

Experimental Characteristics of Bioethanol-Gasoline Blended Fuels: Analysis of Air-Fuel Ratio, Exhaust Emissions, and Fuel Consumption in Spark Ignition Engines

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Abstract. The development of alternative fuels based on bioethanol has been encouraged by the current energy crisis and the increase in motor vehicle emissions. The performance characteristics of Pertamina-bioethanol fuel blends (E0, E20, E40, E60, and E80) in Spark Ignition Engines without modification are examined in this study, with an emphasis on fuel consumption, exhaust emissions, and air fuel ratio. A four-gas analyzer and a flow meter were used to conduct the experiments throughout an engine speed range of 1500–7500 rpm. The results show that a leaner mixture can be produced by increasing the concentration of bioethanol, as seen by higher AFR and lambda values. The E80 blend significantly decreased HC emissions by 81% at 1500 rpm, going from 354 PPM to 66 PPM. The E20 blend reduced CO emissions by up to 70% at higher engine speeds. CO₂ emission increased by 5–10% for all bioethanol mixes, suggesting more thorough burning. Fuel usage increased in direct proportion to the quantity of bioethanol; at 7500 rpm, the E80 blend used 24.2% more fuel than E0. The E20 and E40 mixes provide the best mix of fuel efficiency and emission reduction for driving in cities. At low to medium engine speeds, however, the E60 and E80 perform better. Overall, the findings show that bioethanol blends up to E40 may be accommodated by normal electronic fuel injection systems with just little modifications, supporting the wider use of alternative fuels in standard Indonesian vehicles.

1 Introduction

The global energy crisis and rising emissions from the transportation sector have encouraged initiatives to create more sustainable alternative fuels. A frequently researched approach is the incorporation of bioethanol as a gasoline fuel blend. Bioethanol has attracted significant attention due to its renewable nature and high oxygen content, which can enhance combustion efficiency, which enhances combustion efficiency. However, the enhancement in combustion efficiency caused by ethanol's oxygen content may partially offset the rise in fuel consumption [1]. Ethanol derived from crops or agricultural biomass waste holds significant

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potential as a renewable alternative fuel for gasoline engines. The use of bioethanol in gasoline-powered engines has been widely reported to reduce carbon monoxide (CO) and hydrocarbon (HC) emissions without requiring major engine modifications [2].

Ethanol-gasoline combinations demonstrate distinct stoichiometric and combustion characteristics in comparison to pure gasoline. The oxygen presence in ethanol reduces the air-fuel ratio essential for full combustion [3]. Air fuel ratio (AFR) refers to the mass ratio of air to fuel in the combustion mixture, and it is a critical parameter determining combustion completeness and engine performance. Ethanol contains a high oxygen content, allowing ethanol-gasoline blends to achieve more complete and stable combustion at higher temperatures compared to pure gasoline, thereby improving combustion efficiency. These modifications in stoichiometric characteristics influence thermal efficiency and combustion performance, which subsequently affect vehicle exhaust emissions.

Many studies indicate that increasing the ethanol proportion in the mix generally elevates CO₂ emissions signifying more complete combustion while continuously decreasing CO and HC emissions significantly [4]. The characteristics of the air fuel ratio of ethanol blends are tightly connected to fuel consumption. Ethanol's calorific value is lower compared to that of gasoline, requiring a greater volume of fuel to achieve the same power output [5]. Knowing the relationship among AFR, emissions, and fuel consumption is crucial for assessing the possibility of integrating bioethanol blends into conventional vehicle fuel systems.

The use of bioethanol in spark-ignition engines is becoming increasingly essential not only for its capacity to reduce pollutant emissions but also for its potential to improve combustion quality. The presence of oxygen in ethanol facilitates more thorough combustion, leading to reduced hydrocarbon and carbon monoxide emissions compared to the usage of pure gasoline [6]. However, increasing the ethanol proportion may influence nitrogen oxide (NO_x) production due to variations in combustion temperature, as indicated in previous research on bioethanol combustion [7]. Therefore, a thorough investigation of emission characteristics is essential before determining the best fuel blend formulation.

