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Research Paper

Exploration of Engine Parameters for Emission Reduction in Gasoline-Ethanol Fueled Engines

Wawan Purwanto[1,2], Hasan Maksum[1], Ahmad Arif[1], Muhammad Latifur Rochman[3], Sujito[4], Kathleen Ebora Padrigalan[5]

[1]Departemen of Automotive Engineering, Universitas Negeri Padang, Padang 25171, Indonesia
[2]Energy Efficient Car Research Group, Universitas Negeri Padang, Padang 25171, Indonesia
[3]Center of Energy for Society and Industry (CESI), Universitas Muhammadiyah Magelang, Magelang 56172, Indonesia
[4]Department of Electric Engineering, Universitas Negeri Malang, Malang 65145, Indonesia
[5]Department of Electro-Mechanical Technology, University of Science and Technology of Southern Philippines, 9000, Philippines

wawan5527@ft.unp.ac.id

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Abstract

The main objective of this study is to develop spark ignition engine parameters that allow complete combustion while reducing dependence on fossil fuels. To achieve this goal, optimization of compression ratio, gasoline-ethanol mixture, ignition timing, and spark plug type was used. In addition, this study used water injection that continuously injects water before the intake manifold. In this study, the Taguchi method with the L9 orthogonal array was applied. According to the experimental verification results, the best combination to reduce exhaust emission levels is to utilize gasoline-ethanol (E70), a compression ratio (CR) of 15.6:1, an ignition degree of +4°, and a platinum spark plug. Meanwhile, the presence of water injection at 1.45 ml/s helps reduce vehicle exhaust pollutants.

Keywords: Engine emissions; Gasoline-ethanol blended; Ignition timing; Engine parameter; Water injection

1. Introduction

In the last decade, electric-based vehicles have shown good market potential, although internal combustion engine (ICEs)-powered vehicles still dominate on the road [1]–[4]. ICEs produce emissions contribute to global warming due to their inherent characteristics. Therefore, developing alternative fuels with lower environmental impact is essential to reduce dependence on fossil fuels [5]–[7]. Many countries have introduced policies promoting bioethanol as a renewable fuel, particularly in regions with abundant cassava, corn, and sugarcane. In Indonesia, the bioethanol policy is part of a broader strategy to decrease fossil fuel dependence, promote renewable energy, and reduce greenhouse gas emissions [8]. The Indonesian bioethanol sector faces unique management challenges and opportunities. These differ significantly from those in the United States, the leading producer of corn-based ethanol, and Brazil, known for its large-scale sugarcane ethanol production and strong infrastructure investment [9].

Based on the scientific investigation, ethanol shares similar characteristics and chemical structures with fossil fuels [10]. This finding is particularly relevant in the context of Indonesia, which has significant potential for bioethanol production. Furthermore, ethanol has a higher octane number than gasoline, as reported by some researchers [11]–[14], making it effective in reducing knocking in the combustion chamber. However, using pure ethanol as an engine fuel requires advanced engine modifications. On the other hand, ethanol-gasoline blends can be used with minimal adjustments [15]. For ethanol blends, modifications to combustion components such as ignition timing, fuel injection, compression ratio, and octane number ratio are necessary to ensure optimal performance [16].

Meanwhile, Amaral et al. [17] observed that using E20 improves combustion efficiency at 1500–3000 rpm. They also noted that at λ=0.9, engine torque remained consistent, while NOx emissions were reduced by 50% at λ=1. In a similar study, other researchers explored the effect of modifying the compression ratio (10:1, 11:1, and 12:1) on engine performance with ethanol blends such as E22 and E100 [18], [19]. Their findings showed that increasing the compression ratio at high speeds improved engine performance with both ethanol blends. However, while E100 resulted in higher specific fuel consumption (SFC) compared to E22, the latter showed little impact on SFC when adjusting the compression ratio. Notably, increasing the ethanol content in the blend reduced the engine's SFC and improved thermal efficiency. These studies underline the potential of ethanol blends to optimize engine performance by enhancing combustion efficiency and reducing emissions.

Furthermore, Tamam et al. [20] employed various methods to examine E10 and E20 blends in a spark-ignition two-wheeled motorcycle engine with five different compression ratio (CR). The results showed that as CR increased, HC, CO, and NOx emissions decreased, whereas CO_2 emissions rose due to improved thermal efficiency during the combustion process. The performance curves indicated that increasing ethanol concentration enhances engine torque, brake power, Brake Thermal Efficiency (BTE), and Brake Specific Fuel Consumption (BSFC). Additional studies revealed that emissions are lower in cold engine conditions compared to pure petrol (E0). According to Ismail et al. [21], ethanol addition leads to a lower combustion flame temperature, reducing exhaust gas temperature and consequently lowering exhaust emissions. These findings align with those of Sakthivel et al. [15] and Calam et al. [22], who investigated the impact of CR and spark ignition timing on engine performance using E30. A higher CR results in increased combustion chamber pressure, a faster heat release rate, and a shorter combustion duration. While optimal spark timing improves combustion, excessive spark advance combined with optimal timing negatively affects performance. Especially, when the compression ratio is appropriately matched with spark plug ignition timing, CO emissions are reduced by 52%, and HC emissions by 43%.

