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Research Paper

Performance and Emission Characteristics of an Engine Fueled with Mangrove Bioethanol–Gasoline Blends

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Abstract

Alternative fuels are a primary solution to address fuel scarcity and the adverse effects of fossil fuels, such as air pollution. Bioethanol is notable for its simple production process and the use of flexible raw materials, although it is often derived from crops used in food production. Mangrove bioethanol, however, is produced from Rhizophora mucronata mangrove fruit, which is abundant, rich in carbohydrates, and not part of the human food chain. This study aimed to evaluate the use of mangrove bioethanol as a biofuel on engine performance and emission reduction in gasoline engines. Laboratory-based experiments were conducted using mangrove bioethanol blends at concentrations of 5% (GE5) and 10% (GE10). Pure gasoline (G100) served as the baseline for comparison. The results showed that GE10 delivered better engine performance and lower emissions than both G100 and GE5, likely due to its high octane rating and oxygen content. Performance improvements with GE10 included increases of 7.89% in brake torque (BT) and brake power (BP), 47.55% in brake thermal efficiency (BTE), and 20.33% in exhaust gas temperature (EGT), along with a 98% reduction in brake specific fuel consumption (BSFC). In terms of emissions, GE10 led to reductions in carbon monoxide (CO) and hydrocarbon (HC) emissions by 43.56% and 36.54%, respectively, while carbon dioxide (CO_2) emissions increased by 59.42%.

Keywords: Biofuel; Mangrove; Performance; Emissions; GE10

1. Introduction

Industry, economy, and world population growth have increased fossil fuel exploitation [1], [2]. Fossil fuels harm human health because the emissions produced increase environmental pollution [3], [4]. However, fossil fuels are the main component of transportation that drives the economy [5]. In addition, fossil fuel substitutes are always eliminated due to demands for specifications and resistance to knocking [6]. Alcohol groups such as ethanol are compounds that have potential for being fossil fuels substitution such as gasoline [7], [8], [9]. Ethanol has high octane number properties and oxygen content to support fuel oxidation [10], [11].

Ethanol is currently a priority biofuel substitution for fossil fuels [12], [13], [14]. Brazil, the United States, and China that pioneered ethanol up to the third generation as an alternative non-edible fuel [15], [16]. Calvin et al. [17] studied ethanol biofuel's physical and chemical characteristics to validate the tendency of dummy use. An interesting result is that volatility of domestic fuel forms a positive azeotrope, and resistance of the boiling point is beneficial for the fuel compression process. Ismail et al. [18] also studied ethanol as a biofuel for SI-type engine fuel for 200cc motorcycle-type motor vehicles. Ethanol concentrations above 20% are presented with a graph of exhaust emission reductions of up to

Nomenclature

G100	: Gasoline 100%	EGT	: Exhaust Gas Temperature
GE	: Gasoline Ethanol	CO	: Carbon monoxide
GE5	: Gasoline 95% + Ethanol 5%	HC	: Hydrocarbon
GE10	: Gasoline 90% + Ethanol 10%	CO_2	: Carbon dioxide
rpm	: Rotation per Minute	NOx	: Nitrogen oxide
BT	: Brake Torque	SOHC	: Single Over Head Camshaft
BP	: Brake Power	PC	: Personal Computer
BSFC	: Brake Specific Fuel Consumption	N.m	: Newton meter
BTE	: Brake Thermal Efficiency	kW	: Kilowatt

21.74%. The emission is due to ethanol's oxygenate properties, reducing carbon formation in fuel oxidation.

He et al. [19] conducted flame observations on gasoline fuel with up to 80% ethanol concentrations. Their findings revealed that E20 fuel produces a distinct blue visual color compared to E0. This change is due to the oxygen-rich properties of ethanol, which improve fuel combustion. Previous research has suggested that mixing fossil gasoline with ethanol can improve combustion quality. However, at high ethanol concentrations, the quality may decrease. Verma et al. [20] reported indicating that the use of ethanol biofuel increases engine brake power; however, there is a decrease in fuel efficiency at higher ethanol concentrations. These observations align with physicochemical measurements, which show a decrease in the calorific value to 42.90 kJ/kg and a density of 745 kg/m^3.

Mohammed et al. [21] conducted an experiment that involved mixing ethanol with gasoline, focusing on the homogenization of the fuel to assess the exhaust emissions produced. An ultrasonic mixer device was used to consistently blend E10, E20, E30, and E40 fuels before they were introduced into the spark ignition (SI) engine fuel system. This experiment was carried out in a laboratory setting. The study decreased CO emissions by 26.33%, HC emissions by 31.05%, and NOx emissions by 20.91%. Actualization of the tendency of ethanol effects was also found in the study of Oral et al. [22], with a decrease in CO emissions reaching 2.56%, HC reaching 4.6%, and NOx emissions reaching 2.34%. The oxygen content and octane number specifications in ethanol reflect the differences in research observations [23], [24]. However, using ethanol as a fuel has sustainability challenges where it can be produced with raw materials consistent with living things' food programs [25].

