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# Evaluation of performance, combustion and emission characteristics of blends of soybean biodiesel in a single cylinder diesel engine: An experimental approach

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**Abstract**

This experimental study evaluates the performance, combustion, and emission characteristics of soybean biodiesel blends (10–40% v/v) in a single-cylinder diesel engine. Soybean methyl ester (SME) was produced via single-stage alkaline transesterification due to low free fatty acid content (<2%). Tests were conducted on a variable compression ratio engine (17:1, 1500 rpm) at varying brake power loads. GC-MS analysis confirms a fatty acid methyl ester (FAME) profile dominated by methyl linoleate (48.42%) and methyl oleate (32.35%). Engine testing revealed that B30 optimized performance parameters, increasing brake thermal efficiency by 11.94% and reducing brake-specific fuel consumption by 5.41% relative to diesel. Emission analysis demonstrated that B20 achieved maximal reductions: $CO_2$ (3.5%), NO (19.2 %), HC (18.97 %), and $NO_x$ (18.93 %). Combustion characteristics showed marginal decreases in peak cylinder pressure (≤3.5%) and net heat release (≤6.18%) for most blends, attributable to SME's lower calorific value (33.54–41.66 MJ/kg vs. 42.5 MJ/kg for B0). The study establishes B20–B30 blends as optimal for balancing engine efficiency with emission mitigation, affirming soybean biodiesel's viability in conventional diesel engines without modification.

***Keywords:*** Soybean biodiesel; Methyl ester blends; Diesel engine performance; Combustion characteristics; Emission reduction.

## 1. Introduction

The rising demand for energy alongside concerns about environmental pollution have accelerated the exploration of sustainable alternatives in the transportation sector, which is the primary consumer of fossil fuels [1]. Biodiesel being one of the promising alternatives to fossil fuel derived from animal fats or vegetables oil, is recognized as a sustainable and biodegradable fuel with lower emissions. Extensive research has been conducted on various feedstocks, including edible oils, non-edible oil, waste oil and animal fats [2]. Edible oils like soybean, sunflower, coconut, palm, and others are the raw biodiesel material. They contribute to the reduction of carbon emissions [3].

Biodiesel offers several benefits over conventional diesel, including a higher cetane number, greater oxygen content, significantly lower emissions of $CO_2$, PM, CO, and unburnt hydrocarbons, and enhanced lubricity. Despite these advantages, a notable drawback is its tendency to increase the $NO_x$ emission. The production of the biodiesel has grown rapidly, with soybean being the major feedstock [4]. Vegetable oils cannot be used directly as fuel in diesel engines due to their high viscosity, low volatility, and high degree of unsaturation, which can lead to engine performance issues. Biodiesel, derived from vegetable oils or animal fats through transesterification, offers a promising solution as it possesses properties similar to conventional diesel and can be used in existing engines with little or no modification [5]. Blends of biodiesel with diesel fuel, 5% to 50%, which is derived from various feedstocks show that the higher the biodiesel concentration, the higher the viscosity and the lower the volatility. Moreover, viscosity is also influenced by temperature, the fatty acid chain length, and saturation level [6].

Biodiesel is produced through a transesterification process, in which triglycerides react with an alcohol—typically methanol or ethanol—in the presence of a catalyst to form fatty acid methyl/ethyl esters (biodiesel) and glycerol as a by-product [7]. Based on feedstock characteristics, transesterification can be performed as either a single-stage or two-stage process. When feedstock contains free fatty acids exceeding 2%, a two-stage approach is required involving initial acid-catalyzed esterification followed by transesterification. In this process, the reaction progress and completion are verified using FT-IR and NMR spectroscopy. The fatty acid methyl ester content of the product is determined by GC/MS analysis [8, 9]. In transesterification reactions, methanol and ethanol serve as the most common alcohols, though methanol is generally preferred over ethanol because of its shorter molecular chain, economic advantages, and better ability to reduce biodiesel viscosity while improving pour point characteristics. The choice between single-stage alkaline-catalyzed transesterification or dual-stage acid-alkaline catalyzed processes depends on the specific properties of the feedstock being used [8, 10].

