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Effect of Rubber Seed Oil Biodiesel Additive on Compression Ignition Engines fuelled with Diesel-Ethanol Blends

H. V. Srikanth, S. Vijay Kumar, R. Kousik Kumaar*, Senthil Kumar Madasamy, Beena Stanislaus Arputharaj, Parvathy Rajendran, Vijayanandh Raja*

Abstract: In this study, the primary focus revolved around the utilization of rubber seed oil (RSO) biodiesel as a supplement in blends of diesel-ethanol (DE) for a diesel engine. The DE blends were formulated by combining ethanol with diesel and emulsifying them with RSO biodiesel in a 10% (v/v) proportion. The ethanol concentrations in the blends varied between 5% and 15% (v/v). Under conditions of maximum loading, it was observed that the blend labelled DE15B10, comprising 15% ethanol and 10% RSO biodiesel, demonstrated the highest brake thermal efficiency (BTE). Although all the examined fuels exhibited an elevated Brake Specific Fuel Consumption (BSFC) compared to conventional diesel, DE15B10 displayed a 4.30% increase in BSFC over fossil diesel. Nevertheless, the exhaust emission characteristics of DE15B10 were found to be superior to those of conventional diesel. These results indicate that DE-biodiesel blends, especially DE15B10, show potential as a viable alternative fuel option without requiring any modifications to the engine hardware.

Keywords: biodiesel; diesel-ethanol; emission; performance; rubber seed oil; transesterification

1 INTRODUCTION

The economy of a nation is significantly influenced by energy, a pivotal determinant. According to statistical information on global energy provision presented by British Petroleum (BP 2020), the primary share is attributed to fossil fuels, with crude oil at 33.1%, coal at 27.0%, and natural gas at 24.2%. Subsequent contributors include nuclear at 4.3%, hydro at 6.4%, and other renewable sources at 5%. The overreliance on fossil fuels has resulted in environmental contamination and global warming, prompting researchers worldwide to explore sustainable and environmentally friendly fuel alternatives such as biodiesel, ethanol, and butanol. These substitutes play a vital role in addressing transportation energy requirements while adhering to stringent pollution regulations [1, 2, and 3].

Biodiesel derived from first and second-generation oils is acknowledged as a promising alternative renewable fuel source for both transportation and gas turbine applications [4-6]. In the Indian context, opting for non-edible oil feedstocks in biodiesel production is considered a more secure approach to address the energy-food conflict [7, 8]. Nevertheless, the accessibility of non-edible oils exhibits significant regional disparities [9, 10]. To ensure continuous biodiesel production, numerous studies have explored the utilization of non-edible to produce biodiesel through various sources [11-14].

Several researchers have explored alternative fuels for internal combustion (IC) engines, including bio-ethanol derived from the fermentation of agricultural waste, in addition to biodiesel. The utilization of these fuels, known as Diesel-Ethanol (DE) blends, has shown promise in enhancing engine efficiency and reducing emissions due to their higher oxygen content [15, 16]. However, employing DE directly in IC engines presents notable technical challenges such as a lower cetane number, flash point, and ethanol solubility in diesel.

To address these issues, researchers have investigated the impact of additives, specifically emulsifiers, on the solubility of ethanol in diesel fuel blends like DE. The incorporation of emulsifiers prevents phase separation in Diesel-Ethanol. Emulsifiers function by strengthening the attraction between the two liquid phases, thereby reducing interfacial tension forces and ensuring stable emulsions [17-20].

Some studies suggest that the addition of biodiesel, a fatty acid methyl ester (FAME), as an emulsifier in DE blends can mitigate phase separation issues. FAME acts as an amphiphilic substance, contributing to the stabilization of ethanol and diesel mixtures. Despite these findings, further research is needed to fully establish the viability of biodiesel as an effective emulsifier in Diesel-Ethanol blends, as existing studies on this subject are limited [21-24].

