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RESEARCH ARTICLE

An experimental study on the influence of antioxidant additive on emission traits of CI engine utilizing flamboyant biodiesel blends

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Abstract
Fossil fuels are regarded as a primary source for energy and human transportation. The formation of fossil fuels involves millions of years; furthermore, it produces harmful emissions during their combustion. Biodiesels are regarded as a potential substitute for fossil fuels, as they are sustainable. In contrast to several benefits, the feedstock availability and physicochemical properties are regarded as drawbacks of biofuels. In the present work, flamboyant biodiesel blends recovered from similar seeds through transesterification are utilized on a 5.2-kW CI engine to access the emission traits. The result outcomes revealed that the seed has an oil content of 30%. The transesterification process carried out at 60 °C and 200 rpm with a 1:6 oil-methanol ratio resulted in a better yield of 82%. At peak load, the B25 blend outperformed with better BSFC and BTHE of 0.27 kg/kWh and 30.96%. At a similar load, the EGT and SD of the similar blend were found to be 323 °C and 51 HSU, while the emissions of CO, HC, and NO_X were found to be 0.09 (% by volume), 57 ppm, and 1058 ppm respectively. In the later phase of the investigation, PPDA antioxidant was introduced in varied concentrations to decline NO_X emissions; the outcomes revealed that the 0.20 g PPDA outperformed in declining NO_X emission. Clinical trial number: not applicable.

Keywords Fossil fuel · Harmful emission · Biodiesel · Transesterification · Emission traits · Antioxidant

Nomenclature

CI	Compression ignition
DI	Direct injection
NaOH	Sodium hydroxide
KOH	Potassium hydroxide
rpm	Revolution per minute
FFA	Free fatty acid
CO	Carbon monoxide
HC	Hydrocarbon
NO_X	Nitrous oxide

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Introduction

In order to resolve the fossil fuel conflict, significant numbers of researchers have been searching for alternative fuels. Developed economies began to focus on renewable energy sources, such as solar, geothermal, wind, biofuel, and ocean energy (Palani et al. 2022). Several research studies into sustainable and alternative energy sources have been promoted by the growing concern over the depletion of fossil fuels and environmental degradation (Azad et al. 2012; Ajith et al. 2020; and Bao Quoc Doan et al. 2022). In recent years, fossil fuels play a vital role in transportation and energy sectors; however, the significant drawbacks of fossil fuels are their harmful emissions (Huang et al. 2012) and their formation includes millions of years (Venkatesan et al. 2023). Biodiesel is one of the most potential substitutes for fossil fuels since it is made from renewable resources including algae, vegetable oils, and animal fats (Patel Kamini and Nayak Milap 2017). There seems to be a great deal of potential for biodiesel as a diesel engine fuel substitute (Ma et al.

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2021). A possible option for the potential future is biodiesel, which is made from algae, vegetable oils, and animal fats (Verma and Sharma 2015). The flamboyant tree also called *Delonix regia* has significant non-edible oil content and has been discovered as a possible feedstock for the generation of biodiesel (Islam et al. 2016). The efficiency of biodiesel production, particularly the transesterification yield, and the pollutants it produces when combined with regular fuel must be assessed before it is often employed. Transesterification is the conventional process for turning vegetable oil into biodiesel (Nayak and Vyas 2019). It involves a chemical reaction between the oil and an alcohol. When assessing the feasibility and commercial viability of producing biodiesel, the yield of transesterification and emission characteristics are essential for evaluating the environmental benefits of employing *Delonix regia* biodiesel in practical applications. This study attempts to investigate both the emission characteristics of its *Delonix regia* biodiesel blends with conventional diesel as well as the transesterification outcome of *Delonix regia* oil. By the optimization of transesterification parameters and the assessment of emissions, the present research intends to provide significant insights into the potential of *Delonix regia* as a sustainable biodiesel feedstock, lowering dependency on fossil fuels and promoting cleaner energy alternatives.

Identification of feedstock

In recent years, there has been a growing interest in exploring non-traditional and waste-derived feedstocks for biodiesel production. This shift is driven by the limitations of first-generation biodiesel feedstocks, which primarily utilize edible oils, thereby competing with food resources. In contrast, second-generation feedstocks, which are largely composed of non-edible biomass, offer a more sustainable and food-secure alternative. In this context, the present study investigates the potential of the flamboyant tree (*Delonix regia*) seeds as a source for biodiesel production. These trees are typically found in marginal lands and thrive in environments with minimal water and maintenance. The flamboyant tree is widely recognized for its vibrant red flowers and elongated seed pods. Each pod contains about 10 to 15 small seeds, which can be easily extracted by hammering. Recent research has begun to explore their potential value in renewable energy production, particularly biodiesel. By repurposing the seeds of the flamboyant tree, this study aims not only to produce biodiesel but also to contribute to sustainable waste management practices. Utilizing such neglected biomass helps mitigate the environmental burden of agro-waste while also promoting energy diversification. Figure 1 illustrates the photograph of the flamboyant seeds employed in this investigation.

Fig. 1 Photograph of flamboyant seeds

Process of oil extraction

The seeds used in this study were sourced from waste lands. This makes the feedstock a potential source, as it does not require any cultivation expenses and land acquisition, thus significantly reducing the overall cost of biodiesel production. The economic viability of utilizing such naturally available, non-edible seeds is one of the key advantages of second-generation biofuel sources. Upon collection, the seeds are likely to contain surface contaminants such as dust and soil particles. To ensure purity and prevent contamination during oil extraction, the seeds are thoroughly cleaned using clear water. The washing process is continued until the water appears clear (Gowthaman and Sathiyagnanam 2017). After washing, the seeds undergo a drying phase, but rather than being exposed to direct sunlight which may degrade sensitive oil compounds, they are shade-dried for 3 consecutive days. This method helps in retaining the quality and integrity of the oil within the seeds. Once properly dried, the seeds are stored in containers to avoid moisture absorption. The oil extraction is carried out using a conventional mechanical oil expeller, commonly available in local markets (Dinesh Kumar et al. 2022). The seeds are found to contain 30% of non-edible oil (Dinesh Kumar et al. 2022). The extracted oil typically exhibits a brownish to pale yellow color with an unpleasant odor (Algharib et al. 2021). The physicochemical properties of a biofuel are fundamental in determining its suitability for specific applications, especially in the context of fuel utilization.