Besides emissions, fuel consumption is a critical factor in evaluating the feasibility of bioethanol usage. Increasing ethanol concentration in gasoline blends has consistently been associated with higher brake specific fuel consumption (BSFC). BSFC is a parameter used to evaluate engine efficiency, indicating the amount of fuel consumed per unit of power produced. E30 mixes have been reported to show a fuel consumption increase above 10% under some operating situations, whilst 10–30% ethanol blends can elevate brake specific fuel consumption by around 6–16% across different load and engine speed situations [6]. This point of view aligns with the findings presented in Ansari et al [8], which indicate that the addition of ethanol increases the oxygen level in the mixture, thereby reducing its effective heating value and consequently increasing BSFC in gasoline ethanol blends.

The results indicate that while bioethanol offers advantages regarding emissions, fuel consumption must still be evaluated to ascertain the most effective mix composition. Consequently, alongside environmental advantages, the examination of fuel usage is a critical element in developing the ideal bioethanol-gasoline mixture. Research from Gajewski et al. [9] highlights that increasing the ethanol concentration in fuel blends can influence multiple engine performance metrics, particularly resulting in a reduction of power output. This effect is influenced not only by the gasoline blend composition but also by engine parameters, including fuel injection quantity and ignition time.

Previous research has established that the combustion characteristics of ethanol-gasoline mixtures are significantly affected by the stoichiometric ratio and engine operating parameters. High ethanol blends may create a more stable combustion process and improve engine volumetric efficiency; however, accurate air-fuel ratio adjustments are necessary to avoid lean misfire conditions. The findings Zacarias et al [10] indicate that the integration of E15 bioethanol mixes in current automobiles can occur without substantial alterations,

simply requiring an adjustment of the fuel line material. E10 blends show superior compatibility, requiring minimal modifications to regular vehicles, therefore making them the most feasible choice for rapid implementation.

However, studies examining the simultaneous interaction between air–fuel ratio behaviour, exhaust emissions, and fuel consumption in high-ethanol blends under standard electronic fuel injection (EFI) operation remain limited. Unlike previous studies that primarily focus on emission or performance parameters separately, this study simultaneously evaluates the interaction between AFR behaviour, exhaust emissions, and fuel consumption across a wide engine speed range using Pertamina–bioethanol blends up to E80 in an unmodified small-displacement spark ignition engine. Therefore, this research aims to experimentally investigate the feasibility of high-ethanol fuel utilization in standard EFI motorcycle engines without requiring major modifications.

In the context of standard engines equipped with fuel injection systems, it is essential to evaluate the degree to which bioethanol may be utilised without significant modifications to the fuel delivery system. This study is to investigate the attributes of the AFR relationship with exhaust emissions and fuel consumption rates in small displacement spark ignition engines. This research examines the performance of the combustion system in spark ignition engine vehicle to empirically assess the feasibility of using bioethanol In small, standard manufacturer vehicles without requiring significant engine modification.

This study provides a comprehensive evaluation of the real-time dynamics of the air-fuel ratio, exhaust emissions, and fuel consumption across a wide engine speed range (1500–7500 rpm) with Pertamina–bioethanol blends in an unmodified small-displacement production motorcycle. The experiments utilize a standard electronic fuel injection system to assess the fuel's suitability under realistic operating conditions, unlike other studies that typically examine performance or emissions characteristics separately or rely on recalibrated engine control systems. These findings offer experimental insights into the relationship between blend composition, combustion characteristics, and energy requirements, thus defining practical operational limits for high-ethanol fuels in small spark-ignition engines.

