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Experimental investigation of ternary blends on performance, and emission behaviors of a modified low-heat rejection CI engine

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ABSTRACT

This study investigated the performance, combustion, and emissions of a modified low heat rejection (LHR) diesel engine fueled with a blend of 90 % coconut waste cooking oil (CWCO) biodiesel and 10 % diethyl ether (DEE). The engine combustion chamber components were coated with 300 μm lanthanum-doped partially stabilized zirconia for thermal insulation. Engine testing was performed at varied loads from 0 to 100 % using an eddy current dynamometer. Exhaust emissions, including hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and smoke were measured. Compared to conventional diesel, the CWCO-DEE blend showed a 3 % higher brake thermal efficiency of 33.4 % and 2.42 % lower brake-specific fuel consumption at full load. HC, CO, and smoke emissions decreased by 18 % (39 ppm), 11 %, and 19 % at higher loads with the blend. However, NOx emissions increased slightly by 21.2 %. The DEE compensated for CWCO's lower cetane number and viscosity, while the LHR coating enhanced combustion by providing thermal insulation, raising exhaust gas temperatures by 13 %. The improved efficiency and reduced emissions demonstrate the potential of optimized biodiesel-additive blends in conjunction with LHR engine modifications to sustainably utilize inexpensive waste cooking oil feedstocks as renewable diesel replacements. However, further optimization of blend compositions, additives, and coatings is needed to balance performance benefits against possible NOx increases.

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This study highlights a promising combined approach leveraging engine design and fuel advancements.

Symbol	Definition
CWCO	Coconut waste cooking oil
DEE	Di-Ethyl Ether
PSZ	Lanthanum-doped partially stabilized zirconia
BSFC	Brake-specific fuel consumption
BTE	Brake thermal efficiency
NOx	Nitrogen oxides
HC	Hydrocarbons
CO	Carbon monoxide
EGT	Exhaust gas temperature

1. Introduction

The search for sustainable and renewable fuel sources has increased interest in biodiesels produced from waste oils. Biodiesel offers potential advantages over conventional diesel, including biodegradability, lower emissions, and use of waste feedstocks. However, biodiesels also present technical challenges related to properties like density, viscosity, and cetane number compared to regular diesel. These issues can reduce engine performance and increase emissions.

Various strategies have aimed to improve biodiesel fuel properties and performance, including blending with additives and engine modifications like low heat rejection (LHR) engines. LHR engines use thermal barrier coatings to reduce heat loss and improve thermal efficiency. Biodiesel-additive blends can compensate for undesirable fuel properties. This study explores a combined approach of using an LHR diesel engine fueled with a biodiesel-additive blend.

