**PERFORMANCE AND EMISSION CHARACTERISTICS OF COMPRESSION IGNITION ENGINES FUELLED WITH RUBBER SEED OIL BIODIESEL BLENDED WITH ETHANOL AND DIETHYL ETHER**

**ABSTRACT**

The increasing global demand for sustainable energy and environmental concerns have necessitated the exploration of renewable alternatives to fossil fuels. Biodiesel, derived from vegetable oils and animal fats, presents a viable substitute for petroleum diesel, offering reduced emissions and improved biodegradability. This study investigates the performance and emission characteristics of compression ignition (CI) engines fuelled with rubber seed oil biodiesel blends, incorporating ethanol and diethyl ether as additives. Biodiesel was synthesized via transesterification and blended with petroleum diesel in varying proportions (B20–B100), with 5% ethanol (B20E5–B100E5) and 5% diethyl ether (B20EE5–B100EE5) to enhance fuel properties. The chemo-physical properties of the fuel samples were analysed following ASTM standards, and engine performance tests were conducted under varying loads and speeds. Results indicate that the addition of diethyl ether improved brake thermal efficiency (BTE) and reduced brake-specific fuel consumption (BSFC), while ethanol-blended biodiesel exhibited lower carbon monoxide (CO) and hydrocarbon (HC) emissions. The B80EE5 and B60EE5 blends demonstrated the most favourable performance, balancing efficiency and emissions. The study highlights the potential of rubber seed oil biodiesel with oxygenated additives as an alternative fuel for sustainable CI engine operation.

***Keywords:*** *Biodiesel, Rubber Seed Oil, Compression Ignition Engine, Fuel Additives, Engine Performance, Ethanol, Diethyl Ether*

**1. INTRODUCTION**

The depletion of petroleum reserves, rising global energy demand, and increasing environmental concerns have intensified the search for sustainable alternatives to fossil fuels. Biodiesel, derived from renewable lipid feedstocks, has emerged as a viable substitute for petroleum diesel in compression ignition (CI) engines due to its comparable properties, renewability, low toxicity, and biodegradability. Its energy content allows it to be used in pure form or as a blend without significant modifications to existing engines (Ayhan *et al.,* 2020; Dinesha *et al.,* 2019; Hoang *et al.,* 2021).

Energy security and environmental sustainability necessitate renewable energy sources with minimal ecological impact. Biomass-derived biofuels, particularly ethanol for gasoline engines and biodiesel for CI engines, provide promising solutions. The transport sector, responsible for 15% of global greenhouse gas (GHG) emissions, plays a crucial role in climate change mitigation (Halder *et al.,* 2019). Diesel engines, widely used for their high energy conversion efficiency, are a major focus of research aimed at improving performance and reducing emissions (Doppalapudi *et al.,* 2023; Viswanathan *et al.,* 2020). While advanced exhaust gas after-treatment technologies can lower emissions, cost and catalyst scarcity limit their implementation (Gremminger *et al.,* 2020; Bharathiraja *et al.,* 2016). Biodiesel has gained attention as an alternative fuel due to its potential for emission reduction and improved fuel sustainability.

Biodiesel is produced through transesterification, a process where vegetable oils or animal fats react with alcohol in the presence of a catalyst, yielding fatty acid alkyl esters (biodiesel) and glycerol as a by-product. Feedstocks include edible and non-edible vegetable oils, animal fats, and waste cooking oils (Zarrinkolah & Hosseini, 2022; Ramalingam & Mahalakshmi, 2020; Silitonga *et al.,* 2017). However, biodiesel presents challenges such as poor cold flow properties, lower energy density, and degradation over storage periods. Higher biodiesel blend ratios may require specialized handling and engine modifications (Hoang, 2021). Biodiesel blends are denoted as "BXX," where "XX" represents the biodiesel percentage (e.g., B20: 20% biodiesel, 80% petroleum diesel).

The performance and emissions of CI engines fuelled with biodiesel blends depend on heating value, viscosity, density, and lubricity. Studies indicate that biodiesel combustion lowers carbon monoxide (CO), particulate matter (PM), and smoke emissions compared to petroleum diesel, improving air quality (Semwal *et al.,* 2022; Rajak & Tikendra, 2018). However, widespread diesel engine use in transport, construction, and industry exacerbates urban air pollution, posing health risks (Bakır *et al.,* 2022). The transport sector contributes 14% of global GHG emissions, with road transport accounting for 73%, highlighting the need for alternative fuels (Lamb *et al.,* 2021).

