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Experimental investigation of ethanol–pertamax fuel blends: fuel economy, exhaust emissions, and implications for natural carbon capture

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ABSTRACT

This study experimentally evaluates the influence of ethanol–Pertamax fuel blends on fuel consumption, exhaust emission characteristics, and their contribution to reducing the burden on Natural Carbon Capture (NCC) systems. Experiments were conducted using an unmodified 125 cc fuel-injected spark-ignition motorcycle fueled with four blend compositions, namely pure Pertamax (E0), E5, E10, and E15. Fuel consumption was measured over an engine speed range of 1200–5400 rpm, whereas exhaust emissions, including carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO_2), and oxygen (O_2), were quantified using a calibrated exhaust gas analyzer. Among the investigated fuel formulations, the E15 blend exhibited the most favorable results, lowering average fuel consumption by 14.89%, reducing CO emissions by 18.49%, decreasing HC emissions by 30.93%, and achieving a 2.46% reduction in CO_2 emissions compared with neat Pertamax. In addition, the residual oxygen concentration in the exhaust increased by 36.52%, indicating more effective fuel oxidation during combustion. This avoided emission is equivalent to the yearly carbon sequestration capacity of approximately 9.6286 mature trees.

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1. INTRODUCTION

The transportation sector remains one of the largest contributors to anthropogenic greenhouse gas emissions due to the extensive use of internal combustion engine vehicles. Continuous growth in vehicle ownership has intensified fuel consumption and increased the release of pollutants such as carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x). These emissions are widely recognized as major factors accelerating global climate change, degrading ambient air quality, and threatening public health. Consequently, developing practical technologies capable of reducing vehicle emissions while maintaining engine performance has become an important research priority (Yunus et al, 2025).

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In addition to environmental concerns, transportation systems continue to rely heavily on petroleum-derived fuels. The progressive depletion of fossil fuel reserves, together with increasing global energy demand, has raised significant concerns regarding long-term energy security and fuel supply stability. Furthermore, fluctuations in crude oil prices and the environmental consequences associated with fossil fuel utilization have accelerated the search for renewable energy alternatives. Accordingly, renewable liquid fuels have attracted considerable attention as sustainable substitutes capable of partially replacing conventional gasoline without requiring substantial modifications to existing vehicle technology(Dani et al, 2024).

Among various renewable fuels, ethanol has emerged as one of the most promising alternatives because of its favorable physicochemical properties. Ethanol possesses a relatively high octane number and contains chemically bound oxygen within its molecular structure, characteristics that promote cleaner and more efficient combustion than conventional gasoline. When blended with premium gasoline such as Pertamax, ethanol has the potential to improve combustion efficiency, reduce harmful exhaust emissions, and decrease the overall carbon footprint of transportation. Nevertheless, the influence of different ethanol blending ratios on engine behavior and exhaust emission characteristics remains highly dependent on engine operating conditions and therefore requires systematic experimental investigation(Afif and Firdaus, 2024).

The adoption of ethanol-blended fuels also supports the transition toward low-carbon transportation, particularly in developing countries where conventional internal combustion engine vehicles remain dominant. In Indonesia, for example, the widespread implementation of electric vehicles is still constrained by infrastructure availability and economic considerations. Under these circumstances, ethanol–gasoline blends provide a practical intermediate solution capable of reducing transportation-related emissions without requiring major technological changes. From the perspective of combustion science, ethanol modifies several important combustion parameters, including the air–fuel ratio, flame propagation characteristics, combustion temperature, and oxidation reactions occurring inside the cylinder. Because ethanol supplies additional oxygen during combustion, oxidation of hydrocarbon molecules becomes more complete, thereby reducing emissions of carbon monoxide and unburned hydrocarbons. However, increasing ethanol concentration may also alter combustion temperature and potentially influence nitrogen oxide formation. Therefore, determining the optimum ethanol concentration requires comprehensive experimental evaluation under representative operating conditions (Lutanto et al, 2024).

Although numerous investigations have examined ethanol–gasoline blends, many previous studies have focused primarily on engine performance or exhaust emissions independently, often using laboratory conditions that do not fully represent practical vehicle operation. Consequently, a comprehensive understanding of how fuel consumption, combustion efficiency, emission characteristics, and environmental sustainability are interconnected remains limited. In particular, only a few studies have attempted to relate experimental emission reductions directly to broader carbon mitigation strategies(Mokhtar et al, 2025).