Egbe et al. [26] made a breakthrough in biofuel by utilizing waste paper as raw material for ethanol. The best result obtained was a glucose concentration of the substrate ranging from 0.2-0.8 ppm with 10% sulfuric acid. As done by Rumania et al. [27], using Eucalyptus wood waste with organosolv treatment, ethanol was produced with an initial content of 32% and was distilled in stages to reach 99%. Ahmad et al. [28] also used alternative raw ethanol materials through fermentation of empty oil palm bunches with Saccharomyces Cerevisiae bacteria with the highest glucose content of 11.661 g/L and the highest ethanol content of 6%. Ludfiani et al. [29] also attempted alternative non-food raw materials from rice straw agricultural waste. Fermentation using Saccharomyces cerevisiae yeast produced 40.13–102.84 mg/L of ethanol; another innovation is using fig fruit waste by Abibu [30] as an effort for a non-edible program. Through drying at 72°C, fermentation lasting 40 hours produces high glucose up to 8.2%.

The fruit of the Rhizophora mucronata mangrove contains 6.40% glucose, which makes it unsuitable for human consumption. However, it can serve as an innovative raw material for ethanol production [31]. To facilitate the ethanol fermentation process, the proximate composition of Rhizophora mucronata fruit includes carbohydrates (45.15%), fiber (26.70%), ash (1.18%), amylose (21.90%), and amylopectin (29.10%) [26], [32]. Another important composition is the low ash content of 1.18% of the test weight. High ash content (>10%) can inhibit the glucose fermentation reaction process [3]. Therefore, according to the non-edible program, Rhizophora Mucronata mangrove fruit is an important solution for raw ethanol materials (**Figure 1**).

Currently, mangrove conservation in Indonesia has been successful and helpful in preventing abrasion, breaking sea wind waves, changing water salinity, providing economic value, and helping to settle carbon emissions [33], [34]. However, the characteristics of mangroves that proliferate result in unused mangrove fruit disrupting the water ecosystem [35]. In this study, the raw material for ethanol obtained was unused mangrove fruit (becoming waste). Mangrove fruit is considered a raw material because of its abundant availability in Africa, America, and Asia and its coastal geography. The mangrove population in Indonesia is almost 1/5 of the world's mangrove area with mangrove forest geography [35], thus ensuring the sustainability of the research.

2. Methods

Utilization of mangrove fruit as raw material for bioethanol is an alternative fuel program with raw materials that has no effect in food program for living things. Mangrove bioethanol is used as Biofuel to reduce dependence on fossil gasoline fuels. **Figure 2** illustrates the research process, which begins with the production of bioethanol from mangrove fruit and continues through performance and emission testing, as explained in detail below.

a. Mangrove bioethanol is produced in the Pharmaceutical Technology Laboratory of Politeknik Harapan Bersama through repeated hydrolysis, fermentation, and distillation processes until an alcohol content of 96% is achieved. Hydrolysis is carried out by adding 10% H_2SO_4 to convert dietary fiber or starch into glucose. Fermentation is performed by adding Saccharomyces cerevisiae and sealing the mixture for six days to convert the glucose into bioethanol. Distillation is then conducted by heating the bioethanol mixture at a controlled temperature of 75–80 °C to reduce its water content. To determine the bioethanol concentration, the sample was analyzed using gas chromatography–mass spectrometry (GC-MS) at the Integrated Laboratory of Diponegoro University, resulting in a purity of 96%.
b. Mangrove biofuel production serves as the initial stage in preparing for performance and emission tests on gasoline engines using mangrove-based fuel. The mangrove bioethanol used was independently produced at the Chemical Technology Laboratory of Politeknik Harapan Bersama. The dosage of mangrove biofuel used in the tests is presented in **Table 1**.
c. Performance and emission tests were conducted on a stationary gasoline engine under laboratory conditions. The fuels tested included pure gasoline (G100) and mangrove biofuel (GE), a blend of gasoline and mangrove-derived bioethanol. The pure gasoline was obtained from a Pertamina Indonesia fuel station. The physical properties of both fuels are listed in **Table 2**.