Fossil fuel distribution disparities further emphasize the need for alternatives to ensure energy security. As of 2022, the ten countries with the largest oil reserves controlled over 85% of global reserves, necessitating widely available renewable energy sources ("Oil Reserves by Country 2022," n.d.). Biodiesel offers a solution due to its compatibility with existing diesel engines and infrastructure, reducing fossil fuel dependency (Nguyen & Vu, 2019; Prabhu *et al.,* 2023). However, its high viscosity, lower heating value, and poor cold flow properties require fuel additives to optimize performance.

Oxygenated additives, metal-based additives, antioxidants, cold flow improvers, lubricity enhancers, and cetane number improvers enhance biodiesel properties (Schumacher *et al.,* 2004). Oxygenated additives such as ethanol, diethyl ether, n-butanol, and methanol improve combustion efficiency, reduce emissions, and enhance engine performance. Studies show that diethyl ether and ethanol in biodiesel blends improve brake thermal efficiency (BTE), combustion characteristics, and fuel spray properties (Qi *et al..,* 2010; Shi *et al.,* 2006). Research on *Calophyllum inophyllum* biodiesel with diethyl ether and ethanol additives demonstrated increased net heat release rate, cylinder pressure, and combustion efficiency. Similarly, Mahua biodiesel blended with petroleum diesel and ethanol reduced viscosity and flash point while improving cetane number and heating value.

Despite extensive research on biodiesel from Mahua, Jatropha, and *Calophyllum inophyllum*, limited studies focus on rubber seed oil biodiesel and its blends. This study evaluates ethanol and diethyl ether as additives to improve the performance and emission characteristics of rubber seed oil biodiesel in a CI engine. The research includes biodiesel production through transesterification, physicochemical characterization, and performance testing in a diesel engine. Additionally, the study assesses the influence of bio-additives on emissions, focusing on CO, nitrogen oxides (NOₓ), and particulate matter (PM). By examining ethanol and diethyl ether as biodiesel additives, this research aims to enhance the feasibility of rubber seed oil biodiesel as a sustainable fuel for CI engines.

**2. METHODOLOGY AND THEORETICAL FRAMEWORK**

The study's methodology followed established fuel characterization, experimental, and instrumentation standards, integrating recent research (Karthickeyan *et al.,* 2020; Mubarak *et al.,* 2021). The experimental design included sample preparation, experimentation, and ASTM-compliant validation. Biodiesel from rubber seed oil was produced via transesterification and blended with petroleum diesel, ethanol, and diethyl ether to optimize fuel properties and engine performance. The compositional analysis of the fuels and the chemo-physical properties of the blends were evaluated per ASTM standards (Ogunkunle *et al.,* 2020). The ternary blend aimed to minimize density and viscosity while maintaining a calorific value close to diesel (Thakkar *et al.,* 2021). Engine tests assessed brake power, brake specific fuel consumption, and brake thermal efficiency, while emissions (CO, CO₂, HC, NOₓ) were analysed based on literature (Karthickeyan *et al.,* 2020; Mubarak *et al.,* 2021; Thakkar *et al.,* 2021; Bhuiya *et al.,* 2016). Each experiment was conducted in triplicate, and average values were reported for reliability.

**2.1 Production of Biodiesel from Rubber Seed Oil**

Rubber seed oil from the Rubber Research Institute of Nigeria, Iyanomo, Benin City, was used to produce biodiesel via transesterification. The oil was preheated to 50°C, mixed with 200 mL methanol, and stirred. To enhance the reaction, 2 mL sulfuric acid was added, and heating with stirring continued for 25 minutes at atmospheric pressure. The mixture was then placed in a separating funnel to remove excess alcohol.

In the secondary process, 2 g potassium hydroxide was dissolved in methanol to form potassium methoxide. The esterified product was mixed with this solution in a 500 mL conical flask and heated at 55°C for 67 minutes using a heating mantle with a magnetic stirrer. After settling, the mixture separated into two layers: impurities in the lower layer and glycerol in the upper. The biodiesel was purified by washing to remove residual catalysts and methanol before further blending and testing.

**2.3 Blending of Biodiesel**

Following the production of biodiesel, blending was performed to achieve specific fuel properties that align with standard diesel fuel. The blending process involved mixing biodiesel with petroleum diesel in predefined proportions (B0, B20, B40, B60, B80 and B100). To further enhance fuel characteristics, 5% ethanol and 5% diethyl ether were incorporated into selected fuel samples, as (B0E5, B20E5, B40E5, B60E5, B80E5 and B100E5) and (B0EE5, B20EE5, B40EE5, B60EE5, B80EE5 and B100EE5), respectively. The blending strategy was designed based on two primary hypotheses, which aimed to optimize three key fuel properties. The objective was to closely match the calorific value of the blends to conventional diesel while maintaining the lowest possible values for density and viscosity (Azad *et al.,* 2023).

