

INVESTIGATION OF THE EMISSION AND PERFORMANCE CHARACTERISTICS OF A DIRECT INJECTION DIESEL ENGINE FUELLED WITH DUAL BIODIESEL BLENDS

Original scientific paper

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Abstract:

This research examines the performance and emission characteristics of a direct injection diesel engine fueled by dual biodiesel blends sourced from Pongamia pinnata oil (PPO) and Hevea brasiliensis oil (HBO). Biodiesel blends were formulated in proportions of 10%, 20%, 40%, 60%, 80%, and 100% (B10–B100) and evaluated against regular diesel (D100) in a single-cylinder, 4-stroke, water-cooled engine operating at 1500 rpm under varying loads. B10 exhibited the highest brake thermal efficiency (BTE) at 14.44%, in contrast to 13.34% for diesel and 12% for B100. The mechanical efficiency attained a maximum of 74.26% for B80/B100, comparable to the diesel efficiency of 74.8%. Brake-specific fuel consumption (BSFC) increased with higher biodiesel percentages and remained relatively constant at elevated engine loads. Emission studies demonstrated a significant decrease in (nitrogen oxides) NO_x emissions at full load when utilizing biodiesel blends, with recorded values of 1245 ppm for diesel, 307 ppm for B10, and 601 ppm for B60. Unburned hydrocarbon (UHC) emissions peaked at 103 ppm for B100, whereas diesel exhibited 28 ppm. Higher blends of biodiesel, specifically B40 and B60, resulted in reductions of carbon monoxide (CO) emissions by 0.07% and 0.10%, respectively. Notably, CO₂ emissions were lower in B10–B60 blends by 2.1–3.7% relative to diesel. B10 also demonstrated the lowest smoke opacity due to improved diffusive combustion. These findings indicate that dual biodiesel blends, particularly B10 and B20, are promising diesel alternatives offering enhanced combustion performance and reduced emissions without requiring engine modifications.

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1. INTRODUCTION

The automobile industry is contributing a significant portion of air pollution, as the emitted pollutants significantly affect the ecology of the living system. Indian national policies indicate that global energy demand is expected to reach 37% by

2040; however, the world population rate is high, and the economy should be less intensive [1]. Biofuels have the potential to address the energy crisis and reduce pollution by lessening reliance on fossil fuels and lowering global carbon and greenhouse gas emissions, thus providing a viable and sustainable alternative energy source [2].

Biodiesel represents a more environmentally sustainable option compared to diesel fuel. It is a liquid fuel obtained from renewable sources, encompassing both new and recycled animal and vegetable fats, and it exhibits cleaner combustion compared to petroleum-based diesel fuel [3]. Biodiesel is made by mixing alcohol with either vegetable, animal, or recycled cooking oil. It is safe and biodegradable. In addition to helping to meet the world's increasing energy needs, biofuels can also help lower greenhouse gas emissions. Because they come from natural sources, biofuels burn cleanly and decompose more quickly than fossil fuels [4,5]. Biofuels can be obtained from biomass, methane gas, agricultural residues, and vegetable or animal oils. It is an alternate energy source due to reduced carbon dioxide (CO₂) emissions from IC engines [6].

1.1 Literature Review

Mohan et al. [7] in research added oleic acid to Pongamia ester (PE) along with a 20% synthetic additive and studied the effects on oleic acid and compression ratio (CR) in relation to brake thermal efficiency (BTE) and NO_x emissions. The results showed that as CR increases, cylinder peak pressures also rise; however, the peak pressure decreases at a higher rate with increased oleic acid addition to PE. While increasing CR improves BTE, PE alone yields the highest BTE; however, the addition of a 20% synthetic additive significantly reduces BTE due to increased viscosity. Renuraman et al. [8] evaluated three types of rice bran oil: RB, RB-Al₂O₃, and RB-CeO₂. The results showed that, under partial load conditions, RB-Al₂O₃ achieved 28% better brake thermal efficiency (BTE) than RB-CeO₂ and 13% better BTE than the pure mix. Ramadhas et al. [9] found that the UBHC emissions of RB and RB-CeO₂ were similar, but RB-Al₂O₃ showed a 46% increase in emissions compared to RB-CeO₂. CO₂ and CO emissions remained within limits and were not significantly affected. Engine performance and emissions improved with the use of nano-additives, though nanoparticle dispersion is a key factor. Diluting rubber seed oil (RSO) with diesel in various ratios significantly reduced its viscosity, and no engine modifications were required when using RSO as fuel. Blends with up to 80% rubber seed oil demonstrated acceptable brake thermal efficiency (BTE) and specific fuel usage. Because the fuel in rubber seed oil mixes burns incompletely, more carbon deposits are in the engine's combustion chamber. Bharadwaj et al.