2 Method

This study employs an experimental methodology to examine the impact of bio gasoline on air-fuel ratio characteristics, emissions, and fuel consumption in standard unmodified motorcycle engines. Five ethanol-gasoline blend levels (E0, E20, E40, E60, and E80) were evaluated using a Four Gas Analyzer to get real-time data on hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO₂), oxygen (O₂), lambda (λ), and air-fuel ratio (AFR), while fuel consumption rates were assessed using a flow meter integrated into the supply system. The tests were performed in a laboratory setting with regulated engine speeds ranging from 1500 to 7500 rpm at 1000 rpm intervals to ensure a thorough assessment of different loads and engine operating conditions.

The examination focused on a spark-ignition engine conforming to established manufacturing criteria as outlined in **Table 1** and **Table 2**.

The following procedures were utilized to evaluate exhaust emissions and the air-fuel ratio (**Fig. 1**). Before testing, the engine received comprehensive servicing and inspection, and the specified fuel mixes were made. The four-gas analyser received calibration to ensure measurement accuracy. The engine was thereafter elevated to its standard operating temperature of approximately 80–85 °C before to the initiation of data collection. The analyser probe was affixed to the exhaust pipe, after which the engine was progressively accelerated while the emission and air-fuel ratio values were monitored and recorded. Measurements were taken at engine speeds between 1500 and 7500 rpm, in increments of

1000 rpm. Each fuel mix received three tests, resulting in a total of fifteen trials for emission and air-fuel ratio measurements.

Table 1. Motorcycle specifications

Engine Specifications	
Machine capacity	108.2 cc
Fuel supply system	Injection (PGM-FI)
Diameter x step	50 x 55,1 mm
Transmission type	Automatic, V-Matic
Compression ratio	9,5:1
Maximum power	6.38 KW (8.68 PS)/7,500 rpm
Maximum torque	9,01 Nm. (0,92 Kgf.m)/6.500 rpm
Starter type	ACG Starter, Pedal & Electric
Clutch type	Automatic, Centrifugal, Dry Type

Table 2. Variations of mixtures tested

Fuel Type	Mixture Composition
E0	100% Gasoline
E20	20% ethanol + 80% gasoline mixture
E40	40% ethanol + 60% gasoline mixture
E60	60% ethanol + 40% gasoline mixture
E80	80% ethanol + 20% gasoline mixture

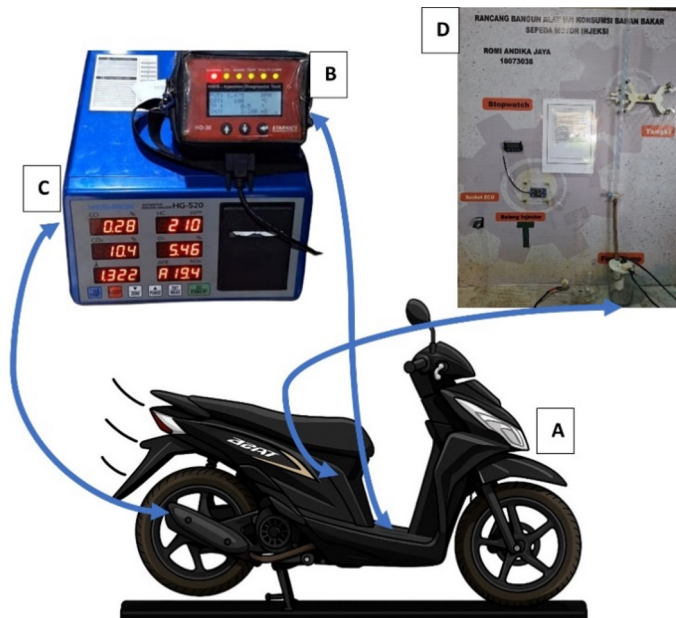


Fig. 1. Emissions and consumption rate measurement; (a). FI motorcycle, (b). scanner, (c). Gaz analyser, (d). flow meter.

Fuel consumption was assessed independently via a flow meter to ascertain the fuel usage rate. For each designated engine speed, the engine was sustained at a constant rpm for 60 seconds, during which the fuel consumption was directly measured from the flow meter tube. The fuel consumption rate was then determined using the given formula [11]:

$$BFC = \frac{Vf}{t} \times \frac{3600}{1000} \quad (1)$$

Where BFC represents fuel consumption (L/hour), Vf is the volume of fuel consumed during the measurement period (mL), and t is the time required to consume the fuel (s).