The blending of biodiesel with ethanol and diethyl ether aimed to improve combustion efficiency, reduce viscosity, and enhance fuel atomization during engine operation. The blended fuel samples were subsequently characterized to determine their chemo-physical properties before being introduced into the diesel engine for performance evaluation.

**2.4 Determination of Chemo-Physical Properties**

Chemo-physical properties were analysed at the Chemical Department Laboratory, Bauchi State Polytechnic, Bauchi, using standard procedures.

Specific gravity was determined per ASTM D4052/150–ADAC using a 20 mL density bottle to compare the mass of the oil sample with an equal volume of water. Moisture content was measured by drying a 2 g oil sample at 105°C until a constant weight was achieved (Emma *et al.,* 2022). The acid number was determined by titrating a mixture of ethanol, toluene, and oil with 0.1M KOH until a persistent pink colour appeared (ASTM D6751). Free fatty acid (FFA) content was calculated from the acid value.

Saponification value was obtained by reacting 1 g of oil with 0.5M KOH and an ethanol-ether mixture, followed by titration with 0.5M HCl (ASTM 1998; Nahak *et al.,* 2010). Iodine value was determined by mixing the oil with chloroform and Hanus solution, allowing the reaction in the dark, then titrating with sodium thiosulfate (Eshetu and Niguse, 2013). Cetane number was calculated per ASTM D613 using established correlations (Vallinayagam *et al.,* 2014). Higher heating value (HHV) was estimated using an empirical formula based on iodine value and sample weight.

Kinematic viscosity was measured using an Ubbelohde glass capillary viscometer at 40°C (ASTM D445). Flash point was determined using a flash point analyser by heating the sample from 120°C under atmospheric pressure until a flash occurred (ASTM D93). Cloud point was recorded by cooling a 10 mL sample in an ice bath until cloudiness appeared, while the pour point was determined by cooling the sample until solidification, applying a +3°C correction factor (ASTM D6751, ULSD).

**2.5 Experimental Setup and Test Procedure**

The experimental setup consisted of a diesel engine, a dynamometer, a fuel supply system, an emission analyser, and data acquisition sensors. The engine was mounted on a rigid foundation to minimize vibrations during operation. The exhaust system was connected to a gas analyser, and thermocouples, torque transducers, and tachometers were installed for data acquisition. The dynamometer was used to apply variable loads to the engine and measure the brake power output, while CO and CO₂ emissions were recorded via the gas analyser.

Before commencing the tests, the engine was warmed up using conventional diesel fuel (B0) for 15 minutes to ensure stable operating conditions. Engine tests were conducted under varying loads (500–2500 N) at constant speeds (1500–3500 rpm) and at varying speeds (1500–3500 rpm) under a constant load (500–2500 N). Performance parameters (BP, BSFC, BSEC, BTE, and BMEP) and emissions (CO, CO₂, NOx, HC) were analysed. The test procedure involved the following steps:

* **Baseline Measurement with Diesel (B0):** The engine was initially run with conventional diesel (B0) to establish a reference for comparison. The fuel consumption rate, exhaust gas temperature, and engine emissions were recorded at each load level.
* **Testing of Biodiesel Blends (B20–B100):** The diesel fuel was replaced with biodiesel blends (B20, B40, B60, B80, and B100), and the engine was operated under identical conditions. The brake power, brake thermal efficiency, specific fuel consumption, and emissions were recorded for each blend.
* **Testing of Biodiesel-Ethanol Blends (B20E5–B100E5):** The engine was then run using biodiesel-ethanol blends to analyse the effect of ethanol addition on engine performance and emissions. Ethanol, being an oxygenated fuel, was expected to influence combustion characteristics and emission levels.
* **Testing of Biodiesel-Diethyl Ether Blends (B20EE5–B100EE5):** Finally, the engine was operated using biodiesel blends containing 5% diethyl ether to assess the impact of diethyl ether as an ignition improver. Diethyl ether has a high cetane number, which can enhance combustion efficiency and reduce emissions.

Each fuel sample was tested three times to ensure reproducibility, and the average values were recorded. The uncertainties in measurement were minimized by calibrating the instruments before the experiments.

**2.6 Performance Analysis**

**2.6.1 Torque Measurement**  
Engine torque was directly measured for each fuel sample using the installed dynamometer.

**2.6.2 Engine Brake Power (BP)**  
Brake power refers to the power developed at the engine’s output shaft and is determined as the product of engine torque and angular speed. It was calculated using the equation 1 (Nabi et al., 2019):

BP (kW) = 1

Where N represents angular speed (rpm) and T denotes engine torque

**2.6.3 Brake Specific Fuel Consumption (BSFC)**  
BSFC quantifies fuel consumption relative to brake power and is defined as the ratio of the mass flow rate of fuel supplied to the engine, to the brake power at the crankshaft . It was determined using equation 2. (Odibi ***et al.,*** 2019):

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**2.6.4 Brake Thermal Efficiency (BTE)**  
BTE evaluates the engine’s overall efficiency by comparing the brake power at the crankshaft to the total power generated from fuel combustion. It was computed using equation 3, (Mostafa *et al*., 2023; Odibi *et al.*, 2019).