Soybean biodiesel is mainly composed of fatty acid methyl esters (FAMEs), such as methyl palmitate, methyl stearate, methyl

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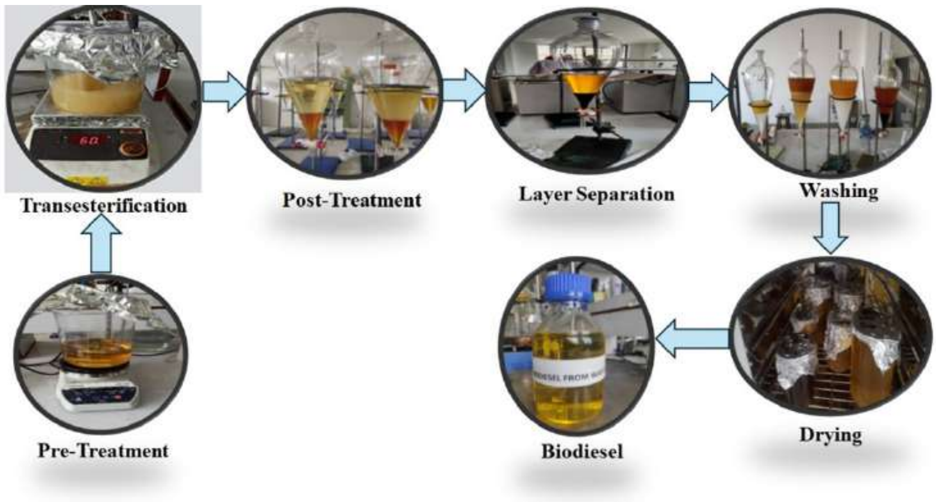



**Figure 1:** Experimental setup and process flow for biodiesel production.

oleate, methyl linoleate, and methyl linolenate. Gas chromatography with a flame ionization detector (GC-FID) was used to quantitate these key FAMEs to determine their precise concentrations in the biodiesel samples [11]. Biodiesel exhibits poor cold flow properties due to its long chain saturated fatty acid methyl esters, which block the fuel system, resulting on ignition issue, poor combustion. The cold flow characteristics can be enhanced by incorporating branched chain monoalkyl ester during transesterification improving low temperature fluidity and engine performance [12, 13].

In CI engines, biodiesel's higher cetane number and oxygen content lower ignition delay and raise combustion, while higher viscosity and cloud point affect atomization. Its higher surface tension produces droplets of larger size, and lowered heating value lowers combustion pressure and IMEP though EGR can boost combustion [14]. Soybean methyl ester (SBME) exhibited quality deterioration during storage, as indicated by reduced calorific value and increased viscosity. Analysis of SBME blends in a compression ignition engine indicated reduced CO with increasing load, stable hydrocarbon emissions, and $NO_x$ and $CO_2$ emissions [15].

In Common Rail Direct Injection (CRDI) engines, the higher oxygen content of biodiesel promotes more efficient combustion by enabling more complete oxidation. This results in reduced emissions of particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO), along with fewer carbon deposits and reduced engine wear. However, biodiesel's lower heating value can lead to a slight increase in fuel consumption, elevated nitrogen oxide ($NO_x$) emissions, and a marginal reduction in power output [16, 17]. Studies on direct injection (DI) engines using various blends of soybean biodiesel (B10–B50) have reported a 1–4% decrease in torque and a 2–9% rise in fuel consumption due to the fuel's lower energy content. Despite this, significant reductions in CO emissions (28–46%) and lower hydrocarbon levels have been observed, while $NO_x$ emissions increased by 6.95–17.62%. These findings suggest improved combustion characteristics through shorter ignition delays and confirm that soybean biodiesel can serve as a drop-in alternative fuel without requiring engine modifications [4]. Research using a multi-cylinder diesel engine further revealed an increase in brake specific fuel consumption with higher blend ratios, along with emission reductions and a slight decline in thermal performance [18]. In a compression ignition (CI) engine operated at 1500 rpm, the B20 blend of soybean biodiesel (20SME) exhibited the highest brake specific fuel consumption at low load, but also demonstrated improved brake thermal efficiency [19].

In the engine of a 5-kVA generator, soybean biodiesel (SME) was blended with diesel at varying proportions (10%, 30%, 50%, and 70%) and analyzed. The findings showed reduced specific fuel consumption at low (750 W) and peak (3000 W) loads, and hence soybean blends up to 30% are viable for partial diesel substitution [20]. Higher soybean biodiesel blend ratios in a one-cylinder DI engine produced higher BSFC and lower BTE, which indicate lower fuel and heat efficiency. B5 and B20 had slightly higher opacity due to incomplete combustion, yet overall emissions were lower than diesel. Soybean biodiesel has cleaner emissions, but higher blends lower combustion efficiency, requiring more adjustment [21].

