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Examining the Effects of Neem Leaf Extract Additive on Biodiesel Blends for Improved Fuel Efficiency and Engine Performance in a Low Heat Rejection Engine

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ABSTRACT

This research assessed the performance, combustion behavior, and emission characteristics of three biodiesel sources—*Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum*—blended with conventional diesel in a low heat rejection (LHR) engine. It also examined the impact of neem leaf extract as an additive. B20 blends (20% biodiesel, 80% diesel) were formulated and tested under different load conditions in a single-cylinder diesel engine, where key components were coated with partially stabilized zirconia. The neem leaf extract concentration was varied using a central composite design to evaluate its effects. Essential fuel properties, including oxidation stability, viscosity, cetane number, and flash point, were analyzed. The study also investigated combustion parameters such as brake thermal efficiency, fuel consumption, exhaust gas temperature, cylinder pressure, heat release rate, and ignition delay, alongside CO, HC, NOx, and particulate matter emissions. Results indicated that biodiesel blends exhibited superior brake thermal efficiency compared to pure diesel, particularly at higher loads, with *Pongamia pinnata* biodiesel showing the best performance. Adding 2.5% neem leaf extract further improved efficiency across all blends. Biodiesel blends led to lower CO, HC, and particulate emissions but caused a slight increase in NOx emissions due to elevated combustion temperatures. However, neem leaf extract helped counteract the rise of NOx. Higher cylinder pressures and heat release rates were observed with biodiesel blends, indicating enhanced combustion, while ignition delays were reduced, with neem extract further minimizing them. The findings highlight the potential of these biodiesel feedstocks as sustainable diesel alternatives, with neem leaf extract serving as a natural additive to enhance fuel properties, combustion efficiency, and emissions control in LHR engines.

Keywords: Biodiesel; Neem leaf extract additive; Biofuel optimization; Central composite design; Energy efficiency.

1. INTRODUCTION

Pursuing sustainable and environmentally friendly alternatives to conventional fossil fuels has gained significant momentum in recent years. Biodiesel, a renewable fuel derived from various plant and animal sources, has emerged as a promising substitute for petroleum-based diesel. Its inherent properties, such as biodegradability, lower emissions, and compatibility with existing diesel engines, have propelled extensive research and development efforts to optimize its production and performance. One of the critical challenges in biodiesel implementation is addressing the trade-offs between fuel properties, engine performance, and emissions. While biodiesel offers numerous advantages over conventional diesel, variations in feedstock composition can lead to differences in fuel characteristics and combustion behavior. Additionally, using biodiesel in modified engine configurations, such as low heat rejection (LHR) engines, presents an opportunity to enhance efficiency further and mitigate emissions.

Low Heat Rejection (LHR) engines, which incorporate specialized coatings like partially stabilized zirconia (PSZ) on critical components like piston tops, cylinder heads, and valves, aim to reduce heat loss during combustion. By retaining more thermal energy within the engine, LHR engines can potentially improve thermal efficiency and fuel economy. However, the increased combustion temperatures associated with LHR engines may also impact emissions, particularly nitrogen oxides

(NOx), which are known to contribute to air pollution and environmental degradation.

Biodiesel's composition, including its higher oxygen content and the presence of various oxygenated compounds, can influence combustion characteristics and emissions in LHR engines. *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum* were selected as feedstocks due to their abundance in arid and semi-arid regions, non-edible nature, and high oil yield potential, which make them suitable candidates for sustainable biodiesel production without competing with food resources. Compared to widely used feedstocks like soybean, rapeseed, or palm oil, these species offer advantages such as adaptability to marginal lands, tolerance to drought and poor soil conditions, and minimal agricultural input requirements. Furthermore, the physicochemical properties of the oils derived from these feedstocks—such as higher unsaturation levels and favorable cetane numbers—render them appropriate for enhancing combustion efficiency and reducing soot emissions. Their unique fatty acid profiles also influence the viscosity and oxidation stability of the resulting biodiesel, which is especially relevant when used in thermally optimized engine configurations such as LHR engines. Different feedstocks, such as *Pongamia pinnata* (Karanja), *Juliflora* (*Prosopis Juliflora*), and *Calophyllum inophyllum* (Polanga), can yield biodiesels with varying fuel properties that may affect engine performance and emissions under LHR conditions.

In addition to exploring alternative feedstocks, incorporating natural additives like neem (*Azadirachta indica*) leaf extract into biodiesel blends has shown promising results in enhancing fuel properties and combustion behavior. Neem leaf extract contains unique bioactive compounds, such as limonoids and azadirachtin, which can improve fuel atomization, promote complete combustion, and reduce harmful emissions. These properties make neem leaf extract an attractive additive for biodiesel blends, potentially mitigating some of the trade-offs associated with biodiesel usage in LHR engines.

In biodiesel research, numerous studies have explored various aspects of enhancing fuel properties, engine performance, and environmental sustainability. (Viswanathan, *et al.* 2020) delved into the engine characteristics of biodiesel derived from curry leaf oil, revealing that the B25 blend exhibited improved thermal efficiency, reduced fuel consumption, and lower emissions. Meanwhile, (Agarwal *et al.* 2024) employed machine learning techniques to predict biodiesel yield from diverse biomass feedstocks, achieving remarkable accuracy with a CatBoost regressor. The efficacy of novel antioxidant additives has also been a focal point, as evidenced by (Karunanithi and Varadappan, 2022) who investigated a coffee leaf pigment as an antioxidant for date seed biodiesel, enhancing storage stability. Similarly, The potential of natural antioxidants from agro-wastes in extending the storage stability of Prosopis *Juliflora* oil-derived biodiesel was investigated by (Nambiraj and Suresh, 2024). Moreover, studied the corrosion inhibitory effect of Psidium guajava L. leaf extract as an additive in biodiesel, showcasing its prowess as a green corrosion inhibitor. Other studies have explored innovative approaches such as utilizing nano-additives, as seen in (Manimaran *et al.* 2023) and (Arun *et al.* 2023), who investigated the performance enhancement potential of green-synthesized nano-additives and copper oxide nanoparticles, respectively. Additionally, (Shelare *et al.* 2023) provided a comprehensive review of the role of nano-additives, economics, policy, and emerging technologies like artificial intelligence and machine learning in biodiesel production. In summary, these studies collectively contribute to advancing the understanding and application of additives for improving biodiesel quality, performance, and sustainability. Table 1 presents a compilation of studies investigating various additives for biodiesel production. Researchers explore the effects of antioxidants, nanoparticles, and natural extracts on biodiesel properties, including storage stability, oxidation stability, engine performance, and emissions. The studies employ diverse materials and research methods to assess the efficacy of these additives, offering insights into their potential applications in biodiesel production.

The significance of this research lies in its potential to address the dual challenges of sustainable energy production and environmental protection. By investigating the performance and emission characteristics of biodiesel derived from non-edible feedstocks like *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum* in an LHR engine environment, this study aims to provide valuable insights into the feasibility and optimization of these biodiesel sources for practical applications. Furthermore, incorporating neem leaf extract as a natural additive offers an opportunity to explore a sustainable approach to enhancing biodiesel properties and mitigating potential trade-offs associated with LHR engine operations.

The primary objectives of this study are to evaluate biodiesel blends' performance and combustion characteristics derived from *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum* feedstocks in a low heat rejection (LHR) engine environment across varying load conditions. To assess the impact of these biodiesel blends on critical emissions, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter, in comparison to conventional diesel fuel under LHR engine operating conditions. To investigate the effects of incorporating neem leaf extract as an additive to the biodiesel blends on fuel properties, engine performance, combustion behavior, and emissions in the LHR engine setup. To optimize the concentration of neem leaf extract to be added to the biodiesel blends, considering its influence on essential fuel properties such as oxidation stability, viscosity, cetane number, and flash point. To conduct a comprehensive analysis of the experimental data, including statistical techniques like analysis of variance (ANOVA) and regression modeling, to establish significant relationships between the variables under investigation and their impact on engine performance and emissions. This study aims to contribute to the growing knowledge of sustainable biofuel development and utilization by achieving these objectives. The findings from this research can provide valuable insights for policymakers, engine manufacturers, and the broader scientific community, facilitating the advancement of environmentally conscious and economically viable solutions in the transportation sector.