[10] produced biodiesel from refined soybean oil using calcined eggshells as a heterogeneous catalyst in the biofuel production process. The results showed that an increase in brake mean effective pressure (BMEP) was linked to a decrease in brake-specific fuel consumption (BSFC) for all mixtures tested. The tailored formulation exhibited reduced levels of carbon monoxide (CO), hydrocarbons (HC), and NO_x, while showing higher concentrations of carbon dioxide (CO₂), indicating its potential as a promising alternative to traditional diesel. Ratna Reddy et al. [11] found that increased injection pressure and advanced injection timing improve the performance of biofuels. Higher injection pressure reduced smoke and NO_x emissions in both low heat rejection (LHR) and conventional engines (CE). The optimal injection timing for the CE engine was 31° bTDC, while the LHR engine showed the best performance with an injection pressure of 190 bars at 29° bTDC.

Prabhakar and Rajan [12] found that the use of 100% biodiesel resulted in a 10% improvement in brake thermal efficiency (BTE) and a decrease in brake-specific fuel consumption (BSFC) during full load testing on a direct injection engine with a TiO₂-coated piston crown, using blends of pongamia oil methyl ester (PME) and diesel (B20 and B100). The coated engine showed reduced diesel fuel consumption and lower emissions of carbon monoxide and hydrocarbons, but produced 15% higher levels of NO_x compared to uncoated engines. Additionally, the coated engine exhibited higher peak pressure and heat release rates than the uncoated engine. Coated engines exhibit decreased diesel fuel consumption and lower emissions of carbon monoxide and hydrocarbons; nonetheless, they produce 15% more NO_x in comparison to uncoated engines. The coated engine demonstrated elevated peak pressure and heat release rate relative to the uncoated engine. The B30GNP60DMC10 sample demonstrated lower concentrations of HC and CO, recorded at 22.87% and 25.67%, respectively, as well as reduced levels of NO_x and smoke opacity at 9.57% and 12.4%, respectively [13]. The application of equal proportions of rubber seed and palm oil as biodiesel led to a decrease in torque and BMEP in an unmodified indirect injection diesel engine when compared to diesel fuel. Exhaust temperature, CO₂, and NO_x exhibited average increases of 1.4%, 1.2%, and 1.1%, respectively, while CO demonstrated a decrease of 2%. The BSFC increased by 1.4% under full load conditions [14].

Murugapoopathi et al. [15] found that using rubber seed oil (RSO) as a biofuel for engine supercharging resulted in a 4.11% decrease in cooling water loss, a 2.99% improvement in brake thermal efficiency (BTE), and a 7.54% reduction in brake specific energy consumption (BSEC). Supercharging also caused a 3.75% increase in peak pressure and a 4.4% reduction in the heat release rate. Additionally, supercharging reduced carbon monoxide (CO) and hydrocarbon (HC) emissions by 10.26% and 21.41%, respectively, compared to diesel. Sultana et al. [16] identified rubber seed cake (RSC), a by-product of oil extraction, as an effective feedstock for bio-oil production through pyrolysis, showing high calorific value and significant volatile matter content. The pyrolysis process at 500°C for 75 minutes produces bio-oil with a calorific value of 29.86 MJ/kg, containing valuable compounds like phenolics and hydrocarbons, while the resulting biochar can be utilized for wastewater treatment.

Adam et al. [17] examined the effect of antioxidants on engine performance using rubber seed biodiesel blends in a multi-cylinder diesel engine. The results showed that antioxidants improved brake power by 4.21%, reduced brake-specific fuel consumption by 6.82%, and decreased NO emissions by 9.78%, while increasing CO, hydrocarbon emissions, and smoke opacity. Bhanu Teja et al. [18] conducted experiments using three emulsion fuels, WME20, W20Bu5D75, and W20Bu10D70, which combine N-butanol and watermelon methyl ester, and compared them to regular diesel. The results showed that adding n-butanol to WME20 shortened ignition delay and increased combustion duration under full load, while improving brake thermal efficiency (BTE), making it comparable to regular diesel.

From the above literature review, it is evident that biofuel plays a crucial role in direct injection compression ignition engines as a viable alternative to offset the depletion of fossil fuel reserves. Engine performance may be enhanced by implementing design modifications, using additives, mixing various biofuels, and applying coatings to engine components. A limited investigation has been performed regarding the application of dual biofuel blends in compression ignition engines alongside diesel fuel. There is a notable deficiency of knowledge about the amalgamation of PPO with HBO in a standard DI-CI engine. This research specifically investigates the performance, combustion, and emission characteristics of different mixes of PPO and HBO. The acid value and

calorific value of the biodiesel blends were assessed using standardized protocols.