This study addresses a critical research gap by pioneering a systematic evaluation of waste cooking soybean oil-derived biodiesel blends (10SME–40SME) in a single-cylinder diesel engine integrated with an eddy current dynamometer, with the novelty centered on identifying the optimum blend ratio that reconciles emission reduction, engine performance, and combustion stability. Unlike prior research focused on virgin feedstocks, the use of waste cooking oil, a sustainable, non-edible resource introduces distinct compositional variables (e.g., elevated free fatty acids, oxidation byproducts) that uniquely influence combustion dynamics in small-scale engines, a domain lacking empirical blend-specific data. By methodically testing incremental blends (10–40% v/v) under controlled loads, this work establishes a comparative framework to optimize waste-derived soybean biodiesel for single-cylinder engines, advancing circular economy principles (waste-to-energy paradigm) while supporting global decarbonization goals without requiring engine modifications.

## 2. Methods and methodology

### 2.1. Biodiesel production

The production process of biodiesel began with the collection of waste soybean oil which serves as the primary raw material, which was filtered to remove debris and solid impurities, and hence producing clean feedstock quality. The Free Fatty Acid test was conducted on the oil, and it was found to contain FFA content less than 2%, making it suitable for direct transesterification without pre-treatment. The filtered soybean oil was then trans esterified under reaction with methanol at a temperature of 60°C under controlled conditions using potassium hydroxide (KOH) as the catalyst in a concentration of 1.25% by weight of all the reactants under a molar ratio of 6:1 of the methanol to the triglycerides of the oil to produce Soybean Methyl Ester (SME). After the reaction was completed, the resulting biodiesel was cleaned to separate and remove glycerol byproduct as well as excess alcohol, ultimately yielding pure Soybean Methyl Ester for engine application. Whole biodiesel production process is summed up in Fig. 1.

## 2.2. Experimental setup

**Figure 2:** Engine test setup.

Experiment was carried out on single cylinder variable compression ratio (VCR) diesel engine. It was four-stroke, single cylinder water cooled engine with rated Brake Power of 3.5 kW and constant speed of 1500 rpm. It had a direct injection system with injection pressure of 220 bars. Engine cylinder bore was 87.5 mm, stroke length was 110 mm, connecting rod length was 234 mm, and swept volume was 661.45 cc. Specific Gas Constant was 1 kJ/kg.K and Adiabatic Index was 1.41. Engine data was taken average for 10 complete engine cycles to provide improved data values from the engine. The compression ratio was set to 17. Both pressure reference cylinder and reference TDC is 0°. A smoothing factor of 2° had also been included with the pressure readings.

Engine was mounted on the eddy current dynamometer. The eddy current dynamometer was used to obtain continuous Brake Power in terms of which several performance parameters like Indicated Power, Brake Thermal Efficiency, Brake specific fuel consumption, and Mechanical efficiency; combustion parameters like cylinder pressure maximum (CPM), Net heat release (NHR), Cumulative heat release (CHR) were determined.

Test of the fuels prepared from different blends of Soybean Methyl Ester and Petroleum based Diesel, i.e. 0SME (SME 0% and Diesel 100%), 10SME (SME 10% and Diesel 90%), 20SME (SME 20% and Diesel 80%), 30SME (SME 30% and Diesel 70%), and 40SME (SME 40% and Diesel 60%), was conducted in the VCR Test Engine present at the Combustion laboratory of Thapathali Campus which was constructed by Kirloskar Company. Pressure Sensor and Temperature sensor were also fitted to measure in-cylinder pressure and exhaust gas temperatures respectively. Fig. 2 shows the experimental engine setup.

## 2.3. Blending operation

Four various volumetric blends of Soybean Methyl Ester and petroleum diesel with proportions 10SME, 20SME, 30SME, and 40SME were made. Blending process was carried out by shaking the fuel mixtures for 5 minutes to ensure thorough homogenization, after which they were examined visually to confirm completion of blending of the ingredients.

## 2.4. Emission measurement

KANE Model: AUTO5-2 gas analyzer was used to measure the emission. The specification of the analyzer is illustrated in the Table 1.

# 3. Result and discussions

## 3.1. Biodiesel characterization

From the Table 3, the major component of the soybean biodiesel were identified as Methyl linoleate, methyl oleate, methyl palmitate and methyl stearate with total percentage of 48.42%, 32.35%, 13.227% and 9.95% respectively. Methyl linoleate and methyl oleate emerged as the dominating component for biodiesel due to presence of natural fatty acid composition. Methyl Linoleate is a polyunsaturated ester derived from the linoleic acid. The double bond present on Methyl Linoleate contributes on fuel fluidity but may reduce oxidative stability. Methyl oleate is a monounsaturated ester formed from the oleic acid which provide balance between cold flow properties, reduce ignition delay and oxidative stability due to single bond present. Methyl palmitate and Methyl stearate are the saturated ester which helps to determine cetane number and enhance fuel stability and combustion quality.

