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IDENTIFYING THE POTENTIAL OF TAMANU OIL AS AN OXYGENATED ADDITIVE IN MULTI-COMPONENT GASOLINE BLENDS TO IMPROVE SPARK-IGNITION ENGINE PERFORMANCE AND EMISSIONS

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Abstract

This research investigates the viability of tamanu oil (Calophyllum inophyllum), a renewable and non-edible vegetable oil, as an oxygenated fuel additive in multi-component fuel blends for spark-ignition (SI) engines. The primary objective of this research is to evaluate how such blends can be utilized to enhance combustion performance and minimize pollutant emissions while maintaining compatibility with existing engine architecture and without requiring changes to the engine hardware. To solve this problem, five fuel blends (PBBT-1 to PBBT-5) were created by varying the ratio of tamanu oil from 2% to 10% along with the addition of 5% n-butanol and 5% 2-butoxyethanol, using Pertasol as the base fuel. Engine tests were conducted at a constant compression ratio of 11:1, over a range of engine speeds from 4000 to 9000 rpm. Of the tested blends, PBBT-5 exhibited the maximum improvements, with a 42.94% enhancement in thermal efficiency and 34.13% reduction in specific fuel consumption and CO (24.26%), HC (20.27%), and NOx (29.04%) emissions reduction. These enhancements are attributed to the synergism between the oxygenated additives and tamanu oil's slow-combustion and lubricating characteristics, enhancing more complete combustion and improved flame propagation. The novel approach adopted in this research is distinguished by the use of sustainable feedstocks, improved combustion quality and efficiency, and the potential for easy integration into current engine designs, thus solving the performance-emission paradox. This research establishes the feasibility of tamanu oil blends as a sustainable and eco-friendly alternative to conventional transportation technologies under normal operating conditions.

Keywords: tamanu oil, oxygenated fuel, engine performance, emissions reduction, alternative energy.

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1. Introduction

Tamanu oil derived from the Calophyllum inophyllum is emerging as a sustainable and environmentally friendly source of energy in the form of biofuels compared to traditional fossil fuels. The non-food oil does not compromise food supplies, contains natural oxygen, and is biodegradable and thus presents itself as a viable option for second-generation biofuels [1, 2]. Its prevalence in tropical environments, along with its favorable chemical characteristics towards transesterification, renders it increasingly suitable [3]. Research shows that the incorporation of tamanu oil into commercial fuel mixtures enhances thermal efficiency, lowers SFC, and decreases CO and HC emissions [4]. In [5] found that the inclusion of tamanu oil in Pertasol-based gasoline reduced SFC by 6.8% and enhanced thermal efficiency by 5.3%, particularly at 2% to 4% volumetric proportions. Conversely, engine performance was negatively affected by heightened viscosity and lowered calorific value at higher blend rates of 8% to 10%, which was indicated by an 18.4%

increase in NOx emissions. The most suitable proportion of tamanu oil was determined as less than 5%, and no engine modification is required. It has also been established that the inclusion of nanoparticles such as Al_2O_3 improves combustion efficiency and emission traits [6]. Additionally, [7] stated that tamanu oil-based port fuel injection systems enabled cleaner and more efficient combustion processes.

N-butanol has also been recognized as an oxygenated bio-additive that can bring beneficial effects on engine performance and emissions. In [8] indicated that with the addition of 30% gasoline, there was a 6% rise in engine torque and 8.4% decrease in brake-specific fuel consumption (BSFC), and 10–20% decrease in carbon monoxide and hydrocarbon emissions. However, the increase in combustion temperature caused a remarkable increase in nitrogen oxide (NOx) emissions by 52%. Addressing this problem, [9] suggested the use of a 9% water injection into a blend of 2.5% n-butanol, causing a 58.37% reduction in NOx emissions and decreases of 10% and 36.78% in brake specific fuel consumption (BSFC) and hydrocarbon (HC) emissions, respectively. Similarly, [10] observed that the 20% n-butanol fuel mixture enhanced thermal efficiency by 5.9% while concurrently lowering BSFC by 7.4%, which is indicative of improved combustion characteristics. Further, [11] observed that a mixture containing 15% n-butanol not only enhanced maximum cylinder pressure and volumetric efficiency but also led to CO and HC emission decreases of 18.2% and 24.7%, respectively, without inducing engine knock. 2-Butoxyethanol has also been identified as a promising oxygenated gasoline fuel additive with beneficial combustion characteristics. In [12] found that 10% blending of 2-butoxyethanol with gasoline increased peak cylinder pressure by 4.8%, thermal efficiency by 5.4%, reduced specific fuel consumption (SFC) by 6.3%, CO emission by 15.2%, and HC emission by 19.6%. However, these improvements were coupled with a significant increase of 22.7% in nitrogen oxide (NOx) emissions, which was attributed to high temperatures in the combustion chamber. In a subsequent study, [13] noted that the addition of 2-butoxyethanol resulted in improved thermal stability and reduced pressure oscillations inside the cylinder, indicating more stable combustion.

