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Characterization of Additive Blended Fuels on Single-Cylinder Motorcycle Engines

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Abstract

Despite their potential, challenges such as corrosion, compatibility issues with older engines, fuel system problems, lower energy content, and increased fuel consumption persist. With the shift toward green technologies and sustainable energy, biofuels like ethanol are seen as promising replacements for depleting hydrocarbons. This study explores the impact of polyisobutylene additives in ethanol-gasoline blends to enhance their use in ICEs. Five test fuels with varying additive concentrations were formulated and designated as E5P100, E5P500, E25P100, E25P500, and E0P100. These fuels were examined for their physicochemical properties. E5P100 had the highest research octane number (RON 96.5), whereas E0P100 had the lowest (RON 95.5). E25P500, with the highest density (0.79342 g/cm^3), had the lowest brake specific fuel consumption (BSFC) value (1.5 kg/kW-hr). The blend with the highest heating value (E0) had 43350 kJ/kg, providing more energy during combustion, which improves engine performance by increasing power output and ensuring smoother operation. Blends E5PIB500 and E25P500 showed the highest engine power (5.8 kW and 5.95 kW, respectively), significantly better than conventional gasoline (E0, 3.65 kW), leading to improvements in brake mean effective pressure (BMEP), brake thermal efficiency (BTE), and brake torque (BT). Additionally, E5P500, E25P100, and E25P500 reduced CO and HC emissions due to their higher ethanol and additive content. Conversely, E5P100 and E0P100, with lower ethanol and additive content, resulted in incomplete combustion, increasing NO_x emissions at higher speeds. Overall, additive-blended fuels enhance combustion efficiency, reduce harmful emissions, and optimize engine performance, supporting green technologies and clean energy.

1. Introduction

Fuel additives can have various impacts on single-cylinder gasoline engines [1]. Some common types of additives include octane boosters, detergents, fuel stabilizers, corrosion inhibitors, lubricity enhancers, emission reducers, and anti-foaming agents. The effects of fuel additives can range from improving engine performance by increasing octane ratings and reducing knocking to enhancing fuel system cleanliness, preventing fuel degradation, and reducing corrosion and emissions [2]. However, the effectiveness of additives can vary depending on engine design, fuel composition, and operating conditions [3]. The process of fuel blending and integrating additives has the potential to broaden fuel sources. Blended fuels serve as pivotal components in the gradual transition from conventional hydrocarbons toward cleaner energy alternatives [4]. They contribute to emission reduction, compliance with regulatory standards, and compatibility with existing infrastructure. Fuel blending ensures energy stability, facilitates a cost-efficient shift, and bolsters supply chain resilience. This approach aligns with emerging technologies while fostering public acceptance [5].

The single-cylinder engine represents the most basic form of internal combustion engine, having a single cylinder for combustion process and widely deployed in small-scale applications such as motorcycles, scooters, lawnmowers, and portable generators (6). These engines are particularly prevalent in entry-level vehicles within developing nations owing to their simplicity and reduced production expenses. In comparison to multi-cylinder engines found in larger vehicles, single-cylinder engines exhibit higher fuel consumption due to their smaller displacement and constrained power output [7]. Consequently, they exert greater effort to generate equivalent power, resulting in elevated fuel consumption rates. Despite their inferior fuel efficiency when compared to multi-cylinder counterparts, single-cylinder engines remain suited for specific applications that prioritize compact dimensions, affordability, and lightweight construction [8].

Various studies have examined the impact of different fuel blends and additives on engine performance and emissions. In a study conducted by [9], E10 and E20 were found to improve performance and emissions compared to pure gasoline. 15% plastic pyrolysis oil (PPO) blends were tested on a 1-cylinder gasoline engine. It was found that the engine produced lower efficiency and higher NO_x emissions; however, the inclusion of ethanol improved performance and lower HC and CO emissions [10]. Similarly, when alumina nanoparticles were explored in a ternary fuel blend, there was significant improvement in performance, efficiency, and a considerable reduction in emissions with the additive. Additionally, the importance of refining high-octane petrol fuel to improve vehicle efficiency and reduce emissions by reviewing various chemical compounds for their effectiveness and potential impacts was emphasized by [11].