## 3.2. Performance characteristics

Fig. 3a illustrates the relation of indicated power with break power. Indicated power is the power generated by gas pressure inside the engine cylinders. On increasing break power, indicated power increases. When compared with diesel, on average IP decreases by 5.62%, 4.96%, 5.39% and 0.71% for 10 SME, 20 SME, 30 SME and 40 SME respectively. This is due to the lower heating value, higher density and viscosity affecting the fuel atomization.

Fig. 3b illustrates the relationship of specific fuel consumption with break power. Specific fuel consumption is a parameter which measures fuel efficiency. On rising the break power for the blend of (10-40) %, SFC goes on decreasing but increases for 40 % blend. SFC decreases by 4.07 %, 4.09% and 5.4% for 10SME, 20SME and 30SME respectively but increases for 40SME by 1.79%. The decrease in SFC for lower blends is is due to the higher cetane number and oxygen content. Also, decreases on 40 SME is due to high viscosity and lower heating value.

Fig. 3c illustrates the relationship of brake thermal efficiency with break power. Brake thermal efficiency is an ability to convert the chemical energy into useful work energy. On rising the break power for the blend of (10-40) %, brake thermal efficiency increases for all the blends. It increases by 6.3%, 9.179%, 11.94% and 0.84% for 10SME, 20SME, 30SME and 40SME respectively. Break thermal efficiency increases due to inherent oxygen content which reduce unburnt hydrocarbon and energy losses.

Fig. 3d illustrates the relationship of mechanical efficiency with break power. Mechanical efficiency measures the effectiveness of converting indicated power (IP) into usable power. With increase in brake power, mechanical efficiency also increases. Mechanical Efficiency increases by 4.5%, 6.02%, 9.30%, and 01.84% for 10SME, 20SME, 30SME and 40SME respectively. It increases due to lubricity enhancement which directly reduces the frictional coefficient minimizing power loss.

Fig. 3e illustrates the relationship of Exhaust gas temperature with Brake Power. With increase in brake power, exhaust gas temperature also increases. On the average when compared with diesel, EGT decreases for 10SME, 30SME and 40SME by 0.6%, 2.64% and 5.53%, increases for 20% by 1.14%. This is due to the higher oxygen content and cetane number, which ensure the efficient heat release.

**Table 1:** Specification of gas analyzer.

| Parameter | Resolution | Accuracy | Range |
|---|---|---|---|
| Carbon Monoxide (Infrared) | 0.01% | ± 5% of reading<br>± 0.06% volume | 0-10 %<br>Over-range: 20% |
| Carbon Dioxide (Infrared) | 0.1% | ± 5% of reading<br>± 0.5% volume | 0-16 %<br>Over-range: 25% |
| Nitric Oxide (Fuel cell) | 1 ppm | 0-1500 ppm<br>± 5% or 25 ppm | 0-1500 ppm<br>Over-range:5000 ppm |

**Table 2:** Fuel property of various blends of biodiesel.

| Sample | Density ($kg/m^3$) | Viscosity ($cSt$) | Flash Point ($^\circ C$) | Calorific Value ($MJ/kg$) | Cetane index |
|---|---|---|---|---|---|
| Test Method | ASTM D 4052 | ASTM D 445 | IS:1448 | Bomb Calorimeter | |
| 0SME | 829.93 | 2.17 | 55 | 42.5 | 46 |
| 10SME | 834.2 | 2.64 | 69 | 41.66 | 46.5 |
| 20SME | 843.57 | 2.879 | 78 | 33.54 | 45.89 |
| 30SME | 856.5 | 3.075 | 87 | 32.89 | 48 |
| 40SME | 858.5 | 3.5 | 96 | 31.72 | 49.23 |

**Table 3:** GCMS composition of soybean biodiesel.

| S.N. | FAME component | Common name | Retention time | Area (%) |
|---|---|---|---|---|
| 1 | 9,12-Octadecenoic acid methyl ester | Methyl linoleate | 40.764 | 48.42 |
| 2 | 9-Octadecadienoic acid methyl ester | Methyl oleate | 40.570 | 32.35 |
| 3 | Hexadecanioc acid methyl ester | Methyl palmitate | 13.674 | 13.27 |
| 4 | Octadecanioc methyl ester | Methyl stearate | 41.131 | 5.96 |

### 3.3. Combustion characteristics

Fig. 4a illustrates the relation between Cylinder Pressure Maximum with brake power. Cylinder pressure is the maximum pressure of cylinder obtained during combustion. With increase in brake power, CPM increases as to generate more brake power, more fuel is ignited, causing higher cylinder pressure. On average when compared to diesel, CPM decreases by 3.5%, 3.04%, 3.41%, 0.5% for 10SME, 20SME, 30SME and 40SME blend respectively which is due to lower energy density resulted in reduced energy release and lower peak pressure obtained inside cylinder.