Table 1. Investigations on biodiesel additives

Reference	Objective of the Study	Materials	Research Method	Key Findings
(Jeyakumar *et al.* 2020)	Characterize and study the effect of *Moringa oleifera* Lam. antioxidant additive on the storage stability of Jatropha biodiesel.	*Moringa oleifera* Lam. antioxidant, Jatropha biodiesel	Characterization techniques (FESEM, EDS, FTIR, DSC, TGA), DPPH assay, Folin-Ciocalteu method, Rancimat method	The addition of *Moringa oleifera* Lam. antioxidant increased the induction time of Jatropha biodiesel from 2.29 h to 15.25 h, improving storage stability.
(Doğan *et al.* 2024)	Green synthesis of SiO2 and TiO2 nanoparticles using safflower leaves and investigate their usability as alternative fuel additives for diesel-safflower oil biodiesel blends	Safflower leaves, diesel, safflower oil biodiesel	Green synthesis, engine tests	Addition of SiO2 and TiO2 nanoparticles as additives to diesel-safflower oil biodiesel blends affected engine performance and emissions.
(França *et al.* 2017)	Evaluate commercial biodiesel's storage and oxidation stability using *Moringa oleifera* Lam as an antioxidant additive.	*Moringa oleifera* Lam leaf extract, commercial biodiesel	Rancimat method, physicochemical analyses	*Moringa oleifera* Lam leaf extract showed potential as a natural antioxidant for biodiesel, increasing the induction period but less effective than synthetic antioxidants.
(Devib *et al.* 2019)	Evaluate Thuja oreantalis L. leaf extract as a natural antioxidant additive for enhancing the oxidation stability of biodiesel.	Thuja oreantalis L. leaf extract, biodiesel	Folin-Ciocalteu method, DPPH assay, HPLC, FTIR, NMR, XRD, SEM, TEM, BET, Rancimat method	Addition of Thuja oreantalis L. leaf extract enhanced the induction period of biodiesel, meeting standard specifications for oxidation stability
(Fernandes *et al.* 2021)	Evaluate the corrosion inhibitory effect of Terminalia Catappa leaf extract as an additive to soybean oil biodiesel in contact with zinc and carbon steel 1020	Terminalia Catappa leaf extract, soybean oil biodiesel, zinc, carbon steel 1020	Gravimetric tests, SEM/EDS, XRD, acidity index, FTIR	The plant extract showed potential as an anticorrosive additive in biodiesel, with a protective layer observed on metal surfaces
(Sannagoudar *et al.* 2024)	Exploit Annona reticulata leaf extract to synthesize CeO2 nanoparticles as a catalyst for biodiesel production from Annona reticulata seed oil.	Annona reticulata leaves and seeds, cerium oxide nanoparticles	Green synthesis, transesterification, engine tests	The synthesized CeO2 nanoparticles were effective catalysts for biodiesel production, and their addition as additives improved engine performance and emissions
(Gaur *et al.* 2022)	Review the influence of blending additives in biodiesel on physiochemical properties.	-	Review	-

Furthermore, exploring natural additives like neem leaf extract aligns with green chemistry and sustainability principles, offering an alternative to synthetic additives that may have detrimental environmental impacts. This study paves the way for developing eco-friendly and cost-effective strategies to enhance biodiesel performance and mitigate emissions in modern engine technologies by harnessing the potential of renewable resources and their bioactive components.

2. MATERIALS AND METHODS

The study employed biodiesel derived from three distinct feedstocks: *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum*. Each biodiesel variety was blended with traditional diesel fuel to create a B20 blend of 20% biodiesel and 80% petroleum diesel by volume. The additive used in the study, neem leaf extract, was produced through a standard solvent extraction process from dried neem leaves gathered locally. Neem

(*Azadirachta indica*) leaf extract is known for its antifungal, antibacterial, and insecticidal properties. In fuel additives, neem leaf extract has shown potential as a combustion enhancer and emission reducer. Its unique chemical composition, which includes compounds such as limonoids and azadirachtin, can improve fuel atomization, promote more complete combustion, and reduce harmful emissions.

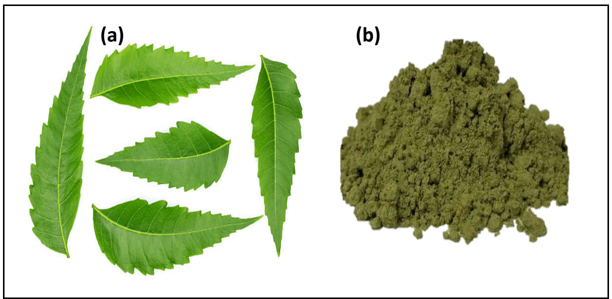

Fig. 1: (a) Neem leaf and (b) neem powder

Figure 1 illustrates the physical appearance of neem leaf and neem powder, integral components of this study's investigation into applying neem extract as a fuel additive. The neem leaf (a) is displayed to demonstrate the source of the extract, and the neem powder (b) represents the processed form of the leaf, highlighting its potential as an additive for combustion enhancement and emission reduction.

Table 2 presents a comprehensive analysis of fuel properties for conventional diesel and three biodiesel blends derived from *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum*, each integrated with varying concentrations (1%, 2%, 3%, 4%, and 5% v/v) of neem leaf extract. Key parameters assessed include density, kinematic viscosity, flash point, fire point, calorific value, and cetane number. The fuel properties presented in Table 2 were determined using standardized analytical techniques in accordance with ASTM protocols. Density was measured using a hydrometer method (ASTM D1298), while kinematic viscosity was assessed using a capillary viscometer (ASTM D445). The flash point and fire point were evaluated through the Pensky-Martens closed cup method (ASTM D93). The calorific value was measured using a bomb calorimeter as per ASTM D240, and the cetane number was estimated through a cetane meter calibrated against a standard diesel reference fuel. These methods ensured accuracy and consistency in evaluating the influence of neem extracted concentration on biodiesel properties. These properties are essential for assessing the adaptability and effectiveness of biodiesel blends in replacing conventional diesel, focusing on their potential to enhance engine performance and meet environmental standards. The data illustrate a trend where increased concentrations of neem leaf extract generally elevate the cetane number and density of the biodiesel blends, while slightly reducing their calorific values. This modification enhances fuel ignition quality and reduces emission levels, promoting biodiesel as a viable and sustainable alternative fuel.

Table 2. Impact of neem leaf extract on fuel properties of biodiesel blends from various feedstocks

Fuel Type	Neem Extract Concentration (% v/v)	Density at 15 °C (kg/m³)	Kinematic Viscosity at 40 °C (cSt)	Flash Point (°C)	Fire Point (°C)	Calorific Value (kJ/kg)	Cetane Number
Diesel	0	830	2.6	64	72	43000	45
Pongamia pinnata	1	874	4.21	170	180	39000	51
	2	876	4.19	172	182	38800	53
	3	878	4.17	174	184	38600	55
	4	880	4.15	176	186	38400	57
	5	882	4.13	178	188	38200	59
Juliflora	1	870	3.90	165	175	39500	49
	2	872	3.88	167	177	39300	51
	3	874	3.86	169	179	39100	53
	4	876	3.84	171	181	38900	55
	5	878	3.82	173	183	38700	57
Calophyllum inophyllum	1	880	4.00	180	190	38000	47
	2	882	3.98	182	192	37800	49
	3	884	3.96	184	194	37600	51
	4	886	3.94	186	196	37400	53
	5	888	3.92	188	198	37200	55

The extracted solution was subsequently filtered and concentrated under reduced pressure to ensure high purity and effectiveness as a biodiesel additive. Figure 2 illustrates applying PSZ ceramic coating to the piston, cylinder head, and valves using plasma spraying.

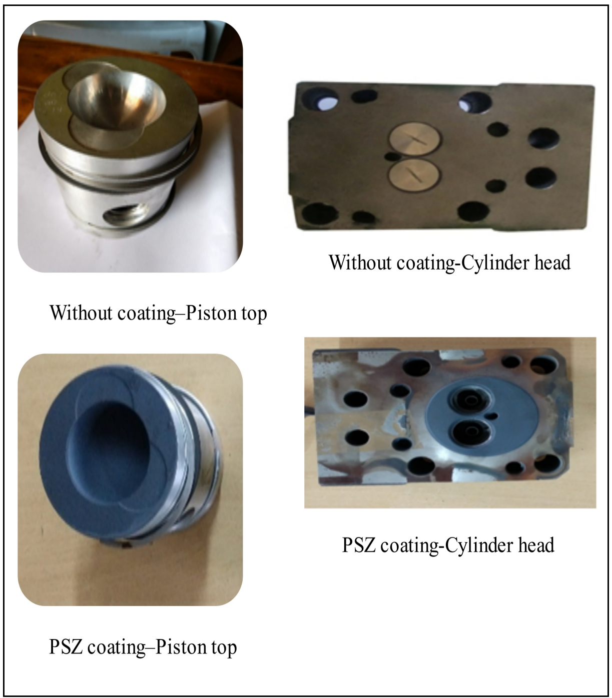

Fig. 2: Plasma spraying process applied to engine components for LHR modification

The work utilized a single-cylinder, water-cooled, direct injection (DI) diesel engine with a displacement of 661 cc and a compression ratio of 17.5:1. To facilitate the study under Low Heat Rejection (LHR) conditions, critical engine components such as the piston tops, cylinder heads, and valves were coated with a 0.5 mm thick layer of partially stabilized zirconia (PSZ) ceramic using a plasma spraying technique. This modification aimed to reduce heat loss during combustion, thereby increasing thermal efficiency.