Abdul-Kader et al. [1] synthesized a nano zeolite catalyst from Iraqi sand to produce biodiesel from waste cooking oil. They found the optimal conditions were 60 °C, 2 h reaction time, 10 % KOH catalyst loading, and 75 μm particle size, achieving 86.67 % conversion and 82.22 % yield.Ahmed et al. [2] blended animal fat and waste cooking oil biodiesels with diesel in a CI engine. They found that 50 % animal fat, 30 % waste cooking oil, and 20 % diesel improved efficiency and reduced emissions compared to other blends.Bello et al. [3] produced hierarchical zeolite Y catalysts by simultaneous desilication and dealumination of commercial zeolite Y. The optimal catalyst with 0.3 M NaOH and 0.3 M EDTA had a high surface area. It gave 94.8 % biodiesel yield from waste cooking oil. Bhan et al. [4] found blending Al_2O_3 nanoparticles into waste cooking oil biodiesel-diesel improved efficiency and reduced emissions in a CRDI diesel engine compared to blending without nanoparticles.Bunaciu et al. [5] reviewed applications of FTIR spectroscopy for discriminating and analyzing edible oils from 2015 to 2022, noting increased use for detecting modifications.Deepak & Mohamed Ibrahim [6] formulated a stable microemulsion fuel using used cooking oil and carbinol, finding 50 % used cooking oil, 25 % carbinol, and 25 % butan-2-ol met biodiesel specifications.Dey & Ray (2021) found that blending 0.50 waste vegetable oil heated for different durations with diesel gave similar properties to diesel and reduced cost by 38 % with lowered emissions.Dinesha et al. [7] found that blending CeO_2 and Al_2O_3 nanoparticles into waste cooking oil biodiesel-diesel reduced exhaust emissions in a CI engine, especially at 50 ppm CeO_2 and 30 ppm Al_2O_3.Eller et al. [8] produced bio-jet fuel from waste coconut oil by catalytic cracking over sulfided transition metal catalysts, finding favorable smoke points and reduced aromatics.Elsharkawy [9] blended castor and waste cooking oil biodiesels with diesel, finding that 15 % of each biodiesel with 70 % diesel improved engine performance and emissions. Etghani & Mirgolbabaei [10] found that increasing biodiesel concentration in vegetable oil biodiesel-diesel blends improved power and emissions but worsened fuel consumption in a diesel engine. Farvardin et al. [11] optimized ultrasound-assisted biodiesel production from waste cooking oil, finding 90.45 % yield at 60 s residence time, 1 % catalyst, 6:1 methanol: oil ratio, and 250 W power. Some other synthesized a K-loaded magnetic catalyst that gave 96.28 % and 84.05 % biodiesel yields from sunflower and waste cooking oils under optimized conditions. Gülüm & Bilgin [12] measured the densities of biodiesel-diesel-alcohol blends at different temperatures and proposed two-dimensional models to predict density as a function of temperature and alcohol content. Hao et al. [13] used Ni–Cu/Al-KCC-1 catalysts to convert waste cooking oil model compound into H_2 and carbon nanotubes, achieving 49.8 % H_2 and 71.4 % H_2 selectivity with 10 % Ni and 5 % Cu catalyst. Hasni et al. [14] optimized microwave-assisted extraction of virgin coconut oil from solid coconut waste, finding 160 W power, 2.5 min time, and 30 ml/g solvent: feed ratio gave a 15.93 % yield. Jain et al. [15] found that the rejuvenation capability of waste cooking oils for asphalt varies based on the oil source, with sunflower oil showing the greatest ability. Karkal et al. [16] produced biodiesel from freshwater fish waste oil using a shrimp shell-derived catalyst, achieving 82.57 % yield under optimized conditions. Katagi et al. [17] reviewed converting wastes to value-added microbial biopolymer PHAs via bacterial fermentation as a waste-to-energy technology.Kathirvel et al. [18] found that blending 20 % waste cooking oil biodiesel, 5 % ethanol, and 75 % diesel showed the best engine performance and emissions at compression ratio 21.Komesli et al. [19] produced lipase and hydrolyzed waste frying oil using Pseudomonas yamanorum LP2 under non-sterile conditions, achieving similar results as sterile conditions.Kumbhar et al. [20] found that biodiesels increased NOx. They reduced CO_2 but showed variability in engine performance compared to diesel in numerical analysis.Researchers found neat restaurant waste sunflower oil performed similarly to fresh sunflower oil in a diesel engine, reducing emissions.Mena-Cervantes et al. [21] found that 10–20 % waste cooking oil biodiesel blends had higher spray penetration and area than 5 % blend and diesel in split injections, improving mixing. Researchers found that waste cooking oil in an LHR diesel engine had higher efficiency and lower smoke and HC emissions than a standard diesel engine. Naik & Udayakumar [22] produced biodiesel from waste cooking oil over coconut shell-derived catalyst, optimizing 96 % yield at 6 % catalyst loading, 1:9 oil: methanol ratio, 65 °C, and 5 h.Nawaz et al. [23] optimized biodiesel production from used frying oils at 1.5 % KOH catalyst, 9:1 methanol: oil ratio, 60 °C, and 600 rpm, confirmed by GC-MS and FTIR.Through environmentally friendly processes, Unugul et al. [24] converted coffee wastes to trimethylolpropane esters as potential bio-lubricants. Yıldırım et al. [25] found vibration amplitude increased slightly and sound level increased with biodiesel from waste cooking oils compared to diesel fuel in a diesel engine. Researchers found cerium oxide and aluminum oxide nanoparticles in waste cooking oil biodiesel-diesel reduced emissions like CO, HC, and NOx in a compression ignition engine.

The improvements in performance and emissions observed with the CWCO-DEE blend in the LHR engine can be attributed to several factors. DEE increases fuel volatility and improves air-fuel mixing, allowing for more complete combustion and higher thermal efficiencies [10,26]. Furthermore, the thermal barrier coating reduces heat losses, raising combustion temperatures, which promote soot oxidation, thereby reducing particulate emissions like smoke [27]. However, the higher temperatures can also lead to increased NOx formation from the thermal fixation of atmospheric nitrogen [7]. The LHR engine concept balances these competing effects to optimize overall efficiency and emissions.

Specifically, this work analyzes an LHR diesel engine's performance, combustion, and emissions fueled with a blend of 90 % coconut waste cooking oil (CWCO) biodiesel and 10 % diethyl ether (DEE). CWCO is an inexpensive and abundant feedstock but has high viscosity and low volatility. DEE can improve these properties as it has a high cetane number and volatility. The coating provides thermal insulation to enhance combustion further. This work assesses the potential of using LHR engines with tailored biodiesel-additive blends to improve performance versus conventional diesel. The outcomes can aid the development of optimized engines and fuels to utilize biodiesel resources sustainably. Most studies have focused on either LHR engines or biodiesel blends, but few have combined both approaches. This work helps fill that gap and evaluate a promising combined biodiesel-LHR system.

