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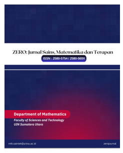

Optimization of Clove Oil Blending Ratio to Gasoline Engine Performance

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ABSTRACT

The increasing need for cleaner and more efficient fuels encourages the use of bio-additives to improve the combustion quality of gasoline engines. However, research on the direct effect of variations in the ratio of clove oil in Pertalite gasoline on engine performance and emissions is still limited. This study examined the effect of mixing clove oil in four fuel compositions, namely pure Pertalite (P0), Pertalite + clove oil 0.5% (P0.5), 1% (P1), and 2% (P2), on engine performance parameters and exhaust emission characteristics. The results showed that the P2 blend provided the most significant improvement in engine performance, characterized by a 4.6% increase in torque and 6.3% power, a decrease in specific fuel consumption of up to 7.1%, and an increase in calorific value of up to 7.8%. Thermal efficiency also increased at high rounds of 1 %, indicating better energy conversion. In terms of emissions, a decrease in CO of 0.006% and a decrease in CO_2 of 0.1% indicate more complete combustion, although HC increases by 34 ppm (parts per million) due to the volatile characteristics of clove oil. Overall, the addition of 2% clove oil has been shown to improve combustion quality without engine modification. These findings confirm the potential of clove oil as a viable and relevant renewable bio-additive to support energy transition efforts towards a cleaner and more sustainable transportation system.

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1. INTRODUCTION

Rising energy needs and depleting petroleum reserves have prompted efforts to develop more sustainable alternative fuels. Gasoline engines still dominate the transportation sector due to their reliability and high power-to-weight ratio, but they are also a major source of emissions of pollutants such as hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) [1], [2]. In Indonesia, the consumption of Pertalite (RON 90) and Pertamax (RON 92) continues to increase, so a strategy to improve combustion quality without modifying the engine is needed.

One emerging approach is the use of bio-additives from essential oils, which serve as oxygenated compounds to improve combustion efficiency and lower exhaust emissions [3]. Clove oil (Syzygium aromaticum) stands out for its high content of eugenol and its derivatives, which are known to have antiknock properties and are able to increase oxidation during combustion [4], [5].

The use of clove oil as an additive has been shown to be effective in diesel engines, increased combustion stability and decreased particulate emissions [6], [7]. However, its application to gasoline engines, especially Pertalite, which is the dominant fuel in Indonesia, is still very limited, despite regulatory demands such as MoEF Regulation No. 8/2023 which further tightens the emission threshold for motor vehicles [8].

Research focused on gasoline fuels—for example, increased oxidation and changes in volatility characteristics can significantly lower CO and HC emissions [9], [10]. However, the studies emphasized more fuel type modification or octane influence, rather than the use of naturally oxygenated bio-additives in Pertalite. In addition, most previous studies used much higher concentrations of additives or were applied to diesel engines, so they cannot be directly generalized to gasoline engines with low mixing ratios.

Based on this gap, this study aims to evaluate the effect of mixing clove oil in low ratios (0.5, 1% and 2%) on gasoline engine performance and exhaust emission characteristics when used with Pertalite. In particular, this study raises the key question, the extent to which clove oil bio-additives can improve the torque, power, and combustion efficiency of gasoline engines, and how they affect CO, CO_2, and HC emissions compared to pure Pertalite.

This study offers an important contribution because for the first time it presents a systematic evaluation of the use of clove oil as a bio-additive in Pertalite without engine modification, with complete parameters including torque, power, fuel consumption, thermal efficiency, exhaust emissions, and calorific value. The results are expected to provide a strong scientific basis for the development of cleaner, economical, and ready-to-use baking materials to support energy transition and emission control policies in Indonesia.

2. RESEARCH METHOD

2.1 Fuel Materials and Additive Preparation

The basic fuel used in this study is commercial Pertalite gasoline (RON 90) obtained from domestic fuel distribution sources in Indonesia. Clove oil (Syzygium aromaticum) is used as a bio-additive, extracted through a steam distillation process from dried clove buds, then filtered to remove residual particles. The main chemical constituents of clove oil, namely eugenol ($C_{10}H_{12}O_2$) and eugenyl acetate ($C_{12}H_{14}O_3$), are oxygenated organic compounds that play a role in improving combustion efficiency and lowering hydrocarbon emissions [11].