Fig. 4b illustrates the relation between Cumulative heat release with brake power. Cumulative heat release refers to the total amount of heat generated during the combustion. With an increase in brake power, CHR also increases. On average, when compared with diesel, CHR of (10-30 SME) blend decreases by 1.993%, 17.415%, and 6.89% respectively due to biodiesel lower calorific value which release less total energy during combustion. CHR increases by 3.06% for 40SME because more fuel volume is injected to compensate lower energy content, resulting higher total heat release.

Fig. 4c illustrates the relation between Net Heat Release with brake power. Net Heat Release is the usable heat energy remained after combustion losses. With increase in brake power, net heat release also increases. On average, when comparing with diesel, NHR of 10SME increases by 2.07% due to the oxygen content which increased the combustion efficiency. NHR decreases for (20-40SME) by 1.97%, 6.18%, 0.165% respectively due to the dominance of lower heating value, reducing the net usable energy.

### 3.4. Emission characteristics

Fig. 5a illustrates the relation of carbon dioxide with brake power. With increase in brake power, carbon dioxide emission also increases, reflecting the increased fuel mass flow rate required to meet the load. On average, when compared to diesel, carbon dioxide emission for 10SME, 20SME and 30 SME decreases by 27.92%, 0.36% and 14.6% respectively. The general carbon dioxide reduction is primarily due to the inherent oxygen content of the biodiesel promoting more complete fuel oxidation. Crucially, the 0.36% reduction for 20SME indicates an optimized balance between this beneficial oxygen effect and the negative impact of reduced energy content. $CO_2$ increases for 40SME by 0.38% due to the higher fuel consumption which compensate lower energy density.

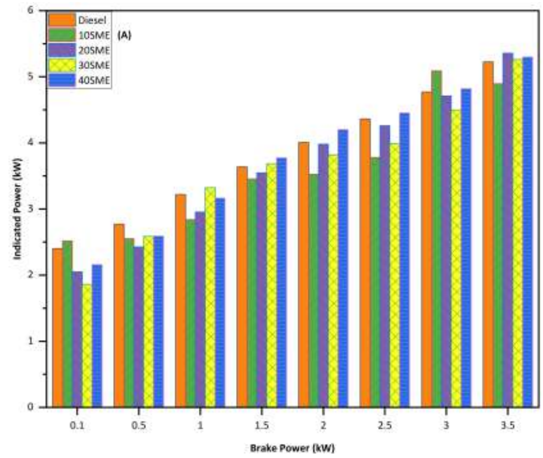
Fig. 5b illustrates the relation of nitric oxide with brake power. On average, when comparing with diesel, NO emission for 10SME, 20SME, 30SME, and 40SME decreases by 32.08%, 8.30%, 21.13%, 5.02% respectively. This reduction (NO) is mainly due to the lower heating value of biodiesel, which results in lower peak combustion temperatures. Since thermal $NO_x$ formation is highly temperature-dependent, the reduced in-cylinder temperature leads to a decrease in NO generation.

Fig. 5c illustrates the relation of hydrocarbon with brake power. With increase in brake power, HC emission also increases. On average, when comparing with diesel, HC emission for 10SME, 20SME, 30SME, and 40SME decreases by 13.34%, 20.20%, 38.94%, and 21.62% respectively. Biodiesel inherent oxygen content promoting more complete combustion, reducing unburned hydrocarbon. Additionally, higher cetane number of biodiesel ensures better ignition quality and efficient fuel burning.

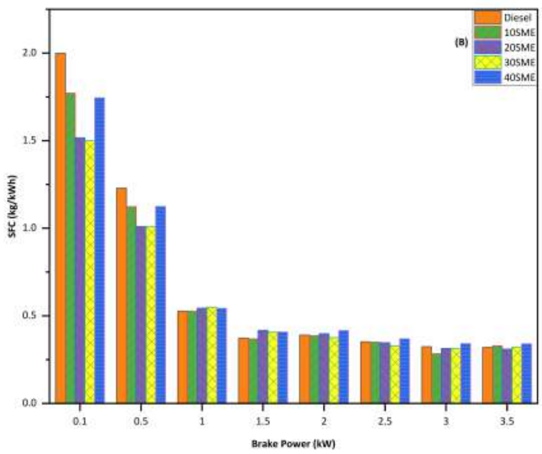
Fig. 5d illustrates the relation of $NO_x$ with brake power. On average, when comparing with diesel, $NO_x$ emission for 10SME, 20SME, 30SME, and 40SME decreases by 31.9%, 8.75%, 21.54%, and 5.31% respectively. This reduction (HC) is mainly attributed to the lower heating value of biodiesel, which leads to reduced peak combustion temperatures. Since the formation of nitrogen oxides is highly temperature-dependent, the lower in-cylinder temperature results in decreased emissions.