3

Where *Mf* is the mass flow rate, and represents the fuel’s calorific value.

**3. RESULTS AND DISCUSSION**

**3.1 Chemo-Physical Properties**

The chemo-physical properties of rubber seed oil biodiesel blends and their modified versions incorporating 5% ethanol (B20E5–B100E5) and 5% diethyl ether (B20EE5–B100EE5) were analysed per ASTM D6751 standards. Specific gravity, a key parameter influencing combustion performance, was observed to decrease with increasing biodiesel content, as shown in Table 1. Lower specific gravity improves atomization, enhancing combustion efficiency, with diethyl ether having a more pronounced effect than ethanol. Density measurements confirmed that all fuel samples exhibited values below the EN 14214 minimum requirement of 860 kg/m³, reinforcing their suitability for efficient combustion. The acid values of B0–B100 were within ASTM D6751 limits, except for B100, which slightly exceeded the standard. The addition of ethanol and diethyl ether effectively reduced acid values, mitigating corrosion risks in fuel system components, with Table 1 illustrating that these additives-maintained compliance with ASTM and EN 14214 standards. Prior studies corroborate that oxygenated additives stabilize acid values, improving biodiesel fuel quality.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **S/N** | **Properties** | **B0** | **B20** | **B40** | **B60** | **B80** | **B100** | **B0E5** | **B20E5** | **B40E5** | **B60E5** | **B80E5** | **B100E5** | **B0EE5** | **B20EE5** | **B40EE5** | **B60EE5** | **B80EE5** | **B100EE5** |
| 1 | specific gravity | 0. 859 | 0.855 | 0.856 | 0.856 | 0.857 | 0.832 | 0.9 | 0.822 | 0.827 | 0.832 | 0.838 | 0.818 | 0.89 | 0.749 | 0.77 | 0.799 | 0.822 | 0.84 |
| 2 | Acid value (mg/KOH/g | 0.04 | 0.14 | 0.16 | 0.18 | 0.21 | 0.51 | 0.45 | 0.28 | 0.46 | 0.54 | 0.59 | 0.40 | 0.04 | 0.28 | 0.4 | 0.52 | 0.56 | 0.45 |
| 3 | Flash point | 120 | 121 | 124 | 126 | 128 | 135 | 119 | 125 | 130 | 132 | 134 | 120 | 110 | 115 | 113 | 112 | 110 | 118 |
| 4 | Free fatty acid (%) | 0.02 | 0.07 | 0.08 | 0.09 | 0.1 | 0.255 | 0.225 | 0.14 | 0.23 | 0.27 | 0.295 | 0.20 | 0.02 | 0.14 | 0.2 | 0.26 | 0.28 | 0.22 |
| 5 | Kinematic viscosity at 40oC | 3.06 | 3.14 | 3.22 | 3.36 | 3.41 | 4.5 | 2.82 | 3.2 | 3.3 | 3.4 | 3.5 | 3.6 | 2.76 | 3.4 | 3.3 | 3.2 | 3.1 | 3.91 |
| 6 | High heating value(ml/kg) | 49.06 | 49.05 | 49.04 | 49.04 | 49.02 | 49.02 | 20.6 | 49.03 | 49.03 | 49.03 | 49.03 | 49.01 | 20.61 | 29.21 | 36.61 | 28.8 | 28.62 | 49.01 |
| 7 | Cetane number | 52.71 | 52.34 | 52.028 | 51.696 | 50.72 | 51.478 | 52,66 | 51.86 | 51.29 | 50.879 | 50.34 | 51.37 | 52.62 | 51.77 | 51.48 | 50.8 |  | 51.07 |
| 50.23 |
| 8 | Cloud point |  | 6 | 8 | 10 | 4 | 10 | 6 | 9 | 9.3 | 9.6 | 9.9 | 8.5 | 5 | 4 | 6 | 8 | 8.4 | 7.9 |
| 9 | Pour point | 3 | 3.2 | 3.4 | 3.7 | 3.9 | 7 | 2 | 4 | 5 | 5.5 | 6 | 6.3 | 1 | 4 | 4.5 | 5 | 5.5 | 6.2 |
| 10 | Iodine value | 40.44 | 41.3 | 42.5 | 43.4 | 44.2 | 40.99 | 41.43 | 41.54 | 43.8 | 45.08 | 47.33 | 41.3 | 41.39 | 40.57 | 41.62 | 44.98 | 47.36 | 42.1 |
| 11 | Carbon residue | 0.7 | 0.51 | 0.47 | 0.45 | 0.43 | 0.4 | 0.6 | 0.5 | 0.36 | 0.28 | 0.26 | 0.25 | 0.5 | 0.56 | 0.48 | 0.46 | 0.44 | 0.23 |
| 12 | saponification values (mg KOH/g) | 352 | 356 | 358 | 360 | 380 | 379 | 350 | 366.2 | 367.2 | 368.2 | 369.0 | 380 | 382 | 380 | 375 | 355 | 373 | 369 |