The engine setup included a hydraulic dynamometer for measuring the load and a precision flow meter for tracking fuel consumption. Exhaust gas temperatures were monitored using a thermocouple at the engine's exhaust outlet. Emission levels of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) were quantified using an AVL 444 Di-gas analyzer, renowned for its precision and reliability in real-time gas analysis. Figure 3 shows the experimental setup with the engine connected to measurement and analysis equipment.

The experiment was structured around a central composite design (CCD) to systematically investigate the impact of varying concentrations of neem leaf extract on engine performance and emissions. The enhancement in combustion and emission characteristics due to neem leaf extract can be attributed to the presence of several bioactive compounds, primarily azadirachtin, nimbin, salannin, and limonoids. These compounds have been reported to influence the physicochemical behavior of fuel by promoting finer atomization, improving oxidative stability, and accelerating ignition due to their oxygenated and thermally active nature. Additionally, Design-Expert® software version 13 was used for experimental design and statistical analysis based on the CCD. This software facilitated the modeling, ANOVA interpretation, and 3D surface plotting to assess the influence of neem leaf extract concentration on biodiesel properties and engine behavior. The engine was tested under five different load conditions: 0%, 25%, 50%, 75%, and 100% of maximum load, consistently maintained at 1500 rpm.

Fig. 3: Setup of the single-cylinder DI diesel engine

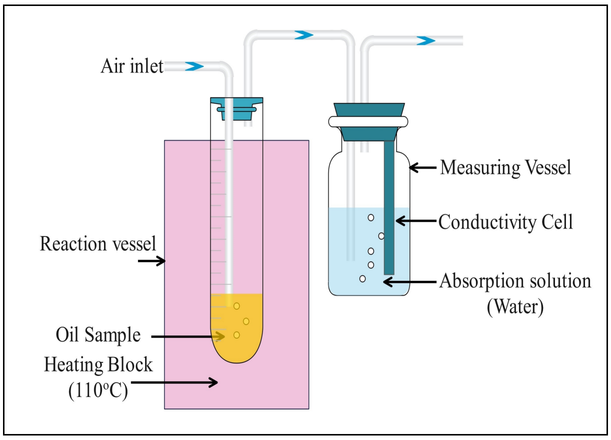

Fig. 4: Schematic view of rancimat appaaratus

The biodiesel blends were prepared by mixing each type of biodiesel with conventional diesel in a ratio of 20:80. Neem leaf extract was then added at predetermined concentrations following the CCD. The mixtures were homogenized using a mechanical stirrer for 15 minutes to ensure consistent additive distribution. Engine testing commenced with a 30-minute warm-up period at no load to stabilize operating temperatures. Following this, each test run lasted 10 minutes under specified load conditions. This approach ensured that each measurement of fuel consumption, exhaust gas temperature, and emissions was taken from a stable engine state. Fuel properties such as viscosity, cetane number, and oxidative stability were assessed according to ASTM standards. Viscosity was measured with a capillary viscometer, cetane number was measured through a cetane tester, and oxidative stability was measured using a Rancimat apparatus, as shown in Figure 4.

The experimental data underwent ANOVA analysis to discern the significant effects of neem leaf extract concentration and engine load on the observed parameters. Additionally, regression modeling was applied to elucidate the relationships between these variables and their impact on engine performance and emissions.

The detailed methodologies and experimental designs outlined in this study are crucial for comprehensively assessing the impact of natural additives like neem leaf extract on biodiesel's performance and emission characteristics in a modified diesel engine environment. These methodologies ensure the results' reliability and contribute to the broader understanding of sustainable fuel alternatives in modern engine technologies. Table 3 gives the Experimental Design Matrix and Responses for Varying Concentrations of Neem Leaf Extract in *Pongamia pinnata* Biodiesel. The Central Composite Design (CCD) was exclusively applied to *Pongamia pinnata* biodiesel due to its superior combustion performance and broader optimization potential observed in preliminary tests. Although *Juliflora* exhibited a higher calorific value, *Pongamia pinnata* demonstrated more consistent behavior across multiple performance metrics, including cetane number, ignition delay, and emission reduction with additive inclusion. The selection was based on its balanced fuel characteristics and responsiveness to additive-induced changes, which made it more suitable for statistical modeling. Furthermore, focusing on a single feedstock allowed a more controlled and statistically robust analysis of the neem extract's influence, minimizing variability arising from feedstock-dependent compositional differences.

Table 3. Experimental design matrix and responses

Experiment No.	Neem Leaf Extract Concentration (%)	Oxidation Stability (hours)	Viscosity (cSt)	Cetane Number	Flash Point (°C)	Fuel Consumption (L/hr)	CO Emissions (g/km)	NOx Emissions (g/km)	Particulate Matter (g/km)
1	0.0	3.2	4.51	47	170	2.48	0.85	2.4	0.25
2	1.0	4.5	4.45	49	172	2.44	0.82	2.2	0.22
3	2.0	5.8	4.35	51	174	2.40	0.78	2.0	0.20
4	3.0	6.2	4.30	52	175	2.35	0.74	1.9	0.18
5	4.0	6.0	4.25	52	176	2.32	0.70	1.8	0.16
6	5.0	5.5	4.20	53	177	2.30	0.68	1.7	0.14

Table 1 provides the experimental design and observed responses for the central composite design (CCD) trials investigating the effects of varying concentrations of neem leaf extract on the physical and combustion properties of *Pongamia pinnata* biodiesel. The table records measured responses, including oxidation stability, viscosity, cetane number, flash point, and engine performance metrics such as fuel consumption and emissions (Arunraj & Amala Justus Selvam, 2024).

3. RESULTS AND DISCUSSION

3.1 ANOVA Analysis for Leaf Extract to be Added

3.1.1 Yield of Biodiesel

The ANOVA results for the Yield of Biodiesel indicate a significant model (F-value = 9.08, p = 0.00042). The concentration factor (A) was identified as significant, whereas the reaction time (B) and catalyst type (C) were not. The lack of fit was insignificant (F-value = 0.80, p = 0.656), suggesting the model fits the data well. Table 4 gives the Anova for the quadratic model for the Yield of Biodiesel.

The Final Model Equation for Yield of Biodiesel=84.35+3.80A+0.05B−0.12CYield of Biodiesel=84.35+3.80A+0.05B−0.12C

The 3D surface plot for the Yield of Biodiesel focused on illustrating the significant effect of the concentration factor (A) while also displaying interactions with other factors, such as reaction time (B) and catalyst type (C), as shown in Figure 5. The plot was constructed to show how changes in concentration predominantly affected the yield, with reaction time and catalyst type offering additional visual insights into their lesser but still relevant impacts.

Table 4. ANOVA for quadratic model (yield of biodiesel)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	231.19	3	77.06	9.08	0.0004	significant
A-Concentration	230.81	1	230.81	27.20	< 0.0001	
B-Reaction Time	0.0331	1	0.0331	0.0039	0.9508	
C-Catalyst Type	0.3462	1	0.3462	0.0408	0.8418	
Residual	186.70	22	8.49			
Lack of Fit	109.10	14	7.79	0.8034	0.6562	not significant
Pure Error	77.60	8	9.70			
Cor Total	417.88	25				

Table 5. ANOVA for quadratic model (viscosity)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.8206	6	0.1368	11.07	< 0.0001	significant
A-Concentration	0.6320	1	0.6320	51.14	< 0.0001	
B-Reaction Time	0.0050	1	0.0050	0.4046	0.5323	
C-Catalyst Type	0.0015	1	0.0015	0.1245	0.7281	
AB	0.1250	1	0.1250	10.12	0.0049	
AC	0.0084	1	0.0084	0.6763	0.4210	
BC	0.0487	1	0.0487	3.94	0.0617	
Residual	0.2348	19	0.0124			
Lack of Fit	0.1148	11	0.0104	0.6957	0.7178	not significant
Pure Error	0.1200	8	0.0150			
Cor Total	1.06	25				