In this study, clove oil was mixed into Pertalite at a ratio of 0.5%, 1%, and 2% [12], [13]. These values are chosen based on several scientific considerations. First, low concentrations (<3%) are generally recommended for oxygenated additives so as not to alter the main physical properties of the fuel, such as density and volatility, and remain compatible with engine injection systems [12]. Second, the range of 0.5–2% has been reported in previous studies as the optimal limit for increasing combustion and suppressing CO and HC emissions without causing detonation or a decrease in octane values [13], [14]. Thus, the concentration variation was chosen to evaluate the effect of increasing oxygen levels in fuel on gasoline engine performance and emission characteristics comprehensively without the need for engine modification. Mixed ingredients can be seen in Table 1.

Table 1. Four volumetric blending ratios of clove oil were prepared:

Volumetric	Mix of ingredients	
P0	100% Pertalite (baseline fuel)	
P0.5	99.5% Pertalite	+ 0.5% Clove oil
P1	99% Pertalite	+ 1% Clove oil
P2	98% Pertalite	+ 2% Clove oil

All mixtures are prepared and weighed on a calibrated scale with an uncertainty value of approximately 0.1g. and the mixture will be processed by a mechanical mixer at 1500 rpm for 5 minutes to ensure homogeneous mixing (Figure 1). The samples were subsequently stored in sealed, dark glass bottles to prevent oxidation and volatile losses. The blending ratios were determined based on prior experimental ranges reported in studies using bio-additives in hydrocarbon fuels [14], [15].

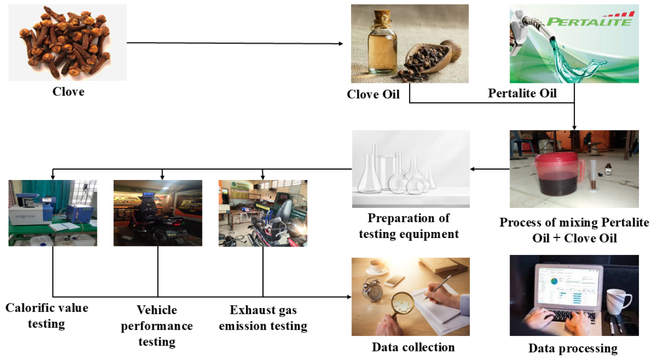


Figure 1. Set of the testing process

2.2. Engine and Experimental Setup

Engine performance and emission testing were conducted using a single-cylinder, four-stroke, air-cooled gasoline engine with the specifications listed in Table 2. The schematic layout of the experimental setup is illustrated in Figure 2.

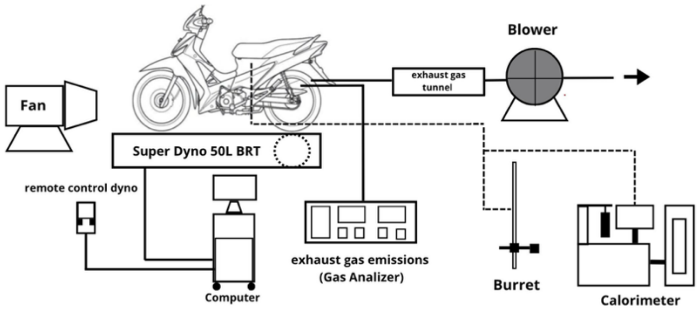


Figure 2. Schematic diagram of the experimental setup used for engine performance & exhaust gas emission testing.

The setup consisted of a Super Dyno 50L BRT dynamometer connected to a control computer for measuring torque and power output, and an exhaust gas analyser for emission measurement. The analyser was connected to an exhaust gas tunnel equipped with a blower to maintain a steady gas flow during measurement. A fan was placed in front of the motorcycle to simulate airflow and prevent the engine from overheating.