The research octane number (RON) of gasoline, when combined with ethanol, affects combustion characteristics. Increasing RON improves fuel sensitivity and enhances anti-knocking properties [23], [24]. Ethanol blends increase vapor formation, leading to higher thermal efficiency. Additionally, charge cooling effects may contribute to improved mean effective pressure. Lin et al. [25] found that ethanol fuel injection timing must be optimized. Delayed fuel injection in gasoline-ethanol mixtures can cause fuel and air to accumulate on the spark plug, raising HC and CO emissions. This finding aligns with research by Badawy et al. [12], which reported increased HC and CO emissions with delayed injection ratios. Furthermore, Sharma [26] investigated the effects of spark timing adjustments on the combustion chamber using RON 91 and 95. Their results indicated that advancing spark timing increased brake power, maximum power, and reduced SFC. However, NOx emissions rose with spark advance, while HC and CO emissions decreased.

Given the environmental challenges posed by traditional fuels, exploring alternative options like ethanol is essential. This study focuses specifically on the potential of ethanol-gasoline blends, which offer environmental benefits and enhanced fuel quality [27]. Despite these advantages, research on engine modifications for blends containing more than 30% ethanol remains limited. Ethanol has several superior properties compared to gasoline. Its high laminar burning velocity and abundant hydroxyl (OH) units enable complete combustion [28]. Additionally, ethanol's low stoichiometric fuel-air ratio and high latent heat contribute to the formation of a dense air-fuel mixture in petrol engines. Its high self-ignition temperature and octane value allow engines to operate at higher compression ratios without knocking [29]. These characteristics, along with ethanol's ignition timing and flash point, make it suitable for small-scale engine operations with a low risk of misfires

[30]. Although ethanol shows promise as a gasoline blend due to its high performance and low emissions [31], it is unsuitable as the primary fuel in gasoline engines because of its low calorific value by both volume and mass [32]. Furthermore, ethanol's corrosive nature and issues with cold starting require modifications to engine design. While using pure ethanol demands significant adjustments, ethanol-gasoline blends can be utilized with minimal changes to the engine [33], [34]. To maximize the adoption of alternative fuels, engineering efforts should focus on optimizing engine parameters that contribute to the long-term goal of reducing fossil fuels.

Despite its advantages, ethanol has some disadvantages, most notably its corrosive nature, which can damage rubber, plastics, and certain metals commonly found in engine components [35]. This can lead to fuel leaks, reduced engine performance, and potentially severe engine damage if not addressed promptly. Ethanol blended fuels are also more susceptible to vapor lock due to their lower boiling point compared to pure gasoline, making starting more difficult and potentially causing engine stalling during operation, especially at high temperatures or altitudes. Additionally, Yadav et al. [36] noted that ethanol can absorb water vapor from the atmosphere, leading to phase separation and accumulation of water at the bottom of the fuel tank. This results in deposits that can clog filters and fuel injectors, further reducing engine performance.

Recent research has focused on bioethanol-gasoline blends, to explore their effects on engine performance [37], multi-cylinder combustion characteristics, emissions [38]–[40]. Meanwhile, the electrolysis process to convert water into hydrogen has shown potential benefits for combustion [41]–[43], and the injection of water in the right amount can help lower the combustion temperature, thereby improving the combustion process [44]. However, this study did not discuss key parameters such as engine components that can be used with unmodified bioethanol blends, such as compression ratio, piston shape, and combustion chamber design. Thus, this study is very important to advance the use of bioethanol gasoline in combustion engines, especially by optimizing parameters such as compression ratio, ignition timing, spark plug type, and gasoline-ethanol blend ratio to minimize exhaust emissions.

The practical contribution of this study is to encourage the promotion of bioethanol as a biofuel. Therefore, appropriate engine parameters are very important to reduce emissions, ensure engine durability, and protect various engine components. Meanwhile, its theoretical contribution is to provide insight into the use of higher ethanol content and its impact on engine parameters. Based on previous studies, this study uses the Taguchi method to optimize engine parameters, including compression ratio and ignition timing, for ethanol blended fuels.

2. Methods

This study employed the Taguchi method of experimental design, selected for its efficiency in minimizing the number of tests required [45]–[50]. By using orthogonal arrays, this approach allows various factors to be assessed simultaneously without testing all possible combinations, thereby saving time and resources. The Taguchi method helps researchers obtain maximum information from a limited number of tests in complex factorial studies. The primary goal of this experiment is to understand how changes in specific variables, such as fuel composition and ignition settings, affect the outcomes. This, in turn, helps clarify the relationships between these factors and their results.

In this study, a mixture of ethanol and gasoline with varying ethanol concentrations (E70, E75, and E80) was used. This mixture, along with other variables like the fuel-air mixture, ignition timing, and ethanol's flash point, is suitable for small-scale engine operation with a lower risk of misfire. Additionally, the fuel interacts with the engine's compression ratio, so higher ethanol concentrations should be used with higher engine compression. The ignition degree and spark plug type were also considered to determine the optimal ignition system configuration. A summary of the factors and their levels is provided in **Table 1**.