The test data was analysed descriptively by calculating the average and range for each quantifiable parameter. The primary analysis concentrated on the characteristics of AFR concerning exhaust emissions through the generation of graphs.

3 Results and discussion

The emission and AFR measurement results in the table offer a summary of the variations in carbon monoxide, hydrocarbons, carbon dioxide, oxygen, lambda, and AFR values across various fuel blend compositions and engine speed levels. The Figure illustrates the correlation between the air fuel ratio and emission characteristics, demonstrating how variations in the fuel-air ratio affect CO, HC, and CO₂ emissions at each bioethanol blend level.

3.1 Emissions characteristics and AFR in baseline fuel (E0)

Table 3. Results of exhaust gas emission and AFR testing with pure Pertamax (E0)

RPM	AFR	CO (%)	CO ₂ (%)	O ₂ (%)	HC (PPM)	LAMDA (λ)
1500	16.23	0.37	10.30	2.22	354	1.11
2500	18.57	0.34	10.37	4.60	183	1.26
3500	19.63	0.58	11.90	6.67	162	1.33
4500	20.57	0.5	12.73	8.16	114	1.4
5500	21.13	0.38	13.33	9.20	87	1.44
6500	22.00	0.14	14.07	10.77	45	1.5
7500	23.13	0.11	14.43	12.41	47	1.58

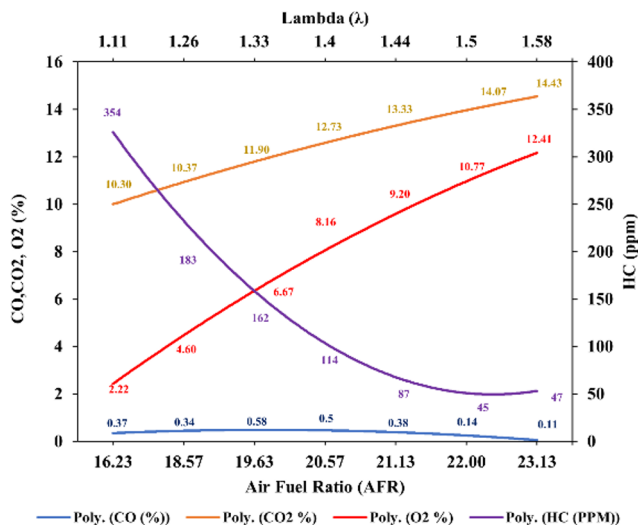


Fig. 2. The effect of AFR on E0 exhaust gas emissions

Table 3 and **Fig. 2** present the emission characteristics of neat Pertamax as the baseline fuel. As engine speed increases, the air fuel ratio rises from 16.23 to 23.13 at 7,500 rpm, indicating progressively leaner combustion. At low engine speed (1,500 rpm), HC emissions remain relatively high due to lower in-cylinder temperature and limited turbulence, which restrict complete oxidation. As engine speed increases, improved fuel atomization and mixture formation reduce HC emissions to 47 ppm. A similar pattern is observed for CO and CO₂ emissions. CO decreases from 0.37% to 0.11%, while CO₂ increases from 10.30% to 14.43%, indicating more complete combustion at higher engine speeds.

This phenomenon occurs because sufficient oxygen availability promotes the oxidation of partially burned carbon compounds, allowing CO to be further converted into CO₂ during the combustion process. The study by Suresh and Porpatham [12] reported that carbon monoxide is predominantly produced under incomplete combustion conditions and can be significantly reduced when adequate oxygen is present to facilitate the oxidation of CO into CO₂ in the combustion chamber. Furthermore, lambda values exceeding unity at high rpm (reaching 1.58) confirm lean-burn operation, which inherently suppresses the formation of carbon-based pollutants.