The main objective of this research is to substitute fossil diesel with ethanol in DE blends, employing RSO biodiesel as an emulsifying agent. RSO exhibits considerable potential as a sustainable alternative fuel derived from non-edible oil sources. The biodiesel was synthesized from RSO using the transesterification process. The study focuses on evaluating the operational and emission features of a diesel engine running on Diesel-Ethanol blends with the inclusion of RSO methyl esters as the emulsifying agent.

2 MATERIALS AND METHODOLOGY

2.1 Synthesis of RSO Biodiesel

Rubber seeds sourced from the coastal region of Karnataka, India, underwent processing utilizing a hydraulic pressing machine for oil extraction. Following extraction, the oil underwent heating at 100 °C and subsequent filtration to eliminate suspended particles and moisture. Chemicals required for biodiesel production, namely methanol, sodium hydroxide, and sulfuric acid, were obtained from Sigma-Aldrich, India. The acid value of the oil was assessed through the standard titrimetric method, initially measuring at 20 mg KOH/g oil. The acid value reduction was achieved through the implementation of saponification during the transesterification process, employing a two-step transesterification method, acid catalyzed esterification followed by base catalyzed transesterification process. The process is explained in the authors previously published papers [25, 26]. The properties of the biodiesel and crude oil are given in Tab. 1.

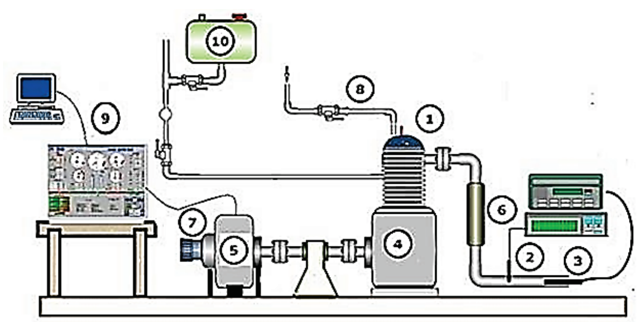
Table 1 Properties of RSO biodiesel

Fuel Properties	RSO	*RSO Biodiesel
Specific gravity	0.92	0.886
Kinematic viscosity 40 °C (mm^2/s)	7.8	3.5
Flashpoint (°C)	198	125
Calorific value (kJ/kg)	38545	40100
Acid value (mg KOH/gm)	10	0.38
Cloud point (°C)	6	16
Pour point (°C)	2	10
Sulphur content (%w/w)	-	0.01
Cetane number	65.50	63.5

*Analysis Results

3 TEST FUELS AND EXPERIMENTAL SETUP

In this present investigation, an analysis is conducted on diesel engines powered by conventional fossil fuel, as well as blends such as DE5B10, DE10B10, DE15B10, and pure B100, assessing their performance and emissions. Different ethanol-diesel mixtures were formulated using RSO biodiesel at a concentration of 10% (v/v) to serve as an emulsifier. To guarantee proper homogenization, the fuel blends underwent agitation for duration of 15 minutes and were then stored for 24 hours to detect any potential phase separation.



1-Pressure sensor
2-Smoke meter
3-Exhaust gas analyser
4-Dual cylinder CI engine
5-Eddy current dynamometer
6-Exhaust gas calorimeter
7- Crank angle encoder
8-Water inlet to engine
9-Control panel & computer
10- Fuel tank

Figure 1 Diesel engine test rig

3.1 Engine Experimental Setup

For the investigation, we employed a Kirloskar TV 1 single-cylinder, water-cooled 4-stroke diesel engine featuring a compression ratio of 17.5:1, a rated speed of 1500 rpm, and a rated brake power (BP) of 5.5 kW. The engine's rotational speed remained constant at 1500 rpm throughout the entire experimental duration. To gauge the emissions of CO, CO_2, NO_x, and HC, an AVL 444 di-gas analyzer was utilized, while smoke opacity was assessed using an AVL 437C smoke meter. The experimental setup, illustrated in Fig. 1, was employed for the study.