Previous experimental work conducted by Rizki et al. reported that ethanol–Pertamax blends substantially reduced hydrocarbon and carbon monoxide emissions across a wide engine speed range. Their study indicated that higher ethanol concentrations significantly improved combustion quality, although carbon dioxide emissions tended to increase slightly as combustion became more complete (Rizki et al, 2025) Similarly, another investigation evaluating ethanol concentrations of 13%, 15%, and 17% demonstrated measurable reductions in CO, HC, and CO_2 emissions, especially under low engine-speed conditions. Collectively, these studies confirm the potential of ethanol as an effective oxygenated fuel additive capable of improving exhaust emission performance(Winoko at al, 2025).

Despite these encouraging findings, most published studies remain limited to evaluating conventional engine performance indicators without considering their implications for environmental carbon management. In particular, the relationship between improved combustion efficiency, reduced fuel consumption, lower carbon emissions, and the corresponding decrease in demand for Natural Carbon Capture (NCC) has received very little scientific attention. As a result, the environmental benefits of ethanol–gasoline blends have not yet been fully quantified from the perspective of ecosystem-based carbon mitigation. NCC is used here as a carbon-mitigation perspective to express avoided CO_2 emissions in terms of the sequestration capacity of natural carbon sinks. This approach links source-level emission reduction with an equivalent ecosystem-based carbon mitigation metric(Sihombing 2026).

To address this research gap, the present study proposes an integrated evaluation framework combining fuel consumption analysis, exhaust emission measurements, and estimation of avoided carbon emissions associated with Natural Carbon Capture. Experimental investigations were conducted using an unmodified 125 cc fuel-injected spark-ignition motorcycle fueled with Pertamax–ethanol blends containing 0%, 5%, 10%, and 15% ethanol. Unlike previous studies that mainly assessed engine performance or emission characteristics separately, this research establishes a direct connection between combustion efficiency improvements and reductions in natural carbon sequestration requirements. Therefore, the proposed approach provides a broader understanding of how renewable fuel blending can simultaneously improve engine performance, reduce

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environmental impacts, and support sustainable decarbonization strategies for transportation systems that continue to rely on internal combustion engine technology. Unlike previous ethanol–Pertamax studies that mainly emphasize engine performance or exhaust emissions, this study integrates fuel consumption and emission measurements with an equivalent natural carbon-sequestration assessment(Waluyo and Purnomo, 2022).

2. RESEARCH METHODS

This research employed a quantitative experimental approach under controlled laboratory conditions to investigate the influence of ethanol–Pertamax fuel blends on engine fuel consumption and exhaust emission characteristics. In addition to the experimental investigation, descriptive and comparative analyses were performed to interpret the measured data and to estimate the corresponding reduction in carbon emissions associated with Natural Carbon Capture (NCC). The entire experimental program was conducted in the Energy Conversion Laboratory, Universitas Gorontalo, where the required facilities for fuel consumption measurement and exhaust gas analysis were available.

The experimental investigation was conducted using a standard automatic motorcycle equipped with a single-cylinder, four-stroke, fuel-injected spark-ignition engine. The test vehicle has an engine displacement of 125 cc, capable of producing a maximum power output of 9.4 HP and a peak torque of 9.6 N·m. Its engine is designed with a 9.5:1 compression ratio, making it suitable for evaluating high-octane fuel formulations, including ethanol–Pertamax blends, without requiring mechanical modifications. The motorcycle has a curb weight of 94 kg and a fuel tank capacity of 4.2 L, ensuring stable operating conditions throughout the experimental procedures. These specifications represent a typical small-displacement motorcycle widely used for daily transportation, thereby enhancing the practical relevance of the experimental findings. All tests were performed using the original factory configuration to ensure that any observed variations in fuel consumption and exhaust emissions were solely attributable to differences in fuel composition rather than changes in engine hardware or operating characteristics.

Four fuel formulations were prepared by blending commercial Pertamax gasoline with anhydrous ethanol at different volumetric proportions. The investigated blends consisted of pure Pertamax (E0), 5% ethanol (E5), 10% ethanol (E10), and 15% ethanol (E15). Prior to engine testing, each fuel blend was thoroughly homogenized to ensure a uniform composition. The measured fuel densities varied from 752.2 kg/m³ for E0 to 769.3 kg/m³ for E15, with values of 767.1 kg/m³ for E5 and 768.6 kg/m³ for E10.