3.2 Emissions and AFR characteristics in the mixture (E20)

Table 4. Results of E20 mixture emission tests on RPM variations

RPM	AFR	CO (%)	CO ₂ (%)	O ₂ (%)	HC (PPM)	LAMDA (λ)
1500	19.80	0.34	10.30	5.85	240	1.35
2500	20.90	0.32	10.50	7.27	220	1.43
3500	23.53	0.32	11.07	10.48	140	1.61
4500	18.05	0.26	11.87	11.71	110	1.65
5500	23.87	0.17	13.10	12.43	69	1.63
6500	23.87	0.14	13.73	12.93	66	1.63
7500	24.40	0.08	14.53	14.30	61	1.66

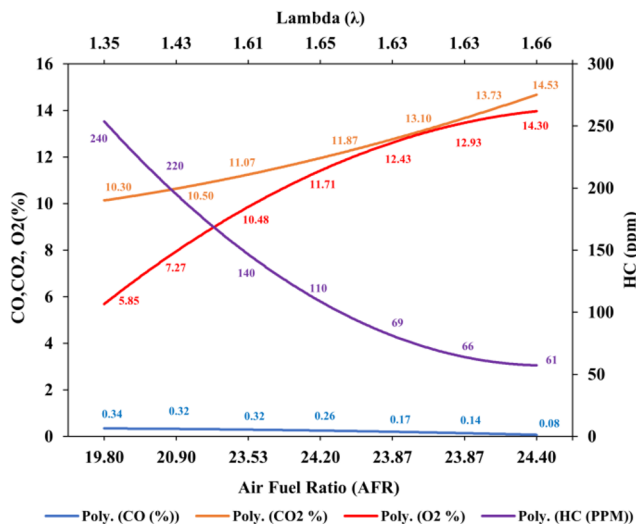


Fig. 2. The effect of AFR on E20 mixture exhaust gas emissions

Table 4 and **Fig. 3** present the effect of AFR on E20 mixture exhaust gas emissions. The addition of 20% ethanol results in a significantly leaner mixture compared to E0. AFR values

ranging from 19.80 to 24.40 indicate the contribution of oxygen inherent to bioethanol, which enhances combustion accuracy and stability. This effect is reflected in the reduction of CO emissions from 0.34% to 0.08% and HC emissions from 240 ppm to 61 ppm across the engine speed range.

These trends are consistent with the findings reported in Wang et al. [13], which show that ethanol blends such as E22 promote more complete carbon oxidation and suppress pollutant formation due to increased internal oxygen availability. The corresponding increase in CO₂ concentration further confirms the enhancement of carbon oxidation, indicating that the oxygenated nature of ethanol plays a dominant role in improving combustion completeness and reducing carbon-based pollutant emissions in the E20 blend.

3.3 Emissions and AFR characteristics in the mixture (E40)

Table 5. Results of E40 mixture emission tests on RPM variations

RPM	AFR	CO (%)	CO ₂ %	O ₂ %	HC (PPM)	LAMDA (λ)
1500	18.2	0.46	11.27	4.65	156	1.24
2500	21.2	0.43	11.17	7.95	127	1.44
3500	23.4	0.45	11.27	10.49	91	1.59
4500	23.4	0.40	12.17	11.34	111	1.60
5500	23.5	0.29	13.03	12.03	99	1.60
6500	23.2	0.18	14.10	12.41	89	1.58
7500	23.8	0.14	14.63	13.62	84	1.62

