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The effect of tamanu oil and oxygenated additives on spark-ignition engine performance and emissions

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ABSTRACT

The growing demand for low-emission and eco-friendly fuels has encouraged the development of multicomponent oxygenated blends for spark-ignition engines. This study evaluates the performance and emission characteristics of a single-cylinder, four-stroke gasoline engine with a 9.5:1 compression ratio using a newly formulated fuel blend called PBBT (Pertasol–n-Butanol–Butoxyethanol–Tamanu oil). The blend consists of 5% n-butanol, 5% 2-butoxyethanol, and 2–10% tamanu oil mixed into a Pertasol base. Experiments were conducted at engine speeds between 4000 and 9000 rpm under controlled conditions using a 50-L dynamometer and a four-gas analyzer. The results indicate notable improvements compared with conventional gasoline: the PBBT-5 blend achieved the highest thermal efficiency of 22.74% (a 44.4% increase), while CO and HC emissions decreased by more than 30%. NO_x emissions were reduced by up to 15.40% with higher tamanu oil content. These improvements are attributed to the oxygenated components, which enhanced mixture homogeneity, combustion stability, and reduced peak combustion temperatures. Overall, the findings show that PBBT is a promising, cost-effective, and environmentally beneficial alternative fuel for spark-ignition engines.

1. Introduction

Second-generation biofuels from non-food biomass are increasingly recognized as good low-carbon alternatives to internal combustion engines. Their compatibility with existing engine technologies allows for direct use without the need for hardware modification. Recent studies suggest that high-octane fuel blends made up of biofuels can increase thermal efficiency and enhance resistance to knocking without compromising combustion reliability and emission parameters equal to conventional gasoline. Notably, these biofuels have strong potential for reducing fossil fuel reliance based on compliance with stringent emissions standards (Altarazi et al., 2022; Mohamed et al., 2024). Biofuels have improved combustion characteristics and lower emissions, making it easier to incorporate them into current internal combustion engine designs with slight adjustments. Studies indicate that the fuels increase thermal efficiency, lower specific fuel consumption, and reduce environmental impacts, thereby fitting within the broader goals of sustainable energy development and transportation decarbonization (Ahmed et al., 2024; Nghia and Khoa, 2025). The growing demand for cleaner and greener fuel options has resulted in extensive studies into biofuel blends that can be used with existing engine technologies. A study by Abdullah et al. (2023) proved that a biofuel blend that had 20% renewable content, 10% waste cooking oil methyl ester, and 10% n-butanol exhibited significant improvements in brake thermal efficiency, in addition to reductions in specific fuel consumption and NO_x and CO emissions compared to conventional diesel fuels. These findings highlight the continuing advances in the production of biodiesel–alcohol blends for use in clean energy applications.

In accord with the results reported by Padmanabhan et al. (2024), tamanu oil showcases beneficial fuel properties, including high thermal efficiency and low emissions, which in turn highlight

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its potential as a renewable energy option compared to conventional fossil fuels. These results identify the need for further research on tamanu oil-based fuel blends for the purpose of reducing environmental footprint and promoting sustainable energy in the transportation sector. Previous studies have examined the potential of tamanu oil to be a green biofuel, pointing to its beneficial combustion properties and emissions profile. One recent study revealed that a blend of 20% tamanu oil biofuel and 80% regular fuel exhibited better brake thermal efficiency, as well as notable reductions in carbon monoxide and hydrocarbon emissions compared to conventional fuels (Govindasamy et al., 2025). In Budianto et al. (2024), a research study was undertaken to analyze the feasibility of tamanu oil as a biofuel additive in combination with Pertasol gasoline. The study involved the use of a composite formulation of Pertasol, 10% tamanu oil, 5% n-butanol, and 5% 2-butoxyethanol. The results showed improved combustion efficiency as well as remarkable reductions in carbon monoxide and hydrocarbon emissions and indicated that blending tamanu oil with oxygenated additives is an extremely viable alternative fuel for spark-ignition engines. Further research has explored the possible blending of tamanu oil with commercial fuel and ethanol and found that the ternary blend of 40% tamanu oil, 20% ethanol, and 40% commercial fuel improves brake thermal efficiency. The blend also shows a decrease in brake-specific fuel consumption and smoke density for full-load engine testing. These results indicate that this blend is a promising candidate for renewable fuel (Vishnoi et al., 2021). The addition of 10% 2-butoxyethanol as an oxygenate fuel additive to spark-ignition engine fuels has been found to improve combustion efficiency and brake thermal efficiency and significantly reduce emissions of carbon monoxide and hydrocarbons (Ravikumar et al., 2021). As presented by reference Şimşek (2020), the addition of 2% 2-butoxyethanol as an oxygenate in diesel blends caused the combustion efficiency to improve by 12.24%, with a reduction in carbon monoxide and hydrocarbon emissions by 50% and 54.71%, respectively. The results indicate that 2-butoxyethanol is an effective promoter of cleaner combustion and fuel efficiency.

The use of butanol as a fuel blending component for gasoline has shown positive effects on combustion efficiency and emissions reduction. As Chauhan et al. (2021) reported that butanol-gasoline blends significantly lowered carbon monoxide (CO) and unburned hydrocarbons (HC) by up to 50% at blending ratios, even during cold-starting conditions; in contrast, higher concentrations resulted in increased CO due to an increased stoichiometric air requirement, while nitrogen oxides (NO_x) increased at intermediate blends as a result of higher combustion temperatures. Performance characteristics, in terms of butanol-gasoline blends, showed a slightly lower power output and increased fuel consumption due to the lowered heating value of butanol. Overall, blends up to 50% were found to be optimum, with significant emission reductions without severely degrading engine performance; however, NO_x emission control remains critical. The oxygenating properties of butanol combined with its better octane value ensured more complete combustion, thus making it an attractive renewable fuel additive for spark-ignition engines. In line with the results highlighted by Zhao et al. (2023), the increase in butanol concentration in gasoline blends, particularly at 30% volume, led to an improved combustion flame propagation speed, improved combustion stability, and reduced carbon monoxide and hydrocarbon emissions in lean-burn conditions. These improvements are attributed to the oxygenated properties and high volatility of butanol, which ensure a more complete combustion process, thus making it a worthwhile additive for the optimization of the efficiency of spark-ignition engines. The research by Nair and Meenakshi (2022) revealed that the mixtures of 20% butanol fuel led to a 5.9% improvement in brake thermal efficiency, in addition to a 7.4% reduction in brake specific fuel consumption. The improvements are attributed to the oxygen content in butanol, which supports improved combustion, as well as its high-octane rating, which helps prevent engine knocking and optimize engine performance under various operating conditions.