2. MATERIALS AND METHODS

2.1 Transesterification of PPO and HBO

Biodiesel is produced by the transesterification of vegetable or animal fats via a chemical process. The original oil comprises a blend of fatty acids; alkyl esters, including methyl esters, are generated when catalysts and alcohol (often methanol) react with vegetable or animal fats [19-21]. A specified quantity of catalyst NaOH (1 wt.%) and methanol was dissolved in the necessary amount in a reflux condenser-connected three-necked round-bottom flask. Once the mixture reached 60 °C, the catalyst was completely dissolved in the mixture under atmospheric pressure for 120 minutes with consistent stirring to produce crude PPO/HBO. The samples were decanted to enable glycerine to settle at the bottom [22]. They were then filtered using Whatman filter paper and transferred to a separating funnel to remove glycerine. The samples were washed with water (500-2000 ml) to eliminate unreactive base, glycerine, and trace amounts of soap [23,24]. Fig. 1 presents the experimental methodology adopted in this work.



Fig. 1. Methodology adopted in this study

2.2 Identification of Blend Properties

The PPO and HBO are included in equal amounts to create the dual blend, which is then mixed with diesel to produce biodiesel, as seen in Table 1. The physicochemical properties of PPO/HBO dual biodiesel are evaluated utilizing Indian standards (IS) techniques. The properties of biodiesel, including viscosity, density, calorific value, fire point, flash point, and exhaust emissions, are assessed using a hydrometer and Pensky-Martens apparatus. Table 1 presents the characteristics of biodiesel blends compared to conventional diesel fuel. Biodiesel has enhanced characteristics relative to traditional diesel.

2.3 Experimental Setup

The experimental setup used a 4.4 kW Kirloskar TAF1 engine, characterized as a single-cylinder, direct injection model with an 80 mm bore and a 110 mm stroke. This water-cooled engine, designed for commercial applications, operates at a compression ratio of 16.5:1. All examinations were conducted at the Saveetha Institute of Medical and Technical Sciences in Tamil Nadu, India. Comprehensive engine characteristics are provided in Table 2. Fig. 2a illustrates the test bed configuration, which includes critical components such as the engine, fuel system, Dynamometer, exhaust gas analyzer, and control unit, all outfitted with sensors to assess performance parameters. Fig. 2b illustrates the configuration of the experimental engine apparatus.

Table 1. Blend ratios of PPO and HBO biodiesel and measured fuel properties

Fuel	Diesel (%)	PPO (%)	HBO (%)	Density	Viscosity value (mm ² /s)	Calorific value (MJ/kg)	Flashpoint value (°C)
D100	100	0	0	0.846	2.6	42.8	51
B10	90	5	5	0.841	4.13	39.78	56
B20	80	10	10	0.848	4.22	38.2	60
B40	60	20	20	0.857	4.28	37.28	71
B60	40	30	30	0.91	4.69	36.96	96
B80	20	40	40	0.919	4.82	35.46	124
B100	0	50	50	0.925	5.12	34.44	156

Table 2. Test engine specifications

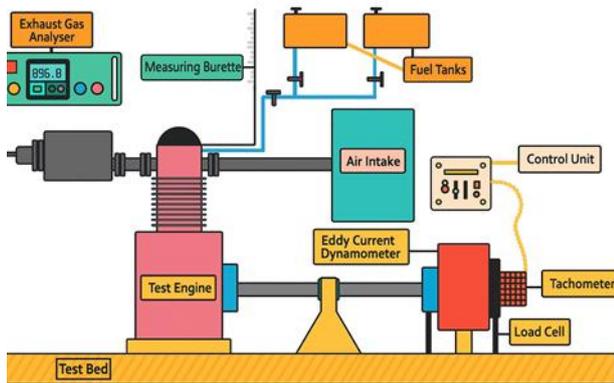
Make and Model	Kirloskar TAF1
Type	Single cylinder 4-stroke diesel engine
Orientation	Vertical
Bore	80 mm
Stroke	110 mm
Clearance Volume	36.87 cc
Displacement Volume	553 cc
Compression Ratio	16.5:1
Rated Power Output	4.4 kW
Operating Speed	1500 rpm
Cooling System	Air cooling
Load Testing Apparatus	Eddy current Dynamometer
Combustion Chamber Design	Open hemispherical type

The studies were conducted at various loads ranging from 0.5 to 2.5 kW, with the speed maintained at 1500 rpm and the fuel injection pressure held constant at 200 psi. The direct injection engine was initially heated, subsequently stabilized, and data was collected thereafter. The evaluation of a direct injection engine's performance involves analyzing attributes including Brake power (BP), Brake-specific fuel consumption

(BSFC), Mechanical efficiency (ME), Indicated thermal efficiency (ITE) and air-fuel ratio. This assessment considers the use of various biodiesel blends. In contrast to regular diesel fuel, this test analyzes emissions in terms of UHC, CO, NO_x, smoke opacity, and exhaust gas temperature. A computerized data collection system was installed on the engine test bench. National Instruments' LabVIEW 2019 enabled the logging and real-time

monitoring of engine performance and pollution data. Using a data acquisition module from National Instruments, the program communicated with various sensors and transducers, including load cells, emission probes, and thermocouples. Emissions (CO, HC, NOx), specific fuel consumption, temperature of exhaust gas, and BTE were all precisely measured with this setup.