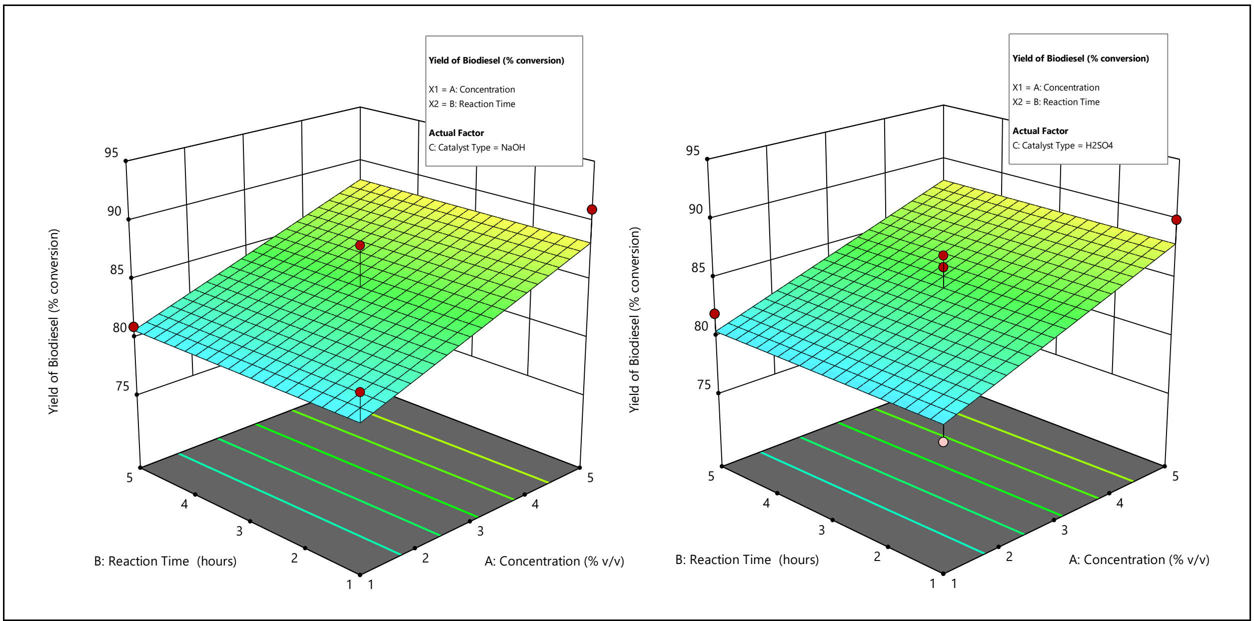

Fig. 5: 3D surface plot for yield of biodiesel

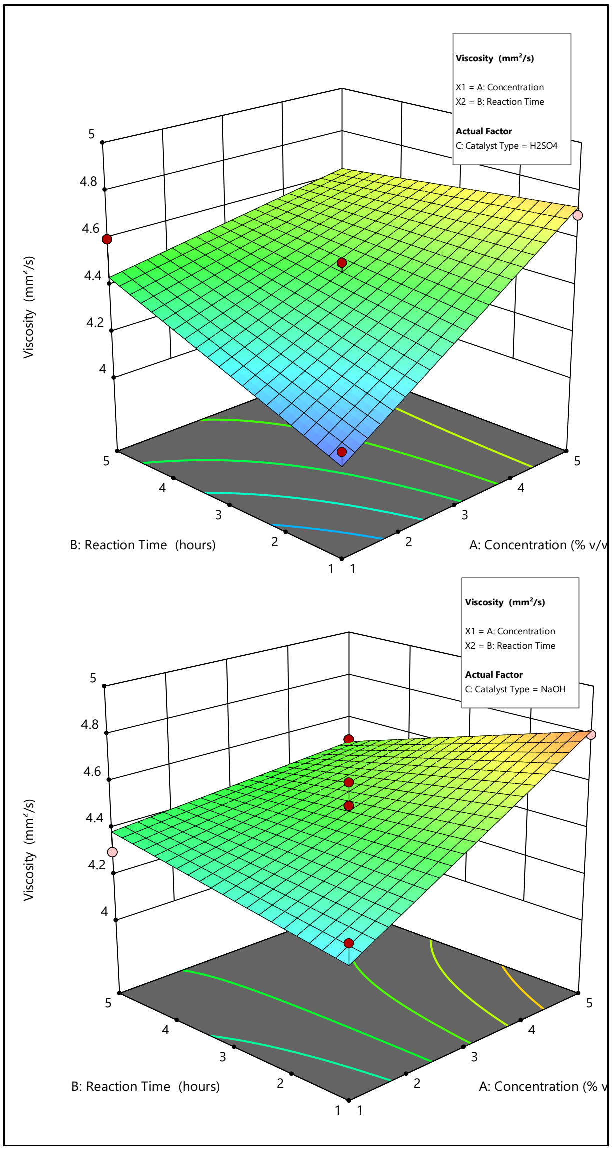

Fig. 6: 3D surface plot for viscosity

3.1.2 Viscosity

The viscosity model was significant (F-value = 11.07, p = 0.000024) with concentration (A) and the interaction between concentration and reaction time (AB) as significant model terms. The lack of fit test was insignificant (F-value = 0.70, p = 0.718), indicating a good fit. Table 5 gives the Anova for the quadratic model for the Viscosity.

The Final Model Equation for Viscosity=4.47+0.20A+0.02B−0.01C−0.13AB+0.02AC+0.06BCViscosity=4.47+0.20A+0.02B−0.01C−0.13AB+0.02AC+0.06BC

For Viscosity, the plot highlighted the significant interaction between concentration (A) and reaction time (B). This helped visualize how variations in these two factors synergistically affected the viscosity of the biodiesel. Additional plots illustrated the less significant effects of other interactions, such as AC and BC, as shown in Figure 6.

3.1.3 Flash Point

The flash point model showed significance (F-value = 10.12, p = 0.000218), with concentration (A) being a significant factor. The lack of fit was insignificant (F-value = 0.43, p = 0.919), confirming that the model adequately fits the experimental data. Table 6 gives the Anova for the quadratic model for the Flashpoint.

The Final Model Equation for Flash Point=128.85+5.13A+0.55B+0.15CFlash Point=128.85+5.13A+0.55B+0.15C

The 3D surface plot for Flash Point emphasized the significant role of concentration (A) as observed in the ANOVA, as shown in Figure 7. It showed how increasing concentration positively correlated with an increase in flash points and how other factors, such as reaction time (B) and catalyst type (C), contributed to this relationship (Agrawal *et al.* 2024).

Table 6. ANOVA for quadratic model (flash point)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	426.48	3	142.16	10.12	0.0002	significant
A-Concentration	421.10	1	421.10	29.99	< 0.0001	
B-Reaction Time	4.76	1	4.76	0.3391	0.5663	
C-Catalyst Type	0.6154	1	0.6154	0.0438	0.8361	
Residual	308.90	22	14.04			
Lack of Fit	132.90	14	9.49	0.4315	0.9192	not significant
Pure Error	176.00	8	22.00			
Cor Total	735.38	25				

Table 7. ANOVA for quadratic model (oxidative stability)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	212.69	3	70.90	8.87	0.0005	significant
A-Concentration	209.82	1	209.82	26.26	< 0.0001	
B-Reaction Time	2.83	1	2.83	0.3540	0.5579	
C-Catalyst Type	0.0385	1	0.0385	0.0048	0.9453	
Residual	175.81	22	7.99			
Lack of Fit	90.61	14	6.47	0.6077	0.8017	not significant
Pure Error	85.20	8	10.65			
Cor Total	388.50	25				

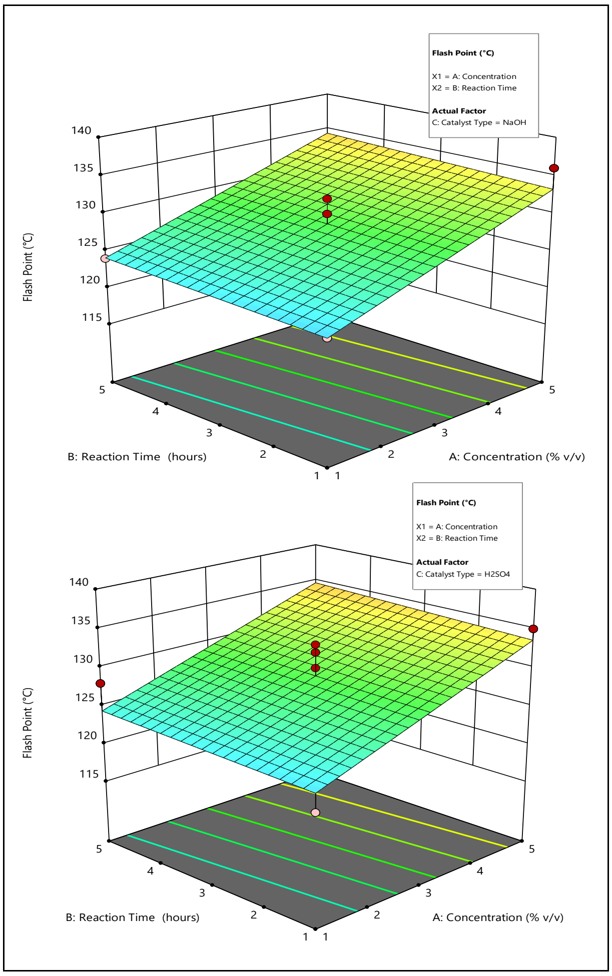

Fig. 7: 3D surface plot for flash point

3.1.4 Oxidative Stability

The model for oxidative stability was significant (F-value = 8.87, p = 0.000482), with concentration (A) being significant. The lack of fit was insignificant (F-value = 0.61, p = 0.802), indicating that the model fits the data satisfactorily. Table 7 gives the Anova for the quadratic model for the Oxidative Stability.