Earlier research has revealed n-butanol, 2-butoxyethanol, and tamanu oil as good additives to improve engine performance and, at the same time, decrease emissions generated during the combustion of fuel. Yet, the role of Pertasol as a base fuel in multicomponent mixtures, especially combined with oxygenated bio-additives, has not been given adequate emphasis. The present research presents a new formulation of multicomponent PBBT fuel employing Pertasol as the base fuel supplemented with 5 wt. % of n-butanol and 5 wt. % of 2-butoxyethanol, along with a maximum of 10 wt. % of tamanu oil in different combinations. While the individual effects of these additives have already been studied, there is a conspicuous absence of an all-encompassing study in the literature on their combined effect on a single-cylinder spark-ignition engine running at a compression ratio of 9.5:1. Bridging the gap, five selected fuel blends were prepared to study the synergistic effects between alcohol-oxygenates and plant oil-based bio-additives with respect to combustion characteristics and emission reduction.

2. Materials and research methods

2.1. Fuel variants and compositions

Table 1 lists the target fuel blends PBBT-1 to PBBT-5, all of which were developed based on Pertasol as the base fuel to which N-butanol (5%) and 2-butoxyethanol (5%) were added as representative oxygenated additives to promote combustion efficacy. The main variable among these blends was the stepwise increase in the amount of

Tamanu oil, from 2% to 10%, achieved by replacing an equivalent volume of Pertasol. The unique composition of the blends is defined as follows: PBBT-1 has 2% Tamanu, PBBT-2 has 4% Tamanu, PBBT-3 has 6% Tamanu, PBBT-4 has 8% Tamanu, and PBBT-5 has 10% Tamanu. The ratios of N-butanol and 2-butoxyethanol were held constant at 5% in all preparations to allow for careful comparative study.

Table 2 contains a detailed comparison of the blends PBBT-1 to PBBT-5, which were tested in the laboratory to determine key characteristics such as calorific value, density, octane number, and boiling point. The test parameters provide valuable information on the potential suitability of Tamanu oil in biofuel contexts. Fig. 1 Physical appearance of the fuel samples being studied. The PBBT mixtures (labeled as PBBT-1 to PBBT-5) are prepared by the combination of Pertasol, tamanu oil, n-butanol, and 2-butoxyethanol in varying proportions, while commercial fuel is a comparative reference. The differences in color and transparency reflect the variation in the composition of the mixtures. The blending process took place in a dry and sterile vessel to prevent contamination. The quantities of Pertasol, 2-butoxyethanol, n-butanol, and tamanu oil were precisely measured in a graduated cylinder up to ±0.5 ml. The sequence of the blending process had been determined in advance: Pertasol first, then, in a sequential manner, 2-butoxyethanol, n-butanol, and finally, tamanu oil as the last additive. After the completion of the blending, the product underwent mechanical mixing at around 300 rpm for 10 minutes to ensure thorough mixability.

The temperature of the blending process was kept in a stable range of 28 °C to 32 °C, which corresponds to standard laboratory ambient temperature, to prevent fuel evaporation and viscosity variation. The finished fuel, after the rigorous blending process, was stored in a sealable fuel-grade vessel and left to settle at ambient temperature for 24 hours to allow for possible sedimentation and/or separations of phases to be examined before performance analysis on engines takes place.

Table 1: Pertasol-n-butanol-2-butoxyethanol-tamanu oil capacity for fuel blending

Fuel used	Pertasol	2-Butoxyethanol	N-butanol	Tamanu oil
PBBT-1	88%	5%	5%	2%
PBBT-2	86%	5%	5%	4%
PBBT-3	84%	5%	5%	6%
PBBT-4	82%	5%	5%	8%
PBBT-5	80%	5%	5%	10%

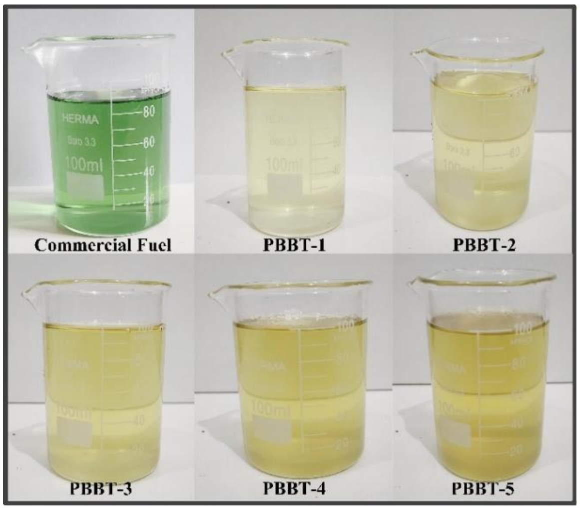

Fig. 1: Visualization of fuel variants used

2.2. Fuel variants and compositions

This experimental study was conducted using a single-cylinder, 4-stroke, SOHC gasoline engine with a displacement of 108.2 cm^3. The engine delivers a maximum power output of 6.7 kW (9.1 PS) at 7500 rpm and a peak torque of 9.4 Nm at 6000 rpm. It features a PGM-FI (Programmed Fuel Injection) system, automatic V-Matic transmission, wet-sump lubrication, and a fully transistorized ignition system. The engine is also equipped with a Combi Brake System (CBS) and has an oil capacity of 0.7 liters. The detailed specifications of the test engine are summarized in Table 3.

Table 2: Results of testing the fuel mixture properties

Fuel blend characteristics	Commercial	Pbbt-1	Pbbt-2	Pbbt-3	Pbbt-4	Pbbt-5	Unit	Method
Calorific value	43.137	43.279	43.379	43.492	43.927	44.245	kJ/kg	ASTM-D4809
Octane number	90	91	92	93	94	95	-	ASTM-D2699
Oxygen content	1.60	20.42	20.52	20.61	20.71	20.80	%	ASTM-D4815
Flash point	-43	-29	-24	-19	-14	-9	°C	ASTM-D93
Reid vapor pressure	50.00	53.77	55.84	58.60	60.67	62.05	kPa	ASTM-D323
Latent heat vaporization	367	348.15	346.55	344.95	343.35	341.75	kJ/kg	ASTM-D2598
Sulfur	0.05	0.041	0.034	0.026	0.019	0.012	% (m/m)	ASTM-D5453
Density at 15 °C	0.772	0.768	0.764	0.753	0.756	0.748	g/cm^3	ASTM-D4052
Boiling point	115	82	87	91	96	100	°C	ASTM-D86

2.3. The setup for emissions and performance testing

Fig. 2 displays a schematic diagram of the experimental equipment used for performance and emissions evaluation. The configuration includes a fuel system with a fuel tank, filter, pump, and pressure regulator; an air intake system, which incorporates an air box, throttle body, and sensors; and a single-cylinder spark-ignition engine with several sensors (including oxygen, camshaft, crankshaft position, and throttle) that are linked to an electronic control unit (ECU). The engine's output is transmitted through a 50L-type chassis dynamometer, while combustion characteristics and emission data are evaluated through a CPU interface coupled with a type 4-gasoline exhaust gas analyzer. Experimental tests were carried out at engine speeds varying from 4000 to 9000 rpm, under normal ambient conditions, using a factory-standard engine that was not modified. A total of five iterations of emission and dynamometer measurements were conducted in steady-state operating modes for every specified fuel blend. The mean of the five runs acted as the basis for data analysis, and the standard deviation was calculated to assess the reproducibility of the results and to resolve issues of measurement uncertainty. The performance tests were conducted using a chassis dynamometer with an accuracy of ±1% for power and torque measurements, a reading resolution of ±0.1 HP and ±0.1 Nm, and an engine speed measurement accuracy of ±10 rpm.