Table 1. Factor and level

Code	Factor	Level		
		1	**2**	**3**
A	Gasoline-ethanol blend	E70	E75	E80
B	Compression ratio	15.6:1	16.1:1	16.6:1
C	Ignition degree	Std (6°)	+2°	+4°
D	Spark plug type	Nickel	Iridium	Platinum

The compression ratio is calculated based on the piston dimensions while maintaining the standard cylinder packing and head size, as shown in **Figure 1**. The study tested three variations of ethanol-gasoline mixtures with RON 92 gasoline at different ethanol concentrations: E70 (30% 92 RON and 70% ethanol), E75 (25% 92 RON and 75% ethanol), and E80 (20% 92 RON and 80% ethanol). Additionally, three ignition degrees were tested: standard (6° BTDC), +2° (ignition advanced by 2°), and +4° (ignition advanced by 4°). Three types of spark plugs were also used: nickel, iridium, and platinum.

This study was conducted on a single-cylinder, single overhead camshaft, two valve motorcycle with a cylinder volume of 113.7 cc, and a bore and piston stroke of 50 x 57.9 mm. The compression ratio is 9.3:1. The maximum power is 6 kW at 7500 rpm, and the maximum torque is 8.3 Nm at 4500 rpm. In this study, engine measurements were taken on a modified engine that transitioned from a carburetor system to an EFI system, as described in our previous research [33], [34]. This modification allows for precise control over all parameters to meet the study's objectives. A combination of sensors from the same vehicle, but employing different technologies and manufacturing years, was used to enhance the accuracy and breadth of the measurements. The ECU used in this study is a modified unit with diagnostic capabilities for adjusting spark ignition. It is connected to a specialized computer system for real-time monitoring and control. For this study, ethanol with a concentration of 99.7%, in compliance with the Indonesian national standard SNI DT 27-0001-2006, was used as the biofuel. The process, as outlined in [27], [40], begins with pre-treatment and material selection, followed by material hydro-analysis, fermentation, distillation, and purification to remove residual water. The final product is bioethanol with a purity greater than 99.5%, classified as fuel-grade ethanol.

In addition to ethanol, the study also used gasoline with a RON of 92, provided by PT Pertamina Indonesia, to assess fuel consumption under various conditions. The properties of the fuel and ethanol are provided in **Table 2** and **Table 3**. **Figure 2** shows a fuel consumption test to determine specific fuel consumption. The equipment includes a mini controller that interfaces with the injector and ECU socket to calculate the amount of fuel injected into the intake manifold. The mini controller then displays the fuel consumption on a monitor after receiving injector spray frequency, voltage, and rotational data from the ECU. This setup allows for accurate fuel consumption measurement at each speed. In parallel, the water injection system, operating at 1.45 ml/s, follows the methodology outlined in [41]. Data analysis was performed using several procedures, starting with the calculation of averages and signal-to-noise ratios (SNR), followed by effect plots, analysis of variance (ANOVA), and verification measurements to ensure the robustness of the results. The optimizing formula used in this study is $Min.(CO, HC) = f\,(A, B, C, D)$. Where, A is the representation of gasoline-ethanol. B is the compression ratio, C is the ignition degree, and D is the spark plug type. Therefore, this research applies smaller the better to calculate the signal to noise ratio.

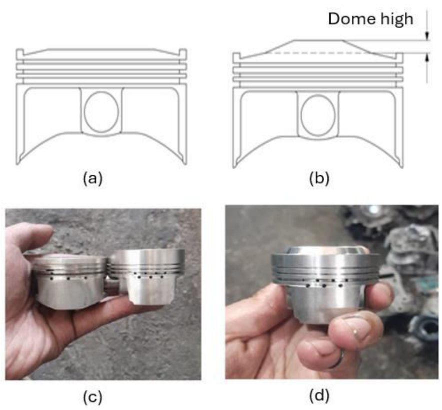


Figure 1. (a) – (d) Piston used

Table 2. Specifications of gasoline and ethanol

Properties	Gasoline	Ethanol
Research octane number (RON)	Various	106 – 115
Chemical formulation	C_8H_{18}	C_5H_5OH
Purity (%)	n/a	99.5
Density (20 °C) [kg/m^3]	3.88	2.06
Viscosity (20 °C) [cSt]	0.64	1.52
Oxygen content	0	34.73
Surface tension (mN/m)	21.58	22.66
Laten heat of vaporization [kJ/kg]	289	854
Stoichiometric (Air to fuel ratio) [kg/kg]	14.7	9.0

Table 3. Properties of gasoline ethanol blended

Properties	E0	E10	E20	E40	E60	E80
Flash Point (°C)	-65	-40	-20	-13	-1	5
Autoignition temperature (°C)	246	260	279	294	345	362
Vapour Pressure (kPa at 37.8 °C)	36	38.9	39	35.6	28	24
Energy Density (MJ/L)	34.2	33.2	32	30	28	26.5
Octane Number (RON)	92	93	94	97	100	104
Specific gravity	0.747	0.75	0.76	0.779	0.781	0.783