### 3.5. Discussions

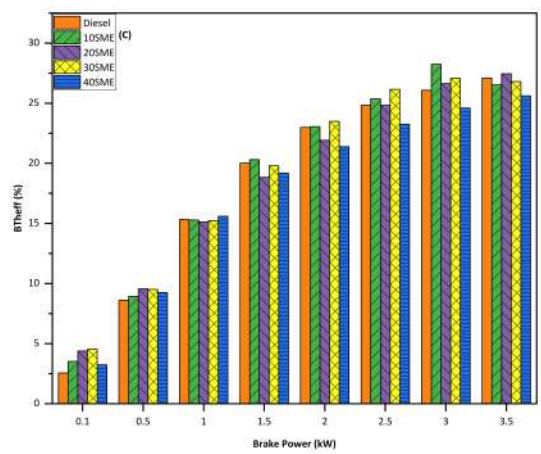
This study systematically evaluates soybean methyl ester (SME) blends as sustainable alternatives to petroleum diesel, with particular focus on 10SME, 20SME, 30SME, and 40SME formulations. Per-



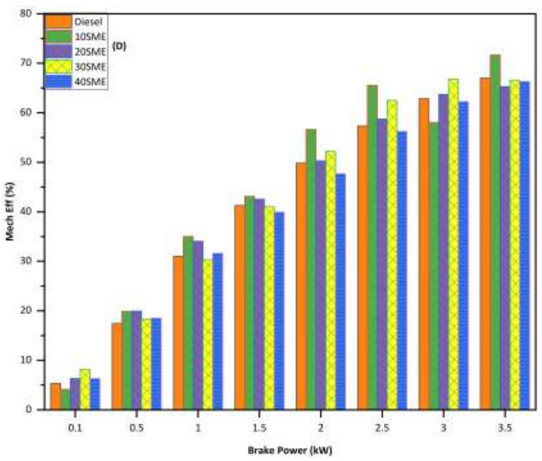

**(a)** Relation of indicated power(IP) with brake power.



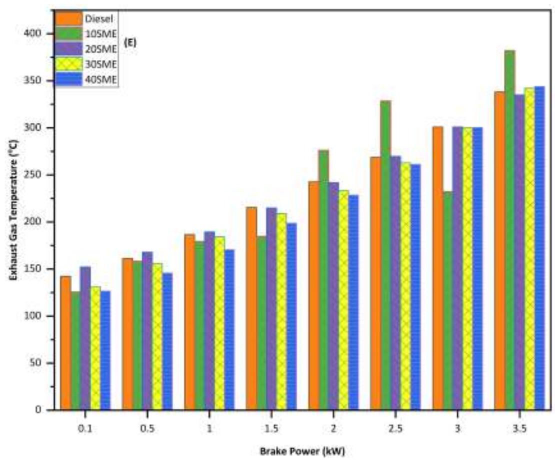

**(b)** Relation of specific fuel consumption (SFC) with brake power.




**(c)** Relation of brake thermal efficiency (BTheff) with brake power.




**(d)** Relation of mechanical efficiency (Mech Eff) with brake power.

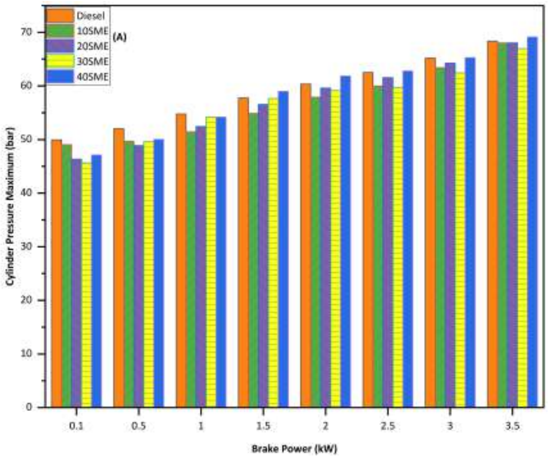



**(e)** Relation of exhaust gas temperature (EGT).

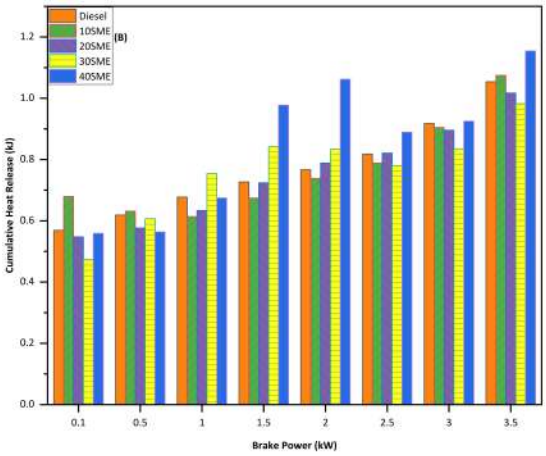
**Figure 3:** Performance characteristics.