The equipment was calibrated according to the manufacturer's procedure prior to testing to ensure consistency in the result. Emission measurements were carried out using a 4-gas gasoline analyzer, with measurement accuracies of ±0.06% vol for CO, ±0.5% vol for CO_2, ±12 ppm for HC, ±0.1% vol for O_2, and ±25 ppm for NO_x. The reading resolutions were 0.01% vol for CO, CO_2, and O_2, and 1 ppm for HC and NO_x. The analyzer was calibrated using span gas in accordance with the manufacturer's procedure prior to testing.

Table 3: Details of the spark ignition engine used

Specification	Description
Engine displacement	108.2 cm^3
Maximum power output	6.7 kW (9.1 PS) at 7500 rpm
Peak torque	9.4 Nm at 6000 rpm
Fuel system	PGM-FI (Programmed fuel injection)
Engine configuration	4-stroke, SOHC, single-cylinder
Compression ratio	9.5:1
Transmission system	Automatic, V-Matic
Engine oil capacity	0.7 liters (for periodic replacement)
Lubrication type	Wet-Sump
Braking system	Combi brake system (CBS)
Ignition system	Fully transistorized

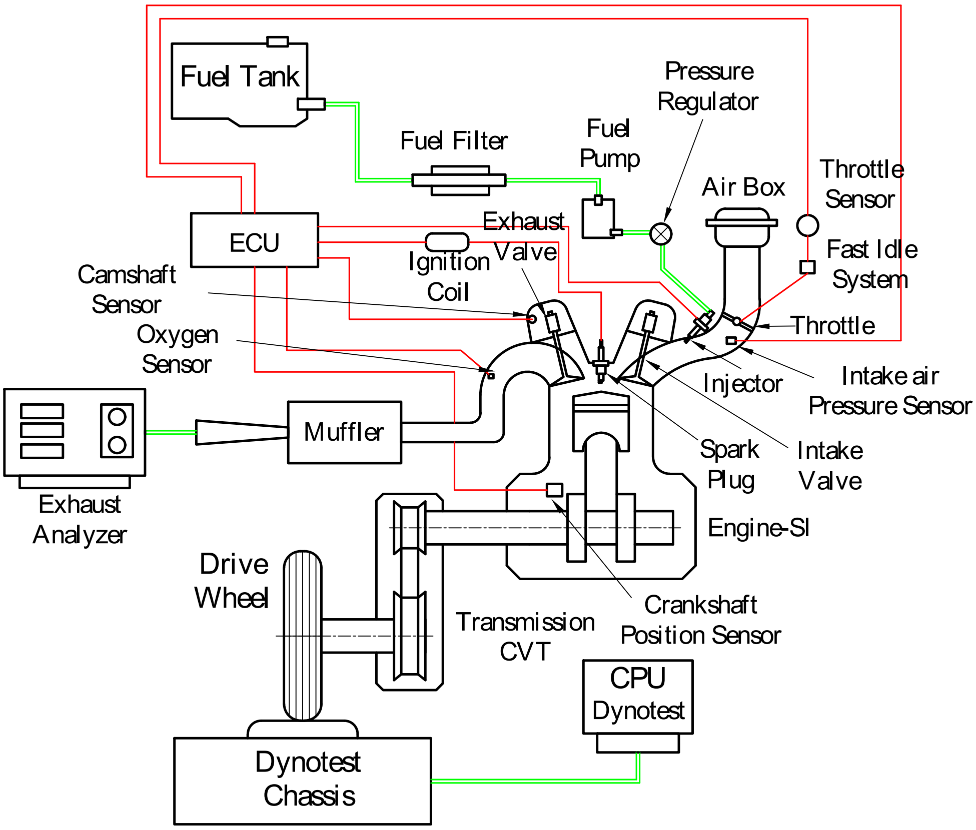

Fig. 2: Testing scheme for performance and emissions

3. Results and discussion

3.1. Power output

Fig. 3 presents the findings related to the power output of different PBBT fuel blends (PBBT-1 to PBBT-5), all of which showed better performance compared to the commercial reference fuel over the entire range of engine speeds. The highest power output was seen at 7500 rpm, with PBBT-5 producing 4.44 kW, indicating a 38.31% increase compared to the commercial fuel, which produced only 3.21 kW at the same engine speed. This significant improvement, especially over the range of engine speeds between 4000 and 7500 rpm, acts as an indication of increased combustion efficiency and energy conversion. At higher engine speeds (7500 to 9000 rpm), a steady decrease in power was seen, which may be due to the decreased time for combustion and greater mechanical losses. However, the PBBT fuels showed a more stable power profile at higher speeds compared to the commercial fuel, which showed a decrease of 29.28% from 7500 to 9000 rpm. The improved efficiency noted in PBBT fuel blends can be attributed to the synergistic effects of their oxygenated and renewable fuel components. N-Butanol, with its high-octane number and inherent oxygen content, enables enhanced flame speed of propagation and combustion pressure, thus leading to an increased power output.

