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Optimization of Clove Oil Blending Ratio for Maximizing Engine Efficiency and Minimizing Emissions

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ABSTRACT

The increasing demand for cleaner and more efficient fuels has encouraged the use of bio-based additives to improve combustion and reduce emissions in gasoline engines. This study investigates the influence of clove oil, an oxygenated essential oil rich in eugenol and eugenyl acetate, as a bio-additive in Pertalite fuel (RON 90). The main objective was to evaluate its effects on engine performance and exhaust emissions under controlled operating conditions. Three fuel samples were tested: pure Pertalite (P0), Pertalite with 0.5% clove oil (P0.5), Pertalite with 1% clove oil (P1), and Pertalite with 2% clove oil (P2). Experiments were carried out on a single-cylinder four-stroke gasoline engine connected to a dynamometer and gas analyzer, as illustrated in Figure 1. The parameters measured include torque, braking power, specific fuel consumption (SFC), fuel consumption (FC), thermal efficiency, and exhaust gas composition (CO, CO_2, dan HC). The results showed that the P2 mixture produced the best overall performance, achieving a 4.62% increase in torque, 6.34% higher braking power, and a 7.14% decrease in SFC compared to pure Pertalite. Fuel consumption (FC) gets a value that is not much different. Thermal efficiency increases from 2.11% to 2.63% at the lowest rpm, indicating an increase in energy conversion. Emissions analysis revealed that CO decreased by 23.08%, HC increased by more than 77.27%, and CO_2 decreased by 25%, confirming more complete combustion. And the heat value test in P2 increased by 9.49%. In conclusion, the addition of 2% clove oil to Pertalite effectively improves combustion efficiency and reduces harmful emissions without the need for engine modifications. These findings show that clove oil is a promising renewable additive to improve fuel quality and support the transition to cleaner and more sustainable transportation energy.

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1. INTRODUCTION

The increasing demand for fossil fuels and the depletion of petroleum reserves have prompted researchers worldwide to seek alternative and sustainable energy sources. In the transportation sector, gasoline engines remain dominant due to their relatively simple operation and high power-to-weight ratio; however, they contribute significantly to air pollution through exhaust gas emissions, including hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) [1, 2].]. In Indonesia, the consumption of petroleum-based fuels, such as Pertalite (Research Octane Number—RON 90) and Pertamax (RON 92), continues to increase, resulting in a growing demand for clean and renewable fuel alternatives that can be directly blended with existing fuels without requiring engine modifications [3].

One of the potential solutions is the utilization of bio-additives derived from natural essential oils, which can act as oxygenated compounds to improve combustion efficiency and reduce exhaust emissions [4]. Among various bio-additives, clove oil (Syzygium aromaticum) has attracted significant attention due to its high content of eugenol and eugenyl acetate—aromatic compounds that possess oxygen atoms and exhibit excellent combustion-promoting characteristics ([5]. These oxygenated functional groups facilitate the more complete oxidation of hydrocarbon fuel during combustion, thereby reducing CO and HC formation and improving the overall thermal efficiency of spark-ignition engines, [6].

Previous research by Kadarohman et al. (2012) demonstrated that blending diesel fuel with 0.2% clove oil, eugenol, or eugenyl acetate effectively increased cylinder pressure and reduced ignition delay, leading to enhanced total heat release and combustion stability [7]. Similarly, Bhangwar et al. (2024) reported that adding 3,000 ppm of clove oil to biodiesel significantly reduced particulate matter (PM1–PM10) emissions and carbon deposition in the injector compared to neat diesel, confirming the antioxidant and oxidative stabilization effects of clove oil [8]. These findings suggest that clove oil additives may not only reduce harmful exhaust emissions but also extend engine durability through improved combustion efficiency.

In the Indonesian context, Sunaryo et al. (2020) investigated the performance and exhaust gas characteristics of gasoline engines fuelled with plastic oil–Pertalite blends, showing reduced HC and CO emissions compared to neat Pertalite [9]. More recently, Suryati et al. (2023) analysed various commercial gasoline fuels (RON 88–98) and concluded that higher-octane fuels (RON 92 and above) substantially lowered CO and HC emissions under idle and variable engine speeds [10]. However, this study explores alternative fuels and transmission variations, such as testing torque, power, fuel consumption, exhaust emissions, and calorific value. Limited research has focused on oxygenated bio-additives such as clove oil when mixed with commercial Pertalite gasoline.

Given these findings, the present study aims to conduct a comparative analysis of exhaust gas emissions and engine performance using Pertalite fuel blended with a clove oil additive. The focus is to determine the extent to which clove oil concentration affects torque, power output, emission characteristics (CO, HC, and CO_2), and Calorific value under constant operating conditions. The results of this study are expected to provide empirical evidence supporting the practical application of essential oil-based bio-additives for reducing air pollution and enhancing combustion efficiency in gasoline engines.