Fuel consumption is measured using a calibrated burette connected to the fuel line. The recorded volume is converted into mass flow based on the fuel density measured with a hydrometer and adjusted at a temperature of 25 °C. Each measurement is taken for 60 seconds at a stable engine condition., A calorimeter is used to determine the energy content (calorific value) of each fuel mixture. Exhaust gases were analyzed for concentrations of CO, CO_2, HC, and O_2 using a four-gas analyzer (Model 10174175) calibrated prior to testing (08:00 WIB) using certified standard gases with ranges of 0–10% for CO_2, 0–5% for CO, 0–2,000 ppm for HC, and 0–25% for O_2. The accuracy of the tool is verified by rereading against the reference gas until the deviation does not exceed ±2% of the standard value. The calibration and verification procedures follow the operational standards (SOP) [16]. So that the emission measurement results can be ensured to be accurate and reproducible. The specifications of the vehicle's engine can be seen in Table 2.

Table 2. Engine Specifications

Parameter	Specification
Engine type	4-stroke, SOHC, single-cylinder gasoline
Displacement	124.8 cc
Bore x Stroke	52,4 x 57,9 mm
Compression ratio	9,3: 1
Max. power	9,92 HP / 8.000 rpm
Max. Torque	9,3 Nm/4.000 rpm
Cooling system	Air-cooled
Ignition system	DC-CDI
Fuel system	Full injection
Dynamometer	Sportgyno V3.3
Gas analyzer	4-Gas (Model 10174175)

2.3. Measurement Parameters and Data Processing

The engine performance parameters were measured and analyzed in terms of brake power (*P*), torque (*T*), specific fuel consumption (SFC), and thermal efficiency (ηt). The torque (*T*) is recorded directly from the dynamometer and is calculated based on the result of the times between the force acting on the torsion arm (*F*) and the length of that arm (*r*), as shown in Equation (1):

$$T = F \, x \, R \quad (1)$$

Symbol description:
T = torsi (N·(m)
F = tangential force on the torsion arm (N)
r = torsion arm length (m)

Equation (1) shows that the torque (*T*) produced by the engine is directly proportional to the force (*F*) applied to the arm and the distance of the point of force to the axis of rotation (*R*). Thus, an increase in the force or length of the arm will result in a greater torque value.

Brake power (*Pb*), which describes the useful mechanical power available on the engine shaft, is calculated based on the rated torque (*T*) and the rotational speed of the engine (*N*). This relationship shows the ability of the engine to convert the chemical energy of the fuel into the mechanical energy of the shaft, as shown in Equation (2):

$$Pb = \frac{2.\pi.N.T}{60} \quad (2)$$

Symbol description:
Pb = brake power (kW)
N = engine rotation speed (rpm)
T = torsi (N·(m)
π = constant pi (3.1416)

Equation (2) shows that the braking power (*Pb*) is directly proportional to the torque (*T*) and the rotational speed of the engine (*N*); the greater the two, the higher the mechanical power produced by the engine.

The fuel consumption level (*FC)* is determined based on the measured fuel volume (*vbb*), fuel density (*pbb*), and measurement time (t) required to consume that volume. The relationship between these parameters is shown in Equation *FC* = (3)

$$FC = \frac{3600.pbb.vbb}{t} \quad (3)$$

Symbol description:
FC = fuel consumption rate (kg/s)
Vbb = volume of fuel consumed (m^3)
UN = Fuel density (kg/m^3)
t = time required to consume fuel(*s*)

Equation (3) describes the amount of fuel mass used per unit of time under a given operating condition. A smaller FC value indicates better fuel efficiency in the engine.

To evaluate the fuel economy of an engine, specific fuel consumption (*SFC*) is calculated as the ratio between the flow rate of the fuel mass (*fc*) and braking power (*BP),* as shown in Equation *SFC* = (4).

$$SFC \, \frac{fC}{BP} \quad (4)$$

Symbol description:
SFC = specific fuel consumption (kg/kWh)
FC = Mass flow rate of fuel (kg/s)
Bp = brake power (kW)

Equation (4) shows that the consumption of a specific fuel is directly proportional to the rate of fuel flow and inversely proportional to the braking power produced. Thus, the smaller the *SFC value*, the more efficient the engine is at converting fuel energy into mechanical energy.Thermal efficiency (*ηt*) is calculated using Equation (5), which states the ratio between engine output power (*Pout*). The incoming energy from the fuel is obtained from the result of the time between the flow rate of the mass of the fuel (*mf*) and the lower calorific value of the fuel (*HHV*), as shown in Equation η_t = (5).

$$\eta_t = \frac{Pout}{mfxHHV} x100 \quad (5)$$

where:
ηt = thermal efficiency (%)
Pout = engine output power (W),

mf = mass flow rate of fuel (kg/s),
HHV = the higher calorific value of the fuel (kJ/kg).