Physicochemical properties of neat oil

A physicochemical analysis of the oil reveals that it possesses high viscosity and density properties that pose challenges for direct use in compression ignition (CI) engines. Therefore, further processing is necessary to meet engine

Table 1 Physicochemical properties of neat oil

Property	Unit	Value	ASTM standard
Density	kg/m^3	935	ASTMD1298
Kinematic viscosity (40 °C)	mm^2/s	38	ASTMD445
Saponification value	mg KOH/g	199	ASTMD5558
Flash point	°C	162	ASTMD92
Fire point	°C	171	ASTMD92
Calorific value	kJ/kg	32,000	ASTMD240
Specific gravity	-	0.93	ASTMD1298
Cetane number	-	43	ASTMD613

compatibility standards. These properties such as density, viscosity, flash point, calorific value, and acid value not only influence the performance of fuel but also have an impact on emissions. The current study outlines the key physicochemical properties of the neat oil extracted from the selected non-edible seed feedstock. Table 1 presents the physicochemical properties of the extracted neat oil.

The tabulated physicochemical analysis clearly indicates that the neat oil extracted from the selected non-edible seed feedstock exhibits relatively high viscosity and density when compared to conventional fuel. High viscosity can hinder proper atomization and fuel injection, while excessive density results in potential damage to engine components. To address these drawbacks and enhance the suitability of the oil for fuel applications, chemical processing is required. An important consideration in selecting the appropriate processing method is the free fatty acid (FFA) content of the oil. The FFA level of the recovered neat oil was found to be 1.6% and therefore base catalyzed transesterification is enough to streamline the biodiesel synthesis; moreover, no pretreatment is required (Awan Ahmed Bilal 2016; Suresh et al. 2018). Among the various chemical treatment methods available, transesterification has emerged as an economically viable approach. This process involves the reaction of triglycerides with an alcohol usually methanol in the presence of a catalyst, resulting in the formation of fatty acid methyl esters (FAME), commonly referred to as biodiesel, and glycerol as a by-product. Although the overall methyl ester yield from transesterification might be lower compared to other approaches, the purity of the biodiesel produced is generally high, making it suitable for engine use with minimal further refinement.

Transesterification and its impact on physicochemical properties

The fundamental chemical transformation involved in transesterification converts the triglycerides present in the oil into methyl esters (biodiesel) and glycerol as a by-product (Raju et al. 2023). Numerous studies have demonstrated that transesterification is a highly effective chemical method for enhancing the fuel characteristics of plant-based oils (Ogunkunle and Ahmed 2019). By lowering these values, the flow characteristics and spray behavior of the fuel are improved, ensuring better atomization and combustion during engine operation. In addition to improving physical properties, transesterification also contributes to enhancing the cetane number of the resulting biodiesel. The cetane number is an important indicator of fuel quality; the higher the cetane number, the more efficient and complete the combustion process. Biodiesel produced through transesterification tends to exhibit a higher cetane number compared to its unprocessed oil counterpart, leading to smoother engine operation, reduced noise, and lower emissions. The transesterification reaction was carried out using a simple batch reactor setup. This apparatus consists of a reaction vessel equipped with a magnetic stirrer, a heating unit, and a thermometer to monitor and control the reaction temperature (Zheng et al. 2022). The magnetic stirrer ensures consistent mixing of the reactants, promoting uniform contact between the oil, alcohol, and the catalyst. Simultaneously, the heating unit maintains the optimal temperature required which is 55 to 60 °C. Figure 2 depicts the photograph of the batch reactor employed in the present work.

In the current study, methanol is used as the alcohol component and sodium hydroxide (NaOH) in powdered form is selected as the catalyst to facilitate and accelerate the transesterification reaction. Methanol is widely favored in biodiesel synthesis due to its low cost, high reactivity, and strong polarity, which enhances its ability to break down triglyceride molecules. The reaction temperature is carefully maintained at 60 °C, which corresponds closely to the boiling point of methanol, ensuring optimal reaction kinetics without excessive methanol vaporization. NaOH is preferred

Fig. 2 Photograph of reactor

over KOH, as NaOH exhibits better solubility in methanol, forming a more stable and reactive methoxide solution. Additionally, NaOH is generally required in smaller quantities than KOH to achieve the same catalytic effect. Incorporating alcohol into the reaction mixture not only aids in ester formation but also reduces the high viscosity of the resulting biodiesel, which is essential for improving its fuel injection and atomization behavior in diesel engines (Surakasi et al. 2023). The transesterification process is conducted for 2 h, with continuous stirring of the flamboyant seed oil at 200 revolutions per minute (rpm) (Dinesh Kumar et al. 2024). The consistent agitation ensures uniform heat distribution and thorough mixing of the reactants. Upon completion of the reaction, the mixture is transferred into a graduated separating flask equipped with a tap valve at the bottom. This setup is left undisturbed for 12 h to allow the two immiscible products biodiesel (methyl esters) and glycerol to separate naturally based on their differences in density. The biodiesel, being less dense, forms the upper layer, while the glycerol, which is heavier, settles at the bottom. The glycerol by-product is removed through gravity separation, using the bottom valve of the flask.