2. Materials and methods

It is commonly known that diesel engines function best when used for biodiesel made from pure coconut oil. However, the commercialization of coconut oil biodiesel is impractical because of its greater price and need as a food ingredient. This work converted waste coconut feedstock derivative coconut waste cooking oil into biodiesel (Fig. 1). The composition and characteristics of fatty acids, including density, calorific value, kinematic viscosity, cloudiness, pourability, boiling points, flash, and fire points, were measured and compared to those of coconut waste cooking oil, biodiesel, and regular diesel. Furthermore, Based on engine testing with blends of coconut waste cooking oil with 10 % DEE, it was discovered that coconut waste cooking oil biodiesel had comparable engine performance, emission, and combustion characteristics [28]. So, with all the benefits of coconut waste, cooking oil can be used as inexpensive feedstock for biodiesel production.

Diethyl ether is chosen as an additional component and a starter improver based on its characteristics. Diethyl ether is also known as sulfuric, ethoxy ethane, and ethyl ether. It is a naturally occurring ingredient from the ether family, and the mixture's formula is $(C_2H_5)_2O$. To produce ethanol, ethanol is dried out and transformed into fume. In this substance reaction, alumina impetuses increase diethyl ether yields by up to 95 % while delivering diethyl ether as a byproduct. Diethyl ether is a highly flammable and potentially hazardous mixture because it has a lower self-start temperature and more viscosity than air. The flash and fire points of diethyl ether are low. The characteristics of the biodiesels and DEE with diesel are shown in Table 1.

Generally, a diesel engine's fuel efficiency is higher than a petrol engine's. Even a diesel engine rejects over two-thirds of the heat energy from the fuel, one-third to the coolant, and one-third to the exhaust, leaving only approximately one-third as useable power production. The thermal efficiency might theoretically increase if the amount of heat rejected could be decreased, at least up to the


(a) (b) (c) (d)

Fig. 1. The picture of Coconut Tree (a), fruits (b), seeds (c), and oil (d).

Table 1
Properties of test fuels.

Properties	Testing Methods	DIESEL	Waste cooking Coconut oil	CWCO Biodiesel	DEE	90 % CWC Biodiesel +10 % DEE
Density @ I5°C in gin cm^3	IS1448.P16	0.8344	0.925	0.87	0.713	0.854
Kinematic viscosity @ 40 °C (m^2/s)	ASTM D445	2.9	13.12	3.65	0.23	3.308
Flashpoint (°C)	IS 1448, P20	60	120	72	−45	68
Fire Point (°C)	IS1448.P20	69	135	88	–	74
Calorific value (kJ/kg)	IS 1448. P25	44125	35625	39992	33900	39382
Cetane Number	IS 1448, P9	49	50	51	49	50.8

limit imposed by the second law of thermodynamics. Low Heat Rejection engines seek to achieve this by minimizing the heat lost to the coolant. LHR engines are diesel engines with ceramic insulation on the walls of the combustion chamber. The LHR engine was designed primarily to maximize fuel efficiency by doing away with the traditional cooling system and using the turbocharged system to convert some of the additional exhaust energy into shaft work [29]. Components of the combustion chamber for CI engines were plasma sprayed with lanthanum-doped PSZ to a thickness of 300 μm over an Al_2 TiO_5 bond coat that was 100 μm thick. Before coating, the surface must be sandblasted to achieve an exterior roughness of 5 μm, gauged using the PCE-RT 11 roughness tester. It was then cleaned with anhydrous ethanol before being dried in cool air. On the sandblasted substrate, Al_2 TiO_5 powder was injected to create the initial coating of the bond. This warm substance makes 100 μm thick contact with the substrate surface. The subsequent layer of 300 μm thick lanthanum-doped PSZ coating was applied similarly. As a result, the total coating thickness is 400 μm[30].

The testing engine is a single-cylinder, four-stroke, water-cooled diesel engine from Kirloskar with a 1500 rpm maximum speed and 5.2 kW of output. The cylinder head, combustion chamber wall, piston head, and surface of the intake and outflow valves are all coated with PSZ's thermal barrier material. The engine's specifications are listed in Table 2 below. An AG10 model water-cooled eddy-current dynamometer with a control system is directly coupled and connected to this engine. On the inlet side of a machine, there is a surge tank with an orifice meter to keep the airflow constant.