A number of recent research papers indicate that carbon-technology innovations like the inclusion of oxygenated additives, e.g., n-butanol, 2-butoxyethanol, and tamanu oil, in Pertasol-blended fuels will improve combustion efficiency, improve thermal efficiency, and decrease pollutant emissions with no problem being compatible with conventional spark-ignition engines. It is surprising that academic literature concerning Pertasol as a major fuel constituent is scant. Thus, this research claims to bridge this gap by ascertaining the technical viability and combustion characteristics of the multi-component mixture of Pertasol and the recognized additives, with the perspective of disseminating cleaner-burning and sustainable fuel alternatives.

2. Materials and methods

2. 1. Fuel variants and compositions

Five fuel mixtures were prepared to examine SI engine performance against tamanu biofuel content. As evident in **Table 1**, PBBT-1 through PBBT-5 had Pertasol as a base and 5% n-butanol and 5% 2-butoxyethanol were added. Tamanu contents were 2%, 4%, 6%, 8%, and 10% with equal volumes of Pertasol substituted. The blends were numbered based on the percentage of tamanu: PBBT-1 (2%), PBBT-2 (4%), PBBT-3 (6%), PBBT-4 (8%), and PBBT-5 (10%), maintaining a constant n-butanol and 2-butoxyethanol percentage. The engine used a minimum research octane number of 90, with commercial gasoline as the control.

Table 1
Fuel blend capacity of Pertasol-butanol-2-butoxyethanol-tamanu oil

Fuel used	Pertasol	2-butoxyethanol	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%

Table 2 shows the physicochemical properties of the blends, which include calorific value, density, octane number, and boiling point. **Fig. 1** is a graphical comparison of the colors and appearances of the mixtures tested.

Table 2
Fuel blend properties of Pertasol-butanol-2-butoxyethanol-tamanu oil

Fuel blend characteristics	Commercial	PBBT-1	PBBT-2	PBBT-3	PBBT-4	PBBT-5	Unit	Method
Calorific value	10.310	10.344	10.395	10.448	10.499	10.575	kCal/kg	ASTM-D4809
Density @15°C	0.772	0.768	0.764	0.753	0.756	0.748	g/cm^3	ASTM-D4052
Octane number	90	91	92	93	94	95	–	ASTM-D2699
Reid vapor pressure	50.00	53.77	55.84	58.60	60.67	62.05	kPa	ASTM-D323
Oxygen content	1.60	20.42	20.52	20.61	20.71	20.80	% (Weight)	ASTM-D4815
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
Flash point	–43	–29	–24	–19	–14	–9	°C	ASTM-D93
Boiling point	115	82	87	91	96	100	°C	ASTM-D86

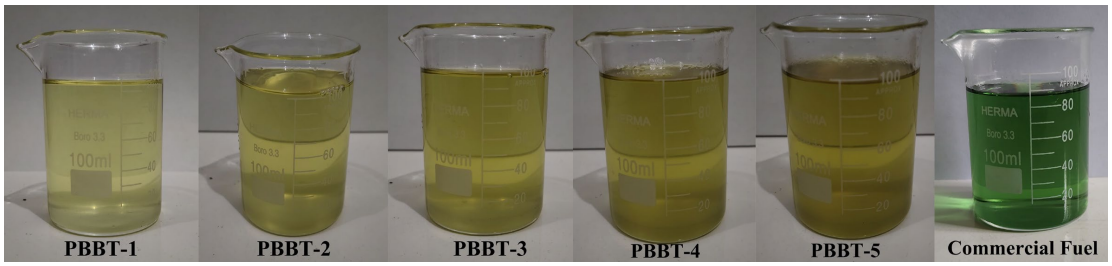


Fig. 1. Color display on the fuel variations used

2. 2. Engine configuration overview

Performance was conducted on a single-cylinder, four-stroke spark-ignition engine equipped with SOHC and PGM-FI technology. Displacement is 124.8 cc, power is a maximum of 8.2 kW at 8500 rpm, and torque is 10.8 Nm at 5000 rpm, as shown in **Table 3**. The engine has a centrifugal dry-type clutch and a fully automatic V-Matic transmission for smooth power delivery. Transistorized ignition provides smooth combustion at any level. The lubrication system is a wet-sump type with 0.8 liters capacity, and the fuel tank capacity is 5.5 liters.