The system facilitated automated plotting, averaging of repeated trials, and accurate synchronization with engine load and speed conditions.



a)



b)

Fig. 2 a) Sketch of the experimental setup, b) Layout of the experimental setup

NOx emissions were quantified utilizing an AVL DiGas 444 gas analyzer, a recognized instrument for accurate multi-gas measurement. Smoke opacity was measured using a Bosch Smoke Meter, a recognized technique for assessing particulate matter in diesel exhaust.

2.4 Performance Calculations

Performance parameters such as BSFC, BTE, and ME were evaluated using standard thermodynamic equations, as outlined below [25,26]:

$$BSFC \left(\frac{kg}{kWh} \right) = \frac{Fuel\ Consumption \left(\frac{kg}{hr} \right)}{Brake\ Power \ (kW)} \quad (1)$$

$$BTE \ (%) = \frac{[Brake\ Power \ (kW) \times 3600]}{[Fuel\ Flow\ Rate \ (kg/hr) \times Calorific\ Value \ (kJ/kg)] \times 100} \quad (2)$$

$$ME \ (%) = \frac{Brake\ Power}{Indicated\ Power \times 100} \quad (3)$$

3. RESULTS AND DISCUSSION

3.1. Performance Characteristics

The performance indicators, such as BP, BTE, ME, SFC, and ITE, indicate the response of biodiesel blends to various conditions. The fuel spray pattern, air-fuel ratio, fuel injection pressure, and fuel properties significantly influence engine performance [27,28].

Fig. 3 displays the engine performance characteristics when fuelled with pure diesel, biodiesel blends, and a pure dual biofuel mix, concerning BTE achieved at different BP. One way to measure the efficiency of internal combustion engines is by looking at their BTE – higher BTE results in reduced fuel consumption, greenhouse gas emissions, and increased compression ratios [29]. BTE was consistently lowest for B100 across all engine load settings as compared to the other fuel mixes. In this case, the BTE values for D100 were 13.34%, B10 was 14.44%, B20 was 13.38%, B40 was 13.47%, B60 was 13.80%, and B100 was 13%, 14%, 13%, and 12%. B10 had the greatest BTE of the biodiesel blends, while B100 had the lowest. Most biodiesel mixes had BTE values comparable to those of pure diesel, as compression ratios remain constant across all fuels. Due to its lower volatility and higher viscosity, B100 has a lower BTE. Pure biodiesel has a decreased thermal efficiency due to its lower calorific value, poor spray properties, and lessened heating potential [30].

ME is the ratio of indicated to brake power, reflecting losses due to engine mechanics. Higher fuel calorific value typically leads to improved ME [31]. In Fig. 4, the ME is shown at different BP. Indicated power and friction are changed to determine the DI engine's efficiency. Efficiency determines the value of the machine's effectiveness. B80 and B100 have the same maximum ME of approximately 74.26% at maximum BP, whereas 74.8% for diesel at the same power and ME. An improvement in engine efficiency is observed with the higher proportion of PPO/HBO mix due to the enhanced lubricating qualities of the blended dual biodiesel samples containing methyl esters [32].

Additionally, biofuels have better combustion since they are denser and stickier than clean diesel [33].