The coconut waste cooking oil (CWCO) used in this study was obtained from local restaurants in Chennai, India. The oil was filtered to remove solid particles before use. The diethyl ether (DEE) additive (99 % purity) was acquired from Sigma-Aldrich. Biodiesel was produced from CWCO via transesterification according to ASTM D6751 specifications (Ahmadi et al., 2022) (Fig. 2). The biodiesel was analyzed for key properties including density (ASTM D1298), kinematic viscosity (ASTM D445), calorific value (ASTM D240) [31], flash point (ASTM D93), and distillation range (ASTM D86). The blended fuel containing 90 % CWCO biodiesel and 10 % DEE was prepared on a volumetric basis. The Kirloskar AV1 single-cylinder diesel engine was used with a rated output of 3.7 kW at 1500 rpm, modified to a low heat rejection (LHR) engine. The combustion chamber components were coated with 300 μm of lanthanum-doped partially stabilized zirconia (PSZ) according to ASTM C633 (Fig. 3). Engine testing was performed according to ASTM D6550 specifications. The engine was loaded from 0 to 100 % in steps of 25 % using an eddy current dynamometer with load control. Exhaust emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) were measured using an AVL DiGas analyzer per ASTM D6522. Smoke opacity was measured using an AVL Smoke meter according to ISO 8178 [32]. The entire setup of the engine used for analysis is shown in Fig. 4 to analyze fuel performance under different conditions.

Table 2
Specifications of the test engine.

Details	Specifications
Type	Four-stroke, Kirloskar make, Compression ignition, Direct injection, and water-cooled.
Rated power and speed	5.2 kW & 1500 rpm
Number of cylinders	Single cylinder
Compression ratio	17.5: 1
Bore & stroke	87.5 mm & 110 mm
Method of loading	Eddy current dynamometer
Injection timing	23° Before TDC
Injection pressure	220 bar

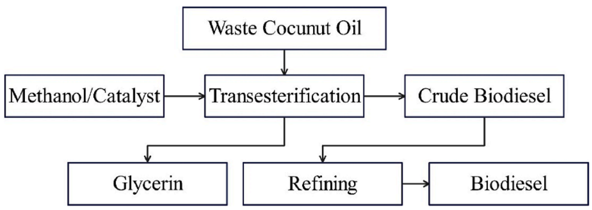

Fig. 2. Transesterification process.

Fig. 3. a–d. Diesel engine hardware components include (a) uncoated cylinder head and valves, (b) uncoated piston, (c) coated cylinder head and valves, and (d) coated piston.

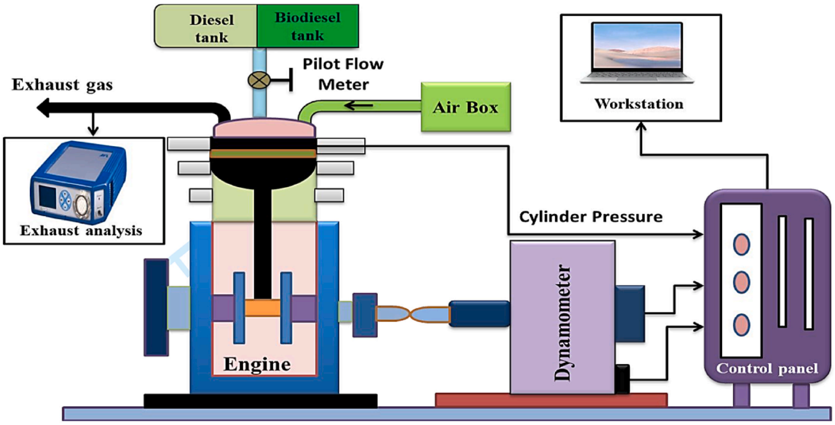

Fig. 4. The engine test setup.

The engine was coupled to an AG10 model eddy-current dynamometer with a load unit control system to apply varying engine loads from 0 to 100 % in 25 % increments. The dynamometer had a maximum rated capacity of 9.8 kW at 10,000 rpm. Engine speed was measured using an optical rpm sensor with a resolution of 1 rpm. Engine torque was measured by a strain gauge-based rotary torque sensor connected to the dynamometer arm. The torque sensor had a maximum rated capacity of 100 Nm with a 0.1 Nm resolution. Intake airflow was monitored using an Autonic make mini air flow sensor installed in the intake pipe with a 0–35 g/s measurement range. The sensor utilized the forward scatter principle with a 0.01 g/s resolution. Exhaust gas emissions of carbon monoxide (CO), unburnt hydrocarbons (HC), and oxides of nitrogen (NOx) were analyzed using an AVL DiGas 444 gas analyzer. The CO was measured by non-dispersive infrared (NDIR), with a 0–10 % volumetric range and 0.001 % resolution. For HC, a heated flame ionization detector (HFID) was used with a 0–20,000 ppm measurement range and 1 ppm resolution. The chemiluminescent detector (CLD) measured NOx over 0–5000 ppm with 1 ppm resolution. Smoke opacity in the exhaust was quantified using an AVL 415 variable sampling smoke meter based on the partial flow optic detection principle, with a measurement range of 0–100 % opacity and 0.1 % resolution.

The brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were calculated from the measured engine parameters using the following equation (1) and (2_:

Brake Thermal Efficiency (BTE):

$$\mathrm{BTE} = \left(\frac{\text{Brake Power}}{\text{Fuel Energy Input}}\right) \times 100\% = \left(\frac{2\pi NT}{mf \times CV}\right) \times 100\% \tag{1}$$

Where:

- N = Engine speed (rev/s)
- T = Engine torque (Nm).
- mf = Fuel mass flow rate (kg/s).
- CV = Calorific value of fuel (kJ/kg).