**Table 1: chemo physical properties of rubber seed oil biodiesel blends with 5% ethanol, and 5% diethyl ether as additive**

Kinematic viscosity, a crucial factor affecting fuel spray and combustion characteristics, was measured at 40°C, confirming that all blends, including those modified with ethanol and diethyl ether, met ASTM D6751 limits. Maintaining viscosity within the specified range ensures optimal atomization, reducing carbon deposits and improving fuel-air mixing, as previously observed in biodiesel combustion studies. Higher heating values (HHV), indicative of energy content, were slightly reduced with ethanol addition and varied with diethyl ether. The observed fluctuations in HHV, depicted in Table 1, align with findings that diethyl ether influences energy density differently based on blending proportions and base fuel composition. Flash point measurements confirmed that all samples met ASTM and EN 14214 safety standards. Ethanol reduced flash points due to its higher volatility, whereas diethyl ether increased them, reinforcing its stabilizing effect on biodiesel fuel blends.

Cold flow properties, including cloud and pour points, are critical for fuel performance in low-temperature conditions. The results in Table 1 demonstrate that biodiesel blends generally exhibited higher cloud points than conventional diesel. Ethanol increased cloud points, while diethyl ether lowered them in most samples, improving cold-weather operability. Pour points followed a similar trend, with biodiesel blends showing higher values than petroleum diesel. Although none of the samples met EN 14213’s strict pour point limit, fuel blends without additives exhibited relatively better cold flow properties. Cetane number, a measure of combustion quality, remained within ASTM D6751 specifications across all fuel samples. The addition of ethanol and diethyl ether slightly reduced cetane numbers due to their oxygenated nature but maintained values conducive to efficient ignition and engine operation.

Iodine values were within EN 14111 limits, indicating lower polymerization tendencies, which enhances oxidative stability. As biodiesel blends tend to exhibit greater susceptibility to oxidation, the observed iodine values suggest improved long-term storage properties. Carbon residue, a key indicator of deposit formation in engines, decreased with the inclusion of ethanol and diethyl ether, as shown in Table 1. These findings are consistent with prior research demonstrating that oxygenated fuel additives reduce

carbon build-up, thereby extending engine longevity. Saponification values, which indicate the soap-forming potential of biodiesel, increased with ethanol and diethyl ether, suggesting a higher ester content in the modified blends. This trend aligns with studies showing

that oxygenated additives influence the chemical composition of biodiesel, leading to increased saponifiable

components.

The results confirm that biodiesel blends modified with ethanol and diethyl ether enhance combustion performance, reduce emissions, and ensure compliance with industry standards. The observed improvements in fuel properties, including optimized viscosity, reduced carbon residue, and enhanced cold flow characteristics, align with findings from previous studies on biodiesel stability and engine compatibility. The effectiveness of diethyl ether in lowering specific gravity, improving cold flow properties, and maintaining higher flash points further highlights its potential as a superior additive compared to ethanol. These findings reinforce the viability of ethanol- and diethyl ether-enhanced biodiesel blends as sustainable alternatives to conventional diesel.

**3.2.1 Torque Variation with Load and Speed for Different Fuel Blends**

Figure 1 illustrates the variation in torque with increasing load for various fuel samples, including B0, B20, B40, B60, B80, B100, B20E5, B40E5, B60E5, B80E5, B100E5, B20EE5, B40EE5, B60EE5, B80EE5, and B100EE5, at a constant engine speed of 1500 rpm. The results indicate a direct correlation between load and torque, where torque increases as load increases. This trend can be attributed to the rise in combustion temperature with increasing load, which enhances the completeness of combustion and facilitates greater conversion of chemical energy into thermal energy.

Among the tested fuel samples, B80EE5 exhibited the highest torque within the load range of 1000 g to 2000 g, surpassing both conventional diesel (B0) and other biodiesel blends. Compared to B80, the B80EE5 blend demonstrated superior torque performance, as shown in Figure 1b. This improvement can be linked to the presence of 5% diethyl ether (DEE), which enhances combustion characteristics. The resulting increase in torque leads to a corresponding rise in brake power, with higher fuel consumption required at elevated loads. However, at lower loads, the total fuel consumption is reduced, consistent with findings reported by Sandeep *et al.* (2018).