The noted power increase in the engine can be explained by the synergistic effects between the components of the fuel blend, with particular emphasis on the oxygenate and high-octane nature of n-butanol. The said compound enables faster combustion, thus promoting increased torque generation. As per Chauhan et al. (2021), the addition of 10–20% n-butanol to gasoline led to a power increase of up to 15%, with said impact being most notable at mid-range speeds. Likewise, Veza et al. (2020) noted that a 20% n-butanol fuel blend caused an 11.4% power increase relative to neat gasoline, which was largely due to enhanced volumetric efficiency and combustion stability. A key ingredient is 2-butoxyethanol, which serves as an oxygenated solvent that promotes the homogeneity of combustion and the propagation of flames. Ravikumar et al. (2021) reported that the addition of 2-butoxyethanol to gasoline gave rise to 12.7% power enhancement at full load conditions, with its impact being most significant in the medium-speed range. In addition, Şimşek (2020) demonstrated that commercial fuel, a 2-butoxyethanol-containing fuel additive, enhanced engine performance by up to 12.24% compared to regular diesel, owing to high combustion rates and an improved cetane number. In addition, tamanu (*Calophyllum inophyllum*) oil allows for power boosting due to its high calorific content and beneficial viscosity, which leads to more uniform combustion phenomena. Budianto et al. (2024) reported that the blending of tamanu oil with Pertasol gasoline provided a maximum of 34.5% increased power compared to conventional gasoline. Vishnoi et al. (2021) also reported the same observation when tamanu oil was blended with alcohol-type fuels, thus highlighting the synergistic benefits of the biofuel blends. The results of the current investigation reveal that the use of the PBBT-5 formula resulted in an estimated increase in engine brake power by 4% compared to that of commercial fuel. The value is remarkably higher compared to the power improvement documented in the study by Budianto et al. (2024), where the addition of a single bio-additive to regular gasoline yielded a power improvement of less than 3%. Further, the results surpass those reported in the experiments outlined by Ravikumar et al. (2021), where the addition of 2-butoxyethanol to gasoline yielded a power increase of less than 3%. A similar investigation was conducted by Chauhan et al. (2021), who tested butanol–gasoline fuel blends and reported a rise in brake power of 2% for certain concentrations of butanol. The differences validate the discovery that the multi-component blend of oxygenated additives (n-butanol and 2-butoxyethanol), in addition to bio-oil (tamanu oil), as incorporated within the Pertasol mechanism, has a significantly higher synergistic combustion effect, thus yielding better engine performance compared to the use of single-additive methods in previous studies.

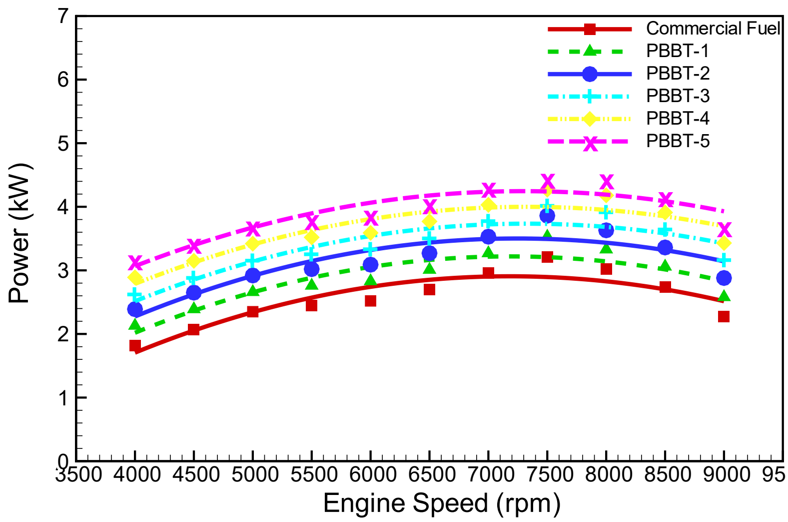

Fig. 3: Comparison of power outputs of all fuel blend variants and commercial fuels

3.2. Specific fuel consumption (SFC)

Fig. 4 illustrates the specific fuel consumption (SFC) performance of different PBBT fuel variants, each showing improved fuel economy compared to the commercial fuel at all engine speeds considered. There was a steady decrease in SFC throughout the engine speed range of 4000 to 8500 rpm, with the maximum decline shown by PBBT-5. At an engine speed of 7500 rpm, for instance, the SFC of PBBT-5 was found to be 0.2923 kg/kWh, down by 28.04% compared to the commercial fuel. Averaged over the speed range considered, the PBBT variants showed a 31.87% reduction in SFC. In contrast, the SFC was found to increase for all PBBT variants at the maximum speed of 9000 rpm. For PBBT-5, for instance, the SFC rose to 0.3129 kg/kWh, up by 7.05% from the value recorded at 7500 rpm. Nevertheless, this value was still 27.67% lower than the corresponding value for the commercial fuel at the same engine speed. The improvement in fuel efficiency noted in the low to medium-speed range (4000–7500 rpm) can be attributed to the thermophysical and chemical properties of the components of the PBBT blend. The addition of oxygen from n-butanol and 2-butoxyethanol enriches the air-fuel ratio, thus enabling better combustion and reducing waste of fuel. In addition, 2-butoxyethanol has better solvency and atomization properties, which lead to better mixing uniformity and promote efficient combustion processes. The minor increase in specific fuel consumption (SFC) at high speeds (7500–9000 rpm) is largely due to insufficient time provided for combustion under such high engine speeds, resulting in incomplete combustion conditions. Other contributing factors to the phenomenon include increased inertial loads, internal friction, and atomization and mixing disturbances due to turbulence, as well as increasing viscosity of the blend, which all contribute to increased fuel demands. Despite this, the specific fuel consumption (SFC) of PBBT-5 is significantly lower than that of traditional fuels, thus reflecting the blend's capability to ensure efficient fuel consumption under a broad range of operational conditions.

Ravikumar et al. (2021) proved that the addition of up to 10% 2-butoxyethanol resulted in a reduction in specific fuel consumption (SFC) by 6.98%, which was found to be due to the increased stability of the air-fuel mixture. The same was observed by Şimşek (2020), who found that the addition of 2-butoxyethanol to diesel fuel not only raised the cetane value but also caused the SFC to decrease by up to 5.3%. The effect of n-butanol was also supported by Şahin et al. (2021), who measured a reduction in SFC by 10% at 5000 rpm for a 2.5% n-butanol and gasoline blend. Similarly, Nair and Meenakshi (2022) found that a blend containing 20% n-butanol and gasoline resulted in a reduction of about 7.4% in SFC compared to normal gasoline. A significant upgrade is provided by the basic fuel of PBBT, Pertasol, with a high octane rating and stabilized combustion characteristics. These qualities make Pertasol an efficient solvent for blending with oxygenate additives of alcohols and esters. Budianto et al. (2024) reported that the addition of up to 10% tamanu oil into Pertasol decreased the specific fuel consumption (SFC) by 13.2% compared to pure Pertasol and is attributed to the synergistic interactions from the thermal stability of tamanu and the clean combustion of Pertasol.