Brake Specific Fuel Consumption (BSFC):

$$\mathrm{BSFC} = \frac{\text{Fuel Consumption Rate}}{\text{Brake Power}} = \frac{mf \times 3600}{2\pi NT} \tag{2}$$

The parameters are the same as those defined for the BTE equation. The units for BSFC are g/kWh. BTE represents the overall efficiency of converting the fuel's chemical energy into useful brake work at the engine's output shaft. Higher BTE values are desirable. BSFC indicates how much fuel is consumed to produce a brake power unit; therefore, lower values are preferred for better fuel economy.

These parameters facilitate the quantitative evaluation of the test fuels' influence on engine combustion and performance. The BTE and BSFC were experimentally determined across various load ranges and compared among the CWCO-DEE blend, conventional diesel, and other test conditions.

3. Results and discussion

Brake Specific Fuel Consumption (BSFC) is a crucial metric in evaluating engine combustion efficiency. It signifies the fuel quantity essential for generating power at the output shaft, directly linked to engine torque and the combustion chamber dynamics. Observations depicted in Fig. 5 reveal a decrease in BSFC with escalating engine load, indicative of improved combustion efficiency. Diesel,

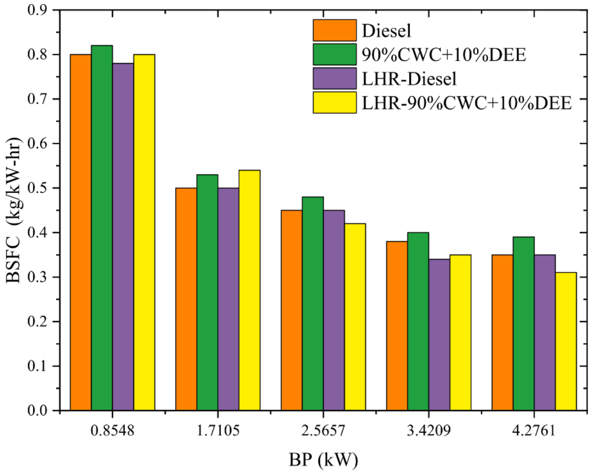

Fig. 5. BP Vs BSFC.

renowned for its lower fuel consumption vis-à-vis other energy sources, owes this efficiency to its higher energy density and exceptional combustion properties compared to alternatives.

The CWCO-DEE blend exhibits higher brake-specific fuel consumption than neat diesel operation across all load conditions. This increase can be primarily attributed to the lower calorific value of the biodiesel component (39,992 kJ/kg for CWCO biodiesel versus 44,125 kJ/kg for diesel as shown in Table 1). Despite the oxygenated nature of biodiesel aiding combustion, its lower energy density results in more fuel being required to produce the same brake power output, hence the higher BSFC values. The viscosity differences between the fuels may also contribute to the BSFC disparity. Although DEE helps reduce the high viscosity of CWCO biodiesel, the blend still exhibits higher viscosity (3.308 mm2/s at 40 °C) than diesel (2.9 mm2/s). This can adversely impact fuel atomization and mixing processes, leading to slightly less efficient combustion and higher BSFC for the blend.

However, it is noteworthy that the BSFC reduction with the CWCO-DEE blend is partially offset by the observed improvements in brake thermal efficiency (Fig. 6), especially in the LHR engine configuration. This indicates that while more fuel is required due to the lower energy density, a greater proportion of that fuel's chemical energy is effectively converted to useful work output. Further advancements in reducing BSFC involve integrating a fuel blend comprising 90 % Conventional Water-Cooled (CWC) and 10 % Diethyl Ether (DEE). This amalgamation notably lowers BSFC. The rationale behind this reduction lies in the heightened volatility of the fuel blend, facilitating a swifter fuel-air blending process. This accelerated blending results in improved combustion efficiency and decreased BSFC [33].

Fig. 6 delineates the correlation between braking power and Brake Thermal Efficiency (BTE) achieved by the fuel. Typically, in an engine, a third of the total thermal power generated by the fuel dissipates as heat through the combustion chamber, another third exits through the exhaust gas, and the remaining third contributes to useful work [34,35]. This distribution remains consistent irrespective of the fuel type used. Advancements in efficiency can be realized through alternative fuels or methodologies, such as employing Low Heat Rejection (LHR) engines featuring insulating layers to curtail heat loss.