With increasing concerns about environmental sustainability and the finite nature of fossil fuels, there is a significant demand for alternative fuels that reduce emissions and enhance the performance of internal combustion engines. Ethanol blended fuels and additive blended fuels have emerged as potential candidates for this purpose. However, their impact on the performance, efficiency, and emissions of single-cylinder engine motorcycles is not fully understood. This study aims to investigate the effects of various ethanol blend ratios and additive compositions on the operational characteristics of single-cylinder motorcycle engines. Considering the limited literature on enhancing the performance of ethanol and gasoline blended fuels using chemical additives, the current research introduces a novel polyisobutylene (PIB) additive aimed at improving the performance of ethanol-gasoline blended fuel in single-cylinder gasoline engines.

1.1 Basic Combustion Chemistry

Combustion is a chemical process in which a fuel combines with oxygen (O_2) and produces carbon dioxide CO_2, water, heat, and light. It is usually a reaction in which hydrocarbons (HC) and O_2 are combined to produce energy in the form of heat, which is needed in transportation and industrial processes. However, the combustion of HC can also produce pollutants such as carbon monoxide (CO), particulate matter (PM) and NO_x. This usually occurs when combustion is incomplete. The equations below show a typical complete combustion reaction for HC and O_2. Generally, when fuel combines with O_2, then:

$$\text{Fuel(l)} + O_2\text{(g)} \rightarrow CO_2\text{(g)} + H_2O\text{(l)} + \text{Heat} \tag{1}$$

For HC fuels such as propane, the complete combustion equation takes the form:

$$C_3H_8\text{(l)} + 5O_2\text{(g)} \rightarrow 3CO_2\text{(g)} + 4H_2O\text{(l)} \tag{2}$$

For polyisobutylene (PIB) additives and ethanol shown in Fig. 1 and Fig. 2, PIB is a branched HC with strong solubility in many hydrocarbons' fuels, while ethanol comprises two carbon atoms, six hydrogen atoms, and one oxygen atom, which is a promising structure for complete combustion. Typical combustion is represented in equations 3 and 4. CO_2 is a main product of complete combustion, and it is formed when carbon in the fuel is fully oxidized leading to production of energy in form of heat.

J. of Advanced Mechanical Engineering Applications Vol. 5 No. 2 (2024) p. 30-39

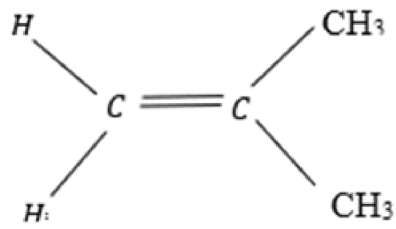


Fig. 1 *Structural formular of polyisobutylene [13].*

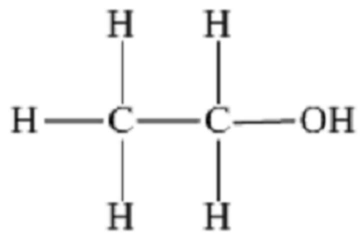


Fig. 2 *Structural formular of ethanol [14].*

$$C_4H_8(\text{l}) + 6O_2(\text{g}) \rightarrow 4CO_2(\text{g}) + 4H_2O(\text{l}) \quad (3)$$

$$C_2H_5OH(\text{l}) + 3O_2(\text{g}) \rightarrow 2CO_2(\text{g}) + 3H_2O(\text{l}) \quad (4)$$

However, the reaction in Eq. 5 is an incomplete combustion, as there was not enough oxygen to fully oxidize the fuel, which leads to the formation of harmful CO emissions:

$$CH_4 + O_2 \rightarrow CO + H_2O \quad (5)$$

Fuel efficiency and economy are crucial for single-cylinder engines such as motorcycles in Nigeria, due to persistent fuel scarcity, energy security, and environmental sustainability. In light of this, engineers strive to optimize single-cylinder engines to achieve improved fuel efficiency without sacrificing performance through advanced fuel technology.