Figure 1. Photographic view of Rhizophora Mucronata mangrove fruit in Java Island, Indonesia

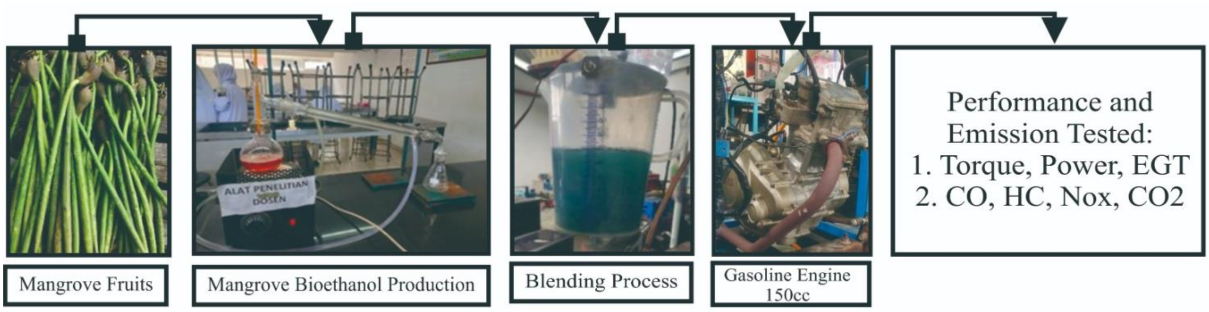

Figure 2. Research stages of mangrove biofuel

Table 1. Experimental fuel composition

Fuel code	Fuel (ml)	
	Gasoline	Bioetanol Mangrove
G100	100	0
GE5	95	5
GE10	85	15

Table 2. Fuel properties

Properties	Methods	Fuels	
		G100 [17]	E100
Octane number	ASTM D 2699	92	101.6
Lower heating value (MJ/kg)	ASTM D 240	44	26.8
Kinematics viscosity (mm2/s), at 40 °C	ASTM D 445	1.2	1.1 [36]
Oxygen content (wt.%)	ASTM D 4815	0.76	30.31
Density at 15°C (kg/m^3)	ASTM D 4052	740.7	794.3
Water content (wt.%)	ASTM D 6304	<0.01	1.16

A 150 cc gasoline engine with a water- and air-cooling system, supported by a cooling fan, was operated and equipped with a Prony brake-type dynamometer, as shown in Figure 3. Table 3 presents the technical specifications of the gasoline engine, which serve as a reference for comparing the performance test results.

The experiment was conducted using an integrated system consisting of a gasoline engine, a dynamometer, and a gas analyzer. Figure 4 illustrates the experimental setup, which includes tests conducted using both pure gasoline and mangrove biofuel.

Table 3. Technical specifications of tested engine

Properties	Specification
Type	3C1
Valve mechanism	4 Valve, SOHC
Fuel system	Fuel Injection
Capacity	150 cc
Maximum power	11.1 kW / 8500 rpm
Maximum torque	13.1 N.m / 7500 rpm
Bore x Stroke	57.0 mm x 58.7 mm