4 TEST FUELS AND EXPERIMENTAL SETUP

Within this section, the focus is on the outcomes of the test engine. Various performance metrics, including Brake Specific Energy Consumption (BSEC) and Brake Thermal Efficiency (BTE), were pinpointed. Subsequent sections utilize graphical representations to analyze and elucidate emission parameters such as carbon dioxide (CO_2), hydrocarbon (HC), nitrogen oxide (NO_x), carbon monoxide (CO), and smoke opacity.

4.1 Performance Characteristics

4.1.1 Variation in BTE

The outcomes of the investigation into the brake thermal efficiency (BTE) of diesel, RSO biodiesel (B100), and ethanol-biodiesel blends (DE5B10, DE10B10, and DE15B10) are illustrated in Fig. 2. The results indicate that, across the entire load spectrum, all tested blends exhibited superior BTE compared to both diesel and B100. Under maximum load conditions, DE5B10, DE10B10, and DE15B10 blends achieved BTE increases of 7.29%, 8.86%, and 10.19%, respectively, over diesel. Furthermore, these blends exhibited BTE enhancements of 10.69%, 12.12%, and 13.51% over B100 under the same conditions. The superior performance of DE15B10 can be attributed to the synergistic effects of viscosity and density reduction, leading to improved combustion characteristics. These findings underscore the potential of ethanol-biodiesel blends as efficient and cleaner alternatives to conventional diesel fuel [27-29].

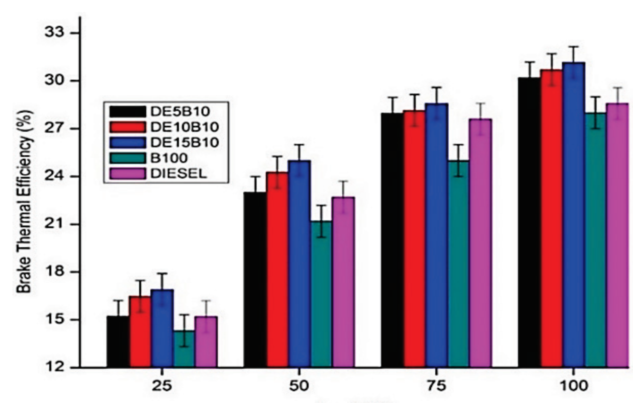


Figure 2 BTE with load

4.1.2 Variation in BSFC

Fig. 3 illustrates the variations in brake-specific fuel consumption (BSFC) across different fuel blends under varying load conditions. As the load increased, a corresponding decrease in BSFC was observed for all tested fuel blends. At full load, B100 exhibited a 12.3% higher BSFC compared to diesel fuel, indicating increased fuel consumption. Similarly, DE5B10 recorded a 7.39% rise in BSFC, while DE10B10 and DE15B10 displayed increases of 10.69% and 4.30%, respectively, relative to diesel. The higher BSFC observed with increasing ethanol content can be primarily attributed to leaner combustion characteristics and the lower calorific value of ethanol, which results in reduced energy output per unit of fuel. These results align with previous studies, reinforcing the influence of ethanol's oxygenation on combustion efficiency and fuel consumption trends [30, 31].