In Nigeria, the adoption of Ethanol-Blended Fuels (EBFs) in Spark Ignition Engine (SIE) is gaining popularity as a method to reduce greenhouse gas emissions (GHG), utilize abundant ethanol sources to lower fuel costs, and lessen dependence on diminishing hydrocarbon resources. However, increasing the ethanol content in these blends has altered fuel composition and properties, creating challenges for engine performance and emissions. Although additives are introduced to enhance fuel economy, combustion efficiency, and emissions, the interaction between additives, gasoline, and ethanol remains underexplored in current literature, highlighting a gap in combustion research. Additionally, there are still challenges in implementing fuels made from ethanol, gasoline, and additives in SIE. Therefore, this study aims to investigate the effects of polyisobutylene (PIB) additive on fuels developed from ethanol, gasoline, and PIB additive on performance and emissions in single-cylinder motorcycle engines. The objectives of this study are: (1) to determine the properties of ethanol-gasoline-polyisobutylene blended fuels; (2) to determine the performance of a single-cylinder motorcycle engine using the developed blended fuels; and (3) to determine the emission characteristics of the developed blended fuels on motorcycle engines.

2. Research Design

The experiments in this study were conducted in several phases as indicated in the research flowchart Fig. 3 and schedule for each activity (see Fig. 4). The first phase of this study involves the formulation of blended fuels with ethanol-gasoline and polyisobutylene additives and their physicochemical properties. This is shown in Fig. 4 as Design of Experiments (DOE) flowcharts 1, 2, and 3, followed by engine selection and bench testing. In these flowcharts, the steps required to achieve the three objectives are presented. The experimental design includes the formulation, characterization, and bed testing of blended fuels on single-cylinder gasoline engines as it affects performance and emission characteristics.