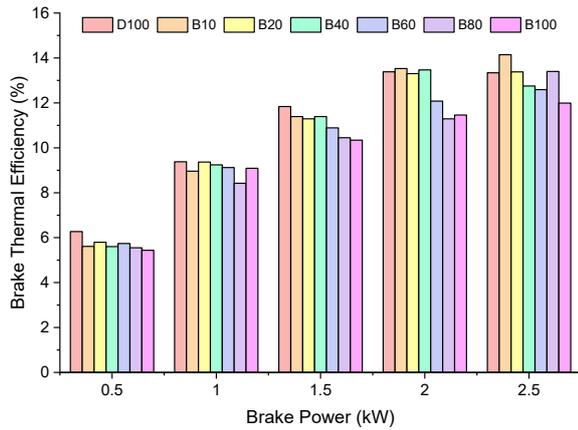


Fig. 3. BTE vs. BP for diesel and PPO/HBO blends at 1500 rpm

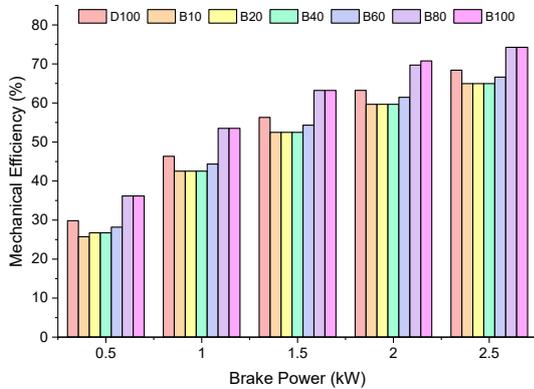


Fig. 4. ME vs. BP for diesel and PPO/HBO blends

The correlation between SFC and BP for diesel is evident, with a similar trend observed for PPO and HBO biodiesel blends, as depicted in Fig. 5. PPO and HBO biofuel blends exhibit higher specific fuel consumption values compared to diesel due to their lower calorific value and greater density. Initial loads exhibit a higher SFC compared to subsequent loads, which maintain a constant level [34]. A low calorific value requires a greater quantity of fuel to produce an equivalent power output, as less energy is released during combustion. The increased density of biofuel blends can result in higher fuel mass flow rates, thereby contributing to elevated specific fuel consumption values [35,36]. The observed trend of increased SFC at lower loads suggests that there may be difficulties in attaining optimal combustion efficiency when starting the engine or operating under low-load conditions with these biofuel blends [37]. It is worth noting that the BSFC remains consistent at different loads. At the same time, the engine runs under heavier loads, suggesting that the effect of a lower calorific value and a larger density becomes less pronounced [38].

This highlights the importance of conducting further research on the combustion characteristics and optimization strategies for biofuel blends to enhance engine performance.

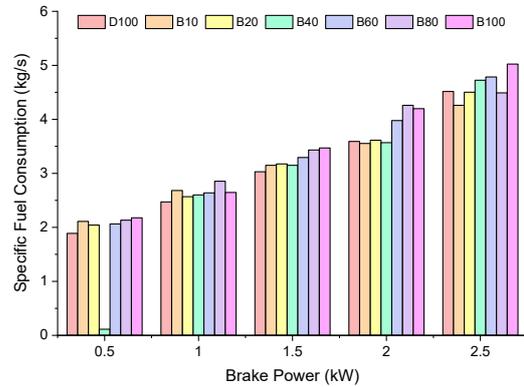


Fig. 5. BSFC vs. BP for diesel and PPO/HBO blends

Fig. 6 displays the change in ITE with BP for pure diesel, dual biofuel, and various biodiesel mixes. The test findings demonstrate that the B10 biodiesel blend has higher efficiency compared to other mixtures. The enhancement is attributed to a rise in energy content and improved combustion dynamics compared to pure diesel [39]. Several variables may be associated with the enhanced efficiency shown in B10. Biodiesel mixes often include oxygen, facilitating more complete combustion. Combining biodiesel with normal diesel may modify the fuel's cetane number, improving ignition and combustion characteristics [40]. A contributing element to an increased energy release during combustion is the elevated energy content of B10. This is likely caused by the chemical characteristics of biodiesel [41,42].

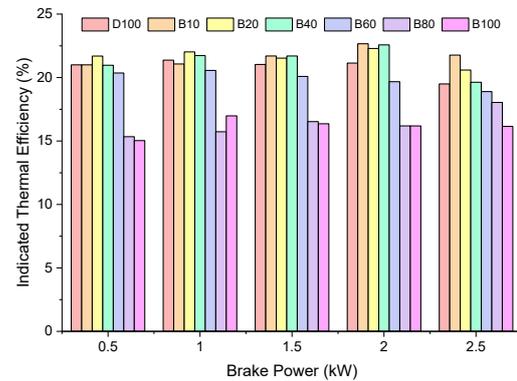


Fig. 6. ITE vs. BP for diesel and PPO/HBO blends

3.2. Emission Characteristics

Biodiesel shows good emission characteristics on environmental effects [43]. The considerable impact of BP on CO emissions is demonstrated in

Fig. 7. The CO value of the B10 and B20 blends' exhaust gas analysis is near that of the D100. The blends B40 and B60 have decreased CO emissions by 0.07%, 0.10%, 0.06%, and 0.11% by volume under full load conditions. CO levels vary practically linearly with braking power. Fig. 8 shows the change in UHC for various BPs when fuelled with biodiesel blends and neat fuels. It is observed that B100 indicates high emission characteristics. Standard diesel emits less UHC than blends B10, B20, and B40. The observed maximum UHC emission is 103 ppm for PPO/HBO biofuel, whereas it is 28 ppm for neat diesel.