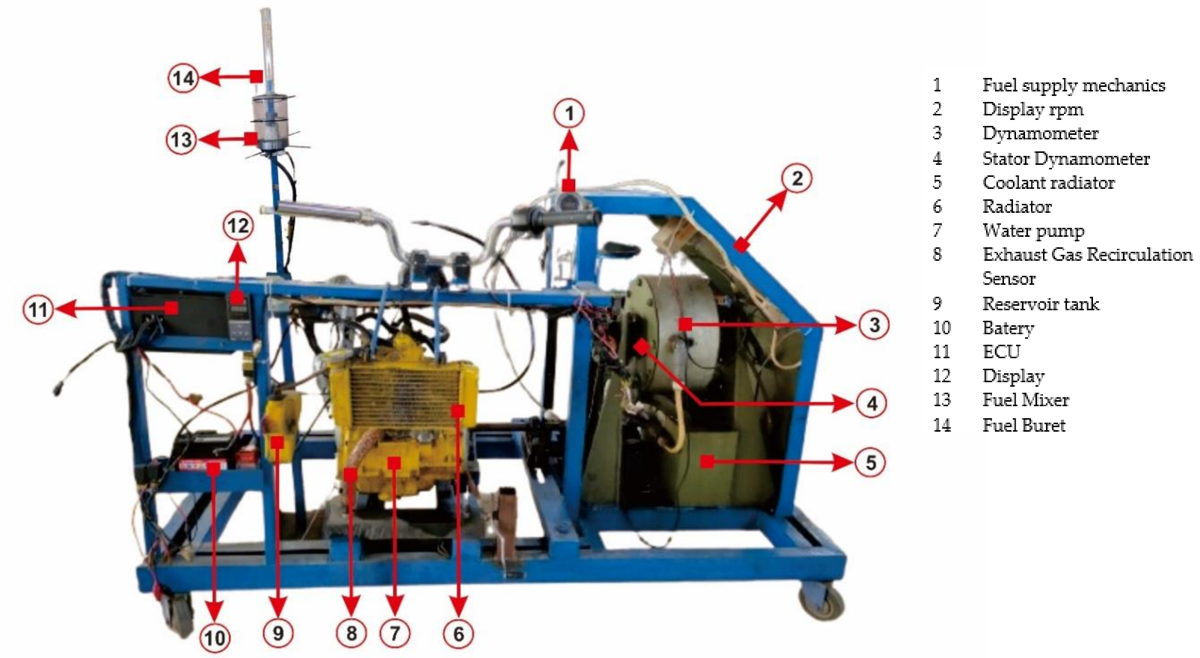

Figure 3. 150 cc gasoline engine with water cooling system

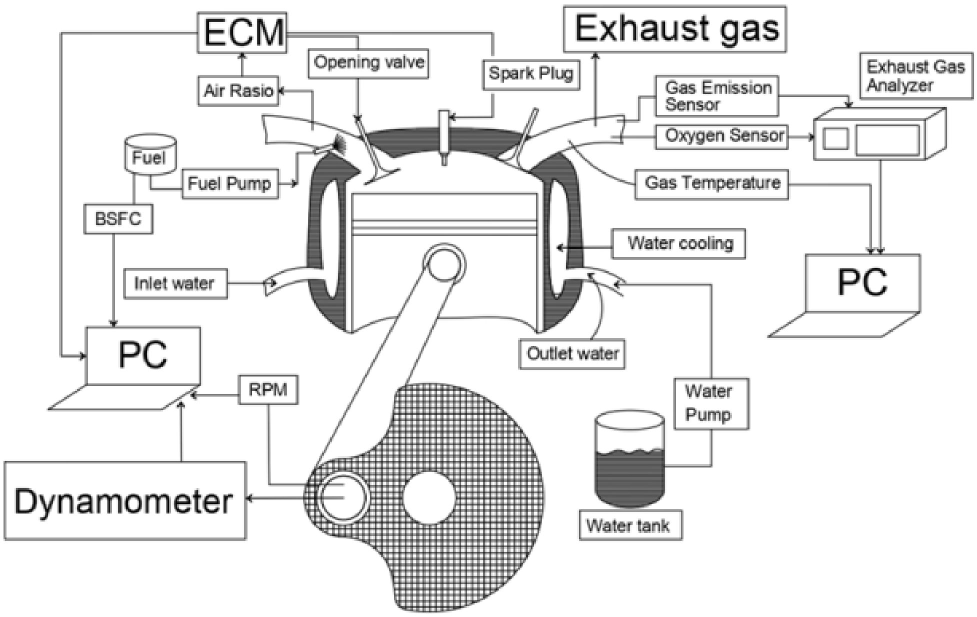

Figure 4. Integration of gasoline engine-dynamometer-gas analyzer setup

A dynamometer is integrated with the gasoline engine to measure the force generated by fuel combustion. The dynamometer is installed adjacent to the engine, with its input connected to the engine's output, allowing the generated force to be transmitted through the rotor and stator. A PC, connected to both the force display and a tachometer, enables the monitoring of performance variations. Additionally, the PC is linked to an exhaust gas analyzer (see **Table 4**), allowing observation of the exhaust gas temperature and emissions released from the engine.

Engine speeds were set at 2000, 3000, 4000, and 5000 rpm using a digital tachometer connected to the PC. During each test, the engine was operated at an initial temperature of approximately 100 °C, with a constant fuel volume of 200 ml. To determine the amount of fuel consumed in producing power, the duration of fuel use was measured using a timing device. The resulting data, include piston rod force (F), fuel flow rate, and operating time were then used to calculate brake torque, brake power, brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE), accounting for measurement error.

Brake torque (T) indicates the magnitude of force (F) generated by the fuel combustion explosion in the engine's combustion chamber [37]. Therefore, the value of F directly influences the resulting brake torque, as shown in Eq. (1). Where, F represents the force resulting from the Dynamometer loading (kg), and b represents the length of the Dynamometer arm (m).

$$T = F \times b \text{ (N.m)} \quad (1)$$

Brake Power (P) represents the amount of torque (T) delivered by the crankshaft per unit of time. Eq. (2) is used to calculate the power output. Whare, N represents engine speed (rpm), T represents Brake Torque (N.m).

$$P = 2\pi \times \frac{N}{60} \times T \times 10^{-3} \text{ (kW)} \quad (2)$$

Brake Specific Fuel Consumption (BSFC) indicates the fuel volume flowing in the combustion chamber per unit of time [38]. Therefore, the magnitude of the fuel flow and the test time length determine the magnitude of the BSFC as in Eq. (3). Where, M_f represents the fuel rate (kg/h).