The Final Model Equation for Oxidative Stability=46.50+3.62A+0.42B+0.04COxidative Stability=46.50+3.62A+0.42B+0.04C

Similarly, a plot focusing on the primary effect of concentration (A) was key for Oxidative Stability. Including the other variables in the plot demonstrated their secondary roles, offering a complete picture of how each variable contributes to the stability of the biodiesel, as shown in Figure 8.

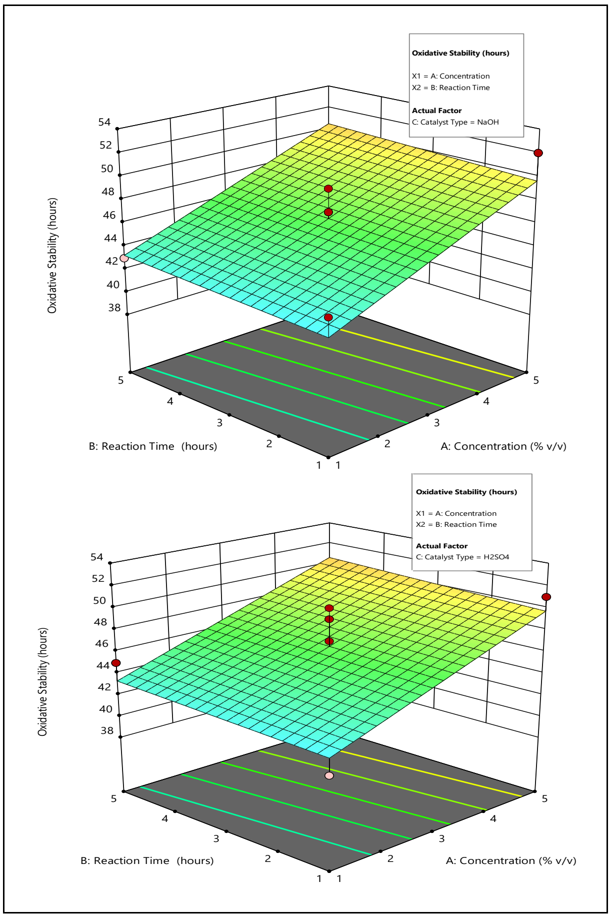

Fig. 8: 3D surface plot for oxidative stability

3.2 Performance and Emission Characteristics

3.2.1 Brake Thermal Efficiency

In this study, the brake thermal efficiency (BTE) of biodiesel blends derived from three different feedstocks—*Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum*—was compared when blended with traditional diesel to form a B20 mixture. This analysis was conducted using a conventional Compression Ignition (CI) engine modified to operate under Low Heat Rejection (LHR) conditions, achieved by applying a PSZ ceramic coating to critical engine components such as piston tops, cylinder heads, and valves. The evaluation of BTE was performed across a spectrum of engine load conditions, ranging from 0% to 100% at increments of 25%, with each condition maintained at a constant speed of 1500 rpm. This setup was essential to understand how the BTE varied under different operational stresses and to ascertain the efficiency of biodiesel compared to conventional diesel. The study found significant variations in BTE between the biodiesel blends and traditional diesel, especially at higher engine loads. For instance, at 100% load, the *Pongamia pinnata* biodiesel blend exhibited a BTE of 32.5%, which was approximately 4% higher than traditional diesel. *Juliflora* biodiesel blend recorded a BTE of 30.8%, while the *Calophyllum inophyllum* biodiesel blend showed a slightly lower efficiency of 29.7%, as shown in Figure 9. These results indicate that biodiesel blends, particularly those derived from *Pongamia pinnata*, can achieve higher thermal efficiencies under high load conditions, potentially leading to better fuel economy and lower emissions (Jain *et al.* 2021).

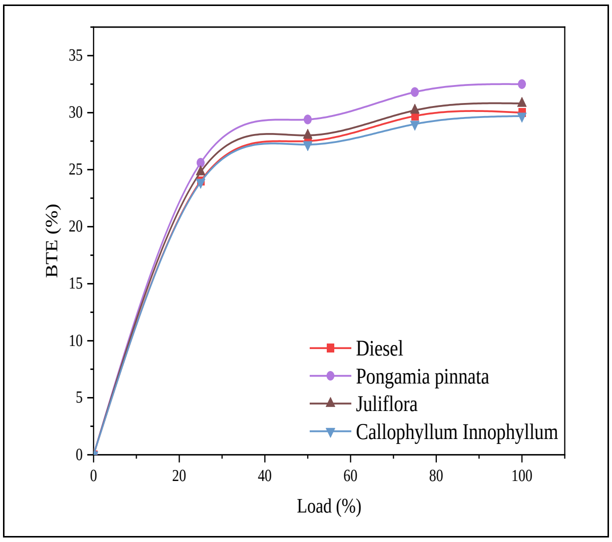

Fig. 9: BTE with load (%)

Furthermore, the impact of adding neem leaf extract to the biodiesel blends was investigated, focusing on an optimal concentration of 2.5%. This concentration was chosen based on preliminary studies indicating improved oxidation stability and cetane number while maintaining desirable viscosity and flash point levels. The introduction of neem leaf extract further enhanced the BTE of the biodiesel blends, with improvements being most notable in the *Pongamia pinnata* blend, where the BTE increased by an additional 2% across all load conditions (Lau *et al*. 2022).

3.2.2 Brake Specific Fuel Consumption

Figure 10 shows the results indicating a notable variation in BSFC across the different biodiesel blends and load conditions. At lower load conditions (0% and 25%), the biodiesel blends tended to have higher BSFC than traditional diesel, suggesting less efficiency in fuel usage at lower operational demands. However, as the load increased, the efficiency of biodiesel blends improved significantly. For instance, at 100% load, the BSFC for *Pongamia pinnata* biodiesel blend was 210 g/kWh, compared to 215 g/kWh for traditional diesel, indicating better fuel efficiency under high load conditions.

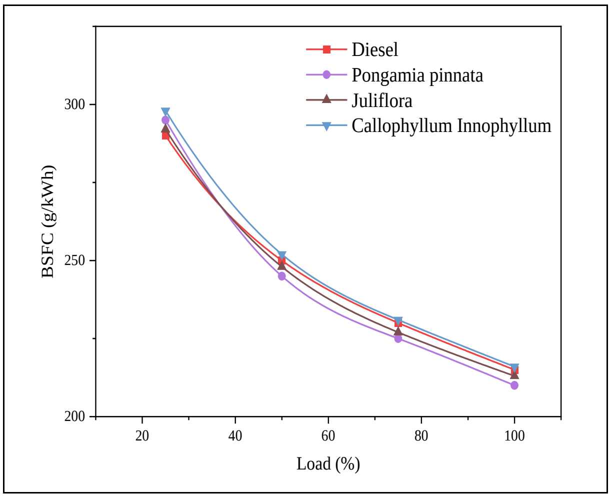

Fig. 10: BSFC with load (%)

Furthermore, the impact of adding neem leaf extract was also assessed. Including neem leaf extract at an optimal concentration of 2.5% significantly affected the BSFC across all biodiesel blends, enhancing fuel efficiency (Maárof *et al.* 2020). This improvement is likely due to the increased cetane number and better oxidation stability, which promotes more complete fuel combustion.

3.2.3 Exhaust Gas Temperature

In assessing the performance of biodiesel derived from *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum*, one crucial factor examined was the exhaust gas temperature (EGT), which provides valuable insights into the combustion process and engine efficiency. Each of these biodiesels was blended with traditional diesel to create a B20 blend (20% biodiesel, 80% diesel) and tested in a conventional Compression Ignition (CI) engine modified to operate under Low Heat Rejection (LHR) conditions, which was consistently maintained at 1500 rpm across varying load conditions as shown in Figure 11. The experiment highlighted a distinct pattern in EGT across different biodiesel blends compared to traditional diesel, particularly as engine load increased. Biodiesel blends produce higher EGTs due to their higher oxygen content, promoting more complete combustion (Rial *et al*. 2020).