Fig. 9 displays the relationship between blood pressure (BP) and the amount of CO₂ generated by various fuels. The graph shows that CO₂ emissions change linearly with BP [44]. Blends B10, B20, B40, and B60 each reduce CO₂ emissions by 2.10%, 2.80%, 3.00%, and 3.70% compared to diesel.

Fig. 10 shows the variation in BP with NO_x, which has a higher NO_x emission, whereas it is low for biodiesel. At 1245 ppm, the diesel emits NO_x at full load, whereas biodiesel blends B10, B20, B40, and B60 show emissions of 307, 424, 502, and 601 ppm, respectively. The effects of nitrogen oxides changed linearly with their BP [45,46]. Fig. 11 depicts the correlation between BP and exhaust gas temperature (EGT) across different fuel types, such as diesel, biodiesel blends, and dual biofuels. The EGT is generally higher for biodiesel-diesel mixtures. Standard diesel and blends such as B10, B20, B40, B60, and B80 exhibit relatively minimal changes in EGT across different load conditions. According to the study, the exhaust gas temperature rises with load at the optimal air-to-fuel ratio, indicating that the cylinder is heated to a high degree [47,48].

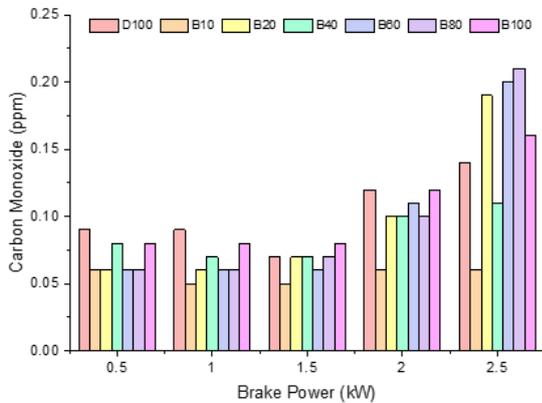


Fig. 7. CO emissions vs. BP for diesel and PPO/HBO blends

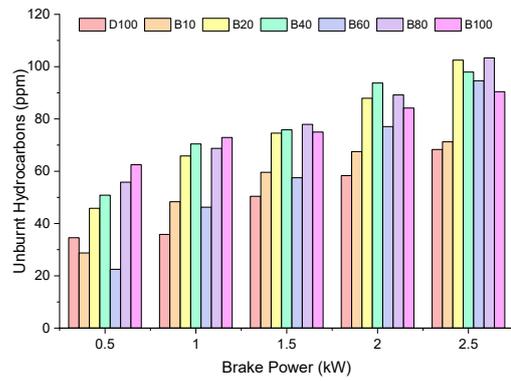


Fig. 8. UHC emissions vs. BP for diesel and PPO/HBO blend

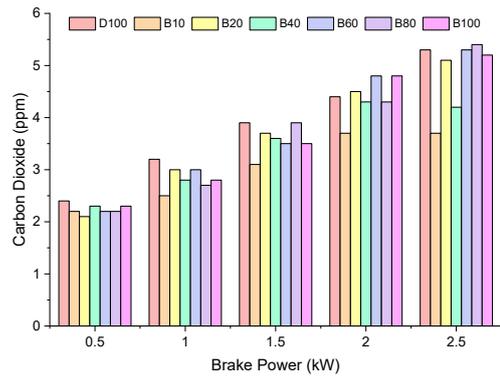


Fig. 9. CO₂ emissions vs. BP for diesel and PPO/HBO blends

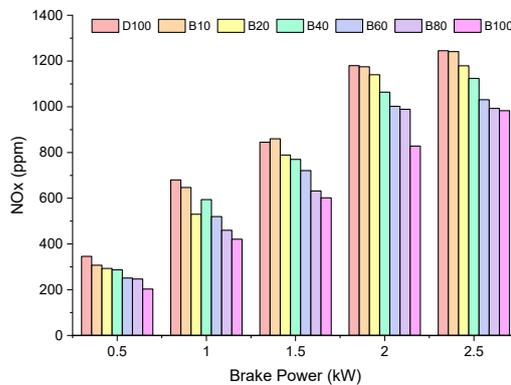


Fig. 10. NO_x emissions vs. BP for diesel and PPO/HBO blends

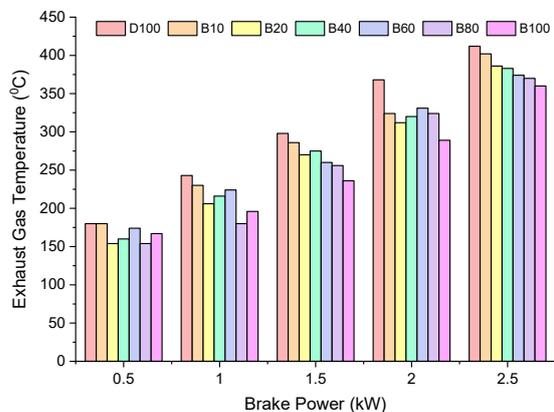


Fig. 11. EGT vs. BP for diesel and PPO/HBO blends