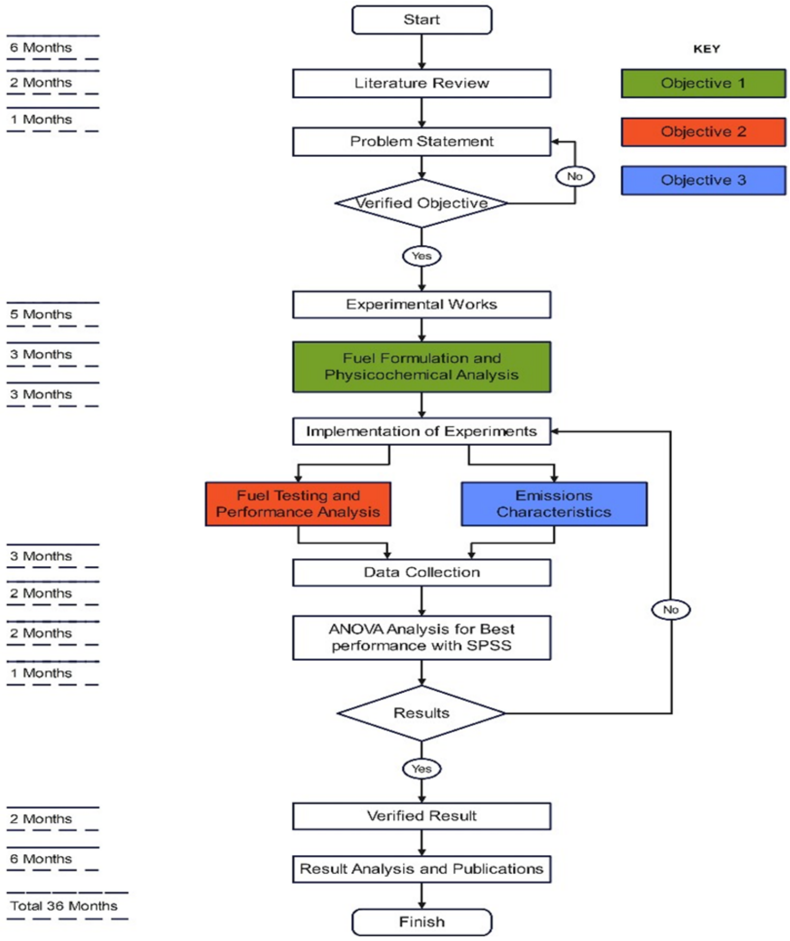


Fig. 3 *Research flowchart*

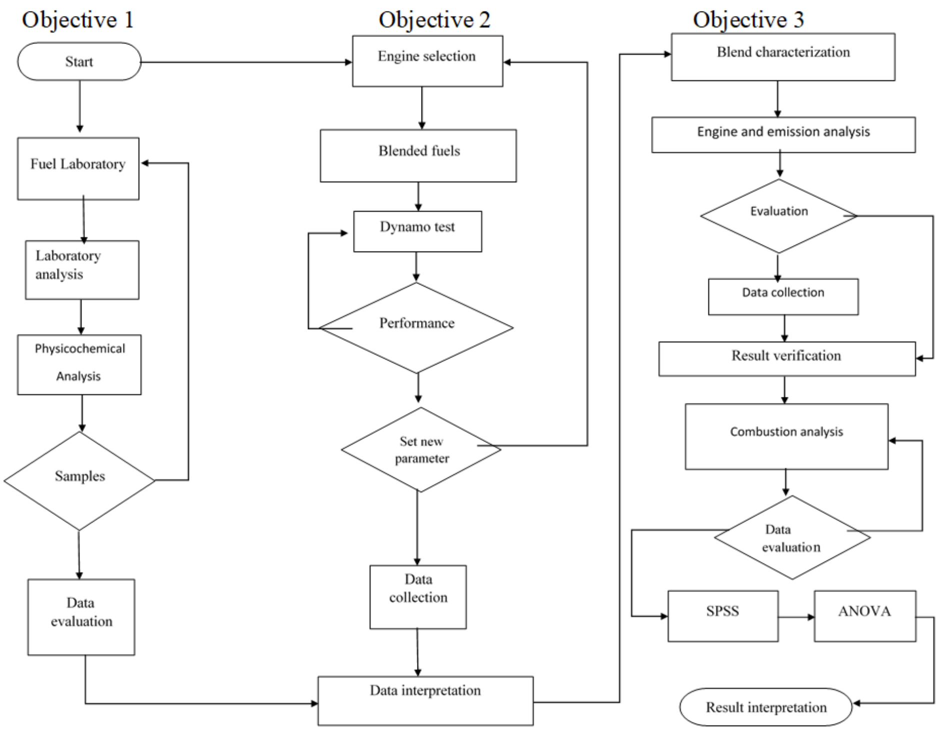


Fig. 4 *Design of experiment*

2.1 Methodology

This section outlines the experimental setup and methodologies used to achieve the study's objectives, which primarily focus on creating blended fuels by combining ethanol-gasoline with polyisobutylene (PIB) additives. The process involved blending 950 ml of commercial unleaded gasoline (RON 95) with 50 ml of pure ethanol to create a blend consisting of 95% gasoline and 5% ethanol, as shown in Table 1. Additionally, PIB additives were incorporated into the blends at a rate of 100 mg per liter per fuel blend. The mixture was stirred for 5 minutes using a magnetic stirrer to ensure proper dispersion of the additive. This process was repeated five times to create five blends with different concentrations of additives, ethanol, and gasoline, following a method described by [15]. Subsequently, the physicochemical properties of these fuel blends were thoroughly analyzed and evaluated.

Table 1 *Formulation of Ethanol-Gasoline-Polyisobutylene (EPIB) blends*

Base fuel	Gasoline (%)	Ethanol (%)	Additive (mg/l)	Sample code
100	95	5	100	E5P100
“	95	5	500	E5P500
“	75	25	100	E25P100
“	75	25	500	E25P500
“	100	-	100	E0P100
“	100	-	-	E0

The formulated fuels were evaluated using a 150-cc motorcycle engine mounted on a chassis dynamometer (MDC 400L). The selection of this motorcycle was based on its prevalent engine type, fuel efficiency, and popularity within Nigeria. Detailed technical specifications are provided in Table 2. Various testing apparatus were employed, including a fuel flow meter, an air-intake flow meter (Fluke 922 model), a pitot tube for air-intake measurement, a 1000 ml calibrated burette serving as an external fuel tank, and an emission measurement instrument (QGA 6000 model). Testing was conducted at different engine speeds of 2000, 2500, 3000, 3500, 4000, 4500, and 5000 rpm under both part-load (PL) and wide-open throttle (WOT) conditions, utilizing both pure gasoline (E0) and the test fuels. During the testing process, the chassis dynamometer shown in Fig. 5 was employed to measure torque and power. Gas samples were systematically collected and subjected to analysis in a gas analyzer to ascertain the concentrations of various emissions, including HC, CO, CO_2, and NO_x.