Table 4. Exhaust gas analyzer specifications

Emissions Parameters	Capacity	Average Total Uncertainty in Measurement
CO	0-9.99%	±0.01
CO_2	0-19.9%	±0.01
HC	0-9999ppm	±0.01
O2	0-25%	±0.01
NOx	0-500ppm	±1

$$BSFC = \frac{m_f}{P} \text{ (kg/kW.h)} \quad (3)$$

Finaly, Brake Thermal Efficiency (BTE) indicates the efficiency of heat energy produced from fuel combustion with the amount of power produced [39]. Eq. (4) are used to determine these parameters. Where, QHV represents the fuel calorific value (MJ/kg).

$$BTE = \frac{3600}{BSFC \times QHV} \text{ (\%)} \quad (4)$$

3. Results and Discussion

3.1. Brake Torque

Figure 5 shows the BT values of a 150 cc gasoline engine fueled by pure gasoline (G100) and mangrove biofuel blends (GE). The BT produced by the engine increases with rising engine speed, due to the higher intensity of fuel supply, which allows for more consistent and reliable engine operation [38].

When comparing fuel types, the engine's BT values increased with GE5 and GE10 fuels compared to G100. The increase in BT for GE5 reached 1.93% at 2000 rpm, 1.49% at 3000 rpm, 3.92% at 4000 rpm, and 5.45% at 5000 rpm. For GE10, the BT increase reached 7.89% at 2000 rpm, 7.55% at 3000 rpm, 7.32% at 4000 rpm, and 7.12% at 5000 rpm. The highest BT increase was observed with GE10 fuel at 2000 rpm, reaching 7.89%.

This improvement is attributed to the high octane value of mangrove bioethanol, which enhances fuel oxidation quality and suppresses engine knocking [39]. Furthermore, the correlation between volume percentage and oxygen content in mangrove bioethanol improves combustion efficiency and contributes to increased engine BT [40].

3.2. Brake Power

Figure 6 presents the brake power (BP) of a gasoline engine using pure gasoline (G100) and mangrove biofuel blends (GE). The BP of the engine shows an increasing trend with each rise in engine speed (rpm) [38], which corresponds to the increase in brake torque (BT) produced by the engine. BP reflects the cumulative force generated from fuel combustion [37]. Overall, the BP of the engine using mangrove bioethanol-blended fuel is higher compared to G100, due to the higher octane rating of mangrove biofuel. This leads to more complete combustion, driven by improved resistance to engine knocking through higher compression [41]. The highest BP increase was observed with GE10 fuel, reaching up to 7.89% at 2000 rpm. Meanwhile, the use of GE5 fuel resulted in a 5.45% increase at 5000 rpm. These variations in BP values correspond to the increasing concentration of bioethanol in the fuel mixture.

3.3. Brake Specific Fuel Consumption

Figure 7 presents the brake-specific fuel consumption (BSFC) of a gasoline engine using pure gasoline (G100) and mangrove biofuel blends (GE). The BSFC decreases as engine speed (RPM) increases. This reduction is attributed to the rise in engine temperature, which enhances combustion efficiency within the combustion chamber [42], [43]. The performance evaluation of