Fuel consumption and exhaust emission measurements were carried out using a chassis dynamometer to simulate practical motorcycle operating conditions while maintaining a controlled laboratory environment. After the motorcycle had been securely positioned on the dynamometer and all measuring instruments had been properly installed, the engine was allowed to warm up until the coolant and lubricant reached the normal operating temperature of approximately 80–85°C. Stabilizing the engine temperature before testing ensured consistent combustion conditions throughout the experimental program.

Figure 1. Experimental setup

Fuel consumption tests were performed at seven engine speed settings, namely 1200, 1800, 2400, 3600, 4200, 4800, 5400 rpm. At each operating point, the engine speed was maintained constant for 60 s before the measurement was recorded. Every test was repeated three times to improve measurement reliability and minimize random experimental errors. Fuel consumption was initially determined from the difference between the initial and final fuel mass measured using a high-precision digital balance (g/min). The measured mass flow

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rate was subsequently converted into volumetric fuel consumption (l/h) using the experimentally determined density of each fuel blend.

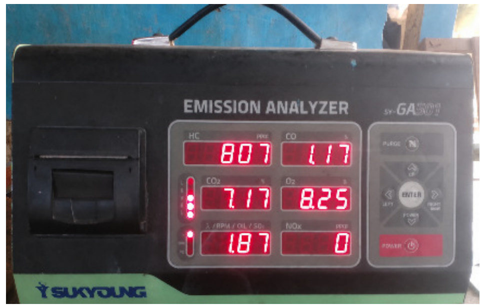

Figure 2. Gas analyzer

Exhaust gas emissions were evaluated over the representative engine operating range of 1200, 3600 and 5400 rpm using a calibrated exhaust gas analyzer. These speeds were selected to represent low-, medium-, and high-speed operating conditions, providing consistent reference points for comparing the emission characteristics of the tested fuel blends. Four principal exhaust components were measured, namely carbon monoxide (CO), unburned hydrocarbons (HC), carbon dioxide (CO_2), and residual oxygen (O_2). These parameters were selected because they provide comprehensive information regarding combustion quality, oxidation efficiency, and the environmental impact of the tested fuel formulations. The gas analyzer had a measurement accuracy of better than 2%, whereas the digital scale provided an accuracy of 0.0033%, supporting the consistency of the recorded emission and fuel-consumption data.

To eliminate contamination between successive fuel formulations, the fuel tank and fuel delivery system were completely emptied after each series of experiments. Fresh test fuel was then introduced into the fuel tank, and the engine was operated for several minutes to ensure that the fuel lines, injector, and combustion chamber were entirely supplied with the new fuel blend before data collection commenced. This procedure prevented residual fuel from influencing the combustion characteristics of subsequent experiments and ensured that all recorded measurements accurately represented the performance of each individual fuel formulation.

Following data acquisition, the measured results were analyzed descriptively and comparatively to evaluate the influence of ethanol concentration on combustion performance. Fuel consumption and exhaust emission data obtained for each blend were compared over the investigated engine speed range to identify performance trends. Furthermore, actual fuel consumption values were employed to estimate carbon dioxide emissions using blend-specific emission factors. The resulting avoided CO_2 emissions were subsequently converted into equivalent annual carbon reductions and expressed as the corresponding carbon sequestration capacity of mature trees and representative natural ecosystems. This integrated analytical approach enabled the assessment of combustion efficiency together with its implications for reducing the demand placed on Natural Carbon Capture (NCC) systems, thereby providing a broader evaluation of the environmental benefits associated with ethanol–Pertamax fuel blends.

3. RESULTSAND DISCUSSION

3.1. Fuel Consumption

The measured fuel consumption values for all tested fuel formulations are presented in Table 1. Regardless of the fuel composition, fuel consumption exhibited a progressive increase as engine speed increased from 1200 to 5400 rpm. This behavior is consistent with the operating characteristics of spark-ignition engines, where higher rotational speeds increase the number of combustion events per unit time, thereby requiring greater energy input to sustain engine operation. Consequently, the electronic fuel injection (EFI) system supplies a larger quantity of fuel to maintain an appropriate air–fuel ratio, resulting in higher overall fuel consumption.

