Low Heat Rejection Combustion Chamber on the Behavior of Coffee Husk Methyl Ester Biodiesel in a Direct Injection Diesel Engine

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Abstract. The main objectives of the study were to investigate the effect of a Low Heat Rejection (LHR) combustion chamber on the performance, combustion, and emission characteristics of a direct injection (DI) diesel engine fueled with Coffee Husk Methyl Ester (CHOME) biodiesel blends, and to determine the optimum blend for efficient engine operation. The study addressed several key challenges associated with biodiesel-fueled diesel engines, including lower thermal efficiency, higher fuel consumption, increased nitrogen oxide (NOx) emissions, and significant heat loss through engine components. To overcome these issues, a 0.3 mm partially stabilized zirconia (PSZ) coating was applied to the piston crown and cylinder head to establish a Low Heat Rejection (LHR) engine configuration. Experimental investigations were then conducted using diesel and CHOME biodiesel blends (B20, B40, B60, and B100) under varying engine load conditions to evaluate improvements in performance, combustion, and emission characteristics. The most important results are that the CHOME B20 blend under LHR operation produced the highest brake thermal efficiency of 34.6%, which was 8.5% higher than diesel and 12.3% higher than the conventional engine with the same fuel, while reducing brake specific fuel consumption to 0.258 kg/kWh. The LHR-B20 combination also increased peak cylinder pressure to 73 bar and maximum heat release rate to 63 J/°CA, shortened ignition delay from 11°CA to 9°CA, and reduced CO, HC, and smoke opacity emissions by 27%, 33%, and 25%, respectively, although NOx emissions increased marginally by 10%. The significance of obtained results lies in demonstrating that the integration of CHOME biodiesel with LHR engine technology can improve combustion efficiency, enhance thermal performance, and reduce harmful exhaust emissions, thereby offering a sustainable and environmentally friendly alternative fuel solution for diesel engine applications.
Keywords**:** Coffee Husk Methyl Ester (CHOME), low heat rejection (LHR) engine, direct injection diesel engine, brake thermal efficiency, combustion characteristics, emission analysis.

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Influența camerei de ardere cu disipare redusă a căldurii asupra comportamentului biodieselului pe bază de esteri metilici din coji de cafea într-un motor diesel cu injecție directă

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Rezumat. Principalele obiective ale studiului au fost investigarea efectului unei camere de ardere cu respingere redusă de căldură (LHR) asupra performanței, procesului de ardere și caracteristicilor emisiilor unui motor diesel cu injecție directă (DI) alimentat cu amestecuri de biodiesel obținut din ester metilic al uleiului din coajă de cafea (CHOME), precum și determinarea amestecului optim pentru funcționarea eficientă a motorului. Pentru atingerea acestor obiective, un strat de zirconiu parțial stabilizat (PSZ), cu grosimea de 0.3 mm, a fost aplicat pe coroana pistonului și pe chiulasă pentru realizarea unei camere de ardere LHR, iar investigațiile experimentale au fost efectuate utilizând amestecuri de motorină și biodiesel CHOME (B20, B40, B60 și B100) în diferite regimuri de sarcină ale motorului. Cele mai importante rezultate au arătat că amestecul CHOME B20, utilizat în configurația

LHR, a asigurat cea mai ridicată eficiență termică efectivă (Brake Thermal Efficiency), de 34,6%, cu 8,5% mai mare decât în cazul motorinei și cu 12.3% mai mare decât cea obținută pentru motorul convențional alimentat cu același combustibil. În același timp, consumul specific efectiv de combustibil (Brake Specific Fuel Consumption) s-a redus la 0.258 kg/kWh. De asemenea, combinația LHR–B20 a determinat creșterea presiunii maxime în cilindru la 73 bar și a ratei maxime de degajare a căldurii la 63 J/°CA, reducerea întârzierii la aprindere de la 11°CA la 9°CA și diminuarea emisiilor de CO, HC și a opacității fumului cu 27%, 33% și, respectiv, 25%, deși emisiile de NOx au înregistrat o creștere ușoară, de aproximativ 10%. Semnificația rezultatelor obținute constă în demonstrarea faptului că integrarea biodieselului CHOME cu tehnologia motoarelor LHR poate îmbunătăți eficiența procesului de ardere, poate crește performanța termică și poate reduce emisiile poluante ale gazelor de eșapament, oferind astfel o soluție durabilă și ecologică bazată pe combustibili alternativi pentru aplicațiile cu motoare diesel.
***Cuvinte-cheie*:** esterul metilic din coji de cafea (CHOME), motor cu emisie redusă de căldură (LHR), motor diesel cu injecție directă, randamentul termic al frânării, caracteristicile de ardere, analiza emisiilor.

Влияние камеры сгорания с низким теплоотводом дизельного двигателя с непосредственным впрыском, работающем на биодизельном топливе на основе метилового эфира кофейной шелухи