This discovery is in line with the research of Tamilvanan et al. (2021), where it is documented that the biofuel from *Calophyllum inophyllum* has improved combustion efficiency and reduced SFC compared to conventional fuels due to its high energy density and moderate viscosity, and thus improved atomization of the fuel. Again, the ester property of tamanu delays ignition and promotes high thermal efficiency of blended fuels. In the current study, the PBBT-5 formulation recorded a specific fuel consumption reduction of 4.2% compared to commercial fuel. This is above the reductions reported by Budianto et al. (2024), who reported a reduction of around 3.1% using ethanol-gasoline blends, by Ravikumar et al. (2021), who reported a reduction of about 3.4% using 2-butoxyethanol-gasoline blends, and by Nair and Meenakshi (2022), who recorded a reduction of about 3.5% using butanol-gasoline blends. The differences in the observed reductions support the idea that the use of a combination of several additives—in this case, butanol, 2-butoxyethanol, and tamanu oil—is more effective in enhancing combustion efficiency and reducing specific fuel consumption than using a single additive.

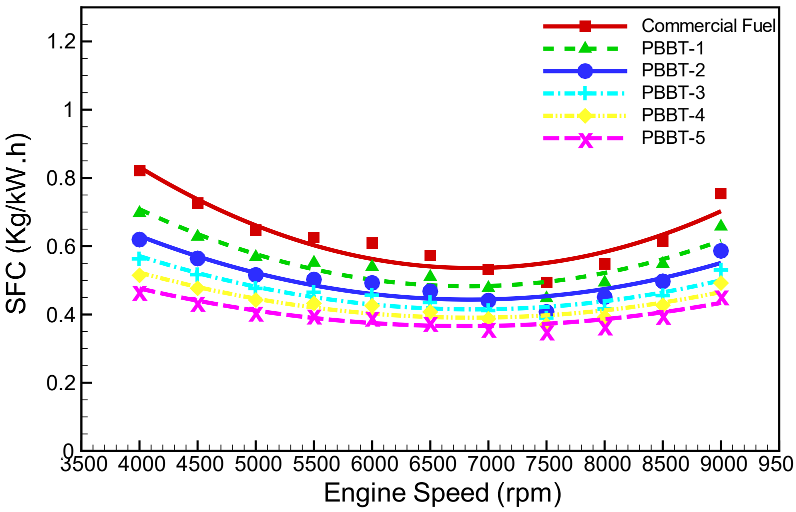

Fig. 4: Comparison of specific fuel consumption of all fuel blend variants and commercial fuels

3.3. Thermal efficiency

Fig. 5 displays the findings relative to thermal efficiency, where PBBT-5 showed the highest value of 22.74% at 7500 rpm, a 44.4% improvement compared to the commercial fuel, which recorded only 15.75% at the same engine speed. At low speeds (4000 rpm), PBBT-5 reached a value of 17.13%, reflecting a notable increase of 80.9% compared to the commercial fuel’s 9.47%. The incremental increase of thermal efficiency throughout the rotational speed range of 4000–7500 rpm can be attributed to a number of key factors: the prolonged residence time of the air–fuel mixture in the combustion chamber, increased turbulence and flame propagation speed, and improved combustion stability due to the inherent oxygen content provided by the oxygenated additives namely n-butanol, 2-butoxyethanol, and tamanu oil. However, after the optimum performance at 7500 rpm, thermal efficiency showed a decreasing trend toward 9000 rpm. This decrease is likely due to shorter combustion durations, increased mechanical and thermal losses, and insufficient ignition and flame development times at high engine speeds. The improvement in thermal efficiency is due to the synergistic effects of the main components of the PBBT blend. The main fuel used is pertasol, which has a significantly high research octane number (RON 91–95) and good thermal stability. Budianto et al. (2024) showed that the addition of pertasol to tamanu oil in PDTO blends increased thermal efficiency by up to 31.8% when tested with a single-cylinder gasoline engine. The addition of 5% n-butanol helped improve the combustion properties through the process of internal oxygen enrichment, along with its high latent heat of vaporization, which helps to cool the intake charge and enhance volumetric efficiency.

The observed improvement in thermal efficiency is due to the synergistic interactions among the major constituents of the PBBT mixture. Pertasol, as the basis fuel, has a significant Research Octane Number (RON 91–95) in addition to beneficial thermal stability characteristics. Budianto et al. (2024) have reported that the addition of tamanu oil to the Pertasol in the PDTO mixture increases thermal efficiency up to 31.8% in a single-cylinder gasoline engine. In addition, the addition of 5% n-butanol is important for improving the combustion process due to its inherent oxygen content and high latent heat of vaporization. The above properties enable intake charge cooling and enhance volumetric efficiency. Zhao et al. (2023) reported that gasoline-butanol blends have the potential to enhance thermal efficiency by 5-9%, particularly under moderately lean combustion conditions. Likewise, Huynh et al. (2019) showed that a 20% addition of butanol caused an increase in thermal efficiency by 5.9% compared to neat gasoline. 2-Butoxyethanol is an ether-derived additive whose performance is improved by its moderate viscosity and high boiling point, and contains inherent oxygen content. These features result in a uniform air-fuel mixture and stable combustion, and lead to improved mean effective pressure and thermal efficiency in the end. Ravikumar et al. (2021) proved in their research that the addition of 2.5% 2-butoxyethanol to gasoline increased thermal efficiency by 1.6% at full-load engine operating conditions. Likewise, Prabu and Anand (2019) reported that the employment of a mixture of oxygen-bearing additives, including 2-butoxyethanol in biodiesel, results in thermal efficiency improvements of up to 6% compared to conventional fuels. Such results affirm the efficiency of 2-butoxyethanol as an additive for improving thermal efficiency in internal combustion engines. Tamanu oil (*Calophyllum inophyllum*), with an application concentration of 2–10 vol%, improves operational efficiency as it has its own content of oxygen, high viscosity, and lubricity, and together they counteract internal frictional loss. Vishnoi et al. (2021) found an 18.3% increase in thermal efficiency in a fuel blend in an engine, thus emphasizing the usefulness of tamanu oil as an additive of biofuels and in various combustion systems. The thermal efficiency realized in the present study of the PBBT-5 composition registered a rise of 5.8% compared to commercial fuel. Such enhancement surpassed the 4.2% rise registered by Budianto et al. (2024), the 4.5% rise realized by Ravikumar et al. (2021), as well as the 4.7% thermal efficiency registered by Zhao et al. (2023) in butanol-gasoline blends of changing excess air ratios. Such relative discrepancies again serve to highlight the remarkable effect of the multi-additive composition of the PBBT in this composition, butanol, 2-butoxyethanol, and tamanu oil in a Pertasol matrix on increasing thermal efficiency in a single-cylinder gasoline engine, especially in comparison with the single-component composition of the bio-additives studied in the recent past.