Table 4. L9 Orthogonal array

No of exp	Factor							
	A	B	C	D	A	B	C	D
1	1	1	1	1	E70	15.6 : 1	Std	Nickel
2	1	2	2	2	E70	16.1 : 1	+2°	Iridium
3	1	3	3	3	E70	16.6 : 1	+4°	Platinum
4	2	1	2	3	E75	15.6 : 1	+2°	Platinum
5	2	2	3	1	E75	16.1 : 1	+4°	Nickel
6	2	3	1	2	E75	16.6 : 1	Std	Iridium
7	3	1	3	2	E80	15.6 : 1	+4°	Iridium
8	3	2	1	3	E80	16.1 : 1	Std	Platinum
9	3	3	2	1	E80	16.6 : 1	+2°	Nickel

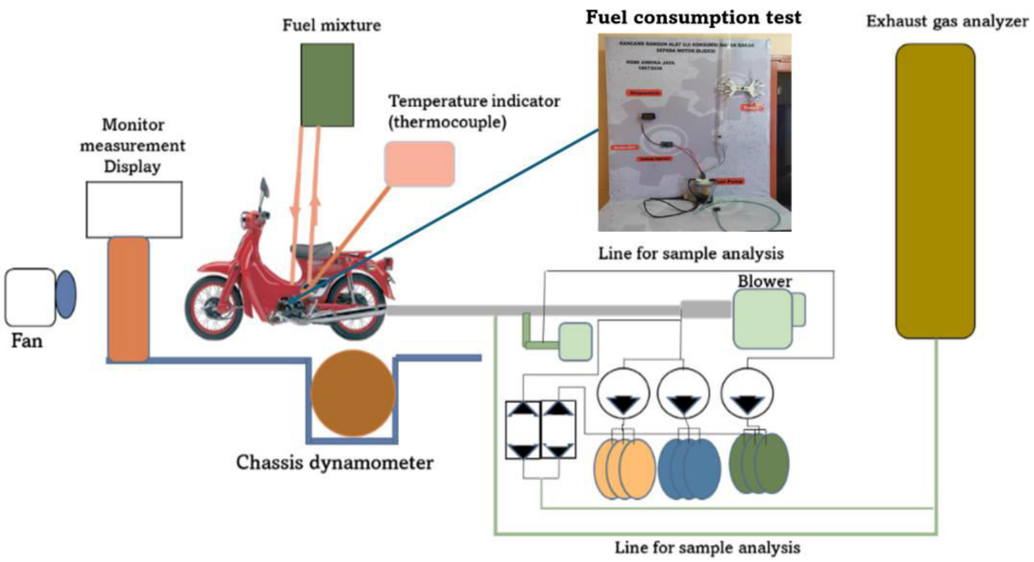


Figure 2. Experimental set up with fuel consumption test

3. Results and Discussion

The experimental approach was designed according to L9 Orthogonal array as shown in Table 4. After completing the experimental procedure (Figure 2), the average values and signal-to-noise ratio (SNR) were computed. The SNR calculation employed the smaller-is-better principle, meaning that the smaller the objective function, the better the outcomes. In this study, the objective function was exhaust emissions, and minimizing them was the primary goal. During the research verification phase, water was injected at a rate of 1.45 mL/s. Water was injected into the intake manifold before it entered the engine. The results from the L9 experimental design are summarized in Table 5.

After calculating the signal-to-noise ratio (SNR), additional computations were carried out to determine the response values, which are summarized in the response table. To calculate the level response value for each factor, the average SNR for each factor-level combination is determined. The results for each factor-level combination are presented in Table 6. Both the average value and SNR calculations follow the 'smaller-is-better' principle, meaning that lower average and SNR values indicate better emission performance. Based on these calculations, the optimal factor-level combination for HC, as determined by both average and SNR values, is combination 2, which produces average and SNR values of 280 ppm and 49.01, respectively. The optimal factor-level combination for CO, based on average calculations, is combination 3, resulting in an average concentration of 1.17% and an SNR of 1.34. After establishing the SNR values, further analysis was conducted to confirm whether combinations 2 and 3 are indeed the most effective in reducing HC and CO emissions. This analysis, a plot effect analysis, used the response table determined from the SNR values, which are shown in Table 7 for HC and Table 8 for CO.

After determining the level response, the next step is to generate a plot effect. Effect plots are useful for visualizing the relationship between the factor levels and their impact on the resulting output. In general, the plot effect is displayed in the form of a line. A horizontal trend in the plot indicates that changes in the factor level do not significantly affect the output. Conversely, a vertical trend indicates a significant change in the output in response to variations in the factor level. The effect plots illustrating the results of HC and CO are presented in Figure 3 and Figure 4, respectively.

The effect plot analysis revealed that the combination of A1, B2, C3, and D1 significantly reduces hydrocarbon emissions. This combination includes E70 biogasoline, a 16.1:1 compression ratio, a +4° ignition degree, and nickel spark plugs, all of which contribute to reduced and more efficient HC emissions. Meanwhile, the most effective combination for reducing CO emissions is A1, B1, C3, and D3, which include E70 biogasoline, a 15.6:1 compression ratio, a +4° ignition degree, and platinum spark plugs. This combination significantly reduces CO emissions, thereby improving emission performance in alignment with the research objectives. Following the response table calculation, ANOVA is performed to determine the percentage contribution of each factor. ANOVA calculations for HC and CO are presented in Table 9 and Table 10, respectively.