Equation (5) shows the ratio between engine output power (Pout) and total fuel chemical energy supplied per unit time ($mf \times LHV$). Higher thermal efficiency values indicate that the engine is able to convert fuel energy into mechanical power more effectively.

The calorific value (Q) of the fuel is determined experimentally by measuring temperature changes during controlled combustion, as stated in Equation (6).

$$Q = m\,c\,\Delta T \tag{6}$$

where:
Q = the amount of heat released during combustion (J),
m = mass of fuel sample (kg),
c = system-specific heat capacity (J/kg·K),
ΔT = temperature change before and after combustion (K).

Equation (6) relates the total heat released (Q) to the mass of the fuel tested (m), the heat capacity of the system (c), and the temperature rise (ΔT). The calorific value obtained through this method is used as the basis for determining the lower calorific value, which then becomes the main input in the calculation of the thermal efficiency of the engine as described in Equation (5).

The exhaust-gas composition—including CO, CO_2, and HC—was measured using infrared and flame ionization detection methods.

All experiments were repeated three times to reduce random uncertainty, with measurement accuracies of ±1 % for power and torque and ±0.5 % for emissions based on calibration certification. Mean values and standard deviations were used to assess data consistency. Here is Table 3 of the properties of the fuel.

Table 3. of Properties of the fuel.

Parameter	Unit	Pertalite	Pure Clove Oil	Pertalite Clove Oil Blend (Approximately)	Test Method
Research Octane Number (RON	-	90	70-80	90-91	ASTM D2699
Density (15°C)	Kg/m3	715-770	1040-1060	740-780	ASTM D4052
Viskositas (40°C)	mm^2/s	0.5-0.8	2.1- 3.0	0.9-1.2	ASTM D445
Lower Calorific Value (LHV)	MJ/kg	43-44	39-40	42-43	ASTM D4809/ Boom Calorimeter
Oxygen Content	% massa	0-2.7	8-10	3-5	ASTM D4815
Color	-	Light green	Brownish yellow	Yellowish-green	Visual

The value of the mixture is estimated, depending on the proportion of mixing (1–5% v/v of clove oil).

2.4. Validation and Comparative Framework

To validate the reliability of the results, the experimental setup was compared with the methodologies while the preparation of clove oil followed the recommendations [7], [8]. This approach allows the identification of the influence of the oxygen content, octane value, viscosity, and antioxidant properties of clove oil on the combustion stability and formation of HC emissions, making the interpretation of the results more measurable and non-speculative.

3. RESULT AND ANALYSIS

3.1. Overview of Experimental Setup

The overall configuration of the test system is shown in Figure 2, which integrates the motorcycle engine, dynamometer, and gas analysis system in one coordinated circuit. The blowers and fans are used to simulate road airflow to maintain engine temperature stability while ensuring consistent exhaust gas sampling. This experimental layout follows the procedures described [9], [10], thus ensuring that the performance and emissions data obtained are accurate and replicable. The description of the system configuration also provides a clearer basis for the transition to the results section, highlighting that the performance and emission patterns that emerge later are a direct consequence of this controlled test setup.

3.2. Torque and Brake Power Analysis

Figure 3 and Figure 4 present the measured braking torque and braking power for pure Pertalite P0, and Pertalite blends with clove oil at concentrations of P0.5, P1, and P2, measured in the engine speed range of 3000–

6000 rpm. The results show that blend P2 provides the most significant performance improvement. Compared with pure Pertalite P0, P2 achieves a maximum braking torque of 10.6 Nm at 6000 rpm, marking a 4.6% improvement (Figure 3). Meanwhile, braking power (Figure 4) for P2 increases by approximately 6.3%, reaching 8.9 kW at the same speed. This performance improvement is most pronounced at mid-range engine speeds, which is attributed to more optimal air-fuel mixing and more efficient flame propagation within the cylinder.