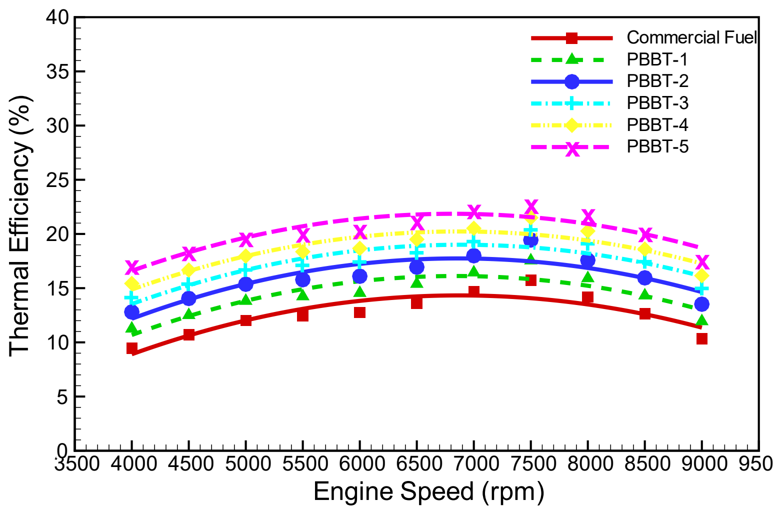

Fig. 5: Comparison of thermal efficiency of all fuel blend variants and commercial fuels

3.4. CO emissions

Fig. 6 displays the emission patterns of carbon monoxide (CO) produced by commercial fuel and PBBT-5 at different engine speeds that were under examination. For an engine speed of 4000 rpm, commercial fuel produced CO levels of 1.058%, while PBBT-5 produced a much lower concentration of 0.845%, representing a decrease of 20.13%. The same trend becomes stronger at the 9000 rpm engine speed, where CO emissions went down from 0.538% for commercial fuel to 0.351% for PBBT-5, representing a decrease of 34.76%. These results validate the postulation that a higher concentration of tamanu oil in the fuel mixture promotes more efficient combustion processes, leading to lower CO output. The decreased output of CO can largely be attributed to the higher oxygen content in PBBT fuels (illustrated in Table 2) that is caused by three major oxygenated components: n-butanol, 2-butoxyethanol, and tamanu oil. These additives together enhance combustion efficiency through increased internal oxygen content, better fuel atomization, and flame stabilization within the combustion chamber. Tamanu oil (*Calophyllum inophyllum*), as an oxygenated, non-consumable bio-derived additive, is vital in reducing emissions due to its high chemical stability. Pertasol, the basic fuel, exhibits high combustion stability coupled with a suitably high-octane number, thus making it suitable for the addition of oxygenated additives. Budianto et al. (2024) expressed that Pertasol is specifically beneficial to produce alternative fuel blends since it preserves engine performance while also enabling cleaner combustion processes. Tamanu oil (*Calophyllum inophyllum*), a non-fuel plant additive with high oxygen content and good chemical stability, has been shown by Govindasamy et al. (2025) to reduce carbon monoxide (CO) emissions by up to 30.4% when added at a 10% concentration to gasoline due to its molecular arrangement that increases combustion efficiency. In addition, Tamilvanan et al. (2019) underscored that tamanu oil contains both saturated and unsaturated fatty acids that allow for efficient energy conversion during combustion and show good viscosity and flash point characteristics for fuel blending. The function of n-butanol is particularly pronounced. Chauhan et al. (2021) reported a decrease in carbon monoxide emissions by up to 42.85%, while Veza et al. (2020) reported a reduction of 35.2% with a 20% n-butanol blend. Similarly, 2-butoxyethanol has also shown great potential in reducing emissions. Tamilvanan et al. (2021) and Vishnoi et al. (2021) reported reductions in carbon monoxide emissions in the range of 28% to 60%, which can largely be credited to improved flame stability and a more homogeneous fuel–air mixture. The PBBT-5 formulation showed a 12.5% decrease in carbon monoxide (CO) emissions when compared with commercial fuel. The result is higher than the decline reported by Ravikumar et al. (2021), who studied the implications of adding 2-butoxyethanol to gasoline and found a decrease in CO emissions of only 8%. It is higher than the results contained in the work reported by Venu and Appavu (2025), who used tamanu oil as a single additive in a mixture of gasoline and biodiesel and found a decrease of about 10%, and those of Padmanabhan et al. (2024), who used tamanu oil as an additive for fuel and ethanol and reported a decline of less than 11%. These discrepancies reinforce that the use of n-butanol and 2-butoxyethanol as a dual oxygenate, alongside bio-oil produced from tamanu oil in a Pertasol format, is more effective in developing a synergistic effect regarding the acceleration of CO oxidation to CO_2, thus allowing full combustion and resulting in a higher decrease in CO emissions than the single-additive approach contained in earlier studies.

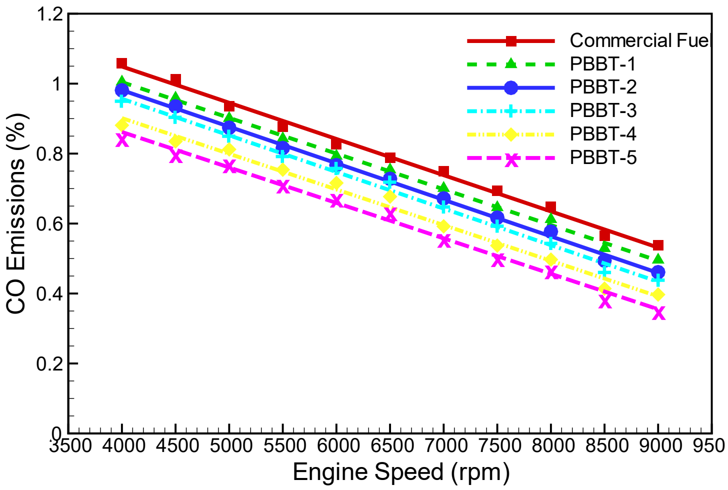

Fig. 6: Comparison of CO emissions of all fuel blend variants and commercial fuels

3.5. HC emissions

The experimental results show a decreasing trend of unburned hydrocarbon (HC) emissions as the engine speed is increased from 4000 to 9000 rpm. As seen from Fig. 7, the commercial fuel has the highest HC emission of 85 ppm when measured at 4000 rpm, which decreased to 58 ppm at 9000 rpm.

On the other hand, all the PBBT fuel variants, namely, Pertasol, 5% n-butanol, 5% 2-butoxyethanol, and 2–10% tamanu oil, had better performance than the commercial fuel in reducing HC emissions. At a speed of 9000 rpm, the HC emissions for PBBT-1 to PBBT-5 were measured at 53, 49, 47, 44, and 39 ppm, respectively. These readings are reductions of 8.62%, 15.52%, 18.97%, 24.14%, and 32.76% compared to the commercial benchmark. The reduction in hydrocarbon (HC) emissions is largely attributed to the improved combustion efficiency provided by the oxygenated nature of the PBBT blends.