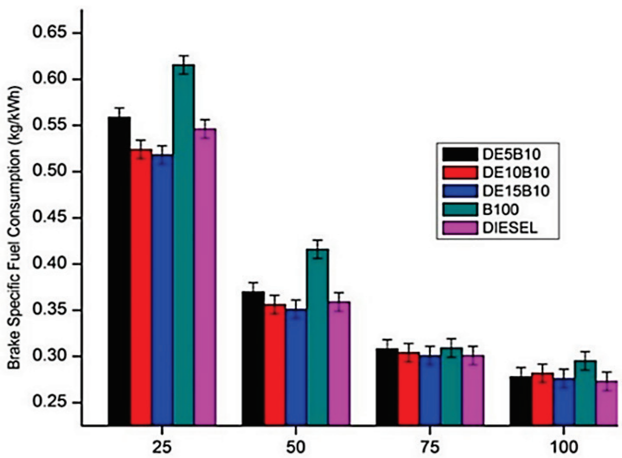


Figure 3 BTE with load

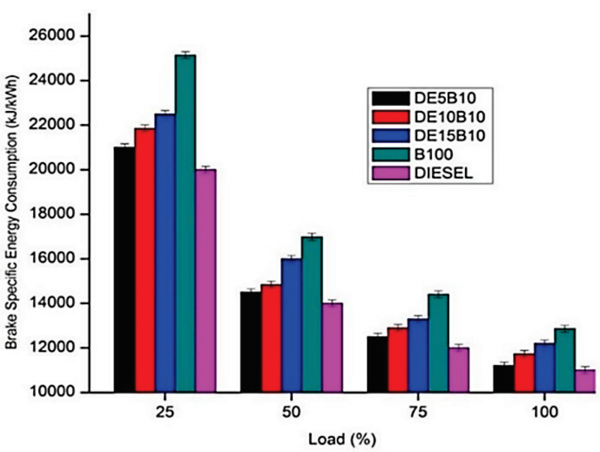


Figure 4 BSEC with load

4.1.3 Variation in BSEC

Fig. 4 illustrates the variations in brake-specific energy consumption (BSEC) across different fuel blends under varying load conditions. The results indicate a consistent decline in BSEC as load increases for all tested blends. This reduction can be attributed to the fact that the percentage increase in brake power (BP) is lower than the corresponding rise in fuel consumption, leading to improved energy utilization at higher loads. Additionally, reduced heat losses at elevated loads further contribute to this trend. Among the tested fuels, DE5B10 exhibited a 1.82% higher BSEC than conventional diesel, while DE10B10 and DE15B10 recorded increases of 6.39% and 9.95%, respectively. B100 demonstrated the highest BSEC, registering a 14.9% increase over diesel due to its higher calorific value and lower energy efficiency. These results align with previous studies, reaffirming the impact of biodiesel and ethanol blends on fuel energy consumption, combustion efficiency, and overall engine performance [32, 25]. Future research should further explore optimization strategies to enhance fuel efficiency in alternative fuel applications.

4.2 EMISSION CHARACTERISTICS

4.2.1 CO_2 Emission

Fig. 5 illustrates the variations in carbon dioxide (CO_2) emissions across different load conditions for various fuel blends. The results indicate a consistent upward trend in CO_2 emissions with increasing load, regardless of the fuel blend. This increase can be attributed to enhanced combustion efficiency at higher loads, which promotes the complete oxidation of fuel carbon content. Compared to conventional diesel, all tested blends exhibited slightly elevated CO_2 emissions. Specifically, DE5B10 recorded a 1.93% increase, DE10B10 showed a 3.75% rise, and DE15B10 demonstrated the highest increase at 7.2%. This trend is primarily due to the enhanced conversion of carbon monoxide (CO) to CO_2, facilitated by the higher oxygen content introduced through ethanol blending. The greater oxygen availability in ethanol-rich blends promotes more complete combustion, leading to increased CO_2 formation. These findings are consistent with previous research, underscoring the trade-off between reduced CO emissions and slightly higher CO_2 emissions in ethanol-biodiesel-diesel fuel blends [33].