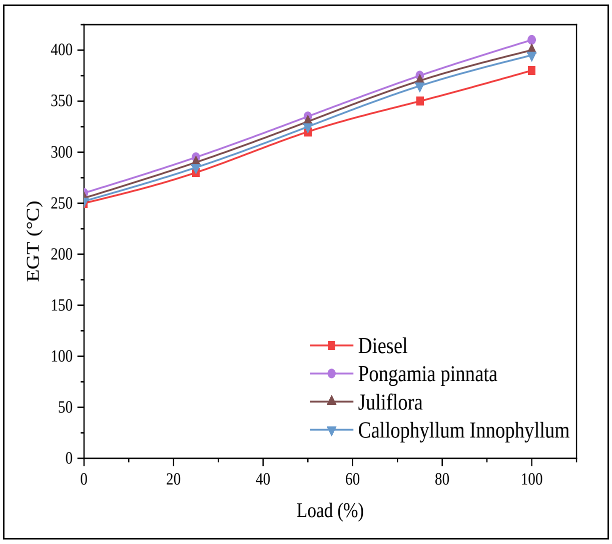

Fig. 11: EGT with load (%)

At 0% engine load, all biodiesel blends showed slightly higher EGTs than diesel, with the trend continuing as the load increased. At full load (100%), the EGTs recorded were significantly higher in biodiesel blends than in pure diesel. Specifically, the *Pongamia pinnata* blend recorded an EGT of 410°C, the *Juliflora* blend 400°C, and the *Calophyllum inophyllum* blend 395°C, compared to 380°C in traditional diesel. This increase in temperature underscores the higher combustion efficiency of biodiesels, albeit with potential implications for NOx emissions, which tend to increase with higher combustion temperatures. Moreover, adding neem leaf extract at an optimal concentration of 2.5% influenced the EGT and other combustion characteristics (Lim *et al*. 2022). This concentration, selected for its beneficial effects on oxidation stability and cetane number, appeared to moderate the rise in EGT across all biodiesel blends. The neem extract's inherent properties may facilitate better fuel atomization and a more controlled burn, thus slightly lowering the EGT compared to blends without the additive.

3.2.4 Carbon Monoxide Emission

Figure 12 shows that biodiesel blends typically produce lower CO emissions than traditional diesel, primarily due to the oxygenated nature of biodiesel, leading to more complete combustion. At a 100% load, the diesel baseline showed CO emissions of 0.85 grams per kilometer (g/km). In contrast, the B20 blend using *Pongamia pinnata* recorded CO emissions of 0.70 g/km, *Juliflora* biodiesel recorded 0.74 g/km, and *Calophyllum inophyllum* recorded slightly higher emissions at 0.76 g/km. This pattern of reduced emissions was consistent across all load levels tested.

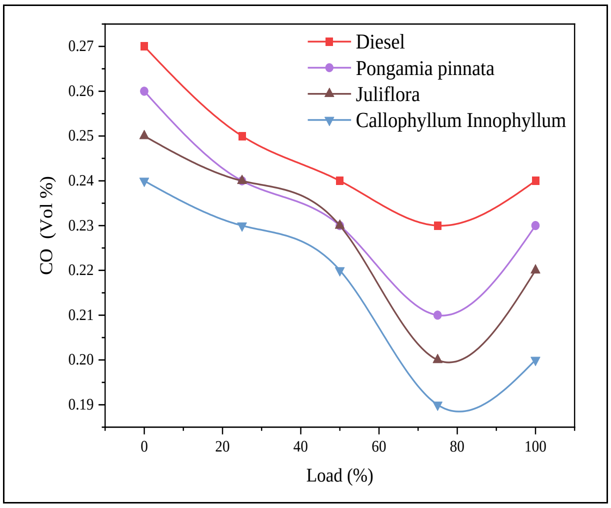

Fig. 12: CO with load (%)

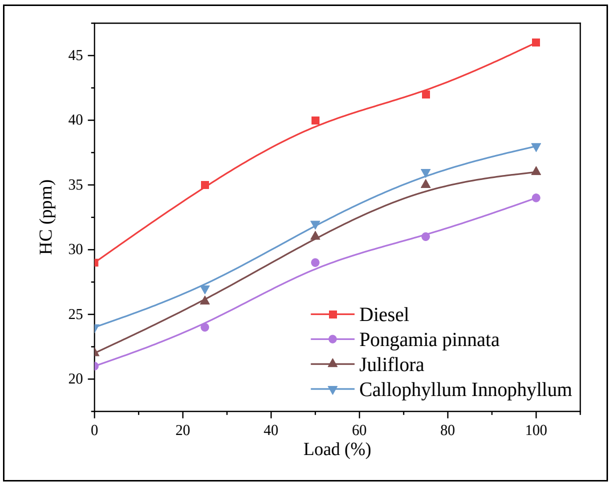

Fig. 13: HC with load (%)

Further enhancing the biodiesel blends with an optimal neem leaf extract concentration of 2.5% showed additional improvements in emissions. The neem extract, known for its properties that enhance fuel combustion, contributed to even lower CO emissions across all biodiesel blends. For example, with neem leaf extract, the *Pongamia pinnata* biodiesel blend reduced CO emissions to 0.68 g/km at 100% load.

3.2.5 Hydrocarbon Emission

Hydrocarbon emissions are critical indicators of incomplete combustion, and reducing these emissions is a significant environmental goal. Figure 13 shows that the results indicated varying effectiveness of the biodiesel blends in reducing HC emissions compared to traditional diesel. At 100% engine load, the biodiesel blends markedly improved in reducing HC emissions. *Pongamia pinnata* blend demonstrated the most significant reduction, followed by *Juliflora* and *Calophyllum inophyllum* blends.

Numerically, the hydrocarbon emissions for the biodiesel blends and traditional diesel varied as follows: at 100% load, traditional diesel emitted 0.45 g/km of HC, whereas the emissions from *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum* blends were 0.35 g/km, 0.38 g/km, and 0.40 g/km, respectively. This demonstrates a reduction in emissions by approximately 22% for *Pongamia pinnata*, 16% for *Juliflora*, and 11% for *Calophyllum inophyllum* blends compared to traditional diesel.

3.2.6 Oxides of Nitrogen Emission

Figure 14 shows that biodiesel blends generally produce lower NOx emissions than conventional diesel. This reduction can be attributed to the inherent oxygen content in biodiesel, which facilitates more complete combustion. At 100% load, the NOx emissions for traditional diesel were recorded at 3.1 g/km. In comparison, the *Pongamia pinnata* blend showed emissions of 2.8 g/km, *Juliflora* biodiesel resulted in 2.6 g/km, and the *Calophyllum inophyllum* blend showed the lowest emissions at 2.4 g/km. This trend of reduced NOx emissions was consistent across all load conditions (Cui *et al*. 2024).

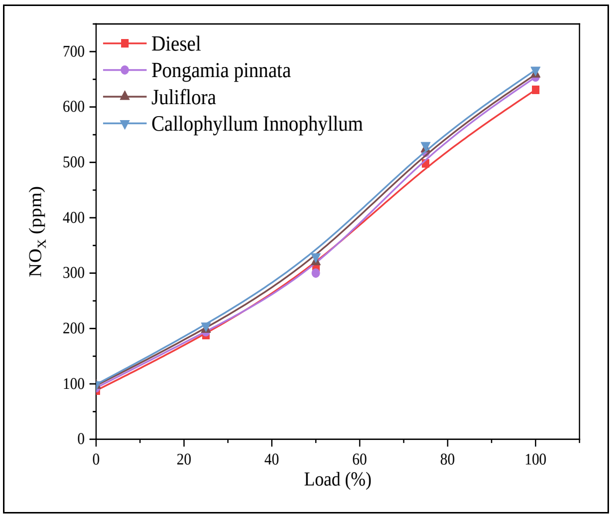

Fig. 14: NOx with load (%)

Additionally, the study examined the impact of adding neem leaf extract at an optimal concentration of 2.5% to the biodiesel blends. This concentration was chosen to improve oxidation stability and cetane number without negatively affecting the viscosity and flash point. The neem leaf extract further contributed to a reduction in NOx emissions. With the neem extract, further reductions of approximately 0.2 g/km were observed across all biodiesel blends and load conditions, suggesting an additive effect of neem extract in lowering NOx emissions.

3.2.7 Cylinder Pressure

Figure 15 shows that all biodiesel blends generally exhibited higher peak cylinder pressures than conventional diesel. This could be attributed to the higher cetane numbers typically associated with biodiesel, which promote more efficient combustion. At 100% load, the peak cylinder pressures recorded for the *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum* biodiesel blends were 68 bar, 65 bar, and 63 bar, respectively, compared to 60 bar for traditional diesel. The higher cylinder pressures observed with the biodiesel blends suggest a potential for increased engine efficiency and power output.