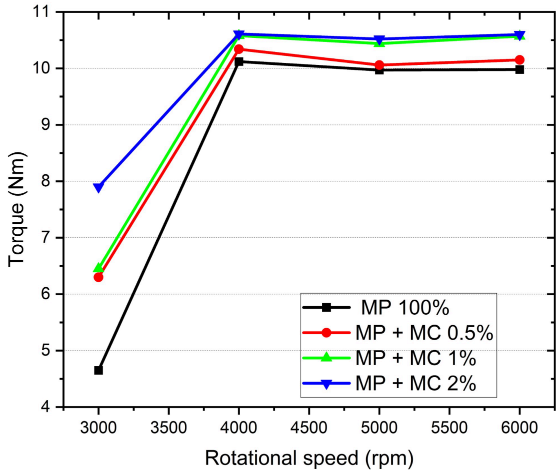


Figure 3. Torque Comparison in P0, P0.5, P1, and P2 Mixtures.

At a higher speed of 6000 rpm, the torque for the P2 decreases slightly from the P2 4000 rpm, a direct consequence of the design and arrangement of the engine system optimized for low to medium rev performance. The high oxygen content has been documented [6], [7] who reported that excessive oxygenation in the fuel can alter the speed of the flame and increase ignition delay.

The concentration range of 0.5-2% was chosen based on the recommendations of the literature that shows that essential oils work most effectively at low concentrations. Although some studies reported using the 1-5% range, concentrations above 2% were not tested in these studies because they risk lowering volatility, increasing the viscosity of the mixture, and worsening the atomization of fuels. This phenomenon has been reported in eugenol additives and other essential oils, where concentrations of >2% often lead to incomplete evaporation and less stable combustion. Thus, the 2% limit is chosen as a compromise between the effectiveness of performance improvement and combustion stability.

These results show that clove oil, at the optimal mixing ratio (about 2%), increases engine output by increasing atomization and combustion completeness, consistent with the behavior of oxygenated bio-additives reported in the journal Fuel and Frontiers in Energy Research.

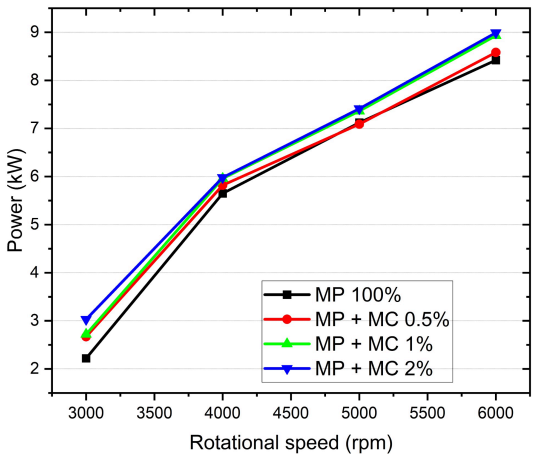
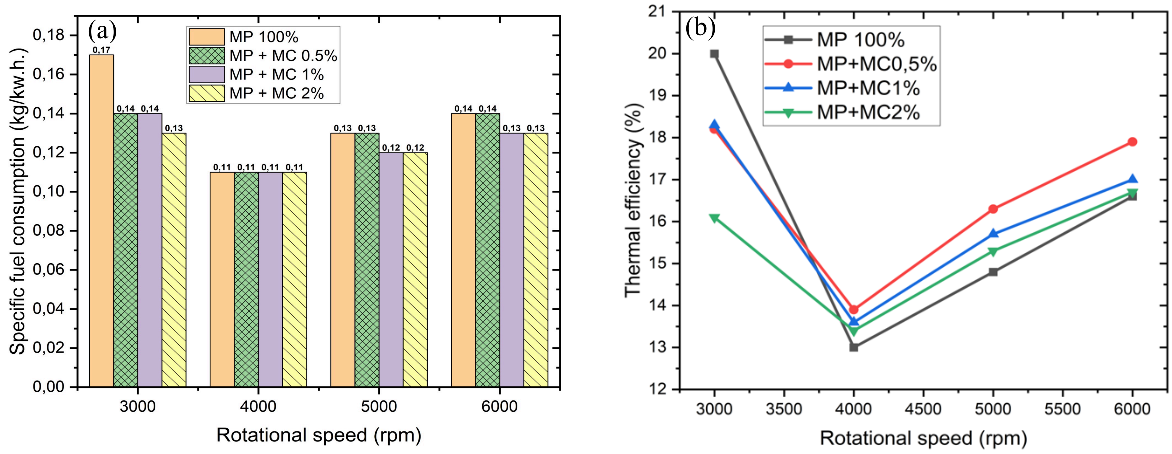