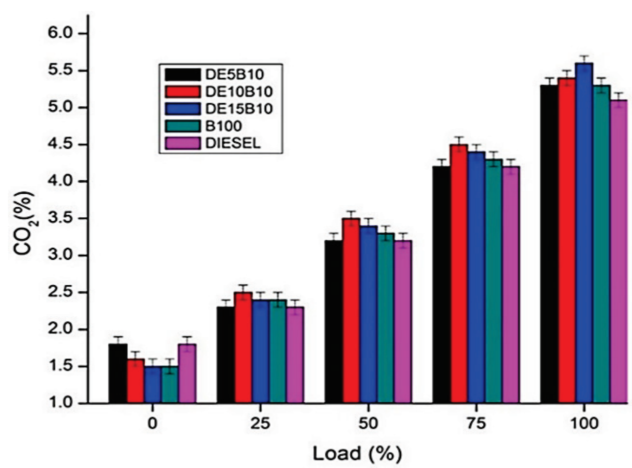


Figure 5 CO_2 emissions with load

4.2.2 HC Emissions

Fig. 6 illustrates the hydrocarbon (HC) emissions for various fuel blends under different load conditions. The results show that HC emissions are highest at full load for all tested fuel mixtures. The increase in HC emissions with higher ethanol content is attributed to unburned ethanol in the fuel blends, which may lead to incomplete combustion. Compared to diesel, DE5B10 exhibited a 21.3% reduction in HC emissions, while DE10B10 and DE15B10 recorded reductions of 26.52% and 13.92%, respectively. Notably, B100 demonstrated the lowest HC emissions, showing a 31.65% reduction compared to diesel fuel. The improved combustion efficiency of biodiesel and ethanol blends, due to their oxygen content, plays a crucial role in lowering HC emissions. These findings indicate that biodiesel and ethanol-enriched blends contribute to cleaner combustion, making them a promising alternative to conventional diesel fuel in reducing unburned hydrocarbon pollutants [27].

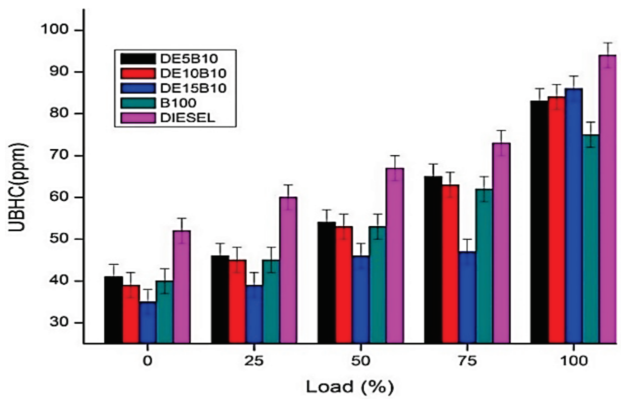


Figure 6 HC emissions with load

4.2.3 NO_x Emissions

Fig. 7 presents a detailed analysis of nitrogen oxide (NO_x) emissions for various fuel blends under different load conditions. The results indicate that, unlike conventional diesel fuel, NO_x emissions increase with higher loads across all tested blends. This trend is primarily attributed to elevated combustion temperatures and increased oxygen availability in ethanol-biodiesel blends, which enhance the formation of NO_x during combustion.

At full load, the NO_x emissions of DE5B10 were 2.15% higher than those of diesel, while DE10B10 exhibited a 3.3% increase. Interestingly, the DE15B10 blend showed NO_x emissions comparable to those of diesel, suggesting a potential balance between combustion efficiency and emissions control. Meanwhile, B100 recorded the highest NO_x emissions, largely due to its high oxygen content, which facilitates more complete combustion but also intensifies NO_x formation.

The increased proportion of ethanol in the blends also plays a significant role in NO_x emissions. Ethanol addition reduces fuel viscosity, improves atomization, and enhances air-fuel mixing, leading to more efficient combustion. However, this also results in higher in-cylinder temperatures and a prolonged premixed combustion phase, which further contribute to NO_x formation.

Despite the slight increase in NO_x emissions, the overall benefits of ethanol-biodiesel blends, such as reduced particulate matter and hydrocarbon emissions, highlight their potential as cleaner alternatives to fossil diesel. Future research should focus on optimizing combustion strategies and exhaust after-treatment technologies to mitigate NO_x emissions while maximizing efficiency and sustainability [27, 34].