Similarly, Figure 1c shows that torque increases linearly with engine speed across all fuel samples, within the speed range of 1500 rpm to 3500 rpm, at a constant load of 2000 N. This can be attributed to the higher thermal energy release associated with increased fuel combustion at higher speeds, as previously observed by Liaquat *et al.* (2010). Notably, B60EE5 demonstrated superior torque performance compared to B60 within this speed range, further confirming the positive influence of diethyl ether as an additive in improving combustion efficiency.

The observed trends align with previous studies, where increased load and speed have been shown to enhance torque output due to improved combustion efficiency (Sandeep *et al*., 2018; Liaquat *et al.*, 2010). The beneficial effects of diethyl ether on torque enhancement are also consistent with earlier findings, highlighting its role in optimizing biodiesel performance. However, this study further demonstrates that the extent of improvement varies depending on the base fuel blend, with B80EE5 and B60EE5 showing the most significant enhancements.

(a)

**(b)**

**(c)**

Figure 1: Influence of Load and Speed on Engine Torque - (a) Variation of Engine Torque with Load at 1500 rpm, (b) Impact of Load on Engine Torque at 1500 rpm Using B20 Fuel Samples, and (c) Effect of Speed on Engine Torque at a Constant Load of 2000 N

**3.2.2 Effect of Load, Speed, and Additive on Brake Power of Biodiesel Blends**

Figure 2a illustrates the relationship between brake power and load at a constant engine speed of 1500 rpm for all tested fuel samples (B0, B20, B40, B60, B80, B100, B20E5, B40E5, B60E5, B80E5, B100E5, B20EE5, B40EE5, B60EE5, B80EE5, and B100EE5). The results indicate a consistent increase in brake power as the load increases, which can be attributed to the rise in combustion temperature enhancing engine torque. Notably, the B80EE5 fuel sample exhibited the highest brake power within the load range of 1000 g to 2000 g, outperforming all other fuel blends. This suggests that the addition of 5% diethyl ether positively influences engine performance, a trend also observed for torque, given the direct proportionality between brake power and torque.

Figure 2b presents the variation of brake power with engine speed at a constant load of 2000 g. Across the speed range of 1500 rpm to 3500 rpm, brake power increases proportionally with speed for all fuel samples. Among them, B60EE5 demonstrated superior brake power compared to its counterparts, including B60, highlighting the beneficial effect of diethyl ether as an additive. The enhanced performance of B60EE5 can be attributed to improved combustion characteristics associated with diethyl ether, which promotes more efficient fuel-air mixing and combustion kinetics.

These findings align with previous studies, such as those by Azad *et al.*, 2023; A.V.S.L *et al*., 2021, which reported similar enhancements in brake power with oxygenated fuel additives. Additionally, the observed trends are consistent with the work of Azad *et al.*, 2023, where an increase in diethyl ether concentration led to improved thermal efficiency and power output. However, while prior studies have focused on lower additive concentrations, the present study demonstrates that a 5% diethyl ether blend yields optimal results, particularly in the B60EE5 and B80EE5 samples.

(a)

(b)

Figure 2: (a) Influence of Load on Brake Power at 1500 rpm for Various Fuel Samples, and (b) Impact of Speed on Brake Power Under a 2000 N Load.

**3.2.3 Effect of Load, Speed, and Additive on Brake specific fuel consumption of Biodiesel Blends**

The brake-specific fuel consumption (BSFC) of all tested fuel samples (B0, B20, B40, B60, B80, B100, B20E5, B40E5, B60E5, B80E5, B100E5, B20EE5, B40EE5, B60EE5, B80EE5, and B100EE5) decreases as engine load increases, as illustrated in Figure 3a. This reduction in BSFC can be attributed to a decline in frictional power, as reported by Khumi and Gupta (2019). A lower frictional power results in reduced fuel mass consumption for the same energy output, thereby improving fuel efficiency. Among all fuel samples, B80EE5 exhibits the lowest BSFC, as shown in Figure 3b, indicating superior fuel consumption efficiency compared to the other blends. The improved BSFC of B80EE5 relative to B80 is due to the presence of 5% diethyl ether, which enhances combustion characteristics and reduces fuel consumption.

Figure 3c reveals that BSFC decreases with increasing engine speed from 1500 rpm to 3500 rpm. This trend aligns with Jehad (2017), who attributed the reduction to a shorter heat loss duration per cycle at higher speeds. The lower heat dissipation at increased speeds leads to improved thermal efficiency, which contributes to the observed decrease in BSFC. Furthermore, among all tested fuel samples, B60EE5 demonstrates the lowest BSFC across this speed range. The improved fuel consumption efficiency of B60EE5 compared to B60 can be linked to the addition of 5% diethyl ether, which enhances combustion efficiency.