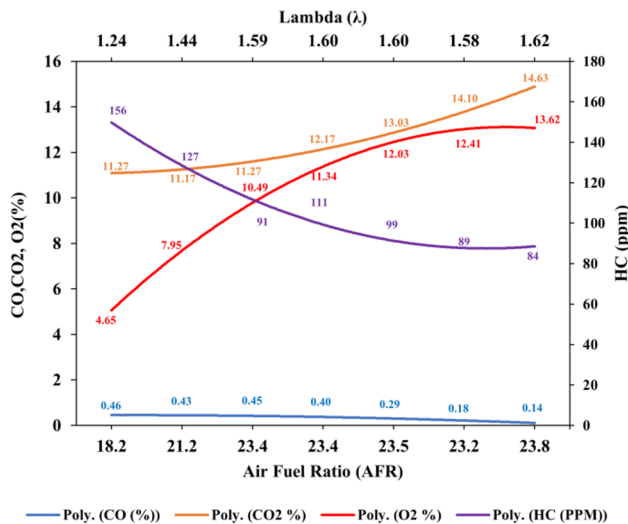


Fig. 4. The effect of AFR on E40 mixture exhaust gas emissions

Table 5 and **Fig. 4** present the effect of AFR on E40 mixture exhaust gas emissions. The E40 blend exhibits more stable and efficient combustion characteristics compared to the lower ethanol fractions. The elevated AFR and lambda values indicate that the engine can sustain lean combustion while maintaining flame stability. Notably, CO₂ emissions are the highest among all tested fuels, reflecting a high degree of combustion completeness. At low engine speeds, CO emissions are slightly higher than those of E20, primarily due to ethanol's high latent heat of vaporization, which slows fuel evaporation at low in-cylinder temperatures and reduces mixture homogeneity during early combustion.

As engine speed increases, CO emissions decrease sharply to 0.14%, consistent with findings in Mohammed et al [7], which indicate that increased engine speeds enhance mixture consistency and raise combustion temperatures, leading to more thorough oxidation. Overall, the E40 blend exhibits a characteristic behaviour of ethanol-based fuels, with reduced combustion stability at low speeds and significantly improved efficiency at higher engine speeds.

3.4 Emissions and AFR characteristics in the mixture (E60)

Table 6. Results of E60 mixture emission tests on RPM variations

RPM	AFR	CO (%)	CO ₂ (%)	O ₂ (%)	HC (PPM)	LAMDA (λ)
1500	17.5	0.35	10.63	3.39	101	1.20
2500	18.4	0.42	10.90	4.51	107	1.25
3500	22.0	0.41	11.10	8.82	127	1.50
4500	23.5	0.36	11.57	10.86	141	1.60
5500	23.6	0.22	12.80	11.82	115	1.61
6500	23.1	0.26	13.63	12.12	148	1.58
7500	23.5	0.30	14.50	13.41	129	1.60

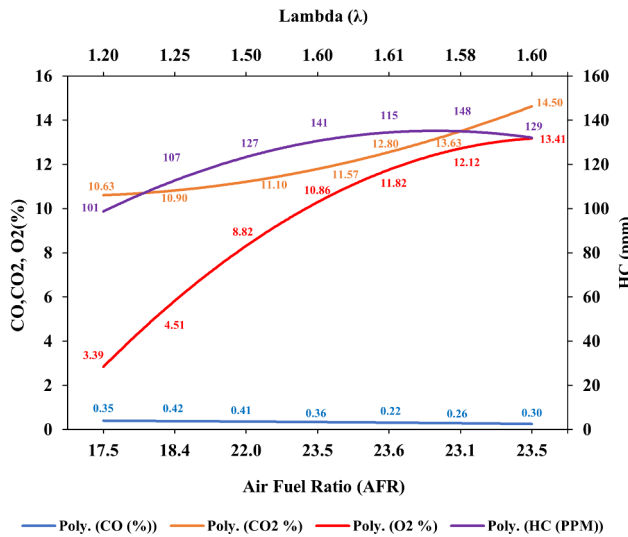


Fig. 5. The effect of AFR on E60 mixture exhaust gas emissions

Table 6 and **Fig. 5** present the effect of AFR on E60 mixture exhaust gas emissions. The E60 blend does not exhibit a linear improvement in combustion performance with increasing ethanol concentration. At low engine speeds, it shows favourable behaviour with the lowest HC emissions among all tested fuels; however, this trend reverses at higher engine speeds, where HC emissions increase markedly, indicating reduced combustion stability. This behaviour is primarily attributed to the lower calorific value of bioethanol and its high latent heat of vaporization. As engine speed increases, the available combustion duration decreases while the energy required for fuel evaporation remains high, lowering the mixture temperature and causing incomplete evaporation or combustion of part of the fuel.