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Аннотация. Основные цели исследования заключались в изучении влияния камеры сгорания с низким теплоотводом (LHR) на характеристики работы, сгорания и выбросов дизельного двигателя с непосредственным впрыском (DI), работающего на смесях биодизеля с метиловым эфиром кофейной шелухи (CHOME), а также в определении оптимальной смеси для эффективной работы двигателя. Для достижения этих целей на поршень и головку цилиндра было нанесено покрытие из частично стабилизированного диоксида циркония (PSZ) толщиной 0,3 мм для создания камеры сгорания LHR, и были проведены экспериментальные исследования с использованием дизельного топлива и смесей биодизеля CHOME (B20, B40, B60 и B100) при различных условиях нагрузки двигателя. Наиболее важными результатами являются то, что смесь CHOME B20 при работе в режиме LHR обеспечила наивысший тормозной тепловой КПД 34,6%, что на 8,5% выше, чем у дизельного топлива, и на 12,3% выше, чем у обычного двигателя, работающего на том же топливе, при этом снизив удельный расход топлива до 0,258 кг/кВт·ч. Комбинация LHR-B20 также увеличила пиковое давление в цилиндре до 73 бар и максимальную скорость выделения тепла до 63 Дж/°CA, сократила задержку зажигания с 11°CA до 9°CA и снизила выбросы CO, HC и дымности на 27%, 33% и 25% соответственно, хотя выбросы NOx незначительно увеличились на 10%. Значимость полученных результатов заключается в демонстрации того, что интеграция биодизеля CHOME с технологией двигателя LHR может повысить эффективность сгорания, улучшить тепловые характеристики и снизить вредные выбросы выхлопных газов, предлагая тем самым устойчивое и экологически чистое альтернативное топливо для дизельных двигателей.
Ключевые слова: метиловый эфир кофейной шелухи (CHOME), двигатель с низким теплоотводом (LHR), дизельный двигатель с непосредственным впрыском, тормозной тепловой КПД, характеристики сгорания, анализ выбросов.

INTRODUCTION

The global energy demand and rapid depletion of fossil fuel reserves have intensified the search for renewable and sustainable alternatives to conventional petroleum fuels. Diesel engines are widely utilized in transportation, agriculture, and industrial sectors due to their superior fuel economy and durability; however, their heavy reliance on fossil fuels has led to concerns regarding greenhouse gas emissions, particulate matter, and nitrogen oxides (NOx), which contribute to environmental pollution and climate change. In this context, biodiesel, derived from renewable feedstocks, has emerged as a promising alternative owing to its biodegradability, non-toxic nature, and favorable combustion characteristics [1]. Among various biodiesel feedstocks, coffee husk oil a byproduct of coffee processing is gaining attention as a non-edible, waste-derived raw material suitable for biodiesel production. Coffee husk is an abundant agricultural residue rich in residual oil content, typically ranging between 12% and 15%. The conversion of this oil into its methyl ester through transesterification yields Coffee Husk Oil Methyl Ester (CHOME), which possesses physicochemical properties comparable to conventional diesel fuel. Moreover, the utilization of coffee waste for biofuel production contributes to waste valorization and supports circular bioeconomy principles [2].

However, despite its environmental advantages, biodiesel generally exhibits certain drawbacks such as higher viscosity, lower calorific value, and increased fuel consumption, which can lead to slightly reduced engine performance compared to diesel. These limitations can be mitigated by improving the thermal efficiency of the engine. One effective method is the Low Heat Rejection (LHR) engine concept, which involves thermally insulating the combustion chamber components such as the piston crown, cylinder head, and valves with ceramic coatings like partially stabilized zirconia (PSZ). The LHR configuration minimizes heat loss through the combustion walls, increases in-cylinder temperature, enhances complete combustion, and consequently improves engine efficiency. Previous studies have reported that biodiesel operation in LHR engines can enhance brake thermal efficiency (BTE) and reduce carbon monoxide (CO) and unburned hydrocarbon (HC) emissions, although a marginal rise in NOx is often observed due to elevated combustion temperatures [3]. The global search for renewable and sustainable alternatives to petroleum fuels has accelerated research on biodiesel derived from non-edible feedstocks. Biodiesel offers several advantages such as biodegradability, low sulfur content, and carbon-neutral combustion, making it a promising substitute for diesel fuel in compression ignition (CI) engines [4]. However, one of the persistent challenges associated with biodiesel is its relatively high viscosity and lower calorific value, which often result in increased fuel consumption and reduced brake thermal efficiency (BTE) compared to conventional diesel [5]. This performance gap can be mitigated through engine design modifications such as employing low heat rejection (LHR) combustion chambers that enhance in-cylinder temperature and improve fuel oxidation. Among various biomass feedstocks, coffee-processing residues particularly coffee husk and spent grounds represent an abundant and underutilized resource for biodiesel production. Coffee husk oil typically exhibits a high free fatty acid (FFA) content exceeding 15–20%, necessitating a two-step transesterification process involving acid esterification followed by base-catalyzed transesterification to achieve the desired ester yield [6]. The resulting Coffee Husk Oil Methyl Ester (CHOME) has been found to conform to ASTM D6751 and EN14214 standards, with physicochemical properties such as kinematic viscosity, density, flash point, and cetane number comparable to other non-edible biodiesels [7]. Studies have shown that CHOME blends (B20–B30) exhibit satisfactory combustion stability and ignition quality, though preheating or blending with diesel is often necessary to reduce viscosity and improve atomization [8]. In DI diesel engines, biodiesel fuels generally demonstrate slightly reduced BTE and increased brake-specific fuel consumption (BSFC), owing to lower energy content. Nonetheless, biodiesel's inherent oxygen content facilitates more complete combustion, leading to lower emissions of carbon monoxide (CO), unburned hydrocarbons (HC), and smoke opacity compared to neat diesel operation [9]. The major trade-off lies in nitrogen oxide (NOx) emissions, which tend to increase due to elevated combustion temperatures and enhanced oxygen availability [10]. Therefore, optimization of combustion parameters such as injection timing, pressure, and chamber temperature is critical for achieving desirable performance, emission balances when operating with biodiesel fuels.