Table 5. Experimental results of L9 with objective functions are HC and CO

No of Exp	Factor				HC (ppm)			CO (%)		
	A	B	C	D	Exp 1	Exp 2	Exp 3	Exp 1	Exp 2	Exp 3
1	1	1	1	1	330	325	318	2,03	2,25	2,15
2	1	2	2	2	267	254	319	2,52	2,61	2,5
3	1	3	3	3	299	375	232	1,2	1,17	1,13
4	2	1	2	3	547	495	597	1,66	1,37	1,7
5	2	2	3	1	267	375	401	2,28	2,19	2,11
6	2	3	1	2	580	586	505	3,06	3,78	3,06
7	3	1	3	2	334	269	377	1,49	1,89	1,66
8	3	2	1	3	486	449	384	1,24	1,93	1,13
9	3	3	2	1	422	397	347	3	3,6	3,05

Table 6. Average experimental value and SNR

No of Exp	Average score of HC	SNR of HC	Average score of CO	SNR of CO
1	324.33	50.22	2.14	6.63
2	280	49.01	2.54	8.11
3	302	49.84	1.17	1.34
4	546.33	54.79	1.58	4.01
5	347.67	51	2.19	6.83
6	557	54.95	3.3	10.44
7	326.67	50.4	1.68	4.57
8	439.67	52.92	1.43	3.51
9	388.67	51.83	3.22	10.19

Table 7. SNR response of HC

Combination	Factor			
	A	B	C	D
Level 1	49.69	51.80	52.70	51.02
Level 2	53.58	50.98	51.88	51.45
Level 3	51.72	52.21	50.41	52.52
Max	53.58	52.21	52.70	52.52
Min	49.69	50.98	50.41	51.02
Diff	3.89	1.23	2.28	1.50
Rank	1	4	2	3
Optimal	A1	B2	C3	D1

Table 8. SNR response of CO

Combination	Factor			
	A	B	C	D
Level 1	5.36	5.07	6.86	7.89
Level 2	7.09	6.15	7.44	7.71
Level 3	6.09	7.33	4.25	2.95
Max	7.09	7.33	7.44	7.89
Min	5.36	5.07	4.25	2.95
Diff	1.73	2.25	3.19	4.93
Rank	4	3	2	1
Optimal	A1	B1	C3	D3

Table 9. ANOVA of HC

Parameters	SS	Df	Ms	F ratio	SS'	Ratio %
A	22.70	2	11.35	4.37	17.51	47.8%
B	2.35	2	1.18	0.45	-	-
C	8.03	2	4.01	1.55	2.84	7.74%
D	3.56	2	1.78	0.69	-	-
Pooled e	10.38	4	2.59		20.76	56.66%
SSt	36.64	8	4.58		36.64	100%
Mean	24020.48	1				
SSTotal	24057.11	9				

Table 10. ANOVA of CO

Parameters	SS	Df	Ms	F ratio	SS'	Ratio %
A	4.53	2	2.27	0.17	-	-
B	7.63	2	3.81	0.28	-	-
C	17.35	2	8.68	0.64	-	-
D	46.93	2	23.47	1.72	19.65	25.71%
Pooled e	54.56	4	13.64		109.13	142.75%
SSt	76.45	8	9.56		76.45	100%
Mean	343.91	1				
SSTotal	420.36	9				