Fig. 12 illustrates the proportion of smoke variation in biodiesel blends. The reduction in smoke emissions from oxygenated mixes, particularly evident in the B10 blend, is due to diffusive combustion. By making more oxygen available for the reaction, oxygenated fuels improve combustion. This enhances fuel combustion, reducing smoke-causing soot particle generation [49,50]. The decreased smoke density in B10 across different fuel loading settings indicates the effectiveness of this blend in minimizing incomplete combustion and the production of particulate matter [51].

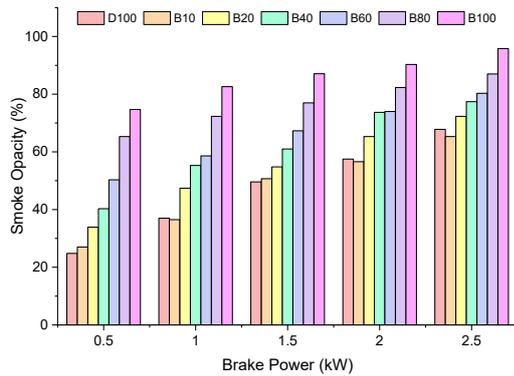


Fig. 12. Smoke opacity vs. BP for PPO/HBO blends and diesel

Fig. 13 illustrates the impact of the air-to-fuel ratio on the braking powers of diesel and mixed engines. Diesel fuel exhibits a higher air-to-fuel ratio, indicating a greater quantity of air in the combustion environment relative to the fuel present [52]. Biodiesel blends have lower air-to-fuel ratios, suggesting a richer combustion mixture. The blended fuels' combustion characteristics and oxygen content likely account for the discrepancy. As engine load increases, the air-to-fuel ratio decreases, indicating that the combustion chamber receives more fuel than air [53].

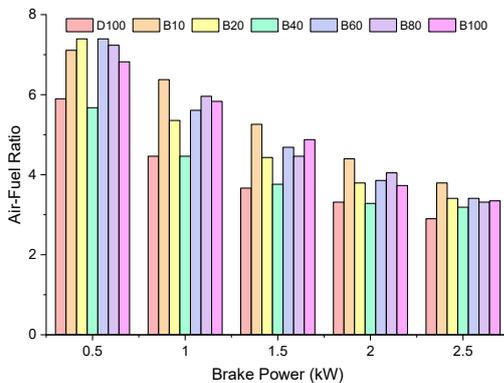


Fig. 13. Air-fuel ratio vs. BP for diesel and PPO/HBO blends

3.3 Influence of Injection Pressure on Engine Performance

Fig. 14 illustrates the changes in brake thermal efficiency (BTE) in relation to engine brake power (BP) for diesel and B10 fuels at injection pressures of 240 bar and 270 bar. Fig. 14 illustrates the brake specific fuel consumption (BSFC) of the engine at an injection pressure of 240 bar, in conjunction with various fuel mix ratios. Fig. 15 illustrates the brake specific fuel consumption (BSFC) at an injection pressure of 270 bar, employing different fuel blends. The results indicate that the cetane number of diesel and its various mixing ratios decline as the boiling point increases [54]. The lowest BSFC was achieved at a BP of 2.5 kW and grew as the BP increased.

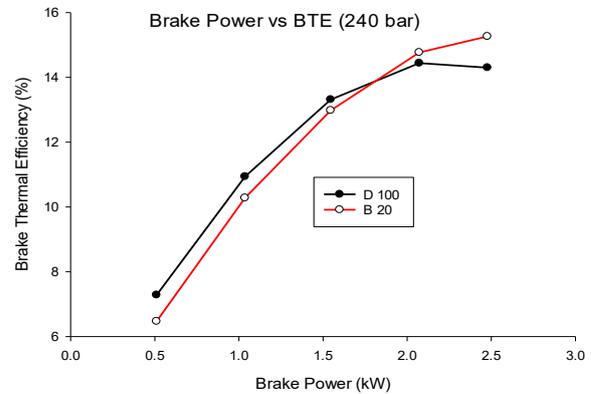


Fig. 14. BTE vs. BP at 240 bar injection pressure (diesel and B10)