Consequently, HC emissions increase due to a greater fraction of unburned fuel, Similar observations have been reported in Ye et al [3], which indicate that high ethanol content

typically enhances HC emissions due to a greater proportion of uncombusted alcohol remaining in the exhaust. Despite the increase in HC, CO emissions remain low and CO₂ concentrations continue to rise, indicating that carbon oxidation proceeds efficiently. Consistent with Iodice and Cardone [14], high ethanol content enhances the latent heat of vaporization, which can lower mixture temperatures and reduce combustion rates under limited combustion durations. These combined effects explain the partial oxidation behaviour observed for the E60 blend at high engine speeds.

3.5 Emissions and AFR characteristics in the mixture (E80)

Table 7. Results of E80 mixture emission tests on RPM variations

RPM	AFR	CO (%)	CO ₂ (%)	O ₂ (%)	HC (PPM)	LAMDA (λ)
1500	19.2	0.22	11.10	5.36	66	1.31
2500	20.4	0.32	11.00	6.72	69	1.39
3500	21.1	0.33	11.67	7.99	71	1.44
4500	20.9	0.32	12.53	8.23	72	1.42
5500	20.5	0.30	13.70	8.40	78	1.40
6500	21.0	0.42	13.77	9.36	127	1.43
7500	21.9	0.28	14.20	10.84	131	1.49

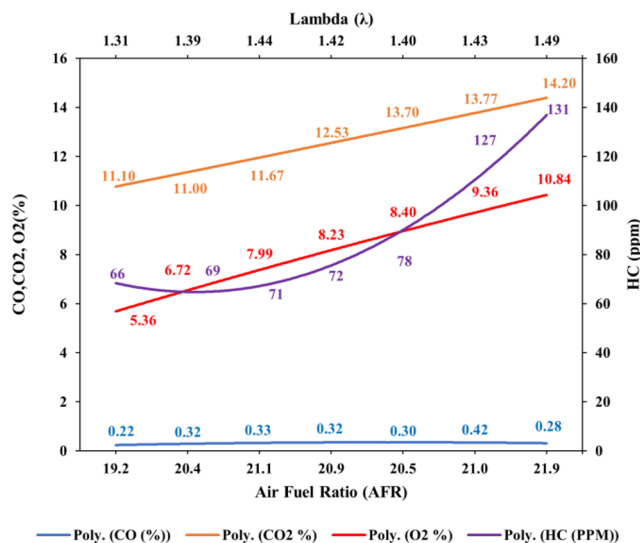


Fig. 6. The Effect of AFR on E80 Mixture Exhaust Gas Emissions

Table 7 and **Fig. 6** present the effect of AFR on E80 mixture exhaust gas emissions. The E80 blend demonstrates traits characteristic of elevated ethanol levels, producing a notably lean mixture with air fuel ratio values of 19.2–21.9 and lambda values of 1.31–1.49 across the engine speed range. At low to moderate engine speeds, these conditions promote efficient combustion, as indicated by low CO emissions (0.22–0.32%) and the lowest HC emissions among all tested blends (66–72 ppm), while higher CO₂ levels (11.10–14.20%) indicate enhanced carbon oxidation due to the oxygenated nature of ethanol.

At increased engine speeds, the E80 blend exhibits reduced combustion stability, leading to a notable increase in HC emissions to 127–131 ppm as combustion duration reduces, while the energy required for ethanol evaporation remains considerable. Furthermore, the reduced

calorific value of ethanol and the diminished flame propagation under severely lean conditions lead to incomplete combustion. This behaviour is consistent with findings reported in Laskowski and Zimakowska-Laskowska [15], which indicate that volatility constraints and increased evaporation energy requirements in high-ethanol blends can increase the fraction of unburned fuel, particularly at elevated engine speeds.