Fuel preparation

In the current study, to evaluate the emission characteristics of biodiesel a series of test fuels were prepared. These fuel samples are essential for assessing pollutant emissions, such as carbon monoxide (CO), nitrogen oxides (NO_X), and unburned hydrocarbons (HC). The prepared test fuels include the following five categories: Conventional diesel fuel (used as a baseline reference), B25 (a blend consisting of 25% biodiesel and 75% conventional diesel), B50 (a 50:50 blend of biodiesel and diesel), B75 (a blend containing 75% biodiesel and 25% diesel), and B100 (neat biodiesel, containing no petroleum-based diesel). These blends were created using a direct blending method. Figure 3 presents a schematic representation of the biodiesel preparation process.

Test engine setup

Diesel engines are widely used in the transportation and industrial sectors due to their high thermal efficiency and better fuel economy compared to spark ignition (SI) engines. Their ability to operate under higher compression ratios allows for more complete combustion, resulting in improved energy output per unit of fuel (Tamilselvan et al. 2017). In this study, the emission characteristics of various methyl ester-diesel blends derived from flamboyant seed oil were evaluated using a single-cylinder, four-stroke, direct-injection (DI) CI engine. The engine was operated at a constant speed of 1500 rpm throughout the testing period to ensure consistency in performance and emission measurements. The test engine is water-cooled, by circulating coolant around the engine block. To measure the response of the engine under varying operating conditions, an electrical dynamometer is integrated into the setup. The load on the engine is gradually increased in 20% increments, starting from zero load up to full load. To monitor and quantify the environmental impact of the test engine, the setup includes an exhaust gas analyzer, used to measure the concentrations of various tailpipe emissions such as CO, unburned HC, and NO_X and a smoke meter, employed to determine the

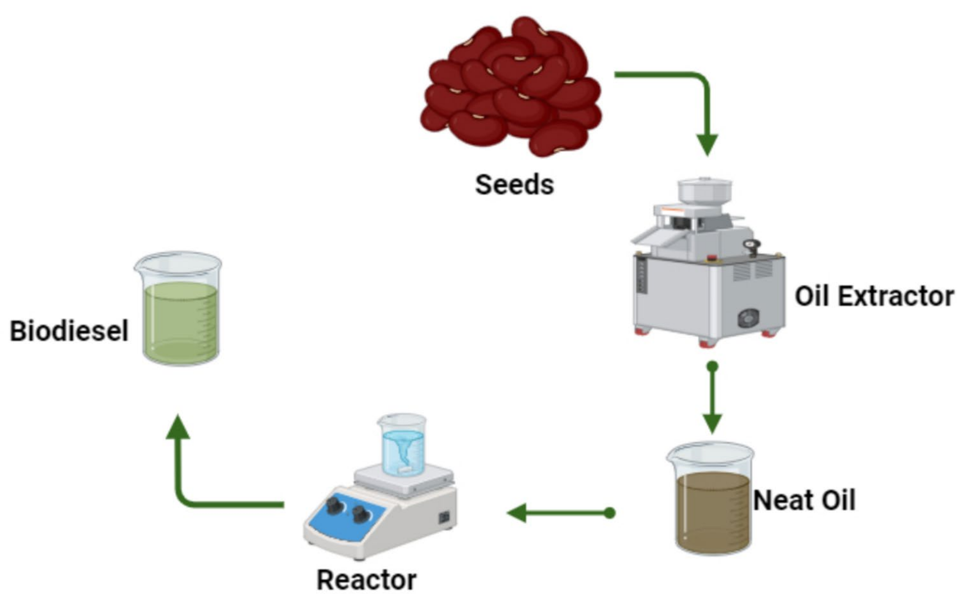

Fig. 3 Schematic representation of biodiesel preparation

Fig. 4 Photograph of test engine

smoke density of the exhaust gases. The photograph of the test engine setup is depicted in Fig. 4.

The test engine utilized in this experimental study is a single-cylinder, four-stroke CI engine, characterized by a bore diameter of 87.5 mm and a stroke length of 110 mm. The engine was operated under controlled conditions with a compression ratio of 17.5:1, a fuel injection pressure of 210 bar, and an injection timing set at 24° before top dead center. Maintaining consistent engine settings throughout the experiment ensures the reliability and repeatability of the emission measurements across different fuel types. The engine was subjected to various load conditions, and at each load, emission characteristics were accessed for both conventional fuel and biodiesel blends (Harish Venu et al. 2025). The emission values recorded using conventional diesel are treated as baseline reference values.

Result and discussion

The performance, emission, and combustion traits of both conventional diesel fuel and the prepared biodiesel blends are assessed and discussed in the subsequent section. This comparative analysis aims to assess the traits under controlled engine operating conditions. In the initial phase of the experimental investigation, the engine is operated using regular diesel fuel, serving as a baseline reference for performance, emission, and combustion features. In the subsequent phase, the same test engine is fueled with prepared biodiesel blends specifically, B25, B50, B75, and B100. The use of incremental blend ratios enables a comprehensive evaluation of the impact of biodiesel content on performance, emission, and combustion characteristics.

Brake-specific fuel consumption

Brake-specific fuel consumption (BSFC), an indicator of the volume of fuel used per unit of power output per hour, is a crucial metric for assessing fuel efficiency (Nair et al. 2025a, b). Better engine efficiency and economy are represented by a lower BSFC value, which shows a more effective conversion of the chemical energy in the fuel into meaningful mechanical energy. Significant insight into the fuel's energy content can be gained from the variance in BSFC across various fuel blends along with operational situations. The relationship between BSFC and BP is seen in Fig. 5.