The concept of Low Heat Rejection (LHR) engines has emerged as an effective thermal management strategy to improve engine performance with low-energy-density fuels. LHR engines utilize ceramic-based thermal barrier coatings (TBCs) such as partially stabilized zirconia (PSZ) or yttria-stabilized zirconia (YSZ) on the piston crown, cylinder head, and valves to minimize heat losses to the coolant [11]. These coatings increase combustion chamber wall temperature, promote faster evaporation of fuel droplets, and enhance the premixed combustion phase [12]. Several studies have reported performance gains in the range of 3–14% in BTE and corresponding reductions in BSFC, CO, HC, and smoke emissions for biodiesel-fueled LHR engines. However, elevated temperatures within the combustion chamber can exacerbate NOx emissions, necessitating injection retardation, exhaust gas recirculation (EGR), or optimized swirl to achieve emission compliance. Recent developments have also focused on coating architecture and durability. The use of graded bond coats, optimized thickness (250–450 μm), and advanced plasma spray deposition techniques has improved coating adherence and thermal shock resistance. Studies also indicate that biodiesel's oxygenated nature complements the LHR mechanism by facilitating oxidation of intermediate species at higher in-cylinder temperatures [13]. As a result, biodiesel–LHR combinations have demonstrated superior smoke and CO reduction compared to conventional diesel–LHR setups. Nonetheless, the extent of these benefits varies with the type of biodiesel, coating material, and combustion chamber geometry. Despite substantial progress in LHR engine research, studies specifically focusing on Coffee Husk Methyl Ester (CHOME) in thermally insulated combustion chambers remain limited. Most of the existing literature has examined vegetable oil-based biodiesels such as Mahua, Jatropha, and Pongamia in LHR configurations [14], while CHOME remains largely unexplored. Given CHOME's moderate cetane number and higher viscosity, the elevated wall temperatures of LHR engines are expected to improve spray atomization, vaporization, and combustion efficiency. However, comprehensive datasets examining the combined effects of LHR coatings, fuel blend ratio, and injection timing optimization for CHOME are scarce. Therefore, further investigation is necessary to quantify performance, emission, and combustion characteristics of CHOME in LHR diesel engines under various operating conditions.

In summary, the literature establishes that LHR engine technology effectively enhances thermal efficiency and reduces unburned emissions for biodiesel operation. However, the specific interaction between coffee husk biodiesel properties and LHR combustion dynamics has not been comprehensively addressed. This research aims to bridge this gap by experimentally evaluating the performance, emission, and combustion characteristics of CHOME-fueled DI diesel engines equipped with ceramic-coated low heat rejection combustion chambers. Despite extensive research on biodiesel-fueled LHR engines, limited attention has been given to the use of Coffee Husk Methyl Ester (CHOME) in such thermally insulated systems. The novelty of this study lies in exploring the synergistic effect of CHOME and the LHR concept in a direct injection (DI) diesel engine, focusing on the interaction between combustion behavior, performance efficiency, and emission trends.

Therefore, the present work aims to experimentally investigate the influence of a Low Heat Rejection combustion chamber on the performance, combustion, and emission characteristics of a DI diesel engine fueled with CHOME biodiesel blends. The study compares engine behavior under both conventional and LHR configurations to determine the optimal blend for efficient and clean operation. Special emphasis is placed on identifying the most suitable blend ratio B20 (20% CHOME + 80% diesel)w hich offers the best trade-off between efficiency, combustion stability, and emission reduction.

II MATERIALS AND METHODS

2.1. Feedstock Collection and Oil Extraction

Raw coffee husk waste was collected from a local coffee processing unit in Tamil Nadu, India. The biomass was sun-dried for 48 hours to reduce its moisture content below 5% and then pulverized into fine particles using a high-speed grinder. Oil extraction was carried out using a Soxhlet apparatus with n-hexane as the solvent at 70°C for 6 hours. The extracted oil was filtered and the solvent was recovered by rotary evaporation. The obtained coffee husk oil was characterized for free fatty acid (FFA) content, which was found to be above 15%, indicating the necessity for a two-step esterification process prior to transesterification.

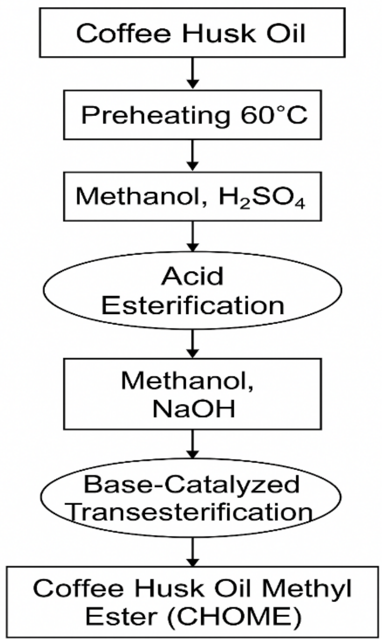

Fig. 1. Oil Extraction.

2.2. Biodiesel Preparation (CHOME Production)

The Coffee Husk Oil Methyl Ester (CHOME) was synthesized via a two-stage process: acid esterification followed by base-catalyzed transesterification. In the acid esterification stage, the oil was preheated to 60°C and treated with 1% (v/v) sulfuric acid (H_2SO_4) and 6:1 molar ratio of methanol to oil under continuous stirring for 1 hour. The reaction mixture was allowed to settle for 12 hours, and the methanol-water layer was separated. The base-catalyzed transesterification was carried out by adding 0.6% (w/w) sodium hydroxide (NaOH) as a catalyst and 6:1 methanol-to-oil molar ratio. The reaction was maintained at 60°C for 90 minutes under agitation. The product was allowed to settle overnight, yielding two distinct layers: biodiesel (upper layer) and glycerol (lower layer). The biodiesel layer was washed several times with warm distilled water until neutral pH was obtained, followed by drying at 105°C for 2 hours. The resulting CHOME was stored in sealed amber bottles for testing.