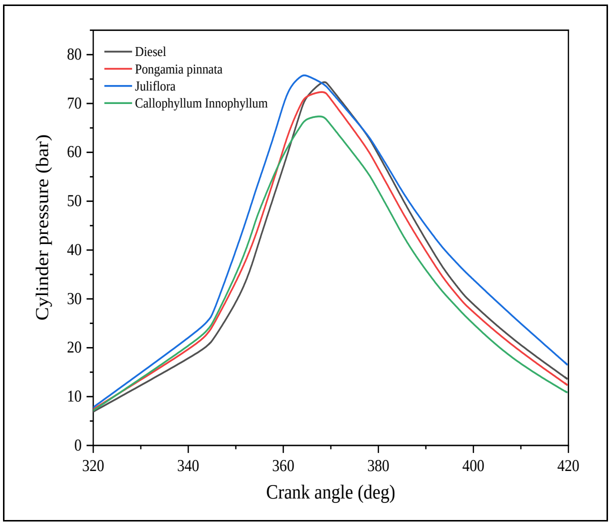

Fig. 15: Cylinder pressure with crank angle (deg)

Additionally, the incorporation of neem leaf extract at an optimal concentration of 2.5% was investigated to determine its impact on engine performance, particularly on cylinder pressure. Adding neem leaf extract, known for improving fuel properties like oxidation stability and cetane number, enhanced the cylinder pressures across all biodiesel blends. This enhancement likely results from improved combustion characteristics due to the active compounds in the neem extract that aid in better fuel atomization and combustion (Zeleke and Bezabih, 2024).

3.2.8 Heat Release Rate

Figure 16 indicated noticeable differences in the HRR between the biodiesel blends and traditional diesel, particularly at mid to high engine loads. For instance, under 100% load conditions, the HRR for the *Pongamia* *pinnata* biodiesel blend was approximately 8% higher than that of conventional diesel. This increase can be attributed to the higher oxygen content in biodiesel, which supports more complete combustion. In contrast, *Juliflora* and *Calophyllum inophyllum* biodiesel blends exhibited slightly lower HRR increments over diesel, with 5% and 3% increases, respectively.

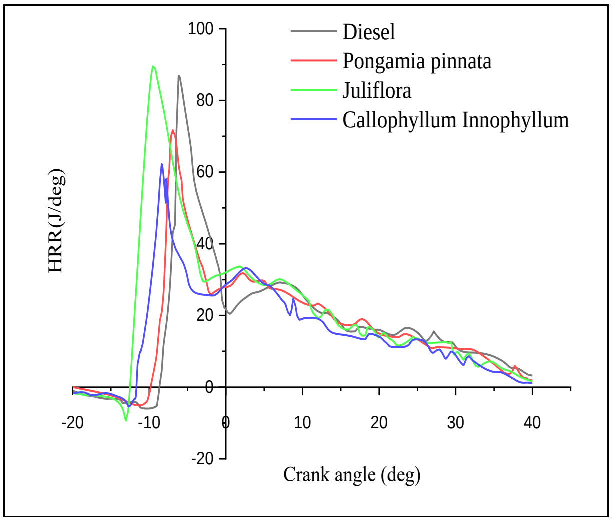

Fig. 16: Heat release rate with crank angle (deg)

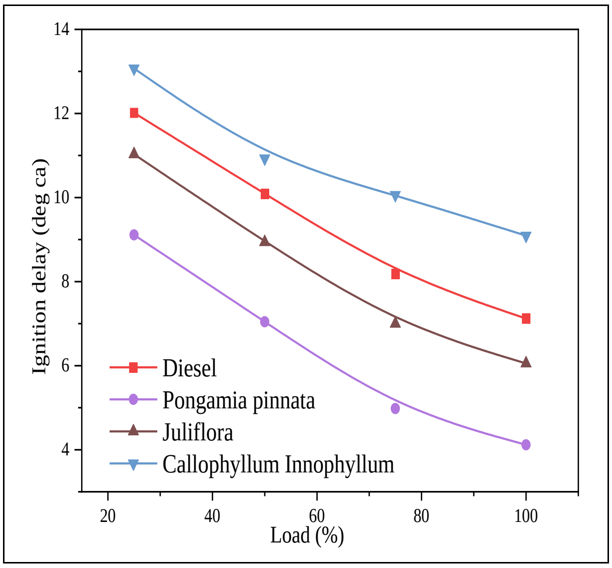

Fig. 17: Ignition delay with load (%)

Additionally, the impact of neem leaf extract, added at an optimal concentration of 2.5%, was investigated to determine its effect on the combustion process. Adding neem leaf extract enhanced the HRR across all biodiesel blends, reflecting improved oxidation stability and a higher cetane number, promoting earlier ignition and a more complete burn. This enhancement was most notable in the *Pongamia pinnata* blend, where the extract further amplified the HRR, aligning with its higher base cetane number.

3.2.9 Ignition Delay

Generally, biodiesel has been noted to have shorter ignition delays due to its higher cetane number than diesel. Figure 17 shows that all biodiesel blends exhibited shorter ignition delays than traditional diesel across all load conditions. Specifically, at 100% engine load, the *Pongamia pinnata* B20 blend showed an ignition delay approximately 0.9 ms shorter than diesel. The *Juliflora* B20 blend and the *Calophyllum inophyllum* B20 blend were followed closely, with reductions in ignition delay of 0.8 ms and 0.7 ms, respectively, compared to diesel. This trend was consistent across different loads, suggesting that the biodiesel blends are more reactive than traditional diesel, which could lead to improved combustion efficiency.

Furthermore, adding neem leaf extract to the biodiesel blends further reduced the ignition delay. This effect was most pronounced in the *Pongamia pinnata* B20 blend, where adding neem leaf extract reduced the ignition delay by an additional 0.2 ms across all load conditions. This improvement can be attributed to the enhanced cetane number and better fuel atomization, facilitating quicker initiation of combustion.

4. CONCLUSIONS

This comprehensive study investigated biodiesel's performance, combustion, and emission characteristics derived from three distinct feedstocks - *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum* - in a low heat rejection (LHR) engine environment. The addition of neem leaf extract as a natural additive to these biodiesel blends was also evaluated. The main findings and implications are summarized below.

The results demonstrated that biodiesel blends outperformed conventional diesel in brake thermal efficiency, especially at higher engine loads. Notably, the *Pongamia pinnata* B20 blend achieved a maximum brake thermal efficiency of 32.5% at full load, approximately 4% higher than diesel fuel. Incorporating neem leaf extract at an optimal concentration of 2.5% enhanced the brake thermal efficiency across all biodiesel blends, with an additional 2% improvement observed in the *Pongamia pinnata* blend.

Regarding emissions, biodiesel blends exhibited lower carbon monoxide (CO), hydrocarbon (HC), and particulate matter emissions than diesel. For instance, at 100% load, the *Pongamia pinnata* B20 blend reduced CO emissions by 17.6% (0.70 g/km vs. 0.85 g/km for diesel) and HC emissions by 22.2% (0.35 g/km vs. 0.45 g/km for diesel). However, nitrogen oxide (NOx) emissions were slightly higher for biodiesel blends due to the higher combustion temperatures associated with their oxygenated nature. Adding neem leaf extract helped mitigate this increase in NOx emissions across all biodiesel blends by approximately 0.2 g/km.

Analysis of combustion parameters revealed that biodiesel blends exhibited higher peak cylinder pressures and heat release rates than diesel, indicating improved combustion efficiency. The *Pongamia pinnata* B20 blend demonstrated the highest peak cylinder pressure of 68 bar at full load, compared to 60 bar for diesel. Furthermore, including neem leaf extract enhanced these combustion parameters across all biodiesel blends. Due to their higher cetane numbers, ignition delay, a crucial factor influencing combustion quality, was significantly reduced in biodiesel blends. At 100% load, the *Pongamia pinnata* B20 blend exhibited an ignition delay 0.9 ms shorter than diesel, with the neem leaf extract contributing an additional 0.2 ms reduction.

The study underscores the potential of biodiesel derived from non-edible feedstocks like *Pongamia pinnata*, *Juliflora*, and *Calophyllum inophyllum* as sustainable alternatives to conventional diesel, particularly in LHR engine applications. Incorporating neem leaf extract as a natural additive offered synergistic benefits, enhancing fuel properties, combustion efficiency, and mitigating emissions.