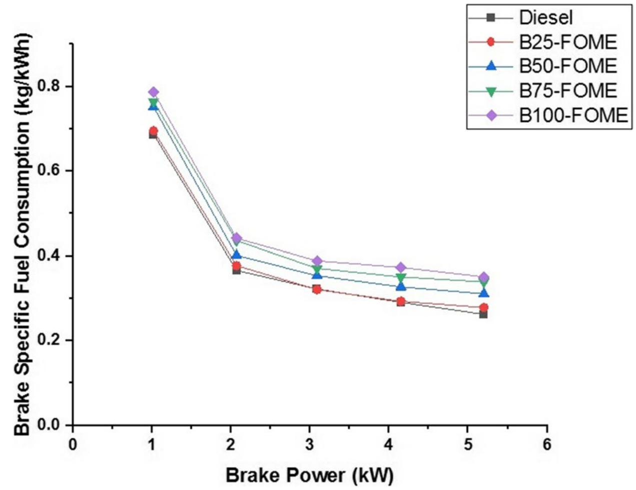

Fig. 5 Correlation among BSFC and BP

As anticipated, as brake power increased, the BSFC for all investigated fuels declined. This is a common tendency as engines perform better at greater loads. Nonetheless, a distinct stratification between the various fuel blends was noted. At maximum load, neat diesel persistently reported the lowest BSFC values of 0.263 kg/kWh. All FOME blends, in contrast, showed more BSFC. With values varying from 0.786 to 0.35 kg/kWh, the B100 blend exhibited the highest consumption, showing an increase in fuel consumption over standard fuel of about 14.6% at minimal load and up to 33.6% when operating at load. B25 demonstrated notable BSFC values among all biodiesel blends, which were comparable to those of conventional fuel. In this case, under maximum load, the BSFC of conventional fuel and the blend B25 was found to be 0.263 kg/kWh, and 0.278 kg/kWh, an insubstantial 5.3% increase. Furthermore, B25 consistently and significantly outperforms the other three combinations of biodiesel (B50, B75, and B100) in terms of BSFC values. Compared to the increases seen for other blends, this marginal difference is considerably less.

Brake thermal efficiency

An engine's capacity to transform the chemical energy contained in fuel into useful mechanical energy is measured by its brake thermal efficiency, or BTHE (Nair et al. 2025a, b). It provides a clear measure of the engine's general

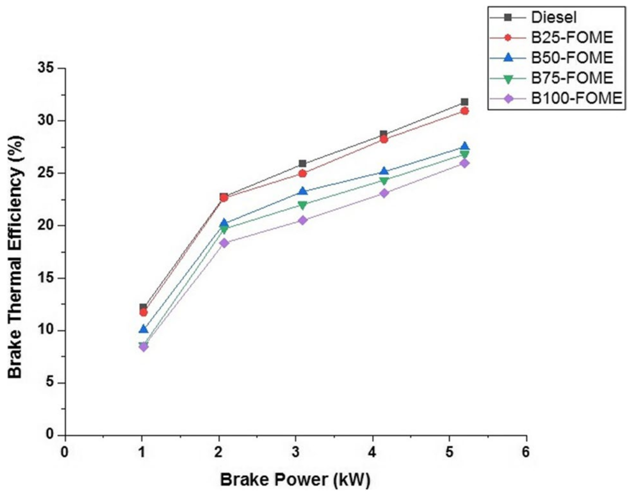

Fig. 6 Correlation among BTHE and BP

performance and efficiency in utilizing fuel. Since a greater BTHE indicates less energy dissipated to exhaust, cooling systems, and friction, it is always preferred. The impact of fuel qualities on the primary combustion mechanism and energy conversion is revealed by the evaluation of BTHE under various fuel blends. The relationship between BTHE and BP is seen in Fig. 6.

For all fuels, the BTHE results show a steady rise with BP. At the maximum load, the conventional fuel had the greatest BTHE values, reaching a maximum value of 31.77%. The B100 blend, on the other hand, revealed the lowest efficiency throughout the load spectrum, with a maximum BTHE that is only 25.96% at a similar load. Higher viscosity that can result in poorer atomization and slower combustion rates and lower calorific value, which necessitates an increased amount of fuel to be infused to preserve the same power output, are the main causes of the decrease in BTHE in higher biodiesel blends. Featuring BTHE values that were considerably similar to standard fuel than any other blend, the B25 blend appeared to be the most effective biodiesel mixture. B25 produced 30.96% BTHE at an elevated load, in contrast to 31.77% of conventional fuel. Because the 75% diesel base preserves sufficient energy density and optimal spray properties, the 25% biodiesel portion offers advantages like intrinsic oxygen content that encourages more complete combustion. The B25 blend is the most practical and effective biodiesel blend for use in unmodified diesel engines because of this synergy, which enables it to reach a better BTHE that is equal to that found in conventional fuel.

Exhaust gas temperature

Exhaust gas temperature (EGT) is a critical parameter in engine performance analysis as it serves as an indicator of combustion efficiency. It provides valuable information regarding the rate at which the fuel is being burned and how efficiently the chemical energy of the fuel is being converted into thermal and mechanical energy. Typically, when combustion is complete and efficient, the amount of heat released to the exhaust gases is minimized, resulting in a lower EGT. Biodiesel, unlike conventional diesel fuel, inherently contains around 10% oxygen. This oxygen-rich structure plays a crucial role in enhancing combustion efficiency by supplying additional oxygen to the combustion chamber. As a result, the presence of these oxygen molecules helps promote more complete oxidation of fuel particles, especially under high load conditions, which may contribute to a reduction in EGT when compared to conventional diesel under similar operating parameters. Typically, as brake power increases with engine load, EGT also rises due to the increased fuel injection and combustion. However, the rate of this increase can vary depending on the type of fuel used and its combustion characteristics. Figure 7 depicts the correlation between EGT and brake power.