Table 3
Engine Configuration Overview

Specification	Description
Engine configuration	4-stroke, SOHC, single-cylinder
Fuel System	PGM-FI (programmed fuel injection)
Engine displacement	124.8 cc
Compression ratio	11:1
Maximum power output	8.2 kW at 8500 rpm
Maximum torque	10.8 Nm at 5000 rpm
Transmission system	Automatic, V-matic
Engine oil capacity	0.8 liters (for periodic replacement)
Fuel tank capacity	5.5 liters
Lubrication type	Wet-sump
Braking system	Combi brake system (CBS)
Ignition system	Fully transistorized

2. 3. Testing scheme for performance and emissions

The emissions and performance of an SI engine were experimented on through the utilization of fuel blends designated as PBBT1 to PBBT5. **Fig. 2** shows an SI engine mounted on a continuously variable transmission (CVT) and a dynamometer for measuring power and torque output. Performance parameters were obtained using a CPU dynamometer under various operating conditions. Exhaust gases were analyzed for nitrogen oxides (NOx), unburned hydrocarbons (HC), and carbon monoxide (CO). The tests were carried out under full load conditions and across a spectrum of 4000 to 9000 revolutions per minute (rpm) in a controlled setup to guarantee credible results. The test measurements were made to establish the influence of fuel mixture ratios on performance and emissions with a view to establishing the most effective and sustainable fuel blend.

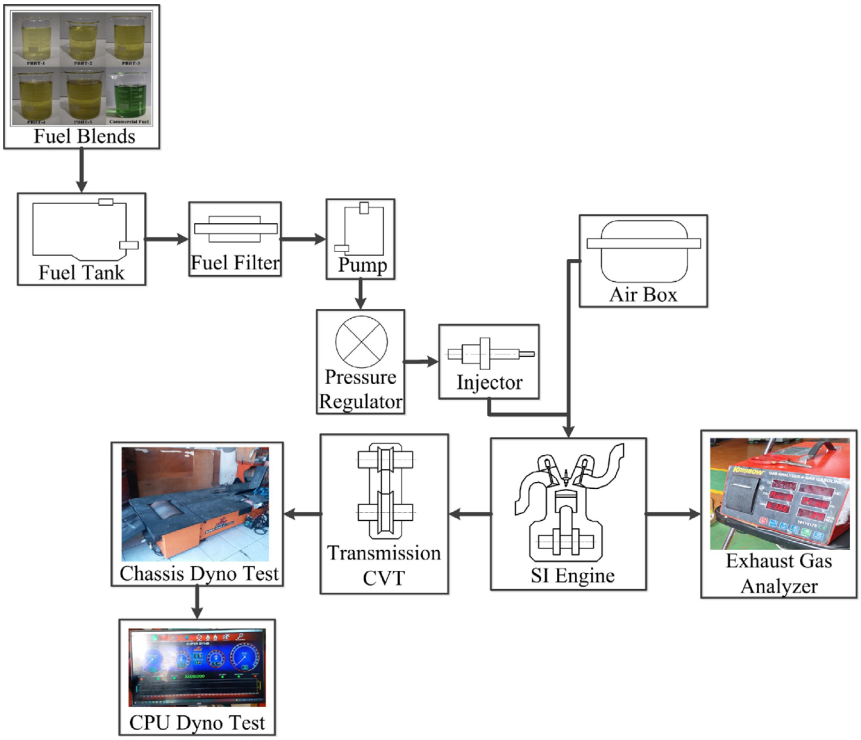


Fig. 2. Testing scheme for performance and emissions

3. Results and discussion

3. 1. Power

Fig. 3 shows that all fuel types exhibited a significant increase in power output within the range of engine speeds from 4000 to 8500 rpm. In this respect, commercial fuel recorded the most significant power improvement, with a 94.29% increase. On the other hand, the PBBT fuel blends, synthesized employing Pertasol as a base and containing 5% n-butanol, 5% 2-butoxyethanol, and different percentages of tamanu oil (2–10%), recorded steady increases in power output of 82.16% (PBBT-1), 73.06% (PBBT-2), 66.22% (PBBT-3), 60.74% (PBBT-4), and 56.86% (PBBT-5) for their original values. These increases result from improved volumetric and combustion efficiencies, combined with the oxygenation effects brought about by the additives that enrich the air-fuel mixture, enabling flame propagation at higher speeds. The findings of this study are consistent with those of [14], who reported a 4.79% power increase due to the application of isobutanol-ethanol-gasoline (IBE) blends. Likewise, [15] indicated that n-butanol improves engine performance when operated within its optimum operating conditions, while [12, 13] highlighted the role of 2-butoxyethanol in promoting in-cylinder pressure and combustion stability. In addition, [5] noted that the addition of tamanu oil leads to higher combustion pressure due to its moderate viscosity and the presence of unsaturated fatty acids, which also provide a lubricating effect within the combustion chamber.