Table 2 *Testing motorcycle technical specifications*

Component	Specifications
Engine	Single-cylinder spark ignition engine
No of stroke	4-strokes
Exhaust pipe	Single exhaust
Combustion chamber	Pent proof/4valves
Valve train	Electro-hydraulic actuation
Compression ratio	11.78:1
Bore x stroke	52.4 mm x 57.9 mm
Air/fuel ratio	Stoichiometric or lean
Carburetor	Spark ignition
Displacement	124.9
Maximum power	9.13
No of cylinder	1
Cooling system	Air-cooled
Fuel type	Petrol
Start option	Kick & electric
Ignition system	CDI

Fig. 5 *Engine test bed.*

3. Results and Discussion

This section presents the results of blending ethanol and gasoline in polyisobutylene additives and their effects on fuel consumption, engine performance, and emissions based on tests in a single-cylinder gasoline engine.

3.1 Physicochemical Characteristics of the Blended Fuels

Physicochemical analysis of test fuels conformed to the American Standard for Testing Materials (ASTM) for gasoline products. Each fuel sample was evaluated to determine density, latent heat of vaporization (LHV), pour point, and flash point temperature. The hydrometer method (ASTM D287) was used to measure density, while flash point and pour point temperatures were measured using the Penskey-Marton apparatus (ASTM D93A). The calorific values of the fuel blends were measured using an IKA bomb calorimeter in accordance with ASTM D86. The properties of the blended fuel, such as octane number, calorific value, and energy density, play a significant role in influencing engine performance and emission levels. The fuel properties investigated are presented in Table 3.

Table 3 *Physicochemical properties of additive blended fuels*

Properties	E5P100	E5P500	E25P100	E25P500	E0P100
Density(g/cm^3)	0.7502	0.7934	0.7668	0.7633	0.7189
Research Octane Number	96.5	94.7	94.2	94.0	93.45
Calorific value (mJ/kg)	43350	43250	43756	43007	42950
Acid value mg/KOH/g	5.95	6.40	6.52	6.75	6.70
Motor Octane Number	81.5	82	81	80	83
Flash point temperature ^{0}C	10	13	12.5	11.8	9.75
Latent heat of vaporization (kJ/kg)	290	300	420	580	605

The study compared various fuel blends; E5P100, composed of 95% gasoline, 5% ethanol, and 100 mg/l polyisobutylene additive, achieved the highest Research Octane Number (RON) of 96.5 as shown in Fig. 6. Conversely, E25P500, comprising 85% gasoline, 25% ethanol, and 500 mg/l additive, exhibited the lowest RON of 93.45. Despite ethanol's lower energy content per unit volume compared to traditional gasoline, its elevated RON justifies its utilization as an additive. This inclusion enhances knock resistance, thereby augmenting engine performance and increasing power output. The fuel blend E5P500 exhibited the highest density value of 0.79342 g/cm^3, which indicates a 35.6% increase over the other blends and E0. However, as the ethanol content increased in the fuel blends, the density value decreased. In contrast, E25P500 showed the lowest density of 0.7189 g/cm3, while conventional gasoline (E0) had a density value of 0.7509 g/cm3. Although higher density is typically associated with lower fuel consumption, the lower energy density of ethanol compared to gasoline results in blended fuels having reduced energy content per unit volume. Consequently, fuel blends with lower density may lead to decreased fuel efficiency and an increase in emissions.

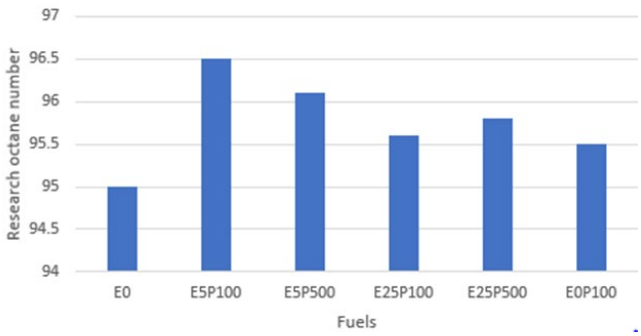


Fig. 6 *Research octane number of different fuel blends*

All tested fuels showed higher calorific values with an increase of 48.3% compared to E0, as shown in Fig. 7. Fuels with higher calorific values have beneficial effects on engine performance by providing more energy during combustion, resulting in increased power output, smoother operation, and reduced knocking noise. Engines using these fuels can operate with higher compression ratios, leading to improved overall efficiency. Conversely, E0 with lower calorific values may result in higher fuel consumption. Nevertheless, the specific effects of fuel blends are contingent on engine design and operating conditions.