The graphical analysis reveals that conventional diesel fuel consistently exhibits higher EGT compared to the biodiesel blends tested. This is primarily attributed to the absence of inherent oxygen content in fossil diesel, which limits the combustion efficiency. Due to this intrinsic oxygen presence, biodiesel blends promote superior combustion characteristics, resulting in a reduction in EGT as compared to pure diesel. As the proportion of biodiesel in the blend increases, the EGT progressively decreases. This is indicative of enhanced combustion quality. Among the tested blends, higher biodiesel concentrations, such as B75 and B100, demonstrate notably lower EGT values than lower blends such as B25. At maximum load, the EGT for

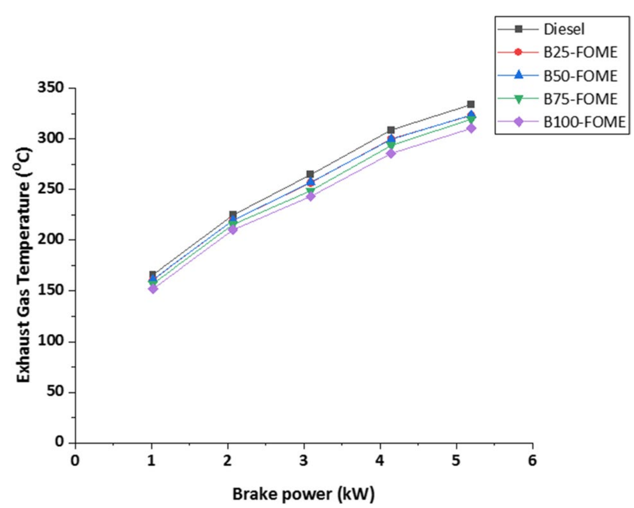

Fig. 7 Correlation among EGT and BP

conventional fuel, B25, B50, B75, and B100 is 334 °C, 323 °C, 324 °C, 319 °C, and 310 °C.

Smoke density

Smoke formation during fuel combustion is generally regarded as an undesirable by-product, as it signifies incomplete combustion and contributes to environmental pollution. The quality of the fuel, including its chemical composition and physical properties, along with the combustion rate, is the primary factor influencing the extent of smoke produced in the exhaust gases. Fuels that do not burn efficiently tend to generate higher levels of particulate matter and visible smoke, negatively affecting air quality and engine performance. High smoke density typically correlates with poor fuel atomization, delayed ignition, or insufficient oxygen availability during combustion. Biodiesel, due to its oxygen-rich molecular structure, enhances the combustion process, as a result produces significantly lower smoke density compared to conventional fuel. The relationship between smoke density and brake power (BP) is crucial for understanding how engine load affects particulate emissions. Typically, as brake power increases with load, smoke density also rises due to the greater quantity of fuel injected and combusted. However, the use of biodiesel blends often mitigates this increase in smoke density because of their better combustion characteristics. The correlation between BP and SD is depicted in Fig. 8.

It is observed from the graph that all biodiesel blends consistently produced lower smoke density (SD) values compared to conventional fuel. This reduction in smoke formation can be largely attributed to the intrinsic oxygen content in biodiesel molecules, which enhances the combustion process by supplying additional oxygen within the combustion chamber. This oxygen enrichment promotes more complete oxidation of fuel particles, thereby significantly reducing the smoke emissions. In contrast, the higher smoke density observed with conventional diesel fuel is indicative of relatively poorer combustion quality. In comparison, the biodiesel blends, namely B25, B50, B75, and B100 exhibited significantly lower smoke densities. At maximum load, the SD for conventional fuel, B25, B50, B75, and B100 is 52 HSU, 51 HSU, 50 HSU, 46 HSU, and 44 HSU. The consistent decline in smoke density with increasing biodiesel proportion suggests potential benefits in lowering emissions of harmful pollutants, and improving overall air quality.

Emission of CO

CO is a toxic and harmful gas emitted during the combustion of fossil fuels, primarily as a result of incomplete combustion processes. When the fuel does not burn fully due to insufficient oxygen or improper mixing, CO is produced instead of carbon dioxide (CO_2), posing serious health risks and contributing to environmental pollution. Biodiesel fuels, by contrast, naturally contain approximately 10–12% oxygen. This intrinsic oxygen content plays a crucial role in facilitating more complete oxidation of the fuel molecules (Duran et al. 2018). The presence of these oxygen atoms helps to ensure that more carbon in the fuel is converted fully to CO_2 rather than to CO. The variations in CO emissions with BP are illustrated in Fig. 9.

From the outcomes, it is observed that the use of biodiesel blends leads to a reduction in CO emissions compared to conventional fuel. At maximum load, conventional fuel resulted in CO emissions which are 0.1% by volume, whereas the blend B25 resulted in a reduced CO emission of 0.09% by volume. Furthermore, blends with higher biodiesel content, such as B50, B75, and B100, exhibit progressively