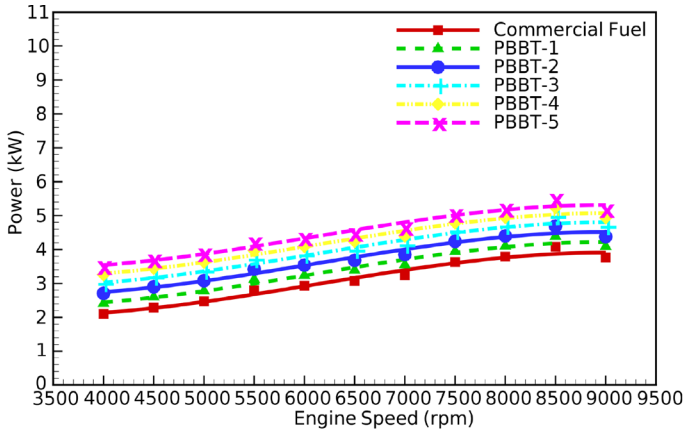


Fig. 3. The power phenomenon of using
Pertasol-N-butanol-2-butoxyethanol-tamanu oil fuel blends on engine speed

The increase in engine speed observed between 8500 and 9000 revolutions per minute (rpm) was linked to a decline in power output across all analyzed types of fuel. Among these, the commercial fuel recorded the most significant decline, measured at 7.60%, while the PBBT blends recorded relatively lower declines, with a range of 6.83 to 5.65% corresponding to PBBT-1 to PBBT-5, respectively. This decline was most closely linked to the lower combustion duration and low-responsive kinematic behavior of oxygen-containing compounds at high engine speeds, as established by [12, 14].

In addition, [6] also linked this phenomenon to poor atomization at high engine speeds. Significantly, tamanu oil's slower combustion nature was found to increase pressure stability within cylinders at high-speed operating conditions, leading to improved combustion stability with the addition of PBB blends compared to regular fuel.

3. 2. Specific fuel consumption (SFC)

Specific fuel consumption (SFC) is a baseline measure to gauge the effectiveness with which fuel's chemical energy is converted to mechanical power. As shown in **Fig. 4**, the lowest SFC value was obtained with PBBT-5 at 8500 rpm, at 0.29 kg/kW · h, a 26.12% decrease compared to that of commercial fuel (0.39 kg/kW · h). The average specific fuel consumption (SFC) of PBBT-5 over the entire operating speed range was found to be 0.3302 kg/kW · h, 34.13% lower than the average SFC of commercial fuel, which was recorded at 0.50 kg/kW · h. This continuous decrease reflects the synergistic effects of tamanu oil, n-butanol, and 2-butoxyethanol, which altogether enhance mixture formation and increase fuel reactivity.

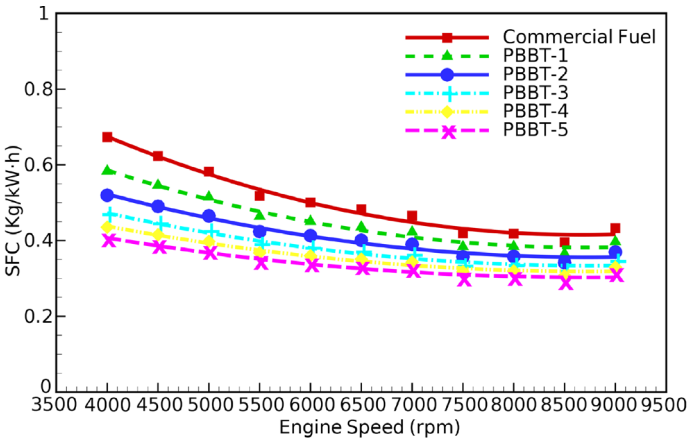


Fig. 4. the specific fuel consumption phenomenon of using
Pertasol-N-butanol-2-butoxyethanol-tamanu oil fuel blends on engine speed

However, a slight increase in SFC was observed between 8500 and 9000 rpm, probably due to reduced volumetric efficiency, shortened combustion duration, increased mechanical friction, and non-optimal intake-exhaust resonance at higher engine speeds. The findings of this study are consistent with those of previous research. [5] reported a 3% reduction in specific fuel consumption (SFC) when a mixture of Pertasol, diethyl ether, and tamanu oil was used. [6] reported SFC reductions between 6.56% and 7.37% with the use of Al_2O_3 nanoparticle additives. [10] reported a 9.54% decrease for a mixture comprising 20% n-butanol, while [16] reported a 7.14% decrease for a gasoline blend consisting of 20% n-butanol (G80B20). Similarly, [12] recorded an 8.27% decrease in SFC for a gasoline-2-butoxyethanol blend at a 20% concentration. These results corroborate the fuel-saving potential of PBBT blends-particularly PBBT-5 – as an efficient, energy-saving, and environmentally friendly alternative to conventional gasoline.