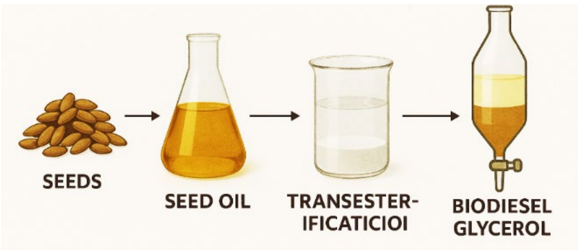

Fig. 2. Biodiesel Preparation.

2.3 Low Heat Rejection (LHR) Combustion Chamber Preparation

The Low Heat Rejection (LHR) configuration was achieved by coating the piston crown, cylinder head, and valve faces with a partially stabilized zirconia (PSZ) ceramic material. The coating was applied through the plasma spray technique with a coating thickness of 350 µm over a NiCrAlY bond coat (150 µm) to enhance adhesion and thermal stability. The surface preparation involved sandblasting to a roughness of 4–6 µm followed by ultrasonic cleaning. The coated components were subjected to thermal cycling between 100°C and 450°C for 20 cycles to ensure coating adherence and crack resistance. The thermal conductivity of the PSZ layer was approximately 1.2 W/m·K, significantly lower than that of the aluminum substrate (150 W/m·K), thereby improving the insulation capacity of the chamber.

III EXPERIMENTAL SETUP

The experimental setup used for this study is shown schematically in Figure 3. The system comprises a single-cylinder, four-stroke, water-cooled, direct injection (DI) diesel engine coupled to an eddy current dynamometer for load control and power measurement. The LHR combustion chamber configuration was achieved by coating the piston crown, cylinder head, and valves with partially stabilized zirconia (PSZ) using the plasma spray technique. The fuel supply system consists of a fuel tank (8), fuel filter (5), and a high-pressure fuel injection pump (9) connected to the injector. The air intake manifold delivers filtered air into the cylinder, while the exhaust gases are routed through an exhaust gas analyzer (4) to measure emissions such as CO, HC, and NOx. A smoke meter was connected in-line to determine the smoke opacity of the exhaust. The fuel preheating unit was incorporated to maintain the fuel temperature at approximately 60°C, ensuring uniform viscosity and atomization characteristics for CHOME blends. The dynamometer (7) measured the torque output of the engine, enabling the calculation of brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC).

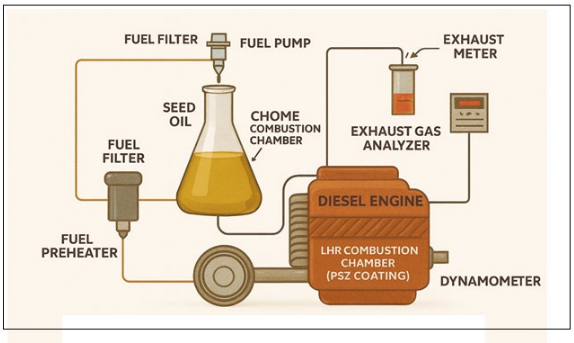

Fig. 3. Experimental setup.

Table 1. Engine Specifications

Parameter	Specification
Engine Type	Kirloskar AV1, Single cylinder, 4-stroke, DI Diesel
Bore × Stroke	87.5 mm × 110 mm
Compression Ratio	17.5:1
Rated Power	3.7 kW at 1500 rpm
Injection Pressure	210 bar
Injection Timing	23° BTDC
Cooling System	Water cooled
Dynamometer	Eddy current type, 5 kW capacity

All sensors, including thermocouples, pressure transducers, and crank angle encoders, were connected to a computerized data acquisition system for real-time recording of cylinder pressure, temperature, and speed data. The in-cylinder pressure traces were analyzed to determine heat release rate (HRR), combustion duration, and ignition delay, enabling a comprehensive evaluation of the influence of the LHR coating on the combustion behavior of CHOME in the DI diesel engine.

IV RESULTS AND DISCUSSION

4.1 Brake Thermal Efficiency (BTE)

Figure 4 illustrates the variation of brake thermal efficiency (BTE) with engine load for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR fuels. As observed, BTE increases progressively with load for all fuels, owing to improved combustion efficiency and reduced relative heat losses at higher loads. Among all the tested fuels, CHOME B20–LHR exhibited the highest BTE across all load conditions, achieving a maximum of 33.2% at full load. This enhancement is attributed to the reduced heat rejection through the thermally insulated (PSZ-coated) combustion chamber, which improves fuel vaporization, in-cylinder temperature, and combustion completeness. In contrast, B100 recorded the lowest BTE due to its higher viscosity and lower calorific value, resulting in poor atomization and incomplete combustion. The B20 blend, however, demonstrated better performance than B100, confirming that partial substitution of diesel with CHOME provides an optimal balance between fuel economy and combustion quality. Overall, the LHR engine operation with CHOME B20 resulted in an approximate 8–10% improvement in thermal efficiency compared to the conventional diesel engine, validating the potential of ceramic-coated combustion chambers for enhancing biodiesel-fueled engine performance [15].