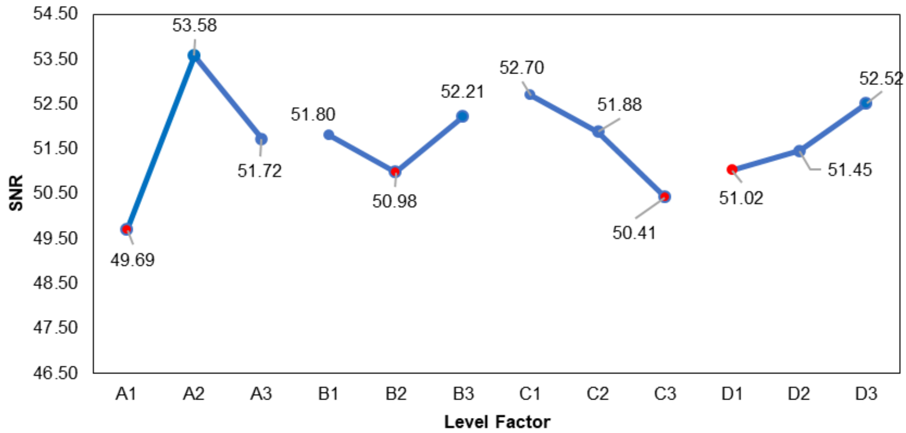


Figure 3. Effect plot of HC

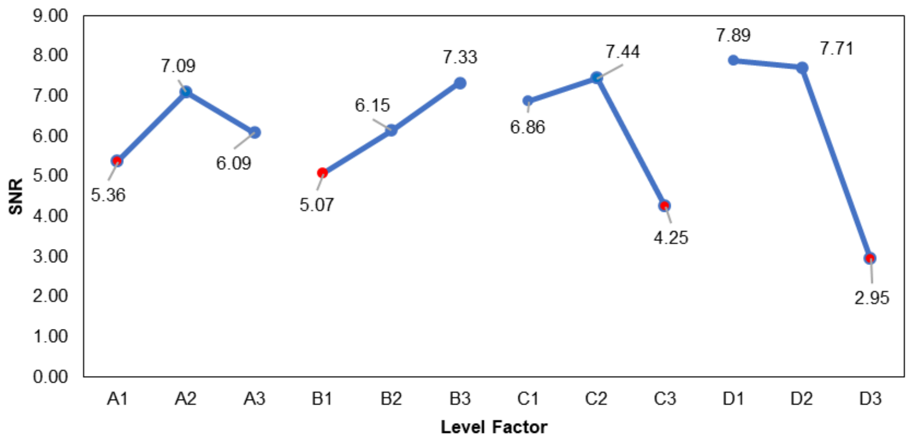


Figure 4. Effect plot of CO

Pooled e refers to a combination of factors that contribute to the smallest sum of squares, accounting for approximately 50% of the total factors. The ANOVA results for HC emissions show that factor A has the largest contribution, accounting for 47.8%, followed by factor C with a contribution of 7.74%. Meanwhile, the ANOVA results for CO emissions indicate that factor D has the largest contribution, accounting for 25.71%. Once the optimal design is determined, the next step is to predict the optimum conditions of the design. Subsequently, a verification test is conducted to compare the predicted optimal conditions with the actual results from the experiment. If the predicted and experimental results closely match, the design can be considered both valid and reliable. The predicted results of the optimal design for HC and CO are presented in **Table 11** and **Table 12**, respectively.

Table 11. Prediction result of HC

Level Factor Optimal				U prediction
A1	**B2**	**C3**	**D1**	
49.69	50.98	50.41	51.02	47.11

Table 12. Prediction result of CO

Level Factor Optimal				U prediction
A1	**B1**	**C3**	**D3**	
5.36	5.07	4.25	2.95	0.91

Table 13. Verification measurement

Experimental	Optimal HC (ppm)		Optimal CO (%)	
	HC (ppm)	**CO (%)**	**HC (ppm)**	**CO (%)**
1	201	2.02	159	0.97
2	213	2.09	113	0.82
3	214	2.08	145	0.91
Average	209.33	2.06	139.00	0.90
STDEV	7.23	0.04	23.58	0.08
SNR	46.42	6.29	42.98	0.88
U Prediction	47.11	0.91	47.11	0.91
Error (%)	1.48	114.46	9.60	2.86
Total Error (%)	112.98		12.46	

Based on **Table 13**, the SNR value for HC in the experimental test is 46.42 ppm, while the average value for CO gas is 0.88%. The experimental results are significantly better than the predicted values, as indicated by the error rates of 1.48% and 2.86%, both of which are below 5%. The error values for CO (114.46%) from optimal HC and error values for HC (9.60%) from optimal CO are not considered significant in this analysis. However, they can still be useful for selecting the optimal combination of factor levels for application to motorcycles based on the total error value. The experiment identified the optimal combination of factor levels for reducing exhaust emissions as A1 (E70 bio-gasoline), B1 (compression ratio 15.6), C3 (ignition degree +4°), and D3 (platinum spark plug). The test results show that all combinations of factor levels reduce hydrocarbon and CO exhaust emissions by 368 ppm and 8.94%, respectively, compared to the standard.

The optimization process also reveals the overall power characteristics of the optimal results, as shown in **Figure 5**. The figure obtained matches the standard conditions described in previous research [33]. The application of optimal conditions resulting in low HC and CO emissions also leads to higher torque and power (**Figure 5a** and **Figure 5c**). At 6000 rpm, these conditions increase power by 8.6%, from 9.8 Nm to 10.65 Nm for optimal CO, and an 8.98 Nm increase for optimal HC. The usage of ethanol is particularly beneficial for emissions reduction because it contains more oxygen than fossil fuels such as gasoline. According to studies [51], [52], suggest that increased oxygen availability enables more complete combustion of the air-fuel mixture, which is crucial for reducing unburned HC. Increased oxygen availability enables a leaner air-fuel mixture, improving combustion efficiency and reducing specific fuel consumption (**Figure 5b**). This results in lower HC and CO emissions, as shown in **Figure 6**.

Table 2 summarizes the properties of ethanol, which play a significant role in influencing combustion characteristics and emissions reduction in the engine. Ethanol contributes to improved combustion characteristics, leading to a slight increase in engine temperature compared to standard settings, as shown in **Figure 5d**. As used in this investigation [53], ethanol was found to have a faster flame speed than fossil fuels. This faster flame speed necessitates adjustments in ignition timing, which enhances the combustion of fuel and air. This leads to higher temperatures and pressures inside the cylinder, promoting complete combustion and reducing overall emissions, as shown in **Figure 6**. At the optimal CO condition, the HC value increases as engine speed rises, as shown in **Figure 6**a. In contrast, the CO value decreases regardless of the optimal HC condition, as shown in **Figure 6**b. According to studies by [54], [55], the key factors influencing HC and CO emissions in spark ignition engines are combustion temperature, degree of combustion, and oxygen concentration. The measuring procedure inquiry examined in this study investigates the optimal parameters for ethanol/gasoline blends containing 70% to 80% ethanol, coupled with high compression ratios, to improve combustion performance.