Figure 4. Comparison of Brake Power in P0, P0.5, P1, and P2 Mixtures

3.3. Specific Fuel Consumption and Thermal Efficiency

Specific Fuel Consumption (SFC) of the engine at various rotational speeds for pure pertalite (P0) fuel and pertalite oil and clove oil blends at concentrations of P0.5, P1, and P2. (b) Thermal efficiency of the engine at various rotational speeds for the same fuel. As shown in Figure 5.



(a) Specific Fuel Consumption (SFC) (b) Thermal Efficiency

Figure 5. Specific Fuel Consumption (SFC) and Thermal Efficiency

The P2 blend achieved the lowest SFC value of 0.13 kg/kWh, showing a 7.14% decrease relative to the base fuel (P0). At thermal efficiency, the P2 mixture showed an increase from 16.6% (P0) to 16.7% (P2) at the highest rpm, terjadi penurunan Thermal Efficiency pada torsi maksimum, caused by heavy load conditions (high torque), knock is the main limit so that spark retard is needed, and this sacrifices thermal efficiency even though the torque is high [17], and eventually the thermal efficiency increase when the RPM increased.

Meanwhile, the total fuel consumption (FC) did not show a significant difference between the mixture variations, as shown in Figure 6.

This trend suggests that clove oil concentrations improve energy utilization efficiency by increasing oxygen availability, thus facilitating more complete oxidation of hydrocarbons. Similar efficiency improvements [18, 19] in gasoline-plastic oil mixtures in eugenol-based diesel mixtures. The results for fuel consumption (FC) are presented in Figure 6.

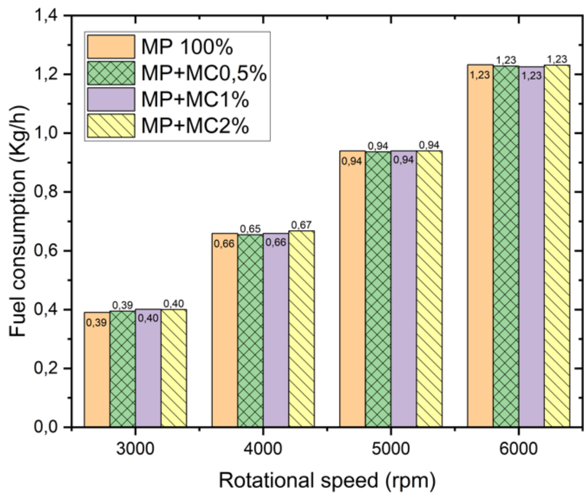


Figure 6. Fuel Consumption (FC).

The absence of a significant difference in fuel consumption (FC) indicates that an injection motor with an electric control unit (ECU) has a stable fuel supply.

3.4. Exhaust Gas Emission Characteristics

Figure 7 illustrates the variation in exhaust emissions (CO, CO_2, and HC) for all fuel mixtures tested. A significant improvement in overall combustion quality is observed with the addition of clove oil, as reflected in the decrease in CO and CO_2 levels compared to P0 fuel. The CO concentration decreased by 0.006% for the P2 mixture, indicating a more complete oxidation process facilitated by the oxygen properties of eugenol, the main compound in clove oil.The reduction in CO_2 concentration by 0.1% P2 indicates a shift towards leaner combustion, consistent with increased air-fuel mixing and more efficient utilization of fuel carbon atoms [20, 21].