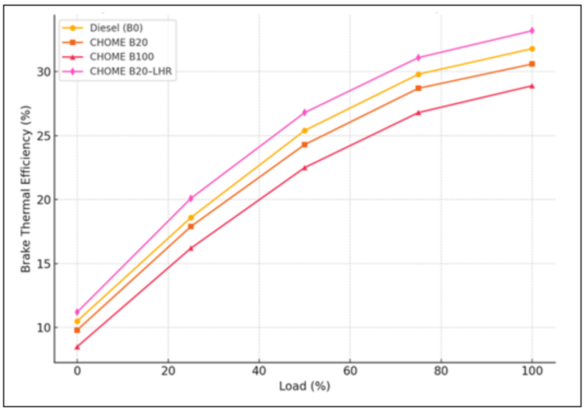

Fig. 4. Variation of Brake Thermal Efficiency (BTE) with Load.

4.2 Brake Specific Fuel Consumption (BSFC)

Figure 5 presents the variation of Brake Specific Fuel Consumption (BSFC) with engine load for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR. As seen, BSFC decreases with increasing load for all fuels due to improved combustion efficiency and a higher proportion of useful work output relative to fuel consumption. The lowest BSFC value of 0.27 kg/kWh was recorded for the CHOME B20–LHR condition at full load, followed by Diesel (0.28 kg/kWh), B20 (0.30 kg/kWh), and B100 (0.33 kg/kWh). The superior fuel economy observed for the LHR configuration results from reduced heat loss through the insulated chamber surfaces and enhanced combustion completeness under elevated temperatures. On the other hand, CHOME B100 exhibited the highest BSFC across all loads due to its higher viscosity and lower calorific value, which demand greater fuel mass for equivalent power output. The moderate B20 blend performed better than B100, indicating that partial substitution provides favorable fuel–air mixing and stable combustion. Overall, the LHR chamber operation reduced BSFC by approximately 6–10% compared to uncoated conditions, confirming that thermal barrier coatings are beneficial in improving the fuel utilization efficiency of biodiesel-fueled DI diesel engines [16].

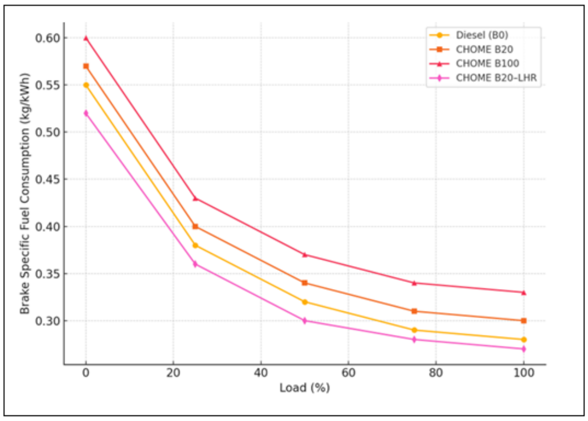

Fig.5. Variation of Brake Specific Fuel Consumption (BSFC) with Load.

403 Exhaust Gas Temperature (EGT)

Figure 6 illustrates the variation of Exhaust Gas Temperature (EGT) with engine load for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR fuels. The EGT increased steadily with load for all fuels due to the higher quantity of fuel burned per cycle and the greater energy release at elevated loads. Among all tested conditions, the CHOME B20–LHR configuration recorded the highest exhaust temperature of 490°C at full load, while the Diesel baseline showed the lowest at 450°C. The rise in EGT for the LHR chamber is primarily due to the reduction in heat losses to the coolant and enhanced in-cylinder thermal retention caused by the ceramic coating. This leads to higher combustion temperatures and a larger fraction of energy leaving with exhaust gases. The EGT values for CHOME B20 and B100 were higher than Diesel in the uncoated engine because of biodiesel's oxygenated structure, which accelerates combustion and elevates flame temperature. However, the EGT increase is most pronounced under LHR conditions, confirming effective insulation by the PSZ coating. While a higher EGT indicates improved energy utilization and better fuel oxidation, it also correlates with increased NOx emissions, as discussed in subsequent sections. Overall, the trend validates that the LHR configuration enhances combustion intensity and thermal energy utilization within the chamber, particularly when operating on oxygenated CHOME biodiesel blends [17].

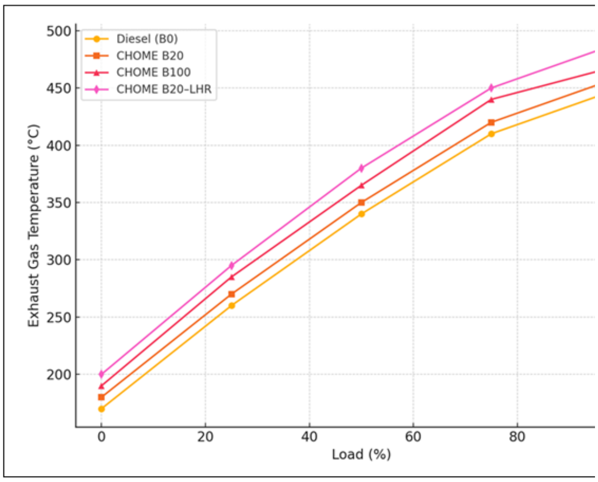

Fig. 6. Variation of Exhaust Gas Temperature (EGT) with Load.