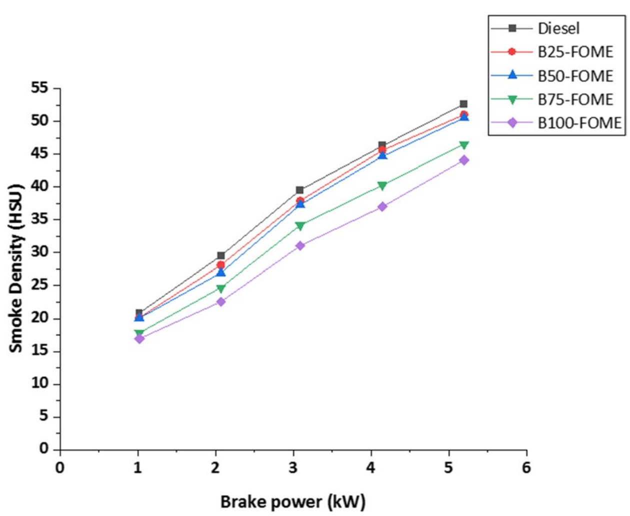

Fig. 8 Correlation among SD and BP

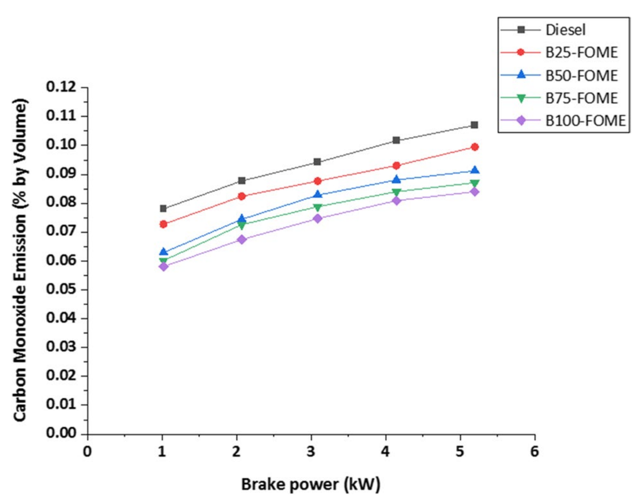

Fig. 9 Correlation among CO emission and BP

lower CO emissions compared to those with lower biodiesel proportions. This indicates that increasing the biodiesel fraction enhances the combustion process, leading to more complete oxidation of carbonaceous compounds in the fuel. On the other hand, conventional fuel relies on ambient air for oxidation. When the oxygen supply is not optimal, incomplete combustion occurs, resulting in higher CO emissions. At maximum load, the emission of CO for conventional fuel, B25, B50, B75, and B100 is 0.1, 0.099, 0.091, 0.087, and 0.084 (% by volume). The gradual reduction in CO with increasing biodiesel concentration supports the potential for higher biodiesel blends to be adopted as cleaner alternatives in compression ignition engines.

Emission of HC

Hydrocarbons are primarily formed due to incomplete combustion, where portions of the fuel do not fully oxidize within the combustion chamber. These unburnt or partially burnt fuel fragments remain in the exhaust as hydrocarbons (Dinesh Kumar et al. 2024). Factors such as inadequate mixing of air and fuel, and insufficient combustion temperature can all contribute to elevated HC emissions. Compared to conventional fuel, numerous studies have indicated that the use of various biodiesel significantly lowers emissions of hydrocarbons, CO, and smoke (Zhang et al. 2022). The correlation among BP and HC emissions is depicted in Fig. 10.

The data presented in the graph clearly indicates that biodiesel blends consistently achieve lower HC emissions compared to conventional fuel. This improvement can be primarily attributed to the oxygen content inherent in biodiesel molecules, which plays a crucial role in optimizing the air-to-fuel stoichiometric ratio during combustion. At maximum load, the HC emission of conventional fuel is 62 ppm. In contrast, the B25 blend shows a modestly lower HC emission of 60 ppm. Furthermore, blends with higher biodiesel proportions such as B75 and B100 significantly lowered HC emissions compared to blends with lower biodiesel content (B25 and B50). This indicates that increasing the percentage of biodiesel in the fuel blend enhances combustion efficiency and further suppresses the formation of unburnt hydrocarbons. The HC emission at maximum load for conventional fuel is found to be 62 ppm, while for B25, B50, B75, and B100 it is 60 ppm, 57 ppm, 53 ppm, and 49 ppm.

Emission of NO_X

Nitrogen oxides (collectively referred to as NO_X) are among the most harmful pollutants generated as a by-product of fuel combustion, particularly in internal combustion engines. These gases primarily include nitric oxide (NO) and nitrogen dioxide (NO_2), both of which contribute significantly to the environment. The NO_X emission resulted from biodiesel blends at peak load is depicted in Fig. 11.

From the graph, it is observed that conventional fuel produces significantly lowered NO_X emissions compared to biodiesel blends. This is primarily attributed to the higher intrinsic oxygen content in biodiesel molecules, which plays a key role in promoting the formation of nitrogen oxides during combustion. At maximum load, the NO_X emission for conventional fuel is 989 ppm, while the emissions for biodiesel blends increased progressively with higher biodiesel content: 1058 ppm for B25, 1074 ppm for B50, 1093 ppm for B75, and reaching 1141 ppm for B100. This is typically due to the chemical composition of biodiesel, which contains 10–12% oxygen. During combustion, this additional oxygen promotes more complete combustion, which reduces the emission of CO and unburned HC. However, it also accelerates