However, an increase in hydrocarbon (HC) emissions of 34 ppm (parts per million) was recorded in the P2 mixture relative to P0. This increase can be attributed to the higher viscosity and lower volatility of clove oil compared to Pertalite, which delays evaporation and prevents the spread of the fire completely in the combustion chamber. The partial combustion of heavier components especially eugenol ($C_{10}H_{12}O_2$) causes unburned hydrocarbons to escape with exhaust gases. A similar phenomenon was reported by [2] [4], who observed that oxygenated bio-additives containing aromatic rings tend to increase HC at high mixing ratios due to limited atomization and slower flame speeds.

Nevertheless, the HC levels recorded in this study remained well below the regulatory threshold and were comparable to the results obtained by [7] for the biodiesel-clove mustard oil mixture, which showed an increase in HC of 20-30% but with an overall reduction in CO and PM emissions. Simultaneous CO depletion and HC enhancement suggest that while oxygen enrichment increases CO oxidation, it can also extinguish fire zones in rich pockets near cylinder walls, resulting in higher residual hydrocarbons—a typical trade-off in oxygenated fuel systems [22], lowering CO & increasing HC trade-offs in oxygen enrichment [23]

Overall emission trends confirm that clove oil acts as an effective oxygenated additive, improving combustion completeness while maintaining environmentally acceptable emission levels. The residual oxygen present in the exhaust implies a leaner mixture and a reduced carbon oxidation load, consistent with studies by [16] [24] on the effects of bio-additives in RON 88–98 fuels. These results collectively show that the addition of 2% (P2) clove oil provides an optimal balance between increased efficiency and emission control.

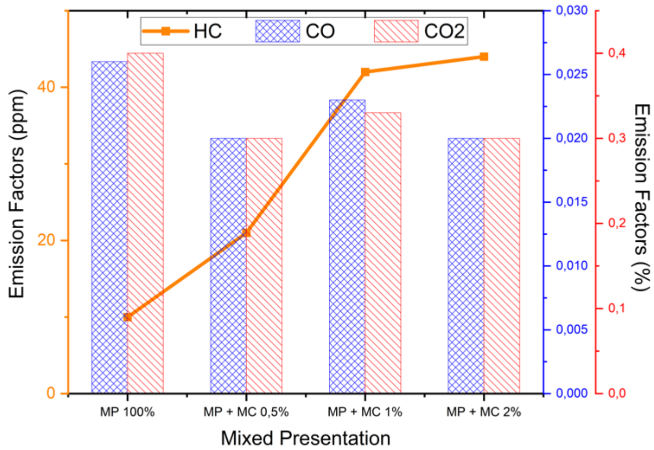


Figure 7. Emission Profiles (CO, CO_2, and HC)

3.5. Characteristics of calorific values

The calorific value of the fuel mixture tested increases with the addition of clove oil. As presented in Figure 8, the total calorific value increases by 7.8% at a 2% blending ratio (P2) compared to base fuel (P0), almost the same value was also obtained in the 0.5% mixture (P0.5) and (P.1). This increase can be attributed to the chemical composition of clove oil, which contains high proportions of oxygenated aromatic compounds such as eugenol. This compound not only improves the stability of combustion but also promotes more complete oxidation during the power step. The increased calorific value suggests that the energy density of the mixture is superior to that of pure Pertalite, allowing for better engine performance without increased fuel consumption [25].

Such an increase supports the theory that a small proportion of oxygenated bioadditives can increase energy release per unit mass of fuel, as reported [6], [7]. Both studies emphasize that essential oil derivatives act as a combustion catalyst by increasing the rate of evaporation and propagation of fire. Therefore, the current results confirm that the 2% addition rate is sufficient to increase energy output while maintaining combustion efficiency and fuel economy. Overmixing, however, can reduce volatility and inhibit atomization, as shown in the emission data for higher concentrations.