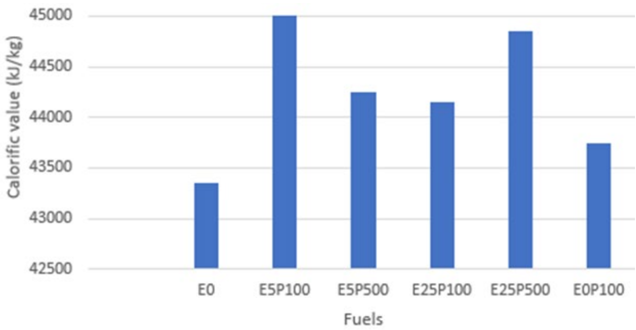
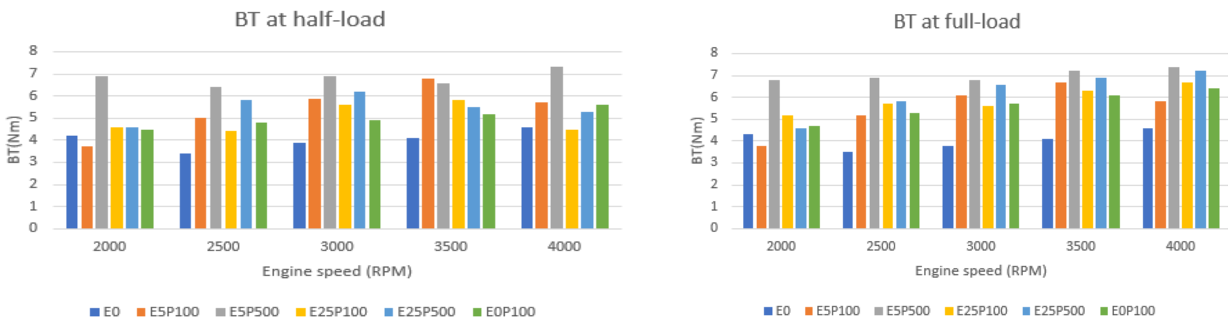


Fig. 7 *Calorific value of blended fuel at different blending ratios*

3.2 Engine Performance and Emission Characteristics of the Blended Fuels

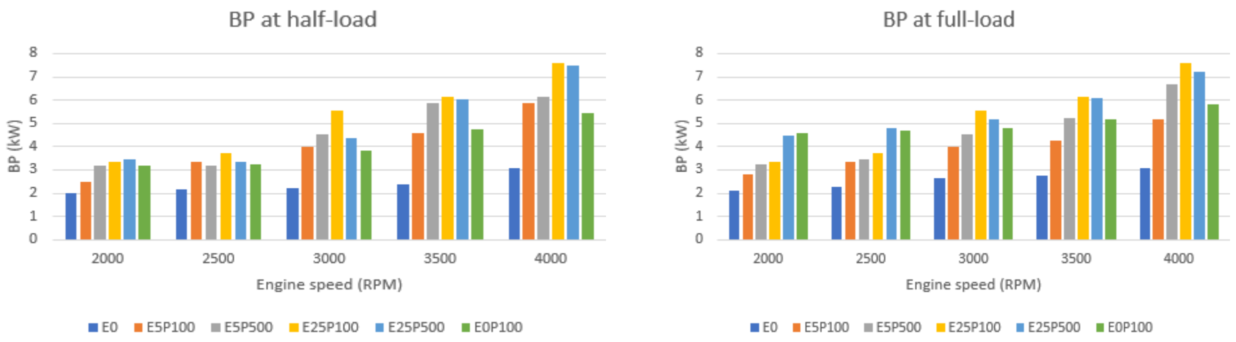
This section discusses the engine parameters such as brake torque (BT), brake power (BP), and brake-specific fuel consumption. Similarly, gas emissions results such as $\boldsymbol{HC}$, $\boldsymbol{CO}$, and $\boldsymbol{NO_x}$ are also presented and discussed. Fig. 8(a) and Fig. 8(b) show the BT torque plotted against engine speed ranging from 2000 rpm to 4000 rpm for the tested engine under two fuel conditions: additive blended fuel and (E0), tested at partial load (PL) and wide-open throttle (WOT). Notably, the formulated fuels consistently yield higher torque compared to E0 across all engine speeds at both PL and WOT conditions. At 4000 rpm, the developed fuels exhibited a maximum torque of 7.6 Nm, while E0 recorded 4.1 Nm, indicating a 45% higher torque output for the additive fuel blends. The observed increase in torque correlates with the additive percentage increase in the fuel blends; higher additive concentrations correspond to greater torque output, making E5P500 and E25P500 the reference benchmarks for fuel blends in terms of torque output.