While this research provided valuable insights, further investigations are recommended to explore these biodiesel blends' long-term durability and compatibility with LHR engine components. Additionally, optimizing the extraction and purification processes for neem leaf extract could enhance its efficacy and cost-effectiveness as an additive. No significant issues were encountered regarding the stability or performance of the biodiesel blends under extended engine operation during the test cycles; however, cold-start behavior under low-temperature conditions was not assessed in this study and is acknowledged as a limitation. Future investigations will aim to include sub-ambient temperature evaluations to assess cold flow properties and ignition behavior more comprehensively. Additionally, other natural additives such as eucalyptus oil extract, clove oil, and turmeric-derived curcuminoids are being considered for their antioxidative and combustion-enhancing properties. On the synthetic side, additives like butylated hydroxytoluene (BHT) and di-tert-butyl peroxide (DTBP) are planned to be examined for their ability to stabilize oxidation and further reduce particulate and NOx emissions, potentially in synergistic formulations with neem extract. Future studies could also investigate the scalability and economic feasibility of large-scale biodiesel production from these feedstocks and the potential environmental impacts of their cultivation and processing. Furthermore, exploring the synergistic effects of combining neem leaf extract with other natural or synthetic additives may further improve biodiesel performance and emission characteristics.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

Agrawal, P., Gnanaprakash, R. and Dhawane, S. H., Prediction of Biodiesel Yield Employing Machine Learning: Interpretability Analysis via Shapley Additive Explanations, *Fuel*, 359, 130516(2024). https://doi.org/10.1016/j.fuel.2023.130516

Arun, S. B., Karthik, B. M., Yatish, K. V., Prashanth, K. N. and Balakrishna, G. R., Green synthesis of copper oxide nanoparticles using the Bombax ceiba plant: Biodiesel production and nano-additive to investigate diesel engine performance-emission characteristics, *Energy,* 274, 127345(2023). https://doi.org/10.1016/j.energy.2023.127345

Arunraj, R. and Amala, J. S. M., An Experimental Study on Algae Biodiesel with Nano-additives for Engine Performance and Emission Reduction, *J. Environ. Nanotechnol.,* 13(3), 361–373 (2024). https://doi.org/10.13074/jent.2024.09.242678

Baradhsundar, V. S. and Srinivaas, A., Simulation Study on the Influence of the Traffic Conditions on Vehicle Performance and Emission, *J. Environ. Nanotechnol.*, 13(2), 88–97 (2024). https://doi.org/10.13074/jent.2024.06.241527

Cui, L., Chen, J., Xu, B., Chen, Y., Pan, Y., Lin, H. and Sheng, H., Effects of purified Ginkgo biloba L. leaf extract on the oxidative stability and cold flow properties of biodiesel-diesel blends, *Ind. Crops Prod.*, 212, 118277(2024). https://doi.org/10.1016/j.indcrop.2024.118277

Devi, A., Das, V. K. and Deka, D. A., green approach for enhancing oxidation stability including long storage periods of biodiesel via Thuja oreantalis L. as an antioxidant additive, *Fuel,* 253, 1264–73(2019). https://doi.org/10.1016/j.fuel.2019.05.127

Doğan, B., Yeşilyurt, M. K., Yaman, H., Korkmaz, N. and Arslan, A., Green synthesis of SiO2 and TiO2 nanoparticles using safflower (Carthamus tinctorius L.) leaves and investigation of their usability as alternative fuel additives for diesel-safflower oil biodiesel blends, *Fuel,* 367, 131498(2024). https://doi.org/10.1016/j.fuel.2024.131498

Fernandes, F. D., Ferreira, L. M. and Silva, M. L. C. P., Application of Psidium guajava L. leaf extract as a green corrosion inhibitor in biodiesel: Biofilm formation and encrustation, *Appl. Surf. Sci. Adv*., 6, 100185(2021). https://doi.org/10.1016/j.apsadv.2021.100185

Fernandes, F. D., Ferreira, L. M. and Silva, M. L. C. P., Evaluation of the corrosion inhibitory effect of the eco-friendly additive of Terminalia Catappa leaf extract added to soybean oil biodiesel in contact with zinc and carbon steel 1020*, J. Clean Prod*., 321, 128863(2021). https://doi.org/10.1016/j.jclepro.2021.128863

França, F. R. M., Santos, F. D. L., Ramos, A. L. D., Silva, G. F. and Brandão, S. T., Storage and oxidation stability of commercial biodiesel using *Moringa oleifera* Lam as an antioxidant additive, *Fuel,* 203, 627–32(2017). https://doi.org/10.1016/j.fuel.2017.03.020

Gaur, A., Dwivedi, G., Baredar, P. and Jain, S., Influence of blending additives in biodiesel on physiochemical properties, engine performance, and emission characteristics, *Fuel*, 321, 124072(2022). https://doi.org/10.1016/j.fuel.2022.124072

Jain, S., Purohit, S., Kumar, D. and Goud, V. V., Passion fruit seed extract as an antioxidant additive for biodiesel; shelf life and consumption kinetics, *Fuel*, 289, 119906(2021). https://doi.org/10.1016/j.fuel.2020.119906

Jeyakumar, N., Narayanasamy, B., Balasubramanian, D. and Viswanathan, K., Characterization and effect of *Moringa oleifera* Lam. antioxidant additive on the storage stability of Jatropha biodiesel, *Fuel*, 281,118614(2020). https://doi.org/10.1016/j.fuel.2020.118614

Karunanithi, G. and Varadappan, A. M. S., Exploring the effectiveness of novel Coffea Arabica leaf pigment as a natural antioxidant additive for date seed biodiesel, *Fuel*, 324, 124561 (2022). https://doi.org/10.1016/j.fuel.2022.124561

Lau, C. H., Gan, S., Lau, H. L. N., Lee, L. Y., Thangalazhy, G. S. and Ng, H. K., Insights into the effectiveness of synthetic and natural additives in improving biodiesel oxidation stability, *Sustainable Energy Technol. Assess.,* 52, 102296 (2022). https://doi.org/10.1016/j.seta.2022.102296

Lim, H. Y., Tang, S. H., Chai, Y. H., Yusup, S., Lim, M. T., Co-pyrolysis of plastics and food waste mixture under flue gas condition for bio-oil production, *Sustainable Energy Technol. Assess.,* 54, 102826 (2022). https://doi.org/10.1016/J.SETA.2022.102826

Maárof, M. I. N., Chala, G. T., Gunness, D. and Saad, I., A study on the performance analysis of bioethanol produced from sugarcane molasses in SI engine, *IOP Conf. Ser. Mater. Sci. Eng.,* 863, 012064(2020). https://doi.org/10.1088/1757-899X/863/1/012064

Manimaran, R., Mohanraj, T. and Ashwin, R., Green synthesized nano-additive dosed biodiesel-diesel-water emulsion blends for CI engine application: Performance, combustion, emission, and exergy analysis, *J. Clean Prod.*, 413, 137497(2023). https://doi.org/10.1016/j.jclepro.2023.137497

Nambiraj, M. and Suresh, K. K., Exploring the role of natural antioxidant additives extracted from agro wastes in prolonging biodiesel's storage stability, *Ind. Crops Prod.*, 212, 118321(2024). https://doi.org/10.1016/j.indcrop.2024.118321

Rial, R. C., Merlo, T. C., Michalski, S. P. H., Dias, M. L. F., Barbosa, R. A., Freitas, O. N., Carlos, E. D. N. and Viana, L. H., Evaluation of oxidative stability of soybean methyl biodiesel using extract of cagaite leaves (Eugenia dysenterica DC.) as additive, *Renew. Energy*, 152, 1079–85(2020). https://doi.org/10.1016/j.renene.2020.01.121

Sannagoudar, B. A., Maleki, B., Prakash, R. M., Mounesh, K. P., Kalanakoppal, V. Y., Exploitation of Annona reticulata leaf extract for the synthesis of CeO2 nanoparticles as catalyst for the production of biodiesel using seed oil thereof, *Energy*, 298, 131335(2024). https://doi.org/10.1016/j.energy.2024.131335

Shelare, S. D., Belkhode, P. N., Nikam, K. C., Jathar, L. D., Shahapurkar, K., Soudagar, M. E. M., Veza, I., Khan, T. M. Y., Kalam, M. A., Nizami, A. S. and Rehan, M., Biofuels for a sustainable future: Examining the role of nano-additives, economics, policy, internet of things, artificial intelligence and machine learning technology in biodiesel production, *Energy*, 282, 128874(2023). https://doi.org/10.1016/j.energy.2023.128874

Viswanathan, K., Ashok, B. and Pugazhendhi, A., Comprehensive study of engine characteristics of novel biodiesel from curry leaf (Murraya koenigii) oil in ceramic layered diesel engine, *Fuel*, 280,118586(2020). https://doi.org/10.1016/j.fuel.2020.118586

Zeleke, D. S. and Bezabih, A. A., Impact of additives from moringa stenopetela leaf extract and ethanol on the emission characteristics and performance of soybean biodiesel for single cylinder CI engine, Heliyon 10(6), e27619(2024). https://doi.org/10.1016/j.heliyon.2024.e27619