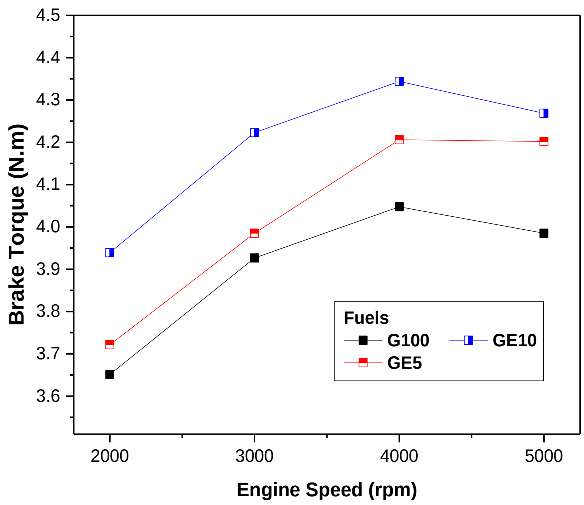

Figure 5. Brake torque of gasoline engine fueled by gasoline-mangrove biofuel

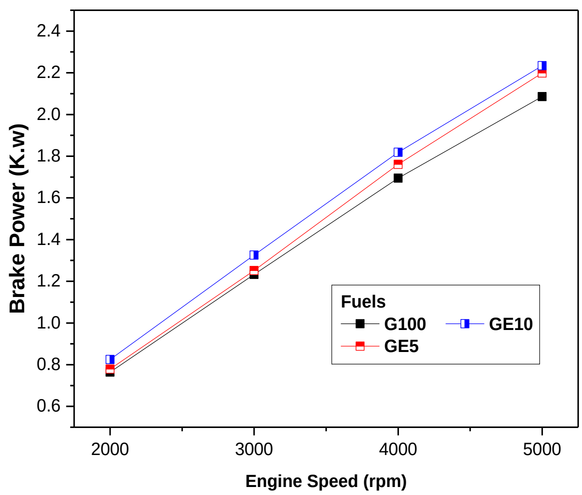

Figure 6. Brake power of gasoline engine fueled by mangrove gasoline-biofuel

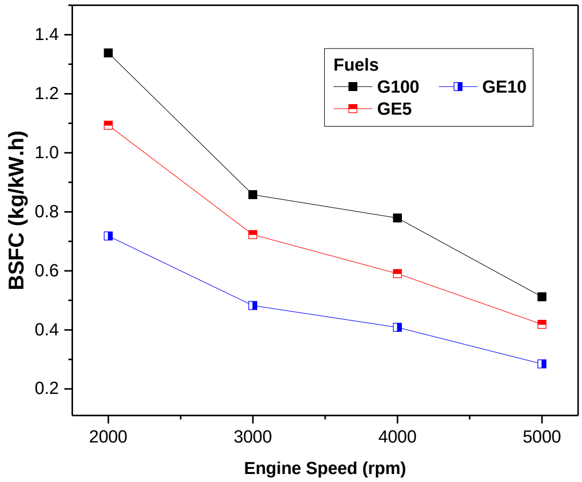

Figure 7. Brake-specific fuel consumption (BSFC) of gasoline engine using gasoline-mangrove biofuel

the engine using mangrove biofuel (GE5 and GE10) shows a decreasing BSFC trend compared to that of G100. The higher oxygen content in mangrove bioethanol promotes better fuel oxidation, resulting in more complete combustion [44]. Additionally, the higher octane rating of mangrove biofuel improves the fuel compression process, which contributes to increased engine performance and reduced BSFC [10], [11].

Among the fuels tested, GE10 exhibited the most significant BSFC reduction, with decreases of 46.35% at 2000 rpm, 43.77% at 3000 rpm, 47.55% at 4000 rpm, and 44.45% at 5000 rpm. In comparison, GE5 showed lower reductions: 18.31% at 2000 rpm, 15.77% at 3000 rpm, 24.19% at 4000 rpm, and 18.26% at 5000 rpm.

3.4. Brake Thermal Efficiency

Figure 8 shows the results of the Brake Thermal Efficiency (BTE) analysis for both pure gasoline (G100) and mangrove biofuel blends (GE) in a gasoline engine. The BTE increases consistently with rising engine speed (RPM) [45]. This improvement is attributed to the combined effect of increased Brake Power (BP) and reduced Brake Specific Fuel Consumption (BSFC) [46]. BTE indicates how efficiently the fuel is converted into useful mechanical energy (piston thrust) during combustion [45]. Engines running on GE5 and GE10 fuels demonstrated higher BTE values compared to G100. This improvement is likely due to the high octane number and oxygen content in mangrove bioethanol, which enhance combustion efficiency [2], [11]. For GE5 fuel, the BTE increased by 24.73% at 2000 rpm, 20.98% at 3000 rpm, 34.41% at 4000 rpm, and 24.65% at 5000 rpm. In contrast, GE10 fuel showed a more significant increase: 93.61% at 2000 rpm, 84.71% at 3000 rpm, 98.00% at 4000 rpm, and 86.96% at 5000 rpm.

3.5. Exhaust Gas Temperature

Figure 9 illustrates the effects of using G100, GE5, GE10, and GE15 fuels on the combustion gas temperatures emitted through the exhaust pipe of a gasoline engine. The exhaust gas temperature (EGT) increases with engine speed, primarily due to the greater fuel supply required to achieve higher RPMs [43].