formance analysis reveals that 30SME delivers the most significant efficiency improvements, increasing brake thermal efficiency by 11.94% while reducing specific fuel consumption by 5.4% compared to baseline diesel. These gains originate from the oxygen-rich composition of soybean biodiesel—particularly its dominant methyl linoleate (48.42%) and methyl oleate (32.35%) content—which enhances combustion completeness and reduces energy dissipation. A similar result was observed in this study, which is in agreement with the findings cited in Özener et al. [4]. The inherent lubricity of SME further minimizes mechanical losses, evidenced by a 9.30% improvement in mechanical efficiency for 30SME. The obtained result is in close agreement with the reason reported by Zetra et al. [22]. Conversely, 40SME exhibits diminished returns due to its elevated viscosity (3.5 cSt) and reduced calorific value (31.72 MJ/kg), increasing fuel consumption by 1.79% and constraining thermal efficiency gains to 0.84%.

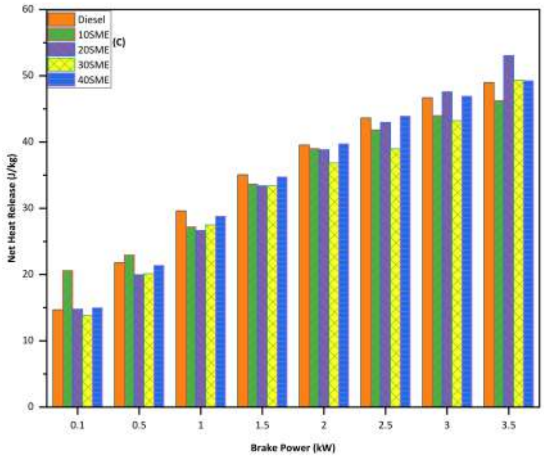
Combustion characteristics demonstrate concentration-dependent behavior. Peak cylinder pressure shows marginal reductions (≤3.5%) across all SME blends, attributable to lower energy density delaying combustion phasing, which is in close




**(a)** Relation of cylinder pressure maximum (CPM) with brake power.




**(b)** Relation of cumulative heat release (CHR) with brake power.




**(c)** Relation of net heat release (NHR) with brake power.

**Figure 4:** Combustion characteristics.

agreement with the research Qi et al. [23]. 10SME increases net heat release by 2.07%, reflecting oxygen-enhanced combustion efficiency, while 30SME decreases it by 6.18% as calorific value limitations dominate. 40SME displays a 3.06% rise in cumulative heat release due to compensatory fuel injection—a critical consideration for high-blend operational strategies.

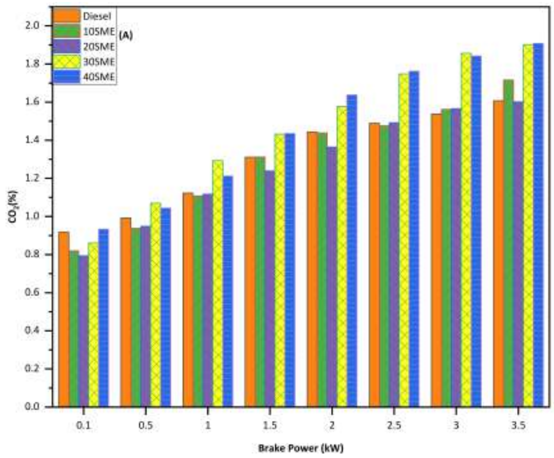
Emission profiles reveal SME's environmental advantages. All blends reduce $NO_x$ emissions (20SME: 8.75% reduction; 40SME: 5.31% reduction), contradicting typical biodiesel trade-offs through two mechanisms: (1) lower adiabatic flame temperatures suppressing thermal $NO_x$ formation, and (2) advanced combustion initiation from favorable cetane indices (20SME: 45.89) which is clearly supported by the research Qi et al. [23]. Hydrocarbon emissions decrease by up to 38.94% (30SME), while carbon monoxide reductions peak at 27.92% (10SME), both resulting from oxygen-driven oxidation completeness. Carbon dioxide emissions decrease significantly for 10SME (27.92%) and 30SME (14.6%), though 40SME shows a 0.38% increase due to higher fuel volumes combusted.