3.6 Analysis of fuel consumption test results

Table 8. Fuel consumption test results

RPM	Fuel Consumption (L/h)				
	E0	E20	E40	E60	E80
1500	0.342	0.328	0.274	0.324	0.324
2500	0.306	0.294	0.326	0.296	0.372
3500	0.283	0.360	0.330	0.444	0.364
4500	0.474	0.400	0.488	0.440	0.492
5500	0.569	0.556	0.560	0.596	0.556
6500	0.605	0.748	0.669	0.784	0.672
7500	0.792	0.896	0.860	0.960	0.984
Average	0.481	0.512	0.499	0.549	0.538

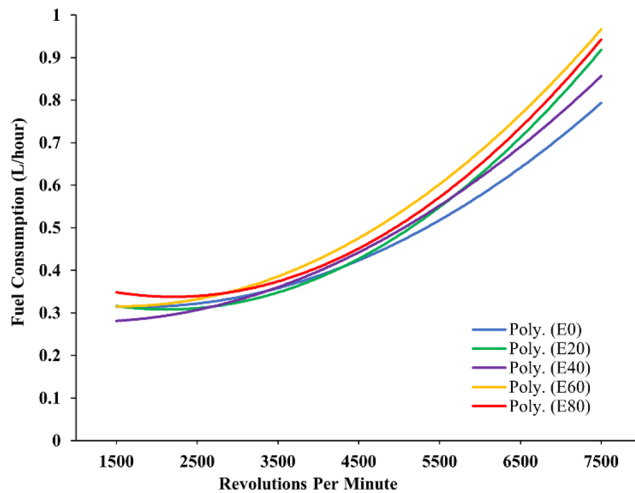


Fig. 7. Comparison of ethanol blend fuel consumption rates

The results indicate that bioethanol blending has a pronounced effect on volumetric fuel consumption (**Table 8** and **Fig. 7**). Compared to neat Pertamina, all bioethanol–gasoline blends exhibit higher average consumption, particularly at high ethanol ratios. Consistent with earlier studies [6], [1], this increase is mainly attributed to the lower heating value (LHV) of bioethanol, which necessitates higher fuel delivery to maintain constant engine power output. However, the increase in fuel consumption is not uniform across all engine speeds. At low engine speeds (1500–2500 rpm), the E40 blend demonstrates comparatively lower fuel consumption, even slightly outperforming E0 under light-load conditions.

This behaviour suggests that ethanol's higher-octane rating and inherent oxygen content can enhance combustion efficiency, allowing more complete combustion at lower loads. In contrast, at higher engine speeds above 5500 rpm, the fuel consumption of all ethanol blends rises rapidly, with E80 reaching the highest value of 0.984 L/hour at 7500 rpm. Under these

conditions, the shorter combustion duration combined with ethanol's lower calorific value requires additional fuel delivery to sustain engine performance.

4 Conclusion

This study demonstrates that bioethanol blend ratios significantly influence air fuel ratio (AFR) behaviour, exhaust emissions, and fuel consumption characteristics in standard spark-ignition engines. Increasing the ethanol proportion generally leads to higher volumetric fuel consumption, particularly at medium to high engine speeds, due to the lower calorific value of ethanol compared with conventional gasoline. Among the tested fuels, the E40 blend exhibited improved combustion stability at low engine speeds, where the higher oxygen content of ethanol contributed to better mixture homogeneity and more efficient combustion. From an emissions perspective, E20 and E40 provided the most favourable balance between pollutant reduction and fuel utilization. These blends reduced CO emissions by up to 70% and HC emissions by up to 81% compared with neat Pertamina while remaining compatible with standard electronic fuel injection systems without engine modification. However, the experiments were conducted under controlled laboratory conditions using a single motorcycle platform. Future studies incorporating multiple vehicle platforms, real-world driving cycles, and additional parameters such as NOx emissions, torque, and power output are recommended.

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