Although fuel consumption increased with engine speed for every fuel blend, the addition of ethanol consistently reduced the amount of fuel required compared with pure Pertamax (E0). At 1200 rpm, the engine consumed 0.5254l/h when fueled with E0, whereas fuel consumption decreased to 0.5035l/h, 0.4640l/h, and 0.4591l/h for E5, E10, and E15, respectively. The same tendency was maintained at the highest tested speed of 5400 rpm, where the E15 blend recorded the lowest fuel consumption of 0.6369l/h, substantially lower than the 0.7881l/h observed for neat Pertamax. These results clearly demonstrate that increasing the ethanol content improves fuel-use efficiency over the entire range of operating conditions investigated.

The average fuel consumption calculated from all engine speeds further confirms this trend. Mean fuel consumption gradually decreased from 0.6596l/h for E0 to 0.6251l/h for E5, 0.5936l/h for E10, and finally 0.5614l/h for E15. The consistent decline observed across every engine speed indicates that the beneficial effect of ethanol is not limited to a specific operating condition but remains effective throughout the experimental range. These findings suggest that ethanol blending provides a stable improvement in combustion efficiency under both low- and high-speed engine operation.

The improvement in fuel economy can be explained by the intrinsic properties of ethanol. Unlike conventional gasoline, ethanol is an oxygenated fuel containing approximately 35% oxygen by weight, which supplies additional oxygen during combustion. The increased oxygen availability promotes a more complete oxidation of hydrocarbon molecules, allowing a greater proportion of the fuel's chemical energy to be converted into useful mechanical work. As combustion becomes more efficient, less fuel is required to generate the same engine output, thereby lowering overall fuel consumption.

Another important factor contributing to the observed reduction is the higher octane number of ethanol compared with gasoline. A higher octane rating increases resistance to engine knock and promotes a smoother combustion process. Improved combustion stability allows the maximum cylinder pressure to occur closer to top dead center (TDC), thereby increasing thermal efficiency. The combination of enhanced oxidation and improved combustion phasing explains the superior fuel economy achieved by the ethanol-blended fuels.

Table 1. Fuel consumption

rpm	Fuel Consumption (l/h)			
	E0	E5	E10	E15
1200	0.5254	0.5035	0.4640	0.4591
1800	0.5700	0.5379	0.5142	0.4871
2400	0.6147	0.5764	0.5474	0.5111
3600	0.6918	0.6629	0.6359	0.6041
4200	0.6971	0.6722	0.6432	0.6104
4800	0.7306	0.6949	0.661	0.6213
5400	0.7881	0.7281	0.6901	0.6369
Rate	0.6596	0.6251	0.5936	0.5614

To provide a clearer evaluation of fuel economy improvement, the percentage reduction in fuel consumption relative to pure Pertamax is summarized in Table 5. The results indicate that every ethanol-containing fuel blend outperformed the baseline fuel, with the magnitude of improvement increasing as the ethanol proportion became higher. Among the investigated formulations, E15 consistently delivered the greatest reduction across nearly all engine speeds. The highest improvement reached 19.1853% at 5400 rpm, whereas the maximum reductions achieved by E10 and E5 were 12.4349% and 7.6132%, respectively. These results confirm that increasing ethanol concentration positively influences fuel utilization efficiency.

Variations in the percentage reduction observed at different engine speeds are associated with changes in in-cylinder combustion characteristics. At high engine speeds, sufficient combustion duration and favorable air–fuel mixing promote efficient utilization of the oxygen supplied by ethanol, leading to more complete combustion and improved thermal efficiency. As engine speed increases, combustion duration becomes progressively shorter, limiting the time available for complete oxidation. Nevertheless, even under moderat speed conditions, ethanol-blended fuels maintained lower fuel consumption than pure Pertamax, indicating that the combustion-enhancing effect of ethanol remained significant throughout the investigated operating range.

The average percentage reductions presented in Table 2 further illustrate the effectiveness of ethanol addition. Compared with E0, average fuel consumption decreased by 5.2363% for E5, 10.0028% for E10, and 14.8927% for E15. The nearly linear improvement observed with increasing ethanol concentration suggests that additional oxygen supplied by ethanol continuously enhances combustion efficiency. Consequently, higher ethanol proportions reduce the quantity of fuel required to produce the same engine power output.