20SME emerges as the optimal blend for emission mitigation, achieving reductions of 3.5% ($CO_2$), 19.2 ppm (NO), 18.97 ppm (HC), and 18.93 ppm ($NO_x$) while maintaining robust thermal efficiency (+9.18%). 30SME prioritizes operational efficiency but exhibits slight $CO_2$ trade-offs at peak loads. This divergence highlights the critical balance between oxygen-driven combustion benefits and viscosity-imposed limitations in high-concentration blends.

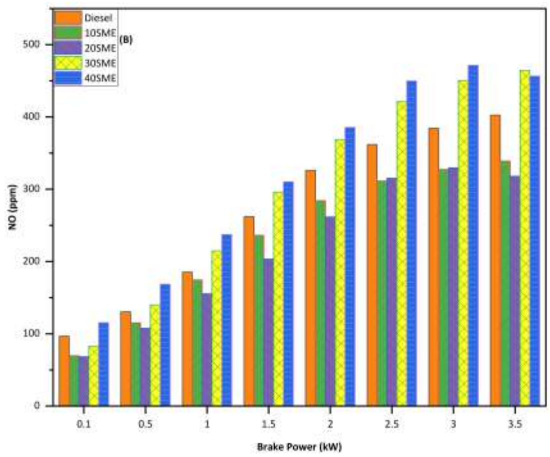
## 4. Conclusion

The comparative experimental investigation of the performance, combustion and emission characteristics of soybean biodiesel methyl ester (SME) blends in single cylinder diesel engine recognizes soybean biodiesel as potential alternative to conventional diesel fuel with no modification. The 20SME and 30SME were the most efficient concentration from the 10-40% SME blends that were experimented upon, enhancing the engine efficiency, combustion behavior and emission. The major findings are discussed below:

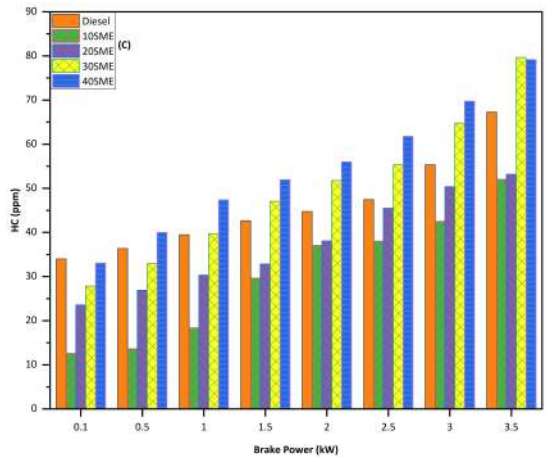
- The 30SME increases the brake thermal efficiency by 11.94% and 5.4% decrease on the specific fuel consumption due to improved fuel lubricity and enhanced oxygen availability.
- Engine thermal efficiency decrease significantly with higher biodiesel blend from 6.3% at 10SME to 0.84% at 40SME and reduced mechanical efficiency due to lower heating value, requiring more fuel for same power output.
- Enhanced combustion was observed for 10SME, with the maximum decrease in cylinder peak pressure (CPM) accompanied by the highest net heat release (NHR).
- 20SME demonstrate the most effective reduction on emission, showing significant decrease in $CO_2$ (3.502%), NO (19.175ppm), HC (18.97ppm) and $NO_x$ (18.93 ppm) when compared with diesel, higher oxygen content indicating complete and efficient combustion.
- Higher blends as 30SME and 40SME resulted in increased



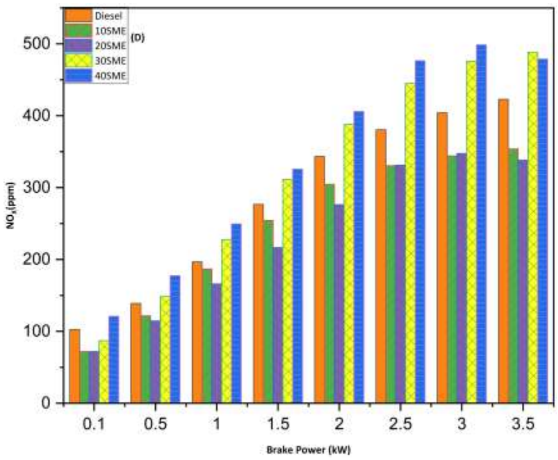

**(a)** Relation of $CO_2$ with brake power.




**(b)** Relation of NO with brake power.




**(c)** Relation of HC with brake power.




**(d)** Relation of $NO_x$ with brake power.

**Figure 5:** Emission characteristics.

$CO_2$ emission, indicating less efficient carbon combustion at higher blends.

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## Conflict of interest

The authors declare that they have no conflict of interest.

## Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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