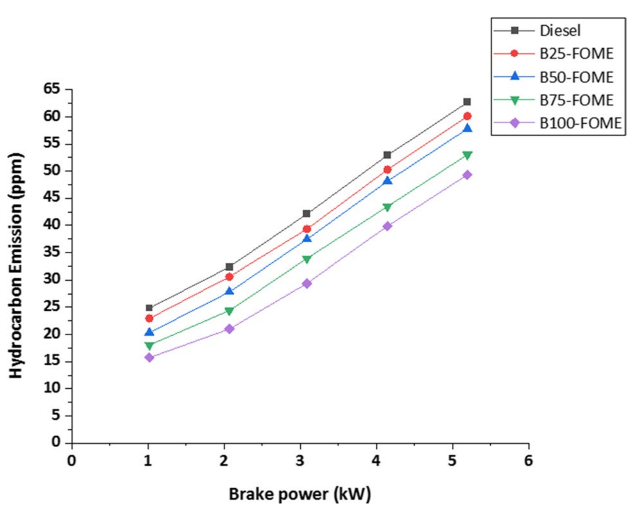

Fig. 10 Correlation among HC emission and BP

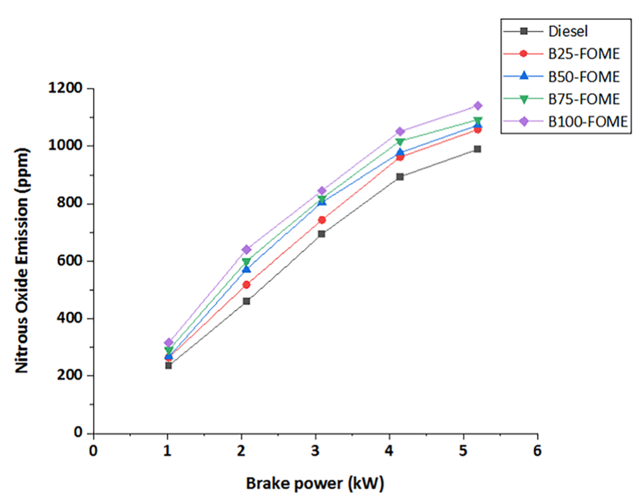

Fig. 11 Correlation among NO_X emission and BP

the formation of NO_X. In contrast, conventional diesel lacks significant oxygen content, relying solely on the atmospheric oxygen for combustion. As a result, the peak combustion temperature is relatively lower, leading to a reduction in NO_X generation. Therefore, optimizing biodiesel blends possibly in conjunction with NO_X mitigation strategies such as exhaust gas recirculation (EGR), selective catalytic reduction (SCR), or antioxidant additives is crucial for maintaining a balance between performance and emissions in CI engines.

Combustion characteristics

Cylinder pressure analysis

An essential indicator of the work output and load encountered during a combustion cycle is cylinder pressure. When assessing engine durability and combustion efficiency, the maximum value and the crank angle at which it originates are significant. Fuel characteristics, which may influence ignition delay and the subsequent pressure rise, have a significant impact on this pressure trace for biodiesel. The relationship between crank angle and cylinder pressure is depicted in Fig. 12.

Due to their reduced energy content, the higher biodiesel blends showed a pressure drop, whereas the lower blends showed no variation. B25 consistently developed a peak pressure value that was the same as conventional fuel. It is found that the peak pressure produced by B25 and conventional fuel is 71 bar and 75 bar, respectively. The result confirms that the B25 blend effectively utilizes the beneficial oxygen content of biodiesel without encountering the calorific deficit that exists in higher-percentage blends, sustaining the potent combustion characteristics and efficient energy release of diesel fuel. The B25 offers an optimal combination for maintaining engine performance while making extensive use of renewable fuel.

Heat release rate analysis

The heat release rate curve provides insight into the mechanics of fuel energy conversion and combustion phases. The relationship between crank angle and heat release rate is depicted in Fig. 13.

The B25 blend, which resembles the combustion properties of conventional fuel, was shown to be the more effective biodiesel blend when comparing the heat release rate. It was found that the heat release rates of the B25 blend and regular fuel were 38.7 kJ/m^{3}deg and 41.8 kJ/m^{3}deg, respectively. With a maximum heat release rate that appeared identical to regular fuel, the B25 blend presented a well-balanced profile.

Influence of para-phenylendiamine (PPDA) on NO_X emission

The essential properties of biodiesel blends, particularly their engine performance and oxidation stability, can be significantly improved through the incorporation of antioxidants in appropriate proportions (Alimin and Babalola 2023). Oxidation stability is a critical factor in biodiesel utilization; biodiesel is more prone to oxidative degradation compared to conventional fuel due to the presence of unsaturated fatty acid methyl esters. Without adequate stability, biodiesel can form deposits, and increase viscosity. Antioxidants scavenge free radicals, thereby preventing the oxidative degradation of biodiesel during storage and combustion (Prabu and Anand 2014). In the current research, PPDA, a synthetic antioxidant, was incorporated into the biodiesel blends in varying concentrations: 0.10 g, 0.20 g, 0.30 g, 0.40 g, and 0.50 g using an ultrasonicator to ensure uniform dispersion. The proportion of antioxidant added plays a pivotal role not only in enhancing fuel stability but also in influencing the emission characteristics, especially NO_X. Figure 14 depicts