The average reduction obtained in this study is greater than the 5.5% improvement reported by Hernandez et al 2014, although it remains lower than the 26% reduction observed by Mara et al 2024. Such differences are reasonable because combustion performance is strongly influenced by engine design, compression ratio, fuel injection strategy, ignition timing, and operating conditions. Therefore, variations among experimental studies should be interpreted within the context of the specific engine configuration and testing methodology employed.

Table2. Percentage reduction

rpm	Percentage reduction (%)		
	E5	E10	E15
1200	4.1682	11.6863	12.6189
1800	5.6315	9.7894	14.5438
2400	6.2306	10.9484	16.8537
3600	4.1775	8.0803	12.6770
4200	3.5719	7.7320	12.4372
4800	4.8863	9.5264	14.9603
5400	7.6132	12.4349	19.1853
Rate	5.2363	10.0028	14.8927

Overall, the experimental evidence clearly indicates that the E15 fuel blend provides the highest level of fuel economy among the tested formulations without requiring any modification to the engine system. The continuous reduction in fuel consumption achieved through ethanol addition demonstrates that renewable oxygenated fuels can significantly improve combustion efficiency while simultaneously decreasing dependence on petroleum-derived fuels. From an energy perspective, this improvement contributes to more efficient utilization of fuel resources, whereas from an environmental perspective it represents an important step toward cleaner and more sustainable transportation. Therefore, incorporating up to 15% ethanol into Pertamax can be regarded as a practical strategy for enhancing engine efficiency while supporting the long-term transition toward low-carbon mobility.

3.2. Exhaust Emissions

3.2.1. CO Exhaust Emissions

The experimental data indicate that increasing the ethanol fraction in the fuel blend consistently suppressed carbon monoxide (CO) formation under all operating conditions. Average CO emissions decreased from 0.65% for neat Pertamax (E0) to 0.61%, 0.56%, and 0.54% for E5, E10, and E15, corresponding to average reductions of 5.83%, 16.67%, and 18.49%, respectively. The largest decrease occurred at 5400 rpm, where E10 lowered CO emissions by 26.25%, while E15 achieved a reduction of 22.50%. These results suggest that the effectiveness of ethanol in reducing CO is influenced not only by blend composition but also by engine operating conditions. At elevated engine speeds, stronger in-cylinder turbulence improves air–fuel mixing, allowing the oxygen contained in ethanol molecules to participate more effectively in oxidation reactions. Consequently, a larger fraction of intermediate CO species is converted into carbon dioxide before exhaust valve opening. The relatively small difference between E10 and E15 at the highest speed further indicates that combustion improvement approaches a practical limit once sufficient oxygen is available within the combustion chamber. Overall, the results confirm that moderate ethanol enrichment enhances oxidation efficiency and reduces incomplete combustion products, demonstrating the potential of low-level ethanol blends to improve exhaust quality in spark-ignition engines without requiring engine modifications.

Table 3. CO Exhaust Emissions

rpm	CO Exhaust Emissions (%)						
	E0	E5	Reduction (%)	E10	Reduction (%)	E15	Reduction (%)
1200	1.17	1.11	4.87	1.04	10.60	0.99	14.96
3600	0.62	0.59	5.14	0.54	13.18	0.51	18.01
5400	0.16	0.14	7.50	0.11	26.25	0.12	22.50
Rate	0.65	0.61	5.83	0.56	16.67	0.54	18.49

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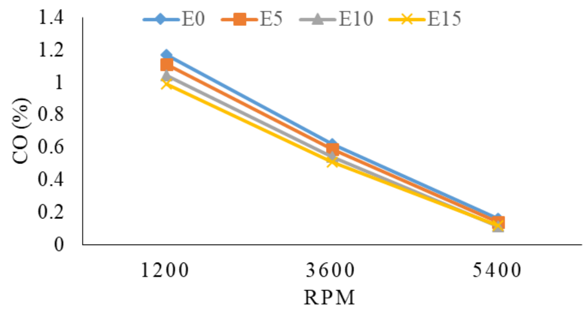