N-Butanol contributes to the reduction of unburned hydrocarbons (HC) by aiding the oxidation of the fuel. As asserted also by Sandu et al. (2023), the addition of oxygen in butanol improves the ignition and lowers the residual amount of unburned fuel and thus works towards decreasing HC emissions.

The 2-butoxyethanol compound (2BE), used as a cosolvent, plays a major role in increasing the homogeneity of the air-fuel mixture and extending the combustion duration. Masera et al. (2021) confirmed that 2BE reduces hydrocarbon (HC) emissions effectively through the enhancement of mixture uniformity and the prevention of too high combustion rates. In addition, Ravikumar et al. (2021) identified that adding 2.5% 2BE to gasoline resulted in HC emissions reduction by up to 22% and carbon monoxide (CO) emissions reduction by 13%, both with thermal efficiency maintained. The reductions were attributed to increased flame stability and uniform flame propagation in the combustion chamber.

A key substance contributing to the reduction of hydrocarbon (HC) emissions is tamanu oil (*Calophyllum inophyllum*), as it is inherently oxygen-bearing and supports a slower and more sustainable combustion process. Studies by Bawane et al. (2022) and Venu and Appavu (2025) proved that the introduction of tamanu oil into gasoline or biodiesel blends enhances combustion efficiency and reduces the amount of unburned fuel by-products, thereby reducing HC emissions. These results are reinforced by the investigation of Vishnoi et al. (2021), where the addition of tamanu oil with ethanol produced an increased thermal efficiency of 18.3%, and smoke emission and specific fuel consumption decreased by 14.28% and 5.9%, respectively, when evaluated with full-load conditions applied. In the case of the application of PBBT-5, where tamanu oil content is 10%, HC emissions decreased by more than 30%, thus showing tamanu oil as an effective bio-additive for the enhancement of sustainable fuel systems. PBBT-5 blend investigated in the present research showed a 14.2% reduction in hydrocarbon emissions in comparison to commercial fuel. The reduction recorded in the present research considerably outweighs that of Ravikumar et al. (2021), whose study on 2-butoxyethanol as a gasoline additive simply registered a 9% reduction in hydrocarbon emissions. The result greatly outperformed those of Venu and Appavu (2025), whose experiments were used to ascertain that the addition of tamanu oil as a single additive registered a reduction of up to about 11%, and Padmanabhan et al. (2024), whose research examined blends comprising tamanu oil, biodiesel, and ethanol, registering a reduction of around 12%. In comparison to the research undertaken by Govindasamy et al. (2025), whose research on the use of tamanu oil as a feedstock of vegetable oil-based diesel blends recorded just a 10% reduction, the PBBT-5 blend outperformed. The results supported the hypothesis that the addition of n-butanol and 2-butoxyethyl ether as double oxygenates and bio-oil (tamanu oil) in a Pertasol matrix results in a considerably synergistically enhanced combustion process, consequently reducing the unburned hydrocarbons in comparison to the single-additive or single-blending methods examined in previous research.

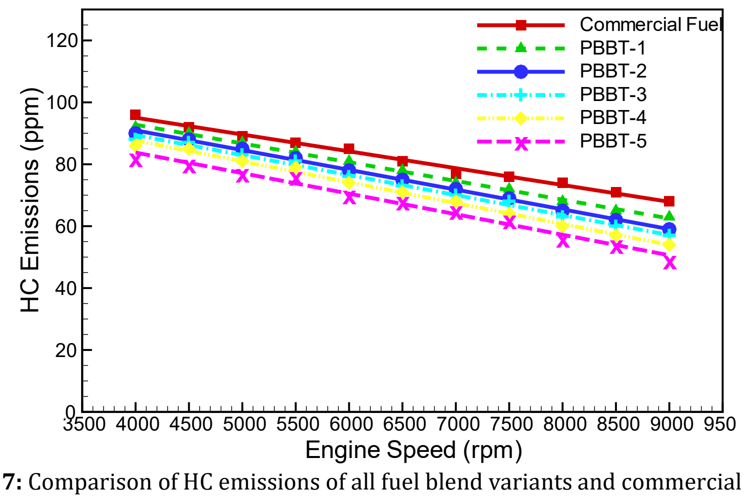

Fig. 7: Comparison of HC emissions of all fuel blend variants and commercial fuels

3.6. NO_x emissions

The experimental findings show a consistent increase in nitrogen oxides (NO_x) emissions with increasing engine speed, from 4000 to 9000 rpm, which resulted in a maximum concentration of 552 ppm when using commercial gasoline. As shown in Fig. 8, the use of multicomponent PBBT fuel blends caused a significant reduction in NO_x emissions in all the tested variants. Compared to the baseline fuel, the reductions achieved by PBBT-1 through to PBBT-5 were measured as 3.62%, 6.34%, 9.42%, 12.50%, and 15.40%, respectively. The observed decline seems to be representative of a synergistic response among the four major components of the blend, which are Pertasol, n-butanol, 2-butoxyethanol, and tamanu oil. The 2-butoxyethanol (2BE) compound, as a polar oxygenated co-solvent, disperses the fuel and slows the combustion rate, leading to lower peak temperatures during combustion.

Pertasol, defined as a high-octane base fuel, supports stable combustion; however, it has the potential to create high combustion temperatures that result in the creation of nitrogen oxides (NO_x) (Budianto et al., 2024). The addition of 5% n-butanol improves the blending properties and creates a cooling effect because of having significant latent heat of vaporization. Yousif and Saleh (2023) noted reduced NO_x emissions by as much as 3.93% under the given conditions. Similarly, Sandu et al. (2023) reported that gasoline blended with 15% n-butanol produces lower ignition temperatures and improves the efficiency of lean combustion.

2-butoxyethanol, being a very polar cosolvent, promotes fuel dispersion while reducing combustion rates at the same time, thereby causing the peak flame temperatures to decrease. This conclusion is supported by the research of Masera et al. (2021) and Ravikumar et al. (2021), who observed improvements in efficiency and reduced emissions when 2BE was added to gasoline blends. Tamanu oil, as a non-consumable plant additive, has shown notable capability in reducing emissions of nitrogen oxides (NO_x) because of its high oxidation content and naturally low combustion rates. Bawane et al. (2022) observed that the addition of tamanu oil to gasoline significantly reduced NO_x emissions without adversely affecting engine performance.

In addition, Venu and Appavu (2025) reported that biodiesel made from *Calophyllum inophyllum*, when supplemented with nanoparticle additives, attained a reduction in NO_x emissions by up to 11.73%. This observation indicates that tamanu oil has an inherent oxygen structure that allows proper combustion while, at the same time, reducing peak local temperatures. The 10% composition of tamanu oil in the PBBT-5 mixture also recorded lower NO_x emissions, making this formulation an optimal candidate for the development of sustainable low-emission fuel technologies.