Overall, engines fueled with GE5 and GE10 exhibit higher EGTs compared to those using G100. This increase is attributed to the higher octane number and oxygen content of mangrove bioethanol. A higher octane number enhances

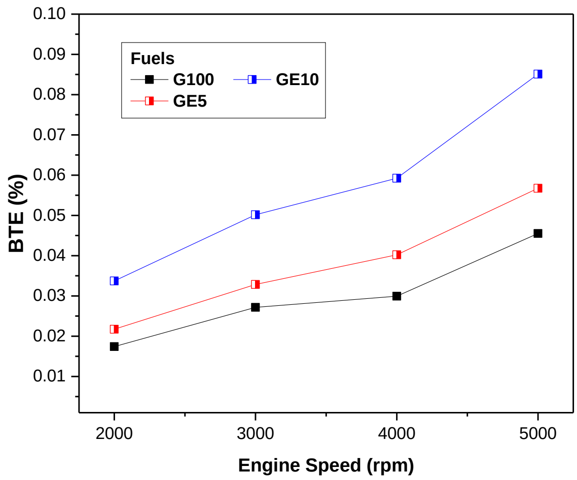

Figure 8. BTE of gasoline engine fueled by gasoline-mangrove biofuel

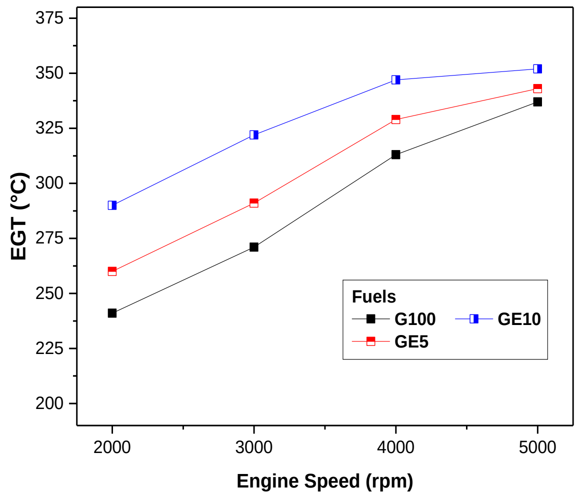

Figure 9. EGT of gasoline engine fueled by gasoline-biofuel mangrove

the engine's resistance to knocking under compression, which in turn raises combustion temperatures during oxidation [47]. Meanwhile, the additional oxygen content in bioethanol supports more complete combustion by supplementing the oxygen normally provided via the air intake [11], [39].

Specifically, the EGT increase when using GE5 fuel was 7.88% at 2000 rpm, 7.38% at 3000 rpm, 5.11% at 4000 rpm, and 1.78% at 5000 rpm. In comparison, GE10 resulted in a more substantial rise: 20.33% at 2000 rpm, 18.82% at 3000 rpm, 10.86% at 4000 rpm, and 4.45% at 5000 rpm.

3.6. *Carbon Monoxide Emissions*

Figure 10 presents the carbon monoxide (CO) emission measurements from gasoline engines running on G100, GE5, and GE10 fuels. The data shows a decreasing trend in CO emissions across various engine speeds (rpm). This reduction is attributed to the increased combustion chamber temperature, which promotes more complete fuel combustion [11]. Overall, CO emissions from engines fueled with GE5 and GE10 are lower compared to those running on G100. The higher oxygen content in mangrove bioethanol plays a key role in enhancing fuel oxidation and reducing CO emissions [38]. Specifically, CO emissions decreased by 37.18% at 2000 rpm, 33.33% at 3000 rpm, 41.08% at 4000 rpm, and 43.56% at 5000 rpm when using GE10 fuel. In contrast, engines running on GE5 showed smaller reductions of 29.55% at 2000 rpm, 25.6% at 3000 rpm, 26.05% at 4000 rpm, and 27.81% at 5000 rpm.

3.7. *Hydrocarbon Emissions*

Figure 11 shows the measurements of hydrocarbon (HC) emissions from gasoline engines fueled by G100, GE5, and GE10 at engine speeds of 2000, 3000, 4000, and 5000 rpm. The data indicate a decrease in HC emissions at all tested speeds [46]. HC emissions from engines using mangrove biofuel exhibit a steeper decline compared to those running on G100. The higher concentration of mangrove bioethanol increases the oxygen content in the fuel, enhancing the oxidation process [38]. Additionally, the high octane number of mangrove bioethanol improves the engine's compression resistance, which correlates with more complete combustion [44]. Specifically, HC emissions decreased more sharply with GE10 fuel—by 30.59% at 2000 rpm, 32.68% at 3000 rpm, 36.89% at 4000 rpm, and 36.54% at 5000 rpm. In contrast, using GE5 fuel resulted in smaller reductions of 15.29% at 2000 rpm, 20.26% at 3000 rpm, 18.03% at 4000 rpm, and 8.65% at 5000 rpm.