Figure 3. Ratio CO Exhaust Emissions

3.2.2. Emisi Gas Buang CO2

Unlike carbon monoxide, carbon dioxide (CO_2) exhibited only a slight reduction with increasing ethanol concentration, although the trend remained consistent throughout the tested engine speeds. The average CO_2 concentration declined from 4.45% for E0 to 4.39%, 4.38%, and 4.36% for E5, E10, and E15, representing reductions of 1.42%, 1.86%, and 2.46%, respectively. The maximum decrease of 3.80% was observed for E15 at 5400 rpm. This behavior reflects changes in the elemental composition of the fuel rather than a decline in combustion efficiency. Ethanol contains fewer carbon atoms per unit of energy than gasoline; therefore, replacing a portion of Pertamax with ethanol inherently decreases the amount of carbon available for oxidation. As a result, even when combustion proceeds efficiently, the total quantity of CO_2 generated becomes lower. Furthermore, the relatively modest reduction demonstrates that CO_2 is the final product of complete combustion, making its concentration less sensitive to combustion enhancement than pollutants associated with incomplete oxidation. These findings indicate that ethanol blending contributes simultaneously to cleaner combustion and lower carbon intensity of the fuel, providing environmental benefits through both improved combustion chemistry and reduced carbon input into the combustion process.

Table 4. CO_2 Exhaust Emissions

rpm	CO_2 Exhaust Emissions (%)						
	E0	E5	Reduction (%)	E10	Reduction (%)	E15	Reduction (%)
1200	7.17	7.08	1.25	7.08	1.25	7.06	1.53
3600	4.35	4.29	1.37	4.28	1.60	4.26	2.06
5400	1.84	1.81	1.63	1.79	2.71	1.77	3.80
Rate	4.45	4.39	1.42	4.38	1.86	4.36	2.46

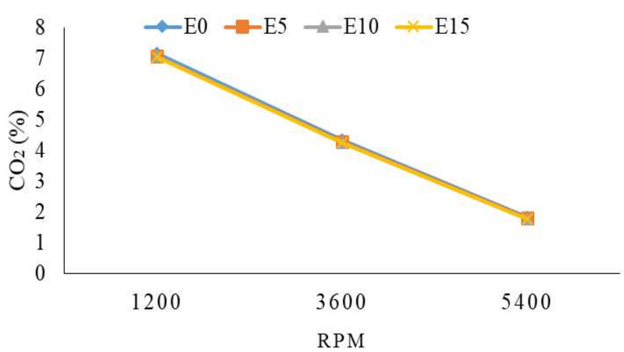

Figure 4. Ratio CO_2 Exhaust Emissions

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3.2.3. Emisi Gas Buang HC

A substantial reduction in unburned hydrocarbon (HC) emissions was observed as the ethanol content increased, indicating a significant improvement in combustion completeness. Average HC emissions decreased from 472 ppm for E0 to 431 ppm, 414 ppm, and 321 ppm for E5, E10, and E15, corresponding to average reductions of 9.74%, 15.44%, and 30.93%, respectively. The greatest reduction reached 35.19% at 1200 rpm with the E15 blend. The pronounced decrease at low engine speed suggests that ethanol effectively enhances flame propagation under operating conditions where conventional gasoline combustion is generally less efficient. Because ethanol vaporizes readily and contains chemically bound oxygen, the resulting mixture burns more uniformly and reduces the occurrence of locally fuel-rich regions that typically generate unburned hydrocarbons. As engine speed increased, HC emissions declined for all fuel formulations, reflecting the combined influence of improved turbulence and faster combustion. Nevertheless, ethanol blends consistently maintained lower HC levels than neat Pertamax over the entire operating range. The superior performance of E15 demonstrates that increasing ethanol concentration strengthens combustion stability while minimizing fuel fragments escaping oxidation. Consequently, ethanol addition offers an effective strategy for reducing hydrocarbon emissions and improving combustion quality in fuel-injected spark-ignition engines.

Table 5. HC Exhaust Emissions

rpm	HC Exhaust Emissions (ppm)						
	E0	E5	Reduction (%)	E10	Reduction (%)	E15	Reduction (%)
1200	807	722	10.53	750	7.06	523	35.19
3600	460	445	3.26	375	18.47	337	26.73
5400	149	126	15.43	118	20.80	103	30.87
Rate	472	431	9.74	414	15.44	321	30.93