Regarding brake power, Figure 2a shows that B80EE5 achieves the highest brake power within the 1000 g to 2000 g load range, surpassing all other fuel samples. This finding highlights the positive influence of diethyl ether as a fuel additive, which enhances combustion and power output. Since brake power is directly proportional to torque, a similar trend is observed for torque performance. Figure 2b illustrates the variation of brake power with speed under a constant load of 2000 g for all fuel samples. Brake power increases linearly with speed within the range of 1500 rpm to 3500 rpm, consistent with the relationship between power and torque. Notably, B60EE5 exhibits the highest brake power in this speed range, outperforming its counterpart B60. The enhanced brake power of B60EE5 is attributed to the presence of 5% diethyl ether, which improves combustion efficiency and overall engine performance.

These findings align with previous studies on alternative fuel blends, where the addition of oxygenated compounds like diethyl ether has been shown to enhance combustion efficiency, reduce BSFC, and improve engine performance (Azad *et al*., 2023; A.V.S.L *et al*., 2021). The results further reinforce the potential of diethyl ether as a fuel additive for optimizing diesel engine operation.

(a)

(b)

(c)

Figure 3: (a) Influence of Load on Brake Specific Fuel Consumption at 1500 rpm, (b) Impact of Load on Brake Specific Fuel Consumption for B80 Fuel Samples with Additives at 1500 rpm, and (c) Effect of Speed on Specific Fuel Consumption at a Load of 2000 N.

**3. 2.4 Brake Thermal Efficiency Variation with Load and Speed**

Brake thermal efficiency (BTE) is a key parameter in assessing how effectively an engine converts fuel energy into useful work. The variation of BTE with load and speed for the tested fuel samples is presented in Figure 4. As illustrated in Figure 4a, BTE increases with load, ranging from 500 N to 2500 N. This improvement can be attributed to the higher in-cylinder temperature at elevated loads, which enhances fuel atomization, evaporation, and mixing with air. Consequently, fuel combustion becomes more efficient, leading to reduced brake-specific fuel consumption and an overall increase in BTE (Xue *et al*., 2011). Among the tested fuels, B80EE5 exhibited the highest BTE across the load range, outperforming B0, B20, B40, B60, B80, B100, B20E5, B40E5, B60E5, B80E5, B100E5, B20EE5, B40EE5, B60EE5, and B100EE5. The superior performance of B80EE5 compared to B80 can be attributed to the presence of 5% diethyl ether, which enhances combustion characteristics.

Similarly, as shown in Figure 4b, BTE improves with increasing engine speed, ranging from 1500 rpm to 3500 rpm. At higher speeds, fuel consumption is optimized due to improved air-fuel mixing, which facilitates more efficient combustion (Pavlos *et al.,* 2020). This leads to increased energy conversion efficiency, thereby enhancing BTE. In this case, B60EE5 exhibited the highest thermal efficiency compared to the other fuel samples. The improved performance of B60EE5 relative to B60 can be attributed to the presence of 5% diethyl ether, which promotes better combustion at varying speeds.

These findings align with previous studies, where the introduction of oxygenated additives, such as diethyl ether, has been shown to enhance combustion efficiency by improving fuel-air mixing and reducing incomplete combustion (Azad *et al*., 2023; A.V.S.L *et al.,* 2021). The observed trends in BTE variation with load and speed are consistent with the general understanding that increased thermal and mechanical efficiencies at higher loads and speeds contribute to overall engine performance improvements.

(a)

(b)

Figure 4: (a) Influence of Load on Brake Thermal Efficiency at 1500 rpm and (b) Impact of Speed on Brake Thermal Efficiency under a 2000N Load