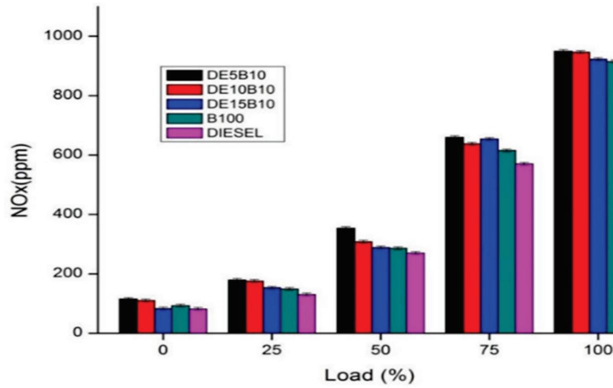


Figure 7 NO_x emissions with load

4.2.4 CO Emission

Fig. 8 illustrates the carbon monoxide (CO) emissions for various fuel blends under different load conditions. The results indicate that at lower loads, CO emissions remain relatively constant, whereas at higher loads, there is a notable increase in CO emissions. However, biodiesel blends consistently exhibit lower CO emissions compared to conventional diesel fuel. This reduction is primarily attributed to the higher oxygen content in biodiesel, which enhances oxidation and promotes the conversion of unburned CO into carbon dioxide (CO_2).

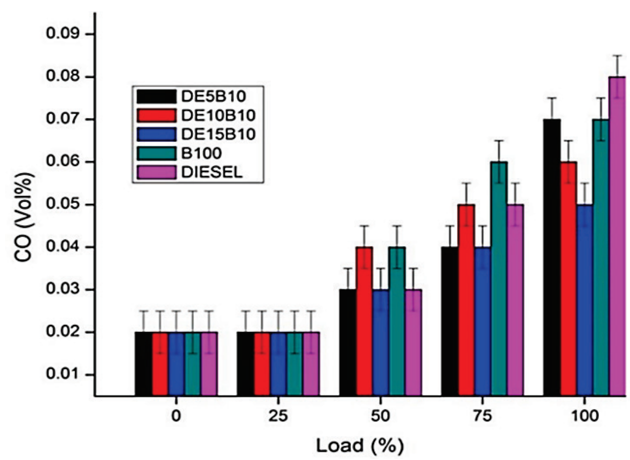


Figure 8 NO_x emissions with load

Under maximum load conditions, DE5B10 recorded a 25.5% reduction in CO emissions, while DE10B10 and DE15B10 demonstrated reductions of 38.3% and 50.5%, respectively, compared to diesel fuel. These significant reductions highlight the potential of ethanol-biodiesel blends in improving combustion efficiency and reducing harmful emissions. The findings confirm that biodiesel-enriched blends serve as an effective alternative to diesel, offering cleaner combustion and contributing to lower environmental pollution levels [34, 35].

4.2.5 Smoke Opacity

Fig. 9 illustrates the smoke opacity levels for various fuel blends under different loading conditions. The results indicate that as the load increases, smoke opacity rises for all tested fuel combinations. Notably, the B100 biodiesel blend exhibits 14.1% higher smoke opacity than diesel fuel across the entire load spectrum, primarily due to its higher viscosity and incomplete combustion at certain operating conditions.

Conversely, ethanol-biodiesel blends (DE5B10, DE10B10, and DE15B10) demonstrate reduced smoke opacity compared to diesel fuel. This reduction is attributed to the presence of free oxygen in ethanol, which enhances combustion efficiency and minimizes particulate matter formation. Specifically, DE5B10 recorded a 3.69% decrease in smoke opacity, while DE10B10 and DE15B10 exhibited reductions of 6.96% and 11.36%, respectively, relative to diesel fuel. These findings highlight the effectiveness of ethanol-biodiesel blends in reducing soot emissions, making them a cleaner alternative to conventional diesel for compression ignition engines [36-39].