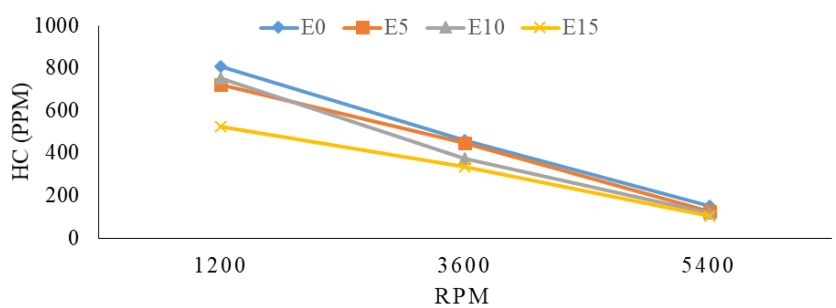

Figure 5. Ratio HC Exhaust Emissions

3.2.4. Emisi Gas Buang O_2

The concentration of residual oxygen in the exhaust gas increased progressively with ethanol addition, indicating changes in combustion characteristics associated with oxygenated fuels. The average O_2 concentration rose from 3.81% for E0 to 5.14%, 5.34%, and 5.43% for E5, E10, and E15, corresponding to average increases of 30.50%, 34.88%, and 36.52%, respectively. The highest increase reached 43.15% at 1200 rpm with the E15 blend. This trend demonstrates that ethanol supplies additional chemically bound oxygen, enabling oxidation reactions to proceed more effectively without relying solely on atmospheric oxygen. Consequently, a fraction of oxygen remains unconsumed after combustion and appears in the exhaust stream. The simultaneous increase in O_2 concentration together with reductions in CO and HC emissions indicates that the additional oxygen primarily enhances oxidation efficiency rather than reflecting poor combustion. Moreover, the relatively stable increase across different engine speeds suggests that the electronic fuel injection system successfully adapted to variations in fuel composition while maintaining favorable combustion conditions. These observations confirm that exhaust O_2 concentration can serve as an indirect indicator of combustion effectiveness in ethanol-blended fuels. Therefore, the higher residual oxygen measured in this study should be interpreted as evidence of improved oxidation processes and cleaner combustion rather than excess-air operation alone.

Table 6. O_2 Exhaust Emissions

rpm	O_2 Exhaust Emissions (%)						
	E0	E5	Increase (%)	E10	Increase (%)	E15	Increase (%)
1200	8.25	11.15	35.15	11.63	40.96	11.81	43.15
3600	2.92	3.94	34.93	4.05	38.69	4.13	41.43
5400	0.28	0.34	21.42	0.35	25.00	0.35	25.00
Rate	3.81	5.14	30.50	5.34	34.88	5.43	36.52

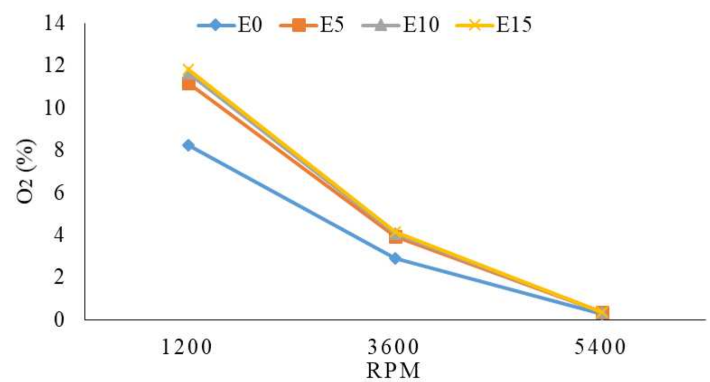

Figure 6. Ratio O_2 Exhaust Emissions

Overall, the exhaust emission results demonstrate a clear interaction between ethanol concentration and combustion behavior throughout the investigated operating range. Increasing the proportion of ethanol progressively reduced the formation of carbon monoxide (CO), carbon dioxide (CO_2), and unburned hydrocarbons (HC), while simultaneously increasing the residual oxygen (O_2) concentration in the exhaust gases. This combination of responses indicates that ethanol addition modifies the combustion process toward more efficient oxidation of the fuel mixture, thereby suppressing the generation of incomplete combustion products and lowering the overall carbon released during engine operation. Among the tested fuel formulations, E15 consistently produced the most favorable emission profile, confirming that a 15% ethanol blend provides the best balance between combustion effectiveness and environmental performance without requiring engine modification. The consistent emission trends observed at different engine speeds further demonstrate that the advantages of ethanol blending are maintained under various operating conditions rather than being limited to a specific regime. These findings confirm that low-level ethanol–Pertamax blends represent a practical approach for improving exhaust emission characteristics while supporting cleaner combustion and reducing the environmental footprint of conventional spark-ignition engines.