3. 3. Thermal efficiency

Fig. 5 reveals that the different mixtures of the PBBT fuel (PBBT-1 to PBBT-5) demonstrated higher thermal efficiency compared to commercial fuel at all engine operating speeds. Maximum efficiency was achieved with PBBT-5 at a speed of 9000 rpm, yielding a value of 25.69%, representing a 42.94% improvement over the commercial fuel, which had a value of 17.98%. The established trend of improved thermal efficiency with increasing tamanu oil concentration indicates the occurrence of a synergistic effect based on the slow combustion nature of tamanu oil and the high oxygen content of both n-butanol and 2-butoxyethanol. The synergistic interaction ensures better combustion completeness and improved energy conversion. The results obtained concur with those of previous studies. [8] reported a 24.6% increase in thermal efficiency using mixtures of gasoline and butanol. [17] also reported a 15.9% increase in efficiency under conditions of higher excess air ratios. [12, 13] also noted that the inclusion of 2-butoxyethanol encourages homogenization and lowers viscosity, resulting in improved flame propagation and a rise of up to 3.7% in combustion efficiency compared to gasoline. At low engine speeds (4000–8500 rpm), the PBBT blends exhibited slightly better thermal efficiencies compared to commercial fuel; however, the differences observed were not statistically significant. It can be due to the lower in-cylinder temperatures at these low speeds, which discourage the complete vaporization of the fuel.

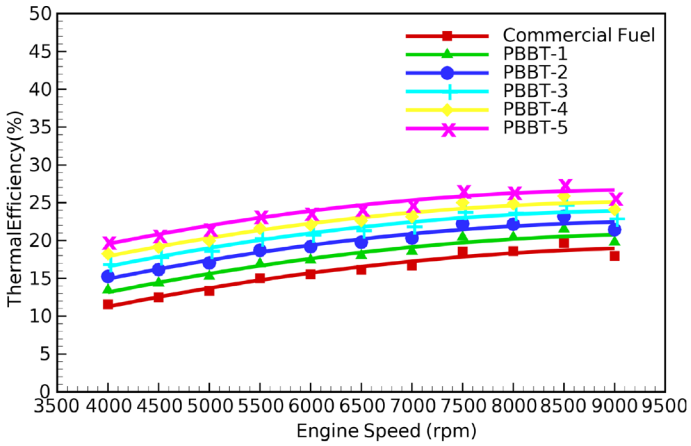


Fig. 5. The thermal efficiency phenomenon of using Pertasol-N-butanol-2-butoxyethanol-tamanu oil fuel blends on engine speed

Conversely, at 9000 rpm, a slight decrease in thermal efficiency was observed, which can be attributed to shorter combustion durations, increased heat losses, and increased mechanical friction, all of which contribute to the lowered conversion of thermal energy to practical work. [5] reported a similar trend with PDTO blends, where efficiency decreased after 7000 rpm due to unstable combustion and increased energy losses. [6] also demonstrated that the addition of Al_2O_2 nanoparticles to tamanu-based biodiesel increased thermal efficiency by up to 6.58%. Briefly, the addition of Pertasol to n-butanol, 2-butoxyethanol, and tamanu oil enhances thermal efficiency,

particularly at high engine revolutions, thereby making its application a viable, energy-efficient, and environmentally sustainable alternative to petroleum-based fuels.

3. 4. CO emissions

Fig. 6 indicates that all PBBT mixtures (PBBT-1 to PBBT-5) released less CO compared to commercial gasoline (RON-90) across the range of engine speeds. At 4000 rpm, PBBT-1 lowered CO by 5.65%, whereas PBBT-5 reduced it by 22.71%. At 4500 rpm, PBBT-5 resulted in a peak reduction of 24.26% and PBBT-1 in a minimum of 6.04%. Every 2% rise in tamanu oil content resulted in a 3–5% reduction in CO. These findings conform with previous research. [18] achieved improved flame stability and reduced CO emissions by adding butanol to gasoline. [15] attributed this reduction to the oxygen content of n-butanol, increasing combustion. [19] demonstrated that bio-butanol injection results in cleaner burning and reduced CO emissions. [20] recorded reduced CO using Calophyllum inophyllum and linseed methyl ester compared to Commercial fuel. [12] recorded a reduction of 12.5% CO using a blend of 2.5% of 2-butoxyethanol (2BE25) at full load. N-butanol, 2-butoxyethanol, and tamanu oil, when incorporated into blends with PBBT, enhance combustion and reduce CO emissions, offering a potential green fuel for improved engine performance.