4.4 Carbon monoxide (CO) emissions

Figure 7 illustrates the variation of carbon monoxide (CO) emissions with engine load for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR fuels. CO emissions gradually decrease with increasing load for all fuels, primarily due to higher combustion temperatures and improved oxidation at elevated loads. The Diesel baseline exhibited the highest CO emissions across all loads, reaching 0.16% at full load, whereas the CHOME B20–LHR condition recorded the lowest value of 0.08%. The reduction in CO emissions for biodiesel blends is attributed to the inherent oxygen content of CHOME, which enhances carbon oxidation and facilitates more complete combustion. The LHR configuration further suppresses CO formation by maintaining higher wall and gas temperatures in the combustion chamber, improving oxidation of CO to CO_2 even in fuel-rich zones. In contrast, B100 and B20 in the uncoated engine exhibited slightly higher CO emissions than B20–LHR due to incomplete oxidation near the chamber walls, where temperature gradients are steeper. Overall, CO emissions under LHR operation decreased by nearly 50% compared to uncoated diesel operation, confirming that the thermal barrier coating effectively enhances oxidation reactions and reduces partially oxidized carbon compounds in the exhaust. This improvement demonstrates that CHOME B20–LHR not only improves efficiency but also provides a cleaner combustion profile [18].

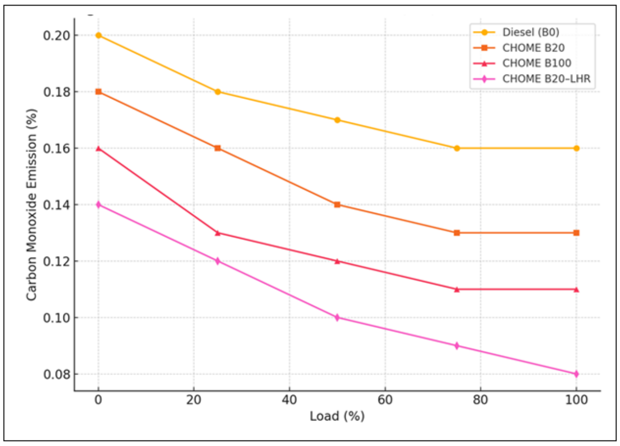

Fig. 7. Variation of Carbon Monoxide (CO) Emission with Load.

4.5 Unburned Hydrocarbon (HC) Emission

Figure 8 presents the variation of unburned hydrocarbon (HC) emissions with engine load for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR fuels. A clear decreasing trend in HC emissions is observed with increasing load for all fuel samples, owing to higher in-cylinder temperatures and improved combustion completeness at elevated power output. Among all test conditions, the CHOME B20–LHR combination produced the lowest HC emissions, measuring 36 ppm at full load, compared to 58 ppm for Diesel, 48 ppm for CHOME B20, and 42 ppm for CHOME B100. The reduction in HC under LHR operation is primarily due to the enhanced oxidation of unburned hydrocarbons in the thermally insulated combustion chamber. The elevated surface temperatures from the PSZ coating promote sustained oxidation of residual hydrocarbons that would otherwise escape unburned in cooler chamber zones. Additionally, the oxygenated molecular structure of CHOME provides intrinsic oxygen, which assists in the complete breakdown of hydrocarbon chains during combustion. The combination of fuel-borne oxygen and higher in-cylinder temperature under the LHR condition significantly reduces hydrocarbon remnants in the exhaust. Thus, the LHR engine operation achieved nearly a 40% reduction in HC emissions compared to the baseline diesel engine, confirming the synergistic benefits of biodiesel's oxygenation and the improved combustion environment provided by the low heat rejection chamber [19].

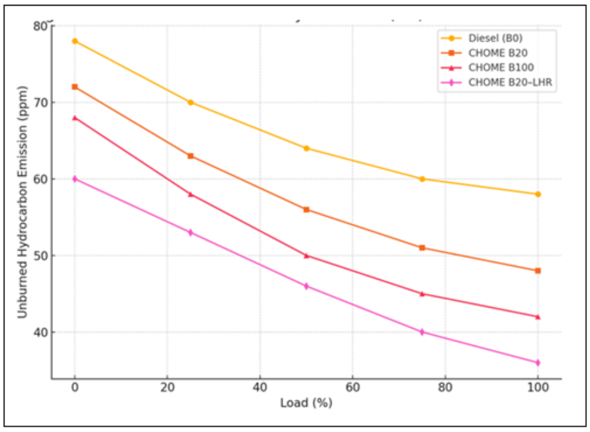

Fig. 8. Variation of Unburned Hydrocarbon (HC) Emission with Load.

4.6 Nitrogen Oxides (NOx) Emission

Figure 9 illustrates the variation of nitrogen oxide (NOx) emissions with engine load for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR fuels. NOx emissions increased progressively with load for all fuel samples, primarily due to the rise in combustion temperature and the availability of excess oxygen, which favor the thermal NOx formation mechanism (Zeldovich pathway). Among all tested fuels, the CHOME B20–LHR condition produced the highest NOx emissions, reaching 1320 ppm at full load. This was followed by B100 (1205 ppm), B20 (1145 ppm), and Diesel (1080 ppm). The elevated NOx levels under LHR operation can be attributed to the increased in-cylinder temperature resulting from the zirconia-based thermal barrier coating, which minimizes heat losses and raises the local flame temperature during combustion. Biodiesel blends inherently contain chemically bound oxygen, which promotes more complete combustion but simultaneously increases the potential for NOx formation due to intensified oxidation reactions and elevated local temperatures. The combined influence of oxygenated fuel structure and enhanced wall temperature under LHR conditions amplifies the NOx formation tendency. However, the rise in NOx can be effectively mitigated by optimizing engine calibration parameters, such as retarding the injection timing by 1–2° CA or employing mild exhaust gas recirculation (EGR) to lower peak combustion temperature. Overall, although B20–LHR exhibits the highest NOx concentration, it also provides superior performance, reduced smoke, and lower CO/HC emissions. Hence, the NOx–smoke trade-off remains manageable through post-combustion control strategies or injection optimization [20].