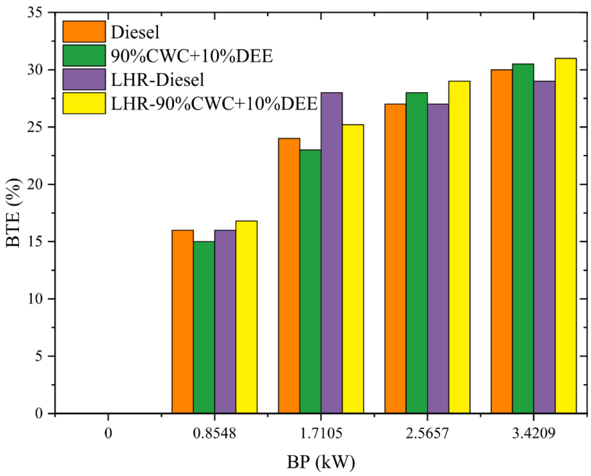

Fig. 6. BP Vs BTE

The observed increase in BTE with the CWCO-DEE blend can be attributed to the higher fuel-air mixing rates facilitated by DEE's high volatility and low viscosity. This allows for more premixed combustion, increasing thermal efficiency [26]. Additionally, the LHR coating minimizes heat losses, recovering a larger fraction of the fuel's chemical energy as useful work [27]. While diesel exhibits a characteristic rise in BTE with increasing load, the CWCO-DEE blend achieves even higher efficiencies, especially in the LHR engine configuration. This can be explained by the synergistic effects of improved air-fuel mixing from DEE and reduced heat losses from the insulating PSZ coating, allowing more of the fuel's chemical energy to be converted to work.

Research by Ref. [15] discerns that a fuel blend of 90 % CWC and 10 % DEE surpasses the efficiency gains achieved by an LHR engine employing the same fuel mixture. This blend led to substantial efficiency enhancements—33.4 %, 2.42 %, 7.5 %, and 10.6 % for respective engine parameters—underscoring its superior efficacy. Blending distinct fuels can positively impact BTE by mitigating ignition latency and augmenting combustion dynamics. This process fosters enhanced fuel-air mixing and combustion, elevating BTE [26].

Fig. 7 presents the variations in braking performance associated with the fuel mixture of 90 % CWC (conventional water-cooled) and 10 % DEE (diethyl ether) accompanied by a moderately configured ignition mechanism. The significant reduction in CO emissions observed with the CWCO-DEE blend compared to neat diesel can be primarily attributed to the oxygenated nature of the biodiesel component. The presence of fuel-bound oxygen in CWCO biodiesel promotes the complete oxidation of carbon compounds during combustion, resulting in lower CO levels in the exhaust [7,10]. Additionally, the DEE additive aids in better air-fuel mixing due to its high volatility, further improving combustion and CO oxidation.

Compared to diesel, the lower CO emissions observed with the CWCO-DEE blend stem from fuel-bound oxygen availability from the biodiesel component and better air-fuel mixing promoted by DEE's high volatility. The LHR engine further amplifies CO oxidation by providing a hotter combustion environment. Integrating 90 % CWC and 10 % DEE in both Low Heat Rejection (LHR) and regular engines resulted in a 22 % and 44 % reduction in CO emissions, respectively, compared to conventional diesel.

Engine Gas Temperature (EGT), a parameter crucial for assessing an engine's structural integrity and its maximum heating threshold, exhibits a noteworthy increase due to reduced wall movement within the combustion chamber (Fig. 8). With the introduction of the 90 % CWC and 10 % DEE blend, EGT sees a substantial rise, registering 3.8 %, 8.3 %, and 13 % higher temperatures in LHR engines compared to a typical engine, highlighting the influence of the fuel mixture on engine temperatures. Additionally, ceramic coatings further increase EGT by enhancing chamber insulation [11].

The alterations in hydrocarbon (HC) emissions reflect the power derived from HC and other pollutants during combustion, as shown in Fig. 9. Notably, the fuel blend encompasses both lean and rich portions. The lean blend exhibits lower HC emissions, whereas the rich blend displays higher HC emissions [36,37]. When 90 % CWC and 10 % DEE are employed, the resulting HC emission is only 39 ppm, showcasing a 34 % reduction compared to a diesel engine. The lower oil temperature helps stabilize the fragile nature of CWC, contributing significantly to the reduction in HC emissions [14] (see Fig. 10).

Like CO emissions, the lower unburnt hydrocarbon (HC) emissions with the CWCO-DEE blend stem from the oxygenated biodiesel component, enabling a more complete combustion of hydrocarbon species. The oxygen availability promotes improved oxidation of HCs, particularly at higher temperatures achieved in the LHR engine configuration [38]. Moreover, the high volatility of DEE enhances fuel-air mixing, resulting in a more homogeneous mixture that undergoes more efficient combustion, leaving fewer unburnt hydrocarbons in the exhaust.