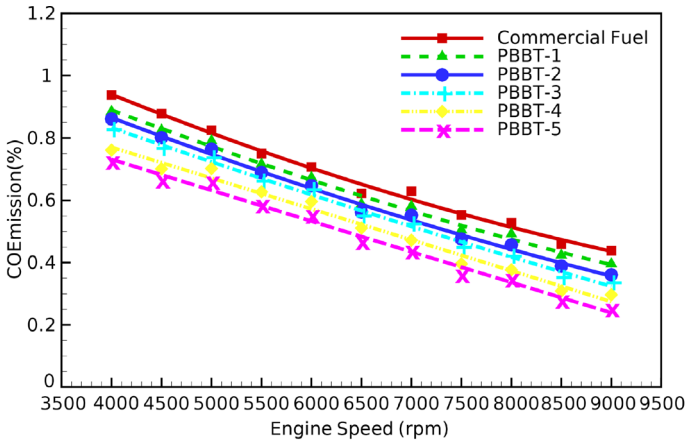


Fig. 6. The CO emissions phenomenon of using Pertasol-N-butanol-2-butoxyethanol-tamanu oil fuel blends on engine speed

3. 5. HC emissions

Fig. 7 indicates that PBBT fuel blends – Pertasol, n-butanol, 2-butoxyethanol, and tamanu oil – significantly lowered hydrocarbon (HC) emissions from spark-ignition engines, mainly because of increased tamanu content.

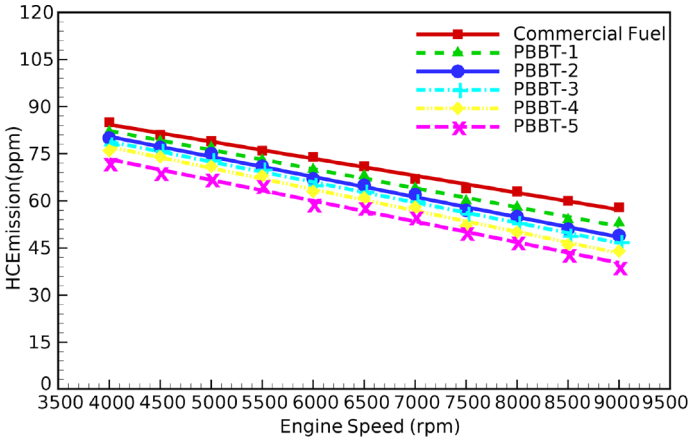


Fig. 7. The HC emissions phenomenon of using Pertasol-N-butanol-2-butoxyethanol-tamanu oil fuel blends on engine speed

Raising tamanu from 2% (PBBT-1) to 10% (PBBT-5) lowered HC emissions. At 6000 rpm, PBBT-1, PBBT-3, and PBBT-5 lowered emissions by 5.41%, 12.16%, and 20.27%, respectively, relative to commercial gasoline, with PBBT-5 doing so without further modification. N-butanol burns more efficiently with oxygen and produces a higher octane rating. [9] observed a decrease of 36.78% THC using a 2.5% blend. [21] affirmed this at elevated levels of n-butanol. Homogeneity of the mixture and burning velocity increase with 2-butoxyethanol, as reported by [12], showed that tamanu ester in an emulsion mixture significantly reduced HC emissions. A decline of 9% was observed at low concentrations. PBBT mixtures, particularly PBBT-5, are environmentally friendly and high-performance gasoline substitutes that require no engine modification.

3. 6. NOx emissions

Fig. 8 shows that all the PBBT fuel blends (PBBT-1 to PBBT-5) achieved considerable reductions in NOx emissions compared to RON-90 gasoline. In particular, the highest reduction of 29.04% was observed with PBBT-5 at an engine speed of 4000 rpm, with more than a 20% reduction consistently at all engine speeds tested, up to 9000 rpm. It demonstrates that the PBBT blends are effective at reducing peak combustion temperatures, which play a significant role in NOx formation. The composition of the blend contains a high proportion of high-octane Pertasol as the primary fuel component, supplemented by oxygenated additives (n-butanol and 2-butoxyethanol), with tamanu oil added as a biofuel component. As the percentage of Pertasol was reduced from 88% (PBBT-1) to a low of 80% (PBBT-5), there was no loss in performance; instead, it was enhanced due to synergistic effects.

N-butanol is a significant component that reduces NOx emissions due to its high latent heat of vaporization, as reported by [10, 16], which potentially leads to reductions of up to 39%. On the contrary, 2-butoxyethanol increases NOx levels individually; however, ideal blends have shown reductions of up to 5.4% [13]. [12] also reported that the use of 2-butoxyethanol alone can cause a 10% increase in NOx due to local temperature spikes. In addition, tamanu oil, with its slow-burning qualities and inherent oxygen content, is effective at buffering thermal peaks, as observed by [22, 23]. Overall, PBBT-5 demonstrated the highest performance in reducing NOx emissions, thereby supporting its potential as a compatible and sustainable alternative engine fuel.