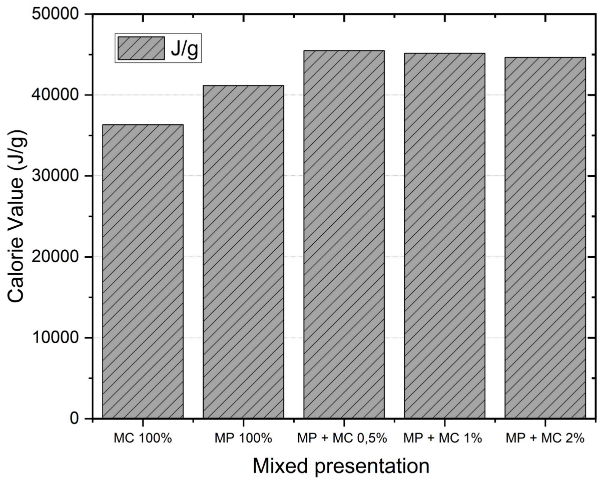


Figure 8. Summary Chart of Emission Reduction Impact

Figure 8 shows that the increase in calorific values shows a clear advantage of oxygenated bio-additives compared to (P0). These results support the research conducted by [6], [7], which states that essential oil bioadditives can improve the quality of energy produced from combustion.

3.6. Comparative Discussion with Literature

To contextualize these findings, Table 4 presents a brief comparison between this study and previous relevant studies. Improved performance and changes in emission characteristics in Pertalite-clove oil blends are generally consistent with trends reported in the literature on oxygenated biofuels. For example, the addition of a 2% oil-based additive to gasoline improved thermal efficiency through faster combustion kinetics [9], while documented a 25% reduction in CO emissions in biodiesel blends containing clove oil [7]. These results are in line with the findings of this study, where CO decreased by 0.006%. Meanwhile, thermal efficiency at high rounds with a slight increase from 16.6% (P0) to 16.7% (P2). These variations are likely to be influenced by different engine operating conditions and short-term testing limitations on one type of engine.

In addition, an increase in hydrocarbons (HC) by 34 ppm (parts per million) in mixtures with a higher clove oil content showed a pattern that was in line with the observation of Og˘uzhan [26], who found that bio-additives with higher viscosity can worsen fuel atomization and inhibit complete oxidation. However, HC levels in this study were still below regulatory thresholds, suggesting that the viscosity effect was still manageable at additive concentrations of up to 2%. However, this interpretation still needs to be considered in the context of the limitations of the experiment: the test was carried out on a single single-cylinder gasoline engine, with a limited operating duration, and without simulation of a real-world driving cycle. These limitations limit the ability to predict long-term impacts, including potential deposit formation in the combustion chamber or performance degradation due to the continued use of bio-additives.

Table 4. Comparison of Previous Research

Study	Fuel/Additive	Observations	Alignment with the present study
Kadarohman et al. (2012)	Diesel + clove oil/eugenol	Higher heat release, shorter ignition delay	Confirmed in enhanced torque and lower CO emissions
Bhangwar et al. (2024)	Mustard biodiesel + clove oil	Reduced PM, CO, and HC by 20–30%	Comparable CO/CO_2 reduction in Pertalite–clove oil
Sunaryo et al. (2020)	Plastic oil + Pertalite	Lower HC and CO emissions	Similar oxygenation-driven efficiency gain
Suryati et al. (2023)	RON 88–98 fuels	Higher octane lowers incomplete combustion	Parallels the oxygenation mechanism from clove oil

4. CONCLUSION

This study aims to evaluate the impact of the addition of clove oil as an oxygenated additive of Pertalite fuel on the performance and emissions of gasoline engines. Overall, the study confirms that mixing clove oil significantly improves both aspects. The optimal mixture, i.e. 2% clove oil (P2), provides the most balanced results. This mixture produces a 4.62% increase in torque and 6.34% braking power at medium engine speeds (3000–6000 rpm). This increase in combustion efficiency is also supported by a decrease in specific fuel consumption of around 7.14% and an increase in calorific value by 7.8%. From an environmental perspective, clove oil substantially reduces emissions of major pollutants. The concentration of carbon monoxide (CO) decreased by 0.006% and carbon dioxide (CO2) decreased by 0.1%. In conclusion, clove oil with a blending ratio of 2% proved to be an effective oxygenated renewable additive, providing improved performance and optimal emission reduction. This significant reduction in CO emissions demonstrates the potential of these additives to support the use of cleaner transportation fuels and help meet the emission thresholds set out in the Regulation of the Minister of Environment and Forestry No. 8 of 2023.

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