3.3. Natural Carbon Capture

The reduction in exhaust emissions achieved through ethanol–Pertamax blends has broader environmental implications beyond improving engine combustion efficiency. A lower quantity of carbon released during engine operation directly decreases the amount of atmospheric carbon dioxide that must subsequently be removed by natural ecosystems. In this context, the concept of Natural Carbon Capture (NCC) can be interpreted as the ecological effort required to offset carbon emissions generated by transportation activities. Therefore, any reduction in carbon emissions represents an equivalent reduction in the burden imposed on forests, mangrove ecosystems, and other natural carbon sinks.

Using carbon emission factors of 2.31 kg CO_2/l for gasoline (Soyler and Karaoglu, 2025) and 1.51 kg CO_2/l for ethanol (Pacheco and Silva, 2019), the estimated CO_2 emissions associated with engine operation exhibited a continuous decline as the ethanol content increased. The calculated emission rate was 1.5236 kg CO_2/h for E0, decreasing to 1.4189 kg CO_2/h for E5, 1.3237 kg CO_2/h for E10, and reaching 1.2294 kg CO_2/h for

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the E15 fuel blend.When projected over an annual operating period of 720 h, the estimated carbon savings increase to 75.3832 kg CO_2/year for E5, 143.9625 kg CO_2/year for E10, and 211.8312 kg CO_2/year for E15 for each motorcycle. Although these values may appear modest on an individual-vehicle basis, widespread implementation would produce a substantial cumulative reduction in transportation-related carbon emissions. From an ecosystem perspective, avoided emissions represent ecological capacity that can be allocated to compensate for carbon generated by other sectors that are more difficult to decarbonize. Assuming that one mature tree absorbs approximately 22 kg CO_2 annually (Ribaski et al, 2024), the avoided emissions obtained with E15 are equivalent to preserving the annual sequestration capacity of approximately 9.6286 mature trees for every vehicle operated under the assumed driving conditions. The mature-tree equivalent represents a carbon-sequestration equivalence and does not indicate direct carbon capture by a specific number of trees.

Table 7. Estimated Carbon Emissions, Avoided CO_2, and Natural Carbon Capture (NCC) Equivalents for Ethanol–Pertamax Fuel Blends

Fuel	FC (l/h)	Emission Factor (kg /l)	Estimated Emission (kg/h)	Avoided (kg/h)	Annual Avoided (kg/year)	Mature Tree Equivalent (trees/year)
E0	0.6596	2.31	1.5236	-	-	-
E5	0.6251	2.27	1.4189	0.1046	75.3832	3.4265
E10	0.5936	2.23	1.3237	0.1999	143.9625	6.5437
E15	0.5614	2.19	1.2294	0.2942	211.8312	9.6286

The progressive decrease in NCC demand observed from E5 to E15 also indicates that increasing ethanol concentration not only improves engine operation but simultaneously lowers the ecological resources required to neutralize transportation-related carbon emissions. Rather than relying exclusively on expanding forested areas to compensate for increasing emissions, reducing carbon generation at the source offers a complementary mitigation pathway that is more practical and economically efficient. This integrated strategy combines cleaner fuel utilization with the preservation of natural carbon sinks, reinforcing the role of renewable fuel blends as an important component of sustainable transportation and long-term climate change mitigation (Chen et al, 2022).

4. CONCLUSION

Progressive increases in ethanol concentration consistently reduced fuel consumption and altered exhaust gas composition toward cleaner combustion. The E15 blend delivered the most favorable overall results, achieving a 14.89% reduction in average fuel consumption, while simultaneously lowering CO emissions by 18.49%, HC emissions by 30.93%, and CO_2 emissions by 2.46%. The E15 blend generated an avoided emission of 0.2942 kg CO_2/h, equivalent to approximately 211.8312 kg CO_2/year for a single motorcycle, or the annual carbon absorption capacity of about 9.63 mature trees. Therefore, ethanol–Pertamax blends provide a dual benefit by simultaneously improving engine operational efficiency and reducing dependence on natural ecosystems for carbon offsetting. These findings demonstrate that low-level ethanol blending can serve as an effective and immediately applicable strategy for supporting low-carbon transportation and strengthening ecosystem-based climate mitigation efforts through the Natural Carbon Capture framework.

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