(a) **(b)**

Fig. 8 *Comparison of BT at different engine speeds and testing conditions*

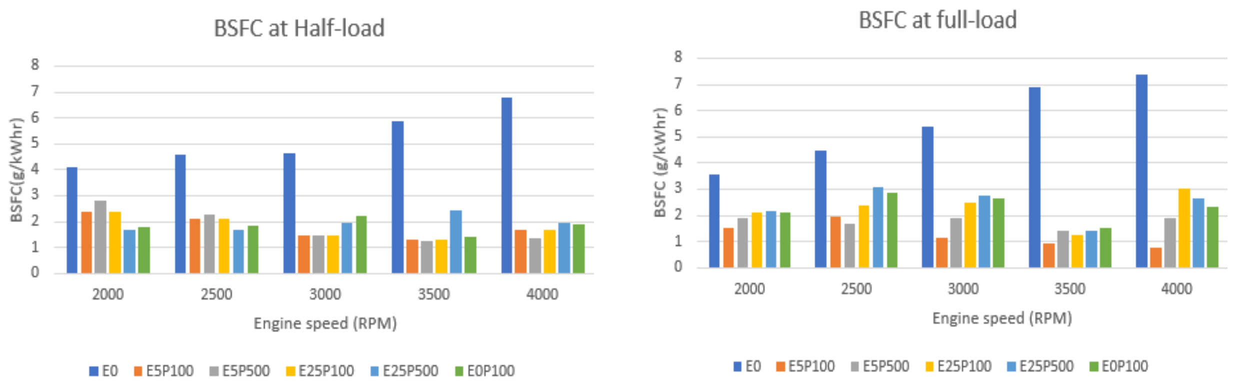
When comparing the performance of the blended fuels and the E0 results of the BP. Fig. 9(a) and Fig. 9(b) clearly show that E0 produces the lowest PB at all engine test conditions and selected engine speeds. The ability of E0 to produce the highest BP was found to be 4.32 kW at an engine speed of 4000 rpm. This value shows a reduction of 35.2% compared to the blended fuels. Fig. 9(a) and Fig. 9(b) showed that the blended fuels generate a higher BP under all test conditions, which is related to the higher-octane rating of the developed fuels. This trend continues until the maximum BP is reached. The increase in BP for all new fuels tested was attributed to the higher-octane content of the blends.