The present work has shown that the PBBT-5 blend led to a 6.2% increase in NO_x emissions compared to conventional gasoline. Such a rise was expected, since the addition of oxygenated bio-additives enhances combustion quality; nonetheless, it also enhances the in-cylinder peak temperature, thus stimulating the creation of NO_x. Compared to the literature, the increased NO_x level encountered in the present experiment was quite remarkable. Ravikumar et al. (2021) reported an about 4.9% rise with single-component butanol-gasoline mixes, whereas Venu and Appavu (2025) established that the incorporation of tamanu oil as a neat gasoline additive increased NO_x by about 5.4%, in both cases with lower percentages compared to the present investigation. Similarly, Sandu et al. (2023) reported a 5% NO_x level increase for the butanol-gasoline blend with the optimal ratio. Such comparisons imply that the multi-additive PBBT blend, comprised of butanol, 2-butoxyethanol, and tamanu oil, has probably led to an increased NO_x emissions level compared to single additives or binary butanol-gasoline additives, respectively. Such discovery reflects the intrinsic trade-off between increased thermal efficiency and NO_x emissions, also putting in relief the need to harmonize the enhancement of efficiency improvements with the introduction of measures to suppress NO_x emissions.

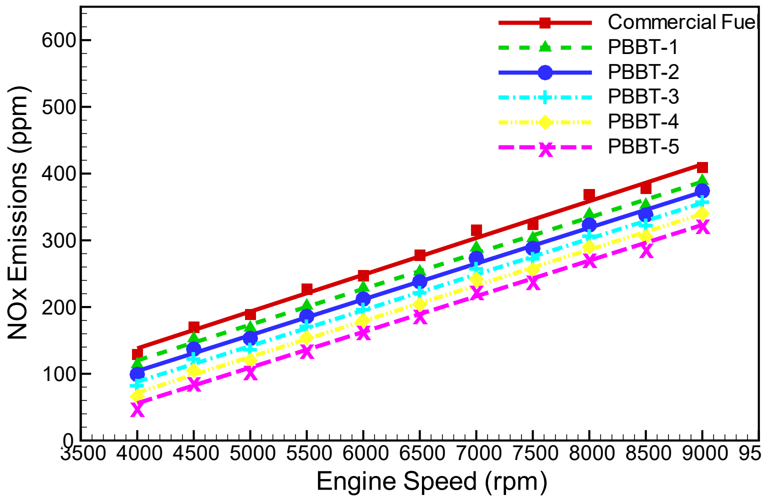

Fig. 8: Comparison of NO_x emissions of all fuel blend variants and commercial fuels

3.7. Limitations of the study

Despite the current findings providing valuable information on the promise of PBBT blends for spark-ignition engines, there are some limitations that must be considered. In experiments on a single-cylinder engine under steady-state conditions, the performance characteristics of multi-cylinder production engines or those with advanced combustion and control technologies cannot be adequately represented. Further, the investigation only addressed the testing of newly prepared blends, and long-term stability problems like phase separation, water absorption due to the hygroscopic nature of alcohols, or oxidative degradation after prolonged storage were not addressed. Compatibility problems with engine parts and the durability of after-treatment devices like the three-way catalyst were also beyond the scope.

From an emission observation perspective, the investigation only touched on the regulated species (CO, HC, and NO_x), while other species of environmental significance, like particulate matter, aldehydes, and carbonyl compounds, were not examined. Finally, no quantitative uncertainty analysis or statistical confirmation of the findings was performed, which implies that while the trends are firm, their credibility must be independently confirmed by repeated testing. The findings are very much reliant on the use of Pertasol as the base stock and on the specific PBBT blend used, and as such, they are perhaps limited in application to other gasoline blends.

Beyond the above experimental considerations, there are some practical concerns that must be considered as well. They are the blended fuels' stability during long storage, the need for the upgrading of existing storage and distribution facilities, and the risk of compatibility problems with engine parts and after-treatment devices. Furthermore, the availability and consistency of biofuel feedstocks, broadly, and their comparatively higher production costs relative to commercial fuel, may impact the viability of mass adoption. In combination, they imply that, despite PBBT blended fuels' promising prospects of being an environmentally pure alternative, much work under more practical operating modes, accompanied by consequential techno-economic analyses, remains necessary prior to mass deployment within the transport sector, achieving commercial viability.

4. Conclusion

The growing need for cleaner, more sustainable transportation fuels has driven increased research into oxygenated multicomponent blends compatible with spark-ignition engines. The current research supports that PBBT fuel blends made up of Pertasol, n-butanol, 2-butoxyethanol, and tamanu oil provide considerable improvements in both performance characteristics and emissions profiles. The experimental results indicated that the PBBT-5 blend produced the highest brake thermal efficiency at 22.74%, representing a 44.4% increase when compared to traditional gasoline. Furthermore, CO and HC emissions reductions exceeded 30%, while NO_x emissions were found to decrease increasingly by up to 15.40% with a rise in the tamanu oil percentage. These improvements are explained by the synergistic interactions among oxygenated alcohols and bio-based esters, which allowed for enhancement in combustion stability and fuel-air mixing uniformity.

The PBBT mixture poses a viable means of developing clean fuel technologies, particularly in applications where there is a limitation of high-quality petroleum fuels. It also uncovers the potential for blending with renewable materials without compromising the engine performance integrity. Subsequent research can be extended further with multi-cylinder engine experiments under more representative operating conditions, such as transient loads and actual driving cycles. Long-term stability and storage studies, as well as material compatibility of such blends with fuel system components, will be demanded to make an estimate of their feasibility for practical application. An extended characterization of the emissions, including particulate and unregulated components, will give us a better assessment of their environmental performance. Use of statistical analysis and optimization methods can be directed towards having better confidence in the conclusions and more optimally selecting the best blending ratios. Finally, research on PBBT with various commercial gasoline base fuels will determine its broader applicability and relevance towards future energy and environmental concerns.

List of abbreviations

2BE	2-butoxyethanol
ASTM	American Society for Testing and Materials
CBS	Combi brake system
CI	Compression ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
CPU	Central processing unit
ECU	Electronic control unit
HC	Hydrocarbons
HP	Horsepower
kPa	Kilopascal
kW	Kilowatt
Nm	Newton meter
NO_x	Nitrogen oxides
O_2	Oxygen
PBBT	Pertasol–n-butanol–2-butoxyethanol–tamanu oil
PGM-FI	Programmed fuel injection
ppm	Parts per million
PS	Pferdestärke (metric horsepower)
RON	Research octane number
RPM	Revolutions per minute
SFC	Specific fuel consumption
SI	Spark-ignition
SOHC	Single overhead camshaft
vol%	Volume percent
WIC	Water-in-calophyllum
wt. %	Weight percent

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Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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