According to research [56], [57], shows that water injections effectively cool the fuel mixture, reducing knock in the combustion chamber, which is beneficial for combustion control. This cooling effect enables the use of higher octane fuels, which improve engine performance and reduce emissions. The results clearly indicate that the optimal combination of factor levels for reducing exhaust emissions consists of A1 (bio-gasoline E70), B1 (compression ratio 15.6), C3 (ignition degree +4°), and D3 (platinum spark plug), based on emission reduction analysis Compared to the standard conditions of the test engine, the highest CO emissions were observed when using standard gasoline, as shown in Figure 6a. Ethanol, with its higher oxygen content and better volatility than RON 92 gasoline, ensures cleaner combustion when used in petrol-ethanol blends. The E70 test fuels produced the lowest CO emissions for each engine speed due to the blend's greater volatility at a higher percentage of ethanol and petrol RON 92 by 30%.

Figure 6 shows that HC emissions decrease as engine speed increases for all test fuels, primarily due to improved air-fuel mixture homogenization at higher compression.This improves combustion efficiency and optimizes temperature within the combustion chamber. However, Figure 6a shows that while CO and HC emissions decrease at optimal conditions, the emissions rise at all engine

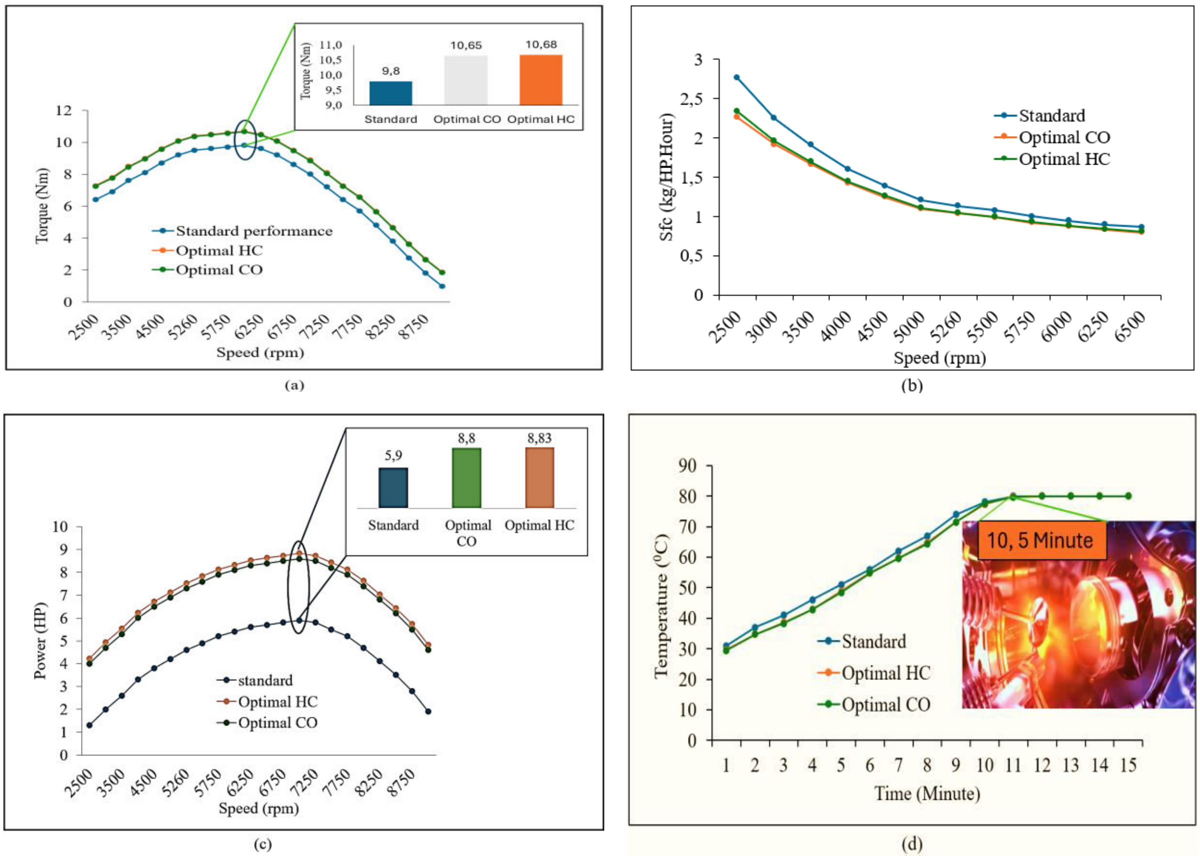


Figure 5. Performance characteristics, a) torque vs speed, b) Specific fuel consumption (Sfc) vs speed, c) power vs speed, d) time to temperature increase

speeds due to the lower cylinder temperatures caused by ethanol addition. This effect is further influenced by the ignition timing and the type of spark plug used. As previously noted, the spark plug ignites the fuel-air mixture in the combustion chamber. The number of sparks and the proper mixing of air and fuel may impact a vehicle's exhaust emission levels. Iridium spark plugs offer three key advantages over standard and platinum plugs: ultra-fine electrodes, U-Groove technology, and a tapered cut, all of which improve combustion efficiency ensuring stable performance under all engine conditions.