3.8. *Carbon Dioxide (CO_2) Emissions*

Figure 12 illustrates the results of CO_2 emissions measurements for gasoline engines using G100 GE5 and GE10 fuels. The data indicates a consistent increase in CO_2 emissions as engine operation progressed. The rising engine temperature (exhaust gas or EGT) enhances fuel oxidation, leading to higher CO_2 production [48]. Overall, CO_2 emissions from gasoline engines fueled by Mangrove Biofuel (GE5 and GE10) were observed to be higher than those using G100. The elevated oxygen content in Mangrove Biofuel

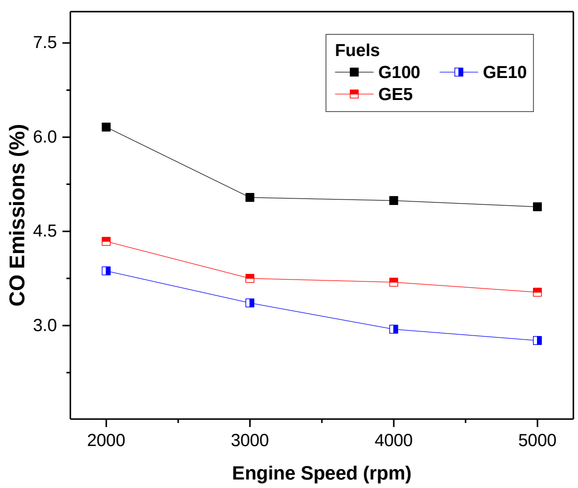

Figure 10. CO emissions of gasoline engines fueled by G100, GE5, and GE10

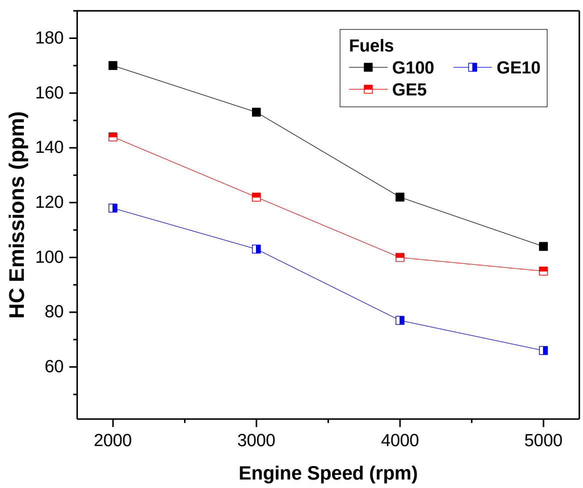

Figure 11. HC emissions from the use of gasoline engines fueled by G100, GE5, and G10

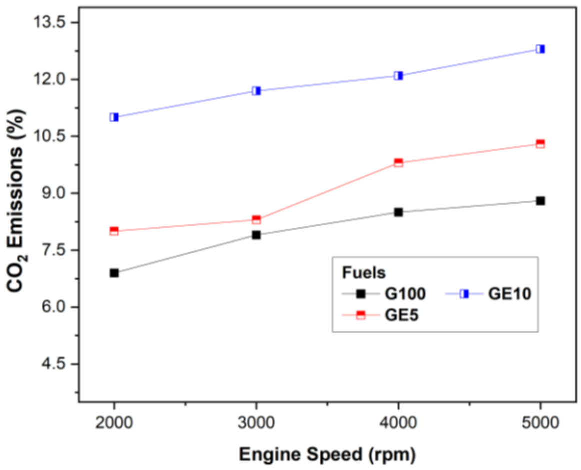

Figure 12. CO_2 emissions measured using G100, GE5, and GE10 fuels

promotes complete combustion, thereby increasing the formation of CO_2 emissions [11], [46]. Specifically, the increase in CO_2 emissions for gasoline engines using GE5 fuel was recorded as follows: a 15.94% increase at 2000 rpm, 5.06% at 3000 rpm, 15.29% at 4000 rpm, and 17.05% at 5000 rpm. Conversely, the increase in CO_2 emissions using GE10 fuel reached 59.42% at 2000 rpm, 48.10% at 3000 rpm, 42.35% at 4000 rpm, and 45.45% at 5000 rpm.

4. Conclusion

A blend of gasoline and mangrove bioethanol produces a biofuel known as mangrove biofuel, characterized by a high octane rating and an oxygen content of 30.31%. Performance and exhaust emissions were evaluated using a 150 cc gasoline engine, yielding promising results. Specifically, the GE10 fuel demonstrated better performance and lower emissions compared to G100 and GE5. The brake torque (BT) and brake power (BP) showed maximum increases of 7.89%, while brake thermal efficiency (BTE) improved by 47.55%. Exhaust gas temperature (EGT) increased by 20.33%. Although CO2 emissions rose by 59.42%, brake-specific fuel consumption (BSFC) significantly decreased by 98%. Moreover, CO emissions were reduced by 43.56%, and hydrocarbon (HC) emissions dropped by 36.54%.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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