(a) **(b)**

Fig. 9 *Comparison of BP at different engine speeds and testing conditions*

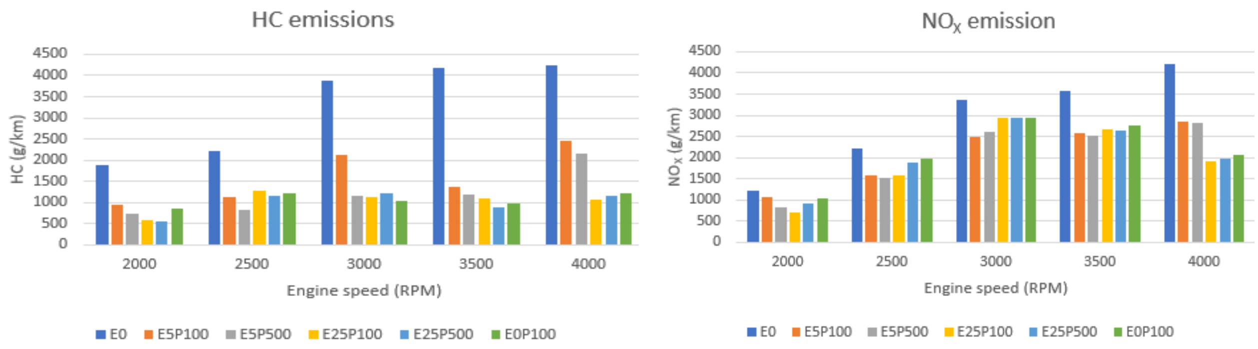
As can be seen in Fig. 10(a) and Fig. 10(b), the fuel consumption of the formulated fuels was significantly lower under all test conditions and all engine speeds. This is expected because E0 has a lower energy density compared to the new fuels. The average energy content of new fuel is 0.796 g/cm3, while that of E0 is 0.64 g/cm3, resulting in lower efficiency and higher emissions of the engine when tested with E0. In the figures, the fuel consumption of E0 increases consistently; on average, BSFC for E0 was found to be 32.2% higher compared to the developed fuels under the same test conditions. Overall, E0 consumed more fuel compared to blended fuels. It was found that the maximum BSFC for E0 was 4.7 g/kWh, which is about 12.4% higher than additive-blended fuels.



(a) **(b)**

Fig. 10 *Comparison of BSFC at different engine speeds and testing conditions*

Fig. 11(a) indicates that E0 exhibits higher $\boldsymbol{HC}$ emissions compared to blended fuels, with E0 emitting 4200 g/km at 4000 rpm while blended fuels emit an average of 1650 g/km under similar test conditions. This difference amounts to a 63.3% increase in $\boldsymbol{HC}$ emissions for E0, attributed to incomplete combustion from non-additive E0. In contrast, blended fuels, containing oxygenated additives, octane improvers, and detergents, promote complete combustion, resulting in lower $\boldsymbol{HC}$ emissions. Fig. 11(b) demonstrates that E0 produces higher $\boldsymbol{NO_x}$ emissions at low engine speeds due to the cold start effect, with blended fuels emitting 30% less $\boldsymbol{NO_x}$ overall. Moreover, as engine speed rises, $\boldsymbol{NO_x}$ emissions increase, with E0 showing an average percentage increase of 84.5% compared to blended fuels at maximum engine speed. Additionally, blended fuels significantly reduce $\boldsymbol{CO}$ emissions, with an 80.5% reduction. Specifically, E25P500, with a higher proportion of additives, consistently emits lower $\boldsymbol{CO}$ than other blends and E0, affirming its efficacy in $\boldsymbol{CO}$ emission control.



(a) **(b)**

Fig. 11 *Comparison of HC and* NO_x *at different engine speeds and testing conditions*

4. Conclusion

Based on the comparative analysis for the characterization of fuels blended with additives and gasoline for a single-cylinder engine. The experimental results can be summarized as follows: Blended fuels produced 65% more power compared to E0 and emitted less CO, NO_x, and HC by 28.2%, 23.3%, and 17.8%, respectively, over the selected engine speeds. Additionally, blended fuels showed a significant improvement in BSFC by 33.4%; BT and BP for blended fuels were found to be higher by 18.7% and 21.2%, respectively. As a contribution to knowledge, this study has discovered a new fuel model capable of reducing fuel consumption and emissions, which is particularly relevant in Nigeria, where the pump price of gasoline is increasing daily. The adoption of this study will likely meet government requirements for alternative renewable fuels in the transportation sector. Furthermore, the study highlights the potential of food waste in Nigeria as a source of bioethanol. It also suggests areas for future research, particularly by adopting the methodology for implementation in four-stroke engines, which could serve as a new platform for education and training.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Kazeem Olawale Babalola, Prof. Dr. Ahmad Jais Alimin;* ***data collection:*** *Kazeem Olawale Babalola;* ***analysis and interpretation of results:*** *Kazeem Olawale Babalola;* ***draft manuscript preparation:*** *All authors reviewed the results and approved the final version of the manuscript.*

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