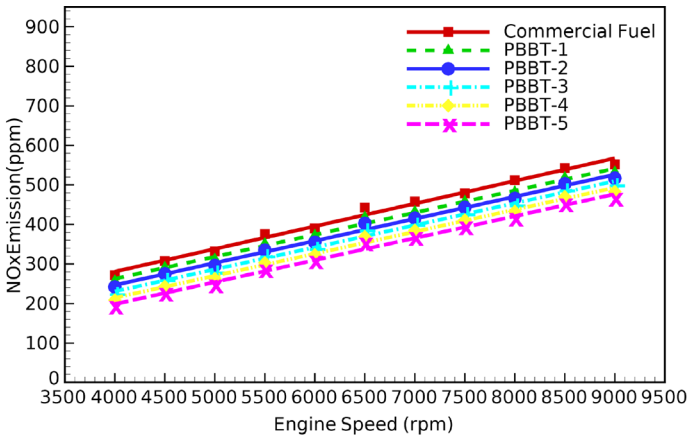


Fig. 8. The NOx phenomenon of using
Pertasol-N-butanol-2-butoxyethanol-tamanu oil fuel blends on engine speed

3. 7. The regression analysis of the performance and emissions of Tamanu oil fractions

The polynomial regression analysis of experimental data obtained at 8500 rpm was used to quantify the influence of the tamanu oil fraction on engine performance and exhaust emissions. In this case, maximum power output and a minimum specific fuel consumption are achieved at the optimum operating conditions. The regression analysis was conducted by considering the tamanu oil fraction (X, % vol) as the independent variable, while power, specific fuel consumption (SFC), thermal efficiency, and emission parameters (CO, HC, and NOx) were treated as dependent variables.

To adequately capture the nonlinear behavior observed in the experimental trends, a second-order polynomial model was selected.

A high coefficient of determination for each response variable indicates an excellent agreement between the experimental data and the regression models developed. According to the following equation, the fraction of tamanu oil in engine power is correlated with engine power

$$\text{Power} = 4.0793 + 0.1599X - 0.0019X^2. \quad (1)$$

The coefficient of determination ($R^2 = 0.9999$) indicates an almost perfect fit between the predicted and experimental values, confirming that increasing the amount of tamanu oil increases engine power as a result of improved combustion quality and oxygen availability. As the negative quadratic term indicates, saturation tends to occur at higher blending ratios gradually.

In the case of specific fuel consumption, a similar trend was observed. The following regression equation explains the trend

$$\text{SFC} = 0.3949 - 0.0153X + 0.0005X^2. \quad (2)$$

As shown by the high goodness of fit ($R^2 = 0.9993$) of this model, there is a strong inverse relationship between the tamanu oil fraction and fuel consumption. Reduction in SFC is associated with improved fuel atomization, enhanced oxygenation, and more complete combustion, whereas the small quadratic term suggests that improvements diminish at higher fractions due to the diminishing rate of improvement.

Based on the relationship between thermal efficiency and tamanu oil fraction, the following equation is given

$$\text{Thermal Efficiency} = 19.7140 + 0.9116X - 0.0144X^2. \quad (3)$$

Tamanu oil addition has a significant positive effect on thermal efficiency as indicated by the high coefficient of determination ($R^2 = 0.9985$). It is thought that this behavior is primarily due to the synergistic interaction between tamanu oil, butanol, and 2-butoxyethanol, which contributes to better flame propagation and more efficient energy conversion, with optimum efficiency gains resulting at higher blending levels.

In terms of emission characteristics, carbon monoxide emissions are characterized as follows

$$\text{CO Emission} = 0.4602 - 0.0177X - 0.0000625X^2. \quad (4)$$

In the regression model, there is a very strong goodness of fit ($R^2 = 0.9881$), indicating that CO emissions are consistently decreasing with increasing tamanu oil fraction, as a result of enhanced oxidation reactions and reduced incomplete combustion.

A description of hydrocarbon emissions can be provided as follows

$$\text{HC Emission} = 59.3212 - 2.2553X - 0.0669X^2. \quad (5)$$

A coefficient of determination for this model ($R^2 = 0.9845$) indicates that unburned hydrocarbons have been significantly reduced due to improved combustion efficiency, and the presence of minor kinetic limitations only becomes apparent at higher blending ratios.

Furthermore, nitrogen oxide emissions are expressed as follows

$$\text{NOx Emission} = 541.1403 - 10.1427X + 0.1429X^2. \quad (6)$$

As demonstrated by the high coefficient of determination ($R^2 = 0.9964$), NOx emissions have consistently decreased as the tamanu oil fraction increases. In addition, the combustion behavior of tamanu oil contributes to the suppression of peak combustion temperatures due to its higher latent

heat of vaporization and prolonged combustion duration. Overall, the regression analysis provides a robust mathematical confirmation of the experimental trends presented in **Fig. 3–8**. All response parameters were found to have consistently high coefficients of determination, demonstrating that the developed regression models can accurately describe how tamanu oil fraction influences engine performance and exhaust emissions. These results can be used to determine the effective blending range of tamanu oil in multi-component gasoline fuels without requiring modifications to existing engine hardware.