**3.3. Emission**

Carbon monoxide (CO) is a colourless, odourless, and toxic gas formed due to incomplete combustion, poor fuel-air mixing, and locally rich fuel zones (Vijayakumar and Mukesh 2017). Figures 5a and b illustrate CO emissions with load and speed variations. CO emissions decrease for B100 (500N–1000N), B100E5 (1000N–1500N), and B100EE5 (2000N–2500N), attributed to fuel additives enhancing combustion efficiency. B80EE5 also exhibits lower CO emissions than B0, B20, B40, B60, and B80, reinforcing the impact of fuel formulation. At higher engine speeds, B100EE5 produces the lowest CO emissions due to its higher oxygen content and diethyl ether additive, promoting complete combustion (Srithar *et al.,* 2017). These findings align with studies emphasizing biodiesel blends and oxygenated additives in reducing CO emissions (Mukesh *et al.,* 2013; Srithar *et al.,* 2014). Carbon dioxide (CO₂), a colourless gas denser than dry air, forms through complete fuel oxidation. Figures 6a and b show CO₂ emissions with load and speed variations. B100EE5 and B80EE5 exhibit higher CO₂ emissions than B100 and B80, indicating more efficient combustion, enhanced by the 5% diethyl ether additive. This aligns with studies demonstrating that oxygenated additives promote complete oxidation, increasing CO₂ emissions while reducing incomplete combustion by-products (Azad *et al.,* 2023; A.V.S.L *et al.,* 2021). Hydrocarbons (HCs) are unburned fuel emissions, indicating incomplete combustion. Figures 7a and 7b show HC emissions under varying load and speed. B100EE5 and B80EE5 have the lowest HC emissions compared to B100 and B80, while B100E5 and B80E5 also show reductions. The 5% fuel additive enhances combustion, reducing unburned fuel and improving thermal efficiency (Azad *et al.,* 2023; A.V.S.L *et al.,* 2021). This supports findings that oxygenated additives improve air-fuel mixing, reducing HC emissions (Azad *et al.,* 2023; A.V.S.L *et al.,* 2021). Nitrogen oxides (NOₓ), primarily NO and NO₂, form at high combustion temperatures. Figure 8 illustrates NOₓ emissions under varying load and speed. A slight decline is observed with increasing load at 1500 rpm and increasing speed at 2000 N, attributed to decreasing combustion temperatures (Murillo *et al.,* 2007). B100EE5 and B80EE5 exhibit the lowest NOₓ emissions compared to B100 and B80, with B100E5 and B80E5 showing a similar trend. The 5% fuel additive influences combustion characteristics, reducing NOₓ emissions by lowering combustion temperatures.

**(a)**

**(b)**

Figure 5: (a) Influence of Load on Carbon Monoxide Emissions at a Fixed Speed of 1500 rpm and (b) Influence of Speed on Carbon Monoxide Emissions at a Constant Load of 2000 N

(a)

(b)

Figure 6: (a) Influence of Load on CO₂ Emissions at a Constant Speed of 1500 rpm (b) Impact of Speed on CO₂ Emissions at a Fixed Load of 2000 N

(a)

(b)

Figure 7: (a) Variation of Hydrocarbon Emissions with Load at a Constant Speed of 1500 rpm and (b) Influence of Speed on Hydrocarbon Emissions at a Fixed Load of 2000 N

(a)

(b)

Figure 8: (a) Variation of Nitrogen Oxides Emission with Load at a Constant Speed of 1500 rpm; (b) Variation of Nitrogen Oxides Emission with Speed at a Constant Load of 2000 N.

**4.0 CONCLUSION**

This study investigated the performance and emission characteristics of a compression ignition (CI) engine fuelled with rubber seed oil biodiesel and blended with ethanol and diethyl ether as additives. The biodiesel was synthesized through transesterification, and its chemo-physical properties were analysed following ASTM standards. The experimental results revealed that blending rubber seed oil biodiesel with ethanol and diethyl ether significantly influenced fuel properties, engine performance, and emissions.

The results demonstrated that the addition of diethyl ether and ethanol improved the combustion characteristics of biodiesel by enhancing brake thermal efficiency (BTE) and reducing brake-specific fuel consumption (BSFC). Among the tested fuel samples, B80EE5 and B60EE5 exhibited superior performance due to their optimized fuel properties, leading to improved combustion and higher energy conversion efficiency. The presence of oxygenated additives contributed to better atomization and reduced ignition delay, resulting in more complete combustion.

From an emissions perspective, the biodiesel blends significantly reduced carbon monoxide (CO) and hydrocarbon (HC) emissions compared to conventional diesel fuel. The addition of ethanol further decreased CO and HC emissions due to its high oxygen content, promoting more complete oxidation of the fuel. However, nitrogen oxides (NOₓ) emissions exhibited a slight reduction at higher loads, which can be attributed to the cooling effect of ethanol and diethyl ether on combustion temperature. Carbon dioxide (CO₂) emissions increased with biodiesel and oxygenated additives, indicating more complete combustion.

The study confirms that rubber seed oil biodiesel, when blended with ethanol and diethyl ether, is a promising alternative fuel for CI engines. The results suggest that B80EE5 and B60EE5 blends offer an optimal balance between performance and emissions, making them suitable for practical applications. However, further studies on long-term engine durability, cold flow properties, and economic feasibility are recommended to enhance the adoption of rubber seed oil biodiesel as a sustainable energy source.

Overall, this research contributes to the ongoing efforts to develop alternative fuels that enhance energy security, reduce environmental impact, and promote sustainable development. The findings underscore the potential of rubber seed oil biodiesel with oxygenated additives as an eco-friendly fuel option for the transportation and industrial sectors.

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