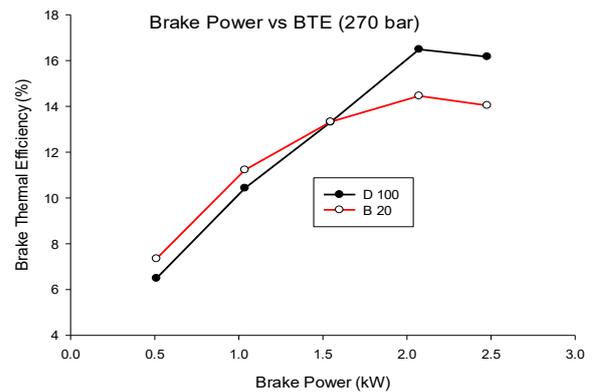


Fig. 15. BTE vs. BP at 270 bar injection pressure (diesel and B10)

Fig. 16 illustrates the variance in BSFC deviation for different mixes of PPO and HBO (10%, 20%, 40%, 60%, 80%, and 100%). At injection pressures of 240 bar and 270 bar, subcutaneous fat thickness and blood pressure are correlated. BTE direct injection engine utilizing various mixed fuel ratios. Fig. 17 illustrates the BTE of the direct injection engine operating with various ratio mix fuels at an injection

pressure of 270 bar. Blends B40 and B60 have decreased CO emissions by approximately 0.07%, 0.08%, 0.06%, and 0.11%, respectively. The exhaust CO demonstrates a nearly collinear relationship with the value of BP [55].

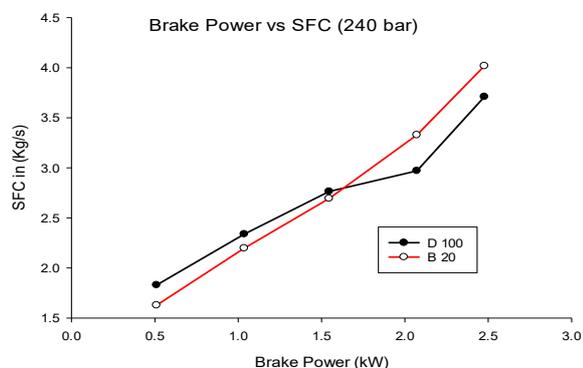


Fig. 16. BSFC vs. BP at 240 bar for PPO/HBO blends

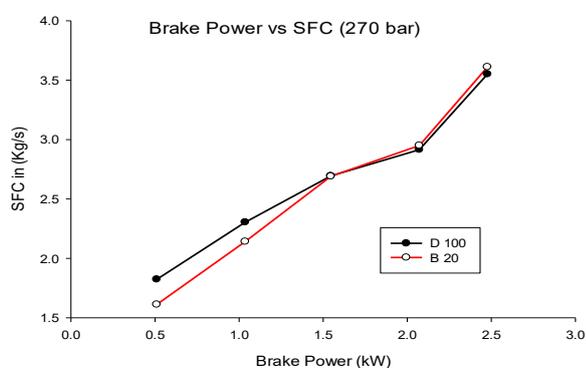


Fig. 17. BSFC vs. BP at 270 bar for PPO/HBO blends

The dataset obtained in this study, which includes detailed performance and emission measurements across various biodiesel blend ratios and engine loads, is well-suited for statistical analysis. Techniques such as Taguchi design of experiments, response surface methodology, machine learning, and artificial intelligence can be employed to gain deeper insights, identify critical influencing factors, and optimize engine parameters [56]. These approaches enable efficient processing of results while reducing experimental cost, time, and resource usage.

4. CONCLUSIONS

This research analyzed the performance, combustion, and emission characteristics of a direct injection diesel engine utilizing dual biodiesel blends sourced from PPO and HBO. Experimental results indicated that lower blend ratios, specifically B10 and B20, attained brake thermal efficiency comparable to or surpassing that of conventional diesel. Conversely, higher blends like B100

exhibited a noticeable decrease in brake thermal efficiency, primarily attributed to elevated viscosity and diminished calorific value.

Among the evaluated blends, B10 demonstrated the highest overall performance, attaining a BTE of 14.44%, slightly surpassing the 13.34% observed for pure diesel. Emission analysis indicated that all biodiesel blends generated reduced levels of CO, HC, and nitrogen oxides (NO_x) in comparison to standard diesel. B10 demonstrated a reduction of up to 75% in NO_x emissions at full engine load, underscoring the efficacy of dual biodiesel fuels in reducing harmful exhaust emissions. Furthermore, smoke opacity exhibited a significant reduction in biodiesel blends, attributable to the intrinsic oxygen content within the fuel that improved the combustion process.

The research demonstrates that PPO-HBO dual biodiesel blends represent feasible renewable substitutes for diesel fuel in unmodified diesel engines, providing environmental and performance benefits.

Future work should focus on using coated engine components to improve thermal efficiency, applying multi-objective optimization for blend ratios and engine parameters, and exploring alternative non-edible oil feedstocks to enhance sustainability and performance.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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