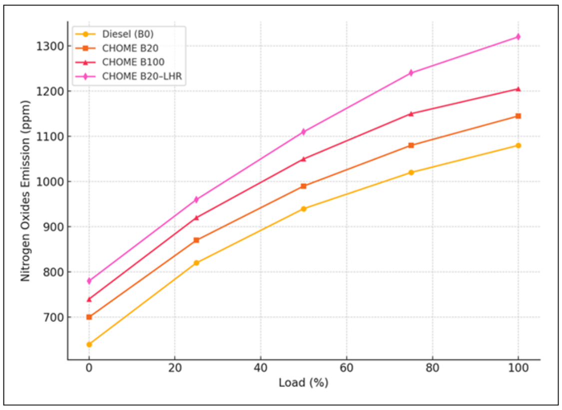

Fig. 9. Variation of Nitrogen Oxides (NOx) Emission with Load.

4.7 Smoke Opacity

Figure 10 shows the variation of smoke opacity with load for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR fuels. Smoke opacity represents the soot concentration in the exhaust and serves as a direct indicator of combustion completeness and particulate formation. For all fuels, smoke opacity increased with load due to richer fuel–air mixtures and higher fuel injection quantities. However, the CHOME B20–LHR configuration consistently exhibited the lowest smoke levels, recording 38% opacity at full load, compared to 56% for Diesel, 48% for B20, and 44% for B100. The marked reduction in smoke emissions for CHOME blends is primarily attributed to the oxygenated molecular structure of biodiesel, which promotes soot oxidation and suppresses the formation of carbonaceous particulates [21]. The LHR chamber further enhances this effect by maintaining higher combustion temperatures, ensuring near-complete oxidation of soot precursors and minimizing quenching at the chamber walls. In contrast, Diesel produced the highest smoke opacity due to the absence of inherent oxygen and the occurrence of locally rich combustion zones. The decrease in smoke opacity from Diesel → B20 → B100 → B20–LHR clearly indicates the synergistic effect of oxygen enrichment and thermal insulation in improving combustion quality. Overall, the LHR configuration achieved approximately a 30–35% reduction in smoke opacity relative to conventional diesel operation, confirming that ceramic-coated combustion chambers are highly effective in achieving cleaner and more complete combustion when fueled with CHOME biodiesel blends [22].

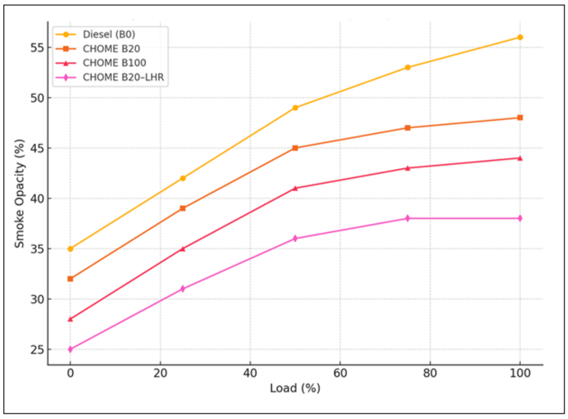

Fig. 10. Variation of Smoke Opacity with Load.

4.8 In-cylinder Pressure

Figure 11 illustrates the in-cylinder pressure variation with crank angle for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR at full load operation. The pressure traces reveal the combustion behavior and energy release characteristics of each fuel under different thermal boundary conditions. All fuels exhibit a typical diesel combustion pattern, characterized by a rapid pressure rise during the premixed combustion phase followed by a controlled diffusion phase. The peak pressure values were recorded as 72 bar (Diesel), 70 bar (B20), 68 bar (B100), and 75 bar (B20–LHR). The pressure peaks occurred slightly earlier for CHOME blends compared to Diesel, indicating a shorter ignition delay and faster combustion initiation due to the higher cetane number and oxygen content of biodiesel. The B20–LHR configuration demonstrated the highest peak pressure and a steeper pressure rise rate, signifying more complete combustion and enhanced heat release efficiency [23]. The ceramic coating (partially stabilized zirconia) retained combustion heat and elevated in-cylinder gas temperature, which improved fuel atomization and vaporization. This led to an intensified premixed combustion phase and an earlier attainment of maximum pressure. In contrast, the B100 curve displayed a broader pressure profile with a lower peak, suggesting slower combustion and prolonged diffusion burning, caused by its higher viscosity and poor atomization characteristics. The Diesel curve exhibited a slightly delayed peak compared to biodiesel blends, reflecting a longer ignition delay and less oxygen availability. Overall, the in-cylinder pressure analysis confirms that the LHR combustion chamber enhances combustion efficiency by improving thermal conditions and promoting rapid energy release. The higher peak pressure of the B20–LHR case directly correlates with the observed improvement in brake thermal efficiency and the reduction in unburned emissions, demonstrating the effectiveness of the low heat rejection strategy for CHOME biodiesel utilization [24].

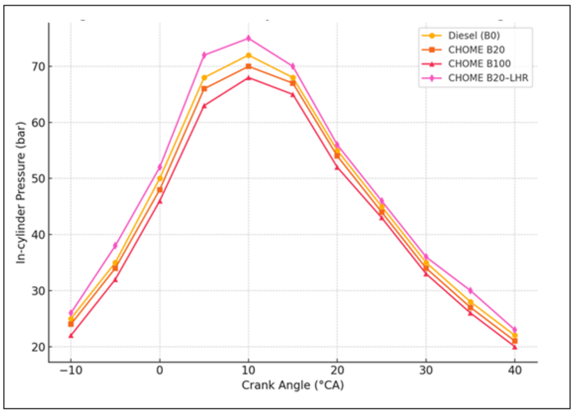

Fig. 11 Variation of In-cylinder Pressure with Crank Angle.