The CO and HC emissions reduction can be explained by improved air-fuel mixing and higher combustion temperatures with the CWCO-DEE blend, particularly in the LHR engine. The DEE promotes leaner, more homogeneous mixtures that undergo more complete combustion, decreasing CO and unburnt HC levels in the exhaust. Moreover, the higher temperatures from the LHR insulation enable further oxidation of CO and HC species during the latter combustion stages. Unburnt hydrocarbon emissions are substantially reduced with the CWCO-DEE blend compared to diesel operation. This can be attributed to the improved fuel atomization, vaporiza-

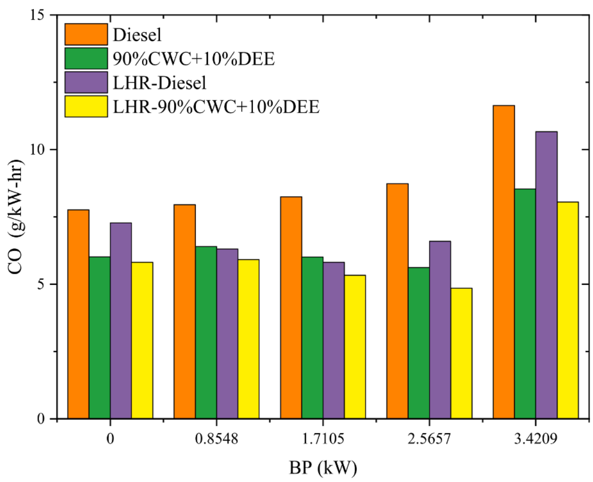

Fig. 7. BP Vs CO.

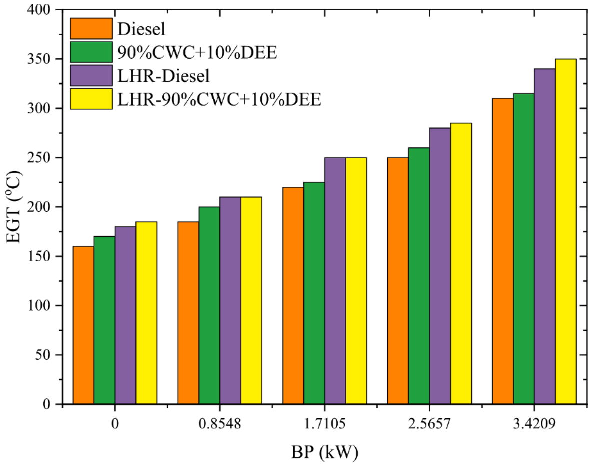

Fig. 8. BP Vs EGT

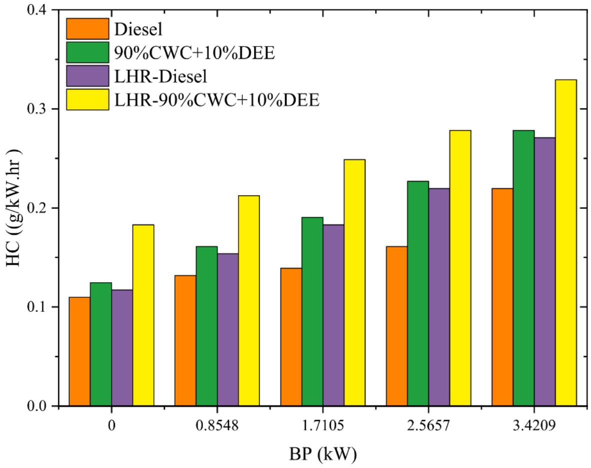

Fig. 9. BP Vs HC.

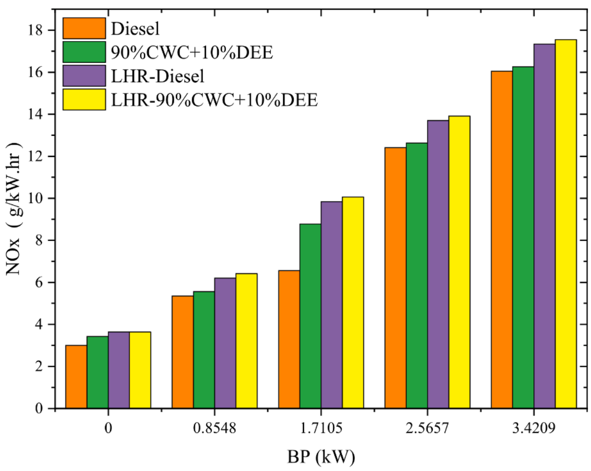

Fig. 10. BP Vs NOx.

tion, and air-fuel mixing facilitated by DEE's low viscosity and high volatility. Moreover, the elevated combustion temperatures, especially in the LHR engine, enable more complete oxidation of hydrocarbon species.

Nitrogen oxide (NOx) emissions, a byproduct of high-temperature combustion reactions, notably vary with load and engine type. Diesel engines inherently produce NOx during combustion. However, the 90 % CWC and 10 % DEE blend, especially in LHR engines, exhibit a 21.2 % reduction in NOx emissions compared to conventional diesel. This reduction is attributed to DEE's high volatility, which acts as a cooling agent, mitigating NOx formation [18].