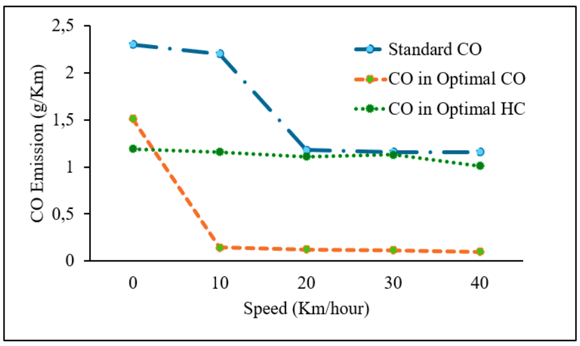
The experimental results in **Table 5** and **Figure 6** show that platinum, iridium, and nickel spark plugs reduce CO and HC emissions at all engine speeds compared to standard spark plugs. CO emissions decreased by 20% with platinum spark plugs compared to standard plugs while CO emission levels with iridium spark plugs decreased by 29% when compared to the standard. Meanwhile, the use of nickel spark plugs reduced CO emission levels by 8%. HC emissions produced by the use of platinum, iridium and nickel spark plugs also decreased by 41%, 61%, and 29% respectively, when compared to the use of standard spark plugs .

Referring to Lin et al. [58], suggests that ethanol has a lower latent heat than gasoline (RON 90), which can reduce its power generation potential under certain conditions. However, for volume cylinder in 113.7 cc engine or equivalent as this investigation's model, the implementation of a high bioethanol blend necessitates appropriate adjustments concerning compression ratio, spark plug type, and ignition timing. This enables stable engine operation from idle to 40 km/hour, resulting in reduced exhaust emissions (**Figure 6**a and **Figure 6**b).

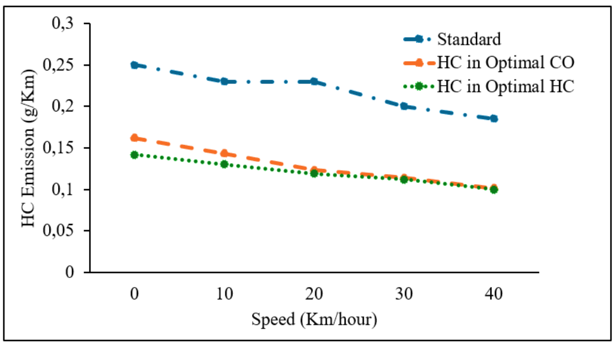
Consequently, The application of ethanol-gasoline blends in motorcycles, based on accurate predictions of spark ignition engine characteristics, offers significant economic benefits such as reduced fuel costs and improved fuel efficiency. Research by Kumar et al. [59] indicate that blending ethanol with gasoline can lower retail gasoline prices by increasing supply and reducing dependence on crude oil, with one study suggesting that incorporating around 330 million barrels of ethanol may reduce prices by \$0.12 to \$1.09 per gallon, depending on regional and market variables, thus offering cost-saving benefits for consumers. The Renewable Fuel Standard (RFS) initiative enhances fuel supply by reducing reliance on imported crude oil, thereby improving fuel security and stability for consumers. The ethanol business significantly contributes to employment in countryside areas. In addition, the ethanol industry provides over 79,000 jobs and contributes approximately \$57 billion to the national GDP, further supporting economic growth and stability. This economic activity not only strengthens local economies but also stabilizes agricultural markets by ensuring sustained demand for key ethanol feedstocks such as maize, sugarcane, and other crops.

4. Conclusion

The optimization processes identified in this study highlight the potential for applying higher ethanol blends (E70 - E80) in future engine technologies, offering improved performance and reduced emissions. The results from this study indicate that using higher ethanol blends, such as



(a)



(b)

Figure 6. Emission characteristics, a) CO characteristics vs speed in optimal CO, b) HC characteristics vs speed in Optimal HC

E70 and E80, leads to an increase in the engine compression ratio, contributing to improved combustion efficiency and performance. Additionally, ethanol's higher heat of vaporization compared to pure gasoline helps reduce the air-fuel charge temperature, increasing the fuel density and promoting more efficient combustion. Moreover, the oxygen content in ethanol facilitates more complete combustion by promoting better mixing of the air-fuel mixture, resulting in a more efficient burn and lower emissions. As a result, careful engineering of ignition timing and spark plug components is essential to optimize combustion efficiency and enhance overall engine performance. This study demonstrates that for optimal engine performance with ethanol blends up to E70, a compression ratio of 16.1, ignition timing advanced by +40, and the use of nickel spark plugs effectively minimize HC emission. To achieve low CO emissions, the study suggests a compression ratio of 15.6, an ignition timing of +40, and the use of platinum spark plugs, which effectively enhance combustion efficiency. A limitation of this study is the lack of variation in the use of water injection within the ethanol-gasoline blends, as well as the absence of an in-depth analysis of the advantages, disadvantages, and efficiency of air injection in blended fuel systems. Therefore, further investigation into the effectiveness of water injection in higher ethanol fuel blends is essential to optimize fuel efficiency and reduce emissions.

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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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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

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