3. 8. Limitations and future directions for research

Although the present results demonstrate clear performance and emission advantages of tamanu oil-based multi-component gasoline blends, several limitations should be acknowledged to define the boundaries of applicability and to support appropriate interpretation. The experimental campaign was conducted on a single-cylinder spark-ignition engine operated at full-load conditions with a fixed compression ratio of 11:1, while the engine speed was varied from 4000 to 9000 rpm. Consequently, the conclusions of this work are most directly applicable to similar engine architectures and comparable operating regimes, particularly within the tested speed range where the fuel-air preparation and combustion characteristics remain consistent with the current setup.

From a quantitative perspective, the formulation space explored in this research was intentionally constrained to ensure blend stability and to isolate the influence of tamanu oil fraction. Specifically, n-butanol and 2-butoxyethanol were maintained at constant levels of 5% vol each, whereas tamanu oil was varied between 2% and 10% by volume in five discrete blends (PBBT-1 to PBBT-5). Therefore, the observed improvements such as the reported reductions in specific fuel consumption and regulated gaseous emissions, together with increases in thermal efficiency should be interpreted as valid within this defined blending window rather than generalized to higher vegetable oil fractions or different additive ratios. In addition, the engine tests were conducted over a finite range of rotational speeds, and the optimum operating point identified in the research reflects the tested conditions rather than an absolute optimum across all possible loads and engine states.

In practical terms, the reproducibility of the results depends strongly on maintaining consistent fuel preparation and experimental procedures. Multi-component fuels containing alcohols and bio-oils are sensitive to blending accuracy, mixing time, and ambient conditions. For this reason, it is important that the volumetric ratios are prepared precisely, the blends are homogenized adequately before testing, and the fuel is handled under stable temperature conditions to avoid phase separation or unintended property changes. Moreover, the present research evaluated brake power, specific fuel consumption, thermal efficiency, and gaseous emissions (CO, HC, and NOx). Other parameters that are relevant for real-world implementation such as particulate number emissions, carbonyl compounds, cold-start behavior, combustion stability indicators, and long-term deposit formation were not investigated and may influence the overall feasibility of extended operation.

Another limitation concerns the operational duration and long-term effects of tamanu oil addition. While tamanu oil fractions up to 10% vol were found to be compatible with the tested spark-ignition engine without hardware modification, prolonged use may introduce additional considerations such as injector cleanliness, deposit formation, and lubricant contamination, especially under high-temperature or high-speed operation. Therefore, the present findings should be considered as a performance-emission assessment under controlled short-term conditions rather than a complete durability validation.

Future research should expand this work toward long-term durability testing and storage stability evaluation of the proposed blends, including oxidation resistance, phase stability during extended storage, and compatibility with fuel system materials. Further experiments under broader operating conditions such as part-load operation, transient speed changes, and different compression ratios are also recommended to better represent real driving scenarios. In addition, deeper combustion diagnostics (e.g., in-cylinder pressure measurement, heat release analysis, combustion phasing, and knock tendency) would strengthen the mechanistic interpretation of how tamanu oil

interacts with oxygenated additives to influence combustion completeness and emission formation. These extensions will provide a more comprehensive basis for assessing the scalability of tamanu oil-based multi-component gasoline blends as practical and sustainable alternatives for spark-ignition engines.

4. Conclusion

Tamanu oil, derived from the Calophyllum inophyllum plant, has additional environmental benefits from a life-cycle perspective, as it is derived from a perennial tropical plant that is non-edible and can be cultivated with relatively low agricultural inputs on marginal land. This minimizes competition with food crops and reduces the amount of greenhouse gases produced upstream. The current research demonstrates that the formation of a multi-component blended fuel, comprising a mixture of Pertasol (containing 5% n-butanol and 5% 2-butoxyethanol) and tamanu oil at concentrations ranging from 2% to 10%, significantly enhances both the operating efficiency and exhaust emissions of spark-ignition engines. The best formula, known as PBBT-5 (with a 10% component of tamanu oil), gives a thermal efficiency boost of 42.94% and a specific fuel consumption (SFC) reduction of 34.13% compared to regular gasoline. Moreover, carbon monoxide (CO) emissions, hydrocarbon (HC) emissions, and nitrogen oxide (NOx) emissions were decreased by 24.26%, 20.27%, and 29.04%, respectively. Although performance decreases slightly at high engine speeds (8500–9000 rpm), overall power stability is retained due to the synergistic interactions of oxygenate additives with the lubrication and slow-burning nature of tamanu oil. Based on the results obtained, developing a formulation of PBBT, particularly those with tamanu oil content levels of up to 10%, for use on regular gasoline engines with no requirement to modify current hardware is recommended.

Conflict of interest

The authors declare that they have no conflicts of interest concerning this research, whether financial, personal, or authorship-related, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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Use of artificial intelligence

The authors confirm that they did not utilize artificial intelligence technologies in the creation of the current work.

Authors' contributions

Gatot Setyono: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft.

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