While biodiesel blends tend to produce lower NOx emissions due to their fuel-bound oxygen content, the CWCO-DEE blend slightly increases, particularly in the LHR engine. This is a consequence of the higher combustion temperatures achieved, which promote thermal NOx formation via fixation of atmospheric nitrogen at elevated thermal conditions exceeding the low-temperature combustion regime [39–41].

Smoke emissions, an undesirable outcome of incomplete combustion, demonstrate a nuanced impact with the 90 % CWC and 10 % DEE blend, as depicted in Fig. 11. While CWC alone emits less smoke due to its leaner composition, adding 10 % DEE resulted in a 7 % increase in smoke emissions compared to diesel. It's worth noting that DEE, in gaseous form below 45 °C, exhibits reduced smoke emissions in high-temperature engine environments [1].

While the higher combustion temperatures in the LHR engine with the CWCO-DEE blend promote soot oxidation, the elevated thermal conditions also increase NOx production via the thermal fixation of atmospheric nitrogen. The slight increase in NOx compared to diesel operation results from this temperature effect overriding the fuel-bound nitrogen-reducing impact of the oxygenated biodiesel component.

The lower smoke emissions observed with the CWCO-DEE blend, except at the highest load, can be explained by the oxygen availability from the biodiesel component and improved fuel-air mixing. However, at full load, the higher smoke levels may result from an over-lean operation or fuel impingement due to the high volatility of DEE, adversely affecting the fuel-air mixing process under those elevated operating conditions.

4. Conclusion

This study investigated the performance, combustion, and emissions of a low heat rejection diesel engine fueled with a blend of 90 % coconut waste cooking oil (CWCO) biodiesel and 10 % diethyl ether (DEE). The key findings demonstrate the potential of biodiesel-additive blends to improve engine efficiency and reduce emissions in suitably modified engines.

The CWCO-DEE blend showed 3 % higher brake thermal efficiency and lower brake-specific fuel consumption than diesel at full load. The DEE compensated for the lower cetane number and higher viscosity of CWCO biodiesel. Meanwhile, the low heat rejection combustion chamber provided thermal insulation to enhance combustion.

Hydrocarbons, carbon monoxide, and smoke opacity emissions were lower with the CWCO-DEE blend at higher loads versus diesel. The reductions were 18 %, 11 %, and 19 % respectively. The blend's higher volatility and leaner combustion reduced particulate emissions. However, nitrogen oxides increased slightly.

This work fills a gap by evaluating a combined approach of low-heat rejection engine technology and tailored biodiesel-additive blends. Most prior works have focused on either modified engines or biodiesel mixtures separately. The outcomes demonstrate the feasibility of utilizing inexpensive biodiesel feedstocks like waste cooking oil in suitably designed engines.

The improved performance and reduced emissions highlight the promise of biodiesel as a renewable fuel. However, further efforts are needed to optimize production methods and engine technologies for sustainable utilization. The CWCO-DEE blend alleviated issues like high viscosity that can affect engine operation.

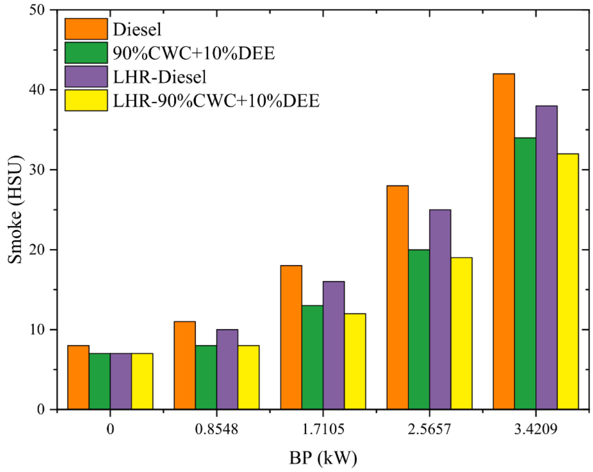

Fig. 11. BP Vs smoke.

Future work should explore the impacts of varying blend concentrations and components. Adding higher shares of additives like DEE may further enhance properties like volatility. However, this could also increase emissions of oxides of nitrogen. Different thermal barrier coatings and thicknesses could also be analyzed to optimize heat insulation versus durability. More comprehensive combustion modeling is needed to predict variables like cylinder temperatures and emissions outputs.

CRediT authorship contribution statement

Sivakumar Ellappan: Methodology, Investigation, Formal analysis, Conceptualization. **Silambarasan Rajendran:** Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Ratchagaraja Dhariyasamy:** Writing – original draft, Methodology, Conceptualization. **Qasem M. Al-Mdallal:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Sher Afghan Khan:** Writing – original draft, Data curation, Conceptualization. **Mohammad Asif:** Writing – original draft, Methodology, Funding acquisition. **Saurav Dixit:** Resources, Funding acquisition, Conceptualization. **Ümit Ağbulut:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing 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.

Data availability

Data will be made available on request.

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