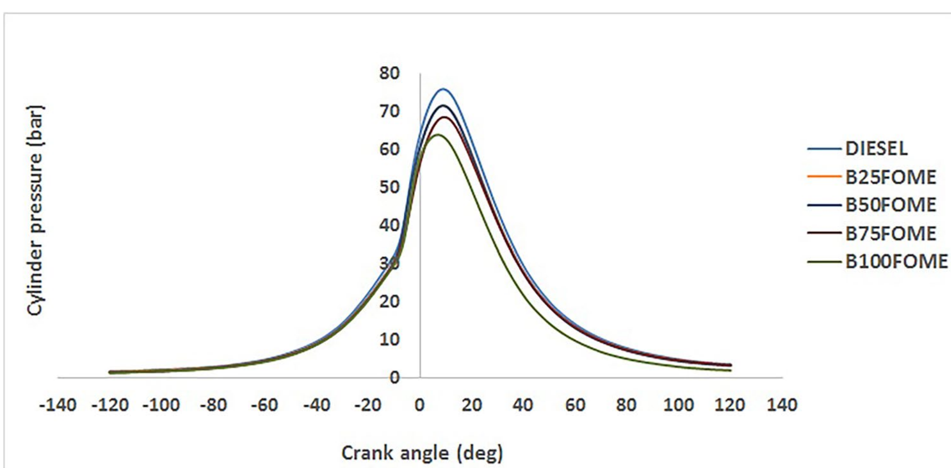

Fig. 12 Variation of cylinder pressure against crank angle

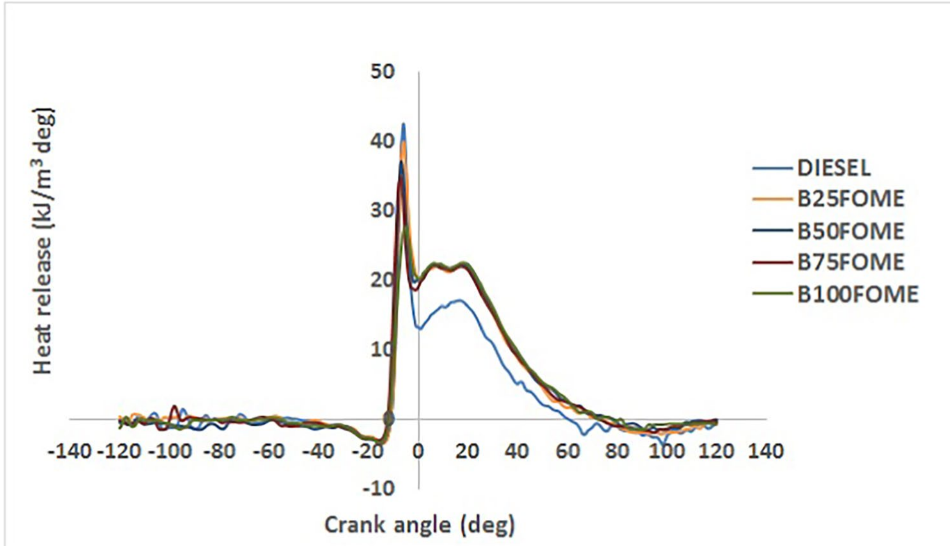

Fig. 13 Variation of heat release rate against crank angle

the emission of NO_X for biodiesel blends with varied PPDA concentrations at peak load.

The experimental results indicate that among the various concentrations of PPDA incorporated into the biodiesel blends, the 0.20-g dosage proved to be the most effective in reducing NO_X emissions. This optimal concentration achieved the greatest improvement in emission performance, particularly at peak engine load, where the NO_X emission from the B25 blend was recorded as 995 ppm a notable reduction of 5.97% compared to the baseline B25 blend without any antioxidant (1058 ppm). The NO_X emission for the blends B50, B75, and B100 with a 0.2-g dosage of PPDA is found to be 1009 ppm, 1028 ppm, and 1095 ppm respectively. Similar dosage declined the NO_X emission of B50, B75, and B100 by 6.05%, 6.1%, and 4% compared with identical blends without additive. This reduction in NO_X can be primarily attributed to the enhanced oxidation stability of the biodiesel blend resulting from the presence of PPDA. The addition of PPDA, a potent synthetic antioxidant, mitigates these oxidative processes by neutralizing free radicals and stabilizing the fuel structure, thereby promoting more controlled combustion. By stabilizing the combustion process, PPDA at 0.20 g helps suppress the formation of these emissions. However, it was also observed that increasing the PPDA concentration beyond 0.20 g (i.e., to 0.30 g, 0.40 g, and 0.50 g) did not further reduce NO_X emissions. In fact, a gradual increase in NO_X output was recorded with higher PPDA concentrations. This phenomenon may be due to over-inhibition of combustion at excessive antioxidant levels, which can lead to incomplete combustion, resulting in conditions that paradoxically elevate NO_X formation.

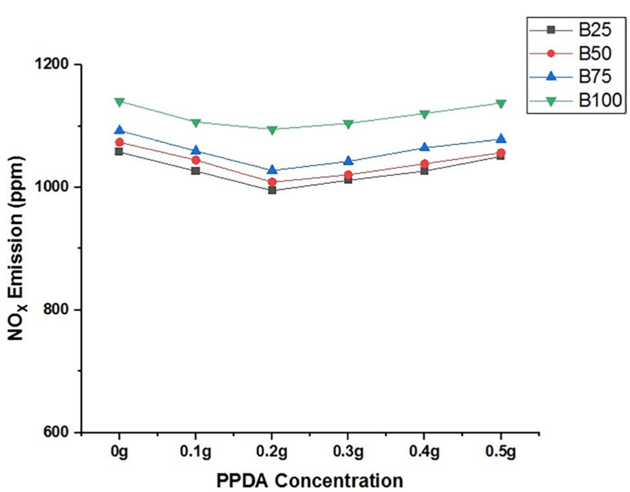

Fig. 14 NO_X emission at varied PPDA concentration

Uncertainty analysis

Physical measures are known to be inaccurate, and an exhaustive evaluation is necessary to confirm the experimental findings. This study assessed the uncertainty of both computed performance metrics and primary measurements. The root-sum-square (RSS) method was used to propagate the uncertainties of the important observed and derived variables in order to establish the overall experimental uncertainty. When the uncertainties were computed together, the result was a cumulative uncertainty of $\pm 2.03\%$.

Conclusion

The experimental outcomes reveal that the feedstock employed has a significant oil content of 30% and the process of transesterification resulted in a better yield of methyl ester ranging 82%. The B25 biodiesel blend outperformed in terms of performance when compared with other blends. At maximum load, the BSFC and BTHE of B25 was found to be 0.278 kg/kWh and 30.96%, which is identical to the BTHE of conventional fuel (31.77%) at similar load. At maximum load conditions, the EGT and SD for B25 was found to be 323 °C, and 51 HSU. Furthermore, at identical load, the emission of CO and HC for B25 was found to be 0.09 (% by volume) and 57 ppm respectively. In terms of emissions, B100 produced 0.084% CO by volume, which is lower than that typically observed for all the tested fuels, reflecting the improved oxidation capacity of biodiesel. At identical load, for B100, the emission of HC is found to be 49 ppm. However, a notable drawback was the elevated NO*x* level; when compared with the blends containing a higher biodiesel proportion, the blend B25 resulted in lower NO_X emission. At maximum load, the NO_X emission of conventional fuel and B25 is found to be 989 ppm and 1058 ppm. The incorporation of PPDA had a positive impact on reductions in NO*x* levels observed across all tested blends. Among the different concentrations examined, the dosage of 0.20 g PPDA proved to be the most effective, delivering the highest reduction in NO*x* without adversely affecting other emission or performance characteristics.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate This study did not involve human participants, and therefore, informed consent to participate was not required.

Consent for publication This study does not include any individual person's data in any form, and therefore, consent to publish is not applicable.

Competing interests The authors declare no competing interests.

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