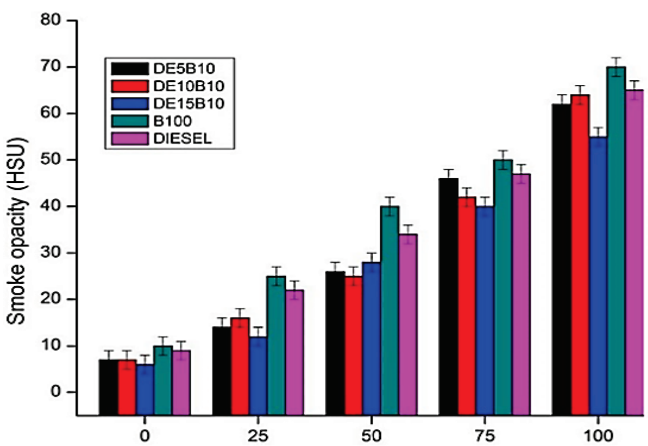


Figure 9 Smoke opacity with load

5 CONCLUSIONS

The primary objective of this study was to synthesize biodiesel from rubber seed oil (RSO) via transesterification and evaluate its feasibility as an additive in diesel-ethanol (DE) blends for compression ignition (CI) engines. Under maximum load conditions, the DE5B10, DE10B10, and DE15B10 blends exhibited increases in brake thermal efficiency (BTE) by 7.29%, 8.86%, and 10.19%, respectively, compared to diesel blends. While all RSO biodiesel blends demonstrated higher brake-specific fuel consumption (BSFC) than diesel, the DE15B10 blend achieved an optimal balance between efficiency and emissions. In terms of emission characteristics, the addition of RSO biodiesel significantly reduced carbon monoxide (CO) emissions. The CO emissions for the DE5B10, DE10B10, and DE15B10 blends were lower than those of traditional diesel fuel, with reductions of 25.5%, 38.3%, and 50.5%, respectively. Hydrocarbon (HC) emissions also decreased, with reductions of 21.3% for the DE5B10 blend, 26.52% for the DE10B10 blend, and 13.92% for the DE15B10 blend. Furthermore, nitrogen oxide (NO_x) emissions were notably lower under low-load conditions for all biodiesel blends compared to diesel fuel, a critical factor for regulatory compliance with emission standards. Additionally, the integration of RSO biodiesel and ethanol contributed to a significant reduction in smoke opacity, enhancing combustion efficiency and decreasing particulate matter emissions. This study underscores the viability of using RSO biodiesel as a sustainable and renewable emulsifier in DE blends, ensuring phase stability and improved fuel performance. The findings indicate that the DE15B10 blend, with its optimal combination of performance enhancement and emission reduction, is a promising alternative fuel for CI engines without requiring modifications to existing engine hardware. Future research should focus on long-term durability tests and economic feasibility assessments to further validate the commercial applicability of RSO biodiesel blends in the automotive industry [40-42].

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Authors' contacts:

H. V. Srikanth
Department of Aeronautical Engineering,
Nitte Meenakshi Institute of Technology,
Nitte (Deemed to be University)
Yelahanka, Bangalore – 560064, Karnataka, India

S. Vijay Kumar
Department of Mechanical Engineering,
Nitte Meenakshi Institute of Technology,
Nitte (Deemed to be University)
Yelahanka, Bangalore – 560064, Karnataka, India

Kousik Kumaar Rajagopal
(Corresponding author)
Department of Aeronautical Engineering,
Nitte Meenakshi Institute of Technology,
Nitte (Deemed to be University)
Yelahanka, Bangalore – 560064, Karnataka, India
kousikkumaarphd@gmail.com

Senthil Kumar Madasamy
Department of Aeronautical Engineering,
Kumaraguru College of Technology,
Coimbatore - 641049, Tamil Nadu, India
senthilkumar.m.aeu@kct.ac.in

Beena Stanislaus Arputharaj
Department of Research and Innovation,
Saveetha School of Engineering, SIMATS,
Chennai-602105, Tamil Nadu, India
beena2192@gmail.com

Parvathy Rajendran
Department of Mechanical and Aerospace Engineering,
United Arab Emirates University,
Al Ain, UAE
aeparvathy@uaeu.ac.ae

Vijayanandh Raja
(Corresponding author)
Department of Aeronautical Engineering,
Kumaraguru College of Technology,
Coimbatore - 641049, Tamil Nadu, India
vijayanandh.raja@gmail.com