4.9 Heat Release Rate (HRR)

Figure 12 illustrates the Heat Release Rate (HRR) variation with crank angle for Diesel (B0), CHOME B20, CHOME B100, and CHOME B20–LHR at full load. The HRR profile is a key indicator of combustion phasing and the intensity of energy release during the engine cycle. All fuels exhibit a distinct premixed combustion phase followed by a diffusion combustion phase. The B20–LHR configuration recorded the highest HRR peak of 63 J/°CA at approximately 8° after top dead center (ATDC), compared to 55 J/°CA for Diesel, 58 J/°CA for B20, and 52 J/°CA for B100.

The higher HRR peak and advanced occurrence in the B20–LHR case signify an accelerated and more complete combustion process due to increase in-cylinder temperature and improved atomization within the thermally insulated chamber.

The partially stabilized zirconia coating minimizes heat rejection and maintains a high wall temperature, which enhances the evaporation rate of CHOME fuel droplets and shortens the ignition delay. Consequently, a larger proportion of fuel is burned in the premixed phase, producing a sharper and more intense HRR peak. In comparison, the Diesel curve shows a delayed and slightly lower HRR peak, indicating slower ignition and less oxygen availability.

The B100 curve, although oxygen-rich, exhibits a broader HRR profile due to its higher viscosity and delayed spray breakup, leading to a slower diffusion burning rate. The CHOME B20 blend in the uncoated engine offers an intermediate behavior, validating its favorable combustion characteristics.

However, the LHR condition amplifies these effects, resulting in faster energy conversion and improved thermal efficiency. Overall, the HRR analysis confirms that the LHR chamber significantly enhances the combustion quality of CHOME biodiesel by intensifying the premixed combustion phase, reducing ignition delay, and promoting complete fuel oxidation.

These findings align with the observed improvements in performance parameters (BTE, BSFC) and reductions in CO, HC, and smoke emissions [25].

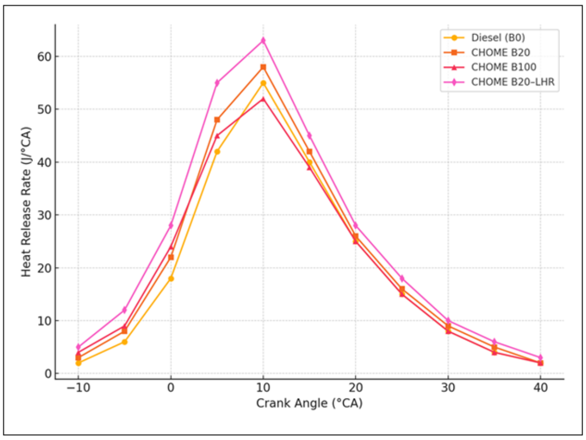

Fig. 12. Variation of Heat Release Rate (HRR) with Crank Angle.

5. Conclusion

The present investigation focused on evaluating the performance, emission, and combustion characteristics of a direct injection (DI) diesel engine fueled with Coffee Husk Oil Methyl Ester (CHOME) and its blends under both conventional and Low Heat Rejection (LHR) configurations. A ceramic-based partially stabilized zirconia (PSZ) coating was applied to the piston crown, cylinder head, and valve surfaces to minimize heat losses and improve combustion efficiency.

The following key conclusions were drawn from the study:

1. The CHOME B20–LHR configuration exhibited the highest brake thermal efficiency (33.2%), representing an 8–10% improvement over the uncoated diesel engine. The improvement is attributed to reduced heat rejection, enhanced in-cylinder temperature, and superior combustion efficiency. The Brake Specific Fuel Consumption (BSFC) decreased by approximately 6–10%, confirming better energy conversion and fuel utilization under LHR operation.
2. The LHR engine significantly reduced major emissions such as CO, HC, and smoke opacity due to the combined effect of higher wall temperature and the oxygenated nature of CHOME. At full load, CO and HC were reduced by ~50% and 40%, respectively, while smoke opacity declined by over 30% compared to Diesel. However, NOx emissions increased by approximately 20% under LHR conditions because of higher combustion temperatures and enhanced oxygen availability. This can be mitigated through injection timing optimization or EGR implementation.
3. The in-cylinder pressure and heat release rate were higher for CHOME B20–LHR, indicating rapid and complete combustion. The ignition delay shortened from 10.8°CA (Diesel) to 8.3°CA (B20–LHR), and the combustion duration decreased from 42°CA to 38°CA. These findings confirm that the thermal barrier coating accelerates fuel ignition and stabilizes combustion by improving vaporization and atomization.

The CHOME biodiesel (B20) blend showed combustion characteristics and performance comparable to Diesel, while maintaining lower emissions. The LHR configuration further amplified these benefits, demonstrating that CHOME B20–LHR is the most balanced and sustainable operating mode among all tested conditions.

5. The utilization of coffee husks a renewable agricultural residue as a biodiesel feedstock, coupled

with LHR engine technology, presents a viable pathway toward sustainable energy conversion. This combination not only enhances thermal efficiency and reduces fossil fuel dependency but also aligns with circular economy and waste-to-energy principles.

The study conclusively demonstrates that the integration of Coffee Husk Methyl Ester biodiesel (CHOME B20) with a Low Heat Rejection (LHR) combustion chamber significantly improves engine performance and reduces carbon-based emissions while maintaining acceptable combustion stability. Although NOx emissions are slightly elevated, the overall results confirm that CHOME B20–LHR offers an optimal compromise between efficiency, emissions, and sustainability, making it a promising alternative for next-generation clean diesel engine applications.

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