2. RESEARCH METHOD

2.1 Fuel Materials and Additive Preparation

The base fuel used in this study was commercial Pertalite gasoline (RON 90), obtained from domestic fuel distribution sources in Indonesia. Clove oil (Syzygium aromaticum) was employed as the bio-additive, extracted through a steam distillation process from dried clove buds, and filtered to remove residual particulates. The primary chemical constituents of clove oil, such as eugenol ($C_{10}H_{12}O_2$) and eugenyl acetate ($C_{12}H_{14}O_3$), act as oxygenated organic compounds capable of enhancing fuel combustion efficiency and reducing hydrocarbon emissions [11].

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 blends were prepared using a mechanical stirrer at 1500 rpm for 5 minutes to ensure homogeneous mixing (**Fig. 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, [12, 13].

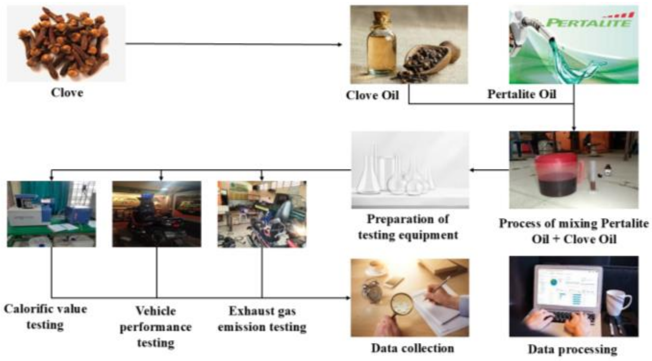


Fig 1. Set of the testing process

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 1**. The schematic layout of the experimental setup is illustrated in **Fig 2**.

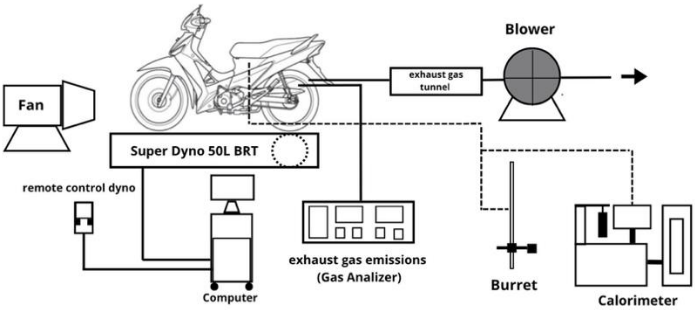


Fig 2. Schematic diagram of the experimental setup used for engine performance and exhaust gas emission testing.

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 was measured using a burette system, while the calorimeter was employed to determine the energy content of each fuel blend. The exhaust gases were analysed for CO, CO_2, HC, and O_2 concentrations using a calibrated four-gas analyser (Model 10174175). The system was validated against standard operating procedures as described by Sunaryo et al. [14] and Suryati et al. [15] .

Table 1. 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 (η_t). Torque was recorded directly from the dynamometer and calculated from the product of the applied centrifugal force and the lever arm length (Eq. 1). The corresponding brake power was obtained using Eq. 2, where the torque and rotational speed were used to determine the shaft power output.

$$T = F \times R \tag{1}$$

The brake power (P), which reflects the useful mechanical power available at the engine shaft, was calculated using Eq. (2). It is derived from the rotational speed (N, in revolutions per minute) and the measured torque (T, in N·m). This relationship indicates the engine's ability to convert chemical energy into mechanical work.

$$P = \frac{2.\pi.N.T}{60} \tag{2}$$

The fuel consumption rate (FC) was determined from the measured fuel volume (V_{nn}), the fuel density (ρ_{nn}), and the time (t) taken to consume that volume, as described in Eq. (3).
This parameter quantifies the mass of fuel consumed per unit time under given operating conditions.

$$FC = \frac{3600.pbb.vbb}{t} \tag{3}$$

To evaluate the engine's fuel economy, the specific fuel consumption (SFC) was computed as the ratio between the fuel flow rate and the corresponding brake power, as expressed in Eq. (4).
A lower SFC value indicates a more efficient engine, as it requires less fuel to produce the same power output.

$$SFC \frac{fC}{BP} \tag{4}$$

The thermal efficiency (η_t) was calculated using Eq. (5), representing the ratio of the engine's output power (Pout) to the total fuel energy supplied per unit time. Here, the fuel energy input is obtained by multiplying the fuel mass flow rate ($\dot{m}f$) by its lower heating value (LHV).
This expression determines how effectively the chemical energy of the fuel is converted into mechanical work.

$$\eta_t = \frac{Pout}{mf x LHV} x100 \tag{5}$$

The calorific value (Q) of the fuel was determined experimentally by measuring the temperature change during controlled combustion (Eq. 6).
This equation relates the total heat released (Q) to the sample mass (m), the specific heat capacity (c), and the temperature rise (ΔT), thus providing the fundamental data for energy input analysis.

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

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.

2.4. Validation and Comparative Framework

To validate the reliability of the results, the experimental setup was benchmarked against methodologies from Sunaryo et al. (2020), who analysed plastic oil–Pertalite blends under similar conditions, and Suryati et al. (2023), who examined the effects of fuel octane variations on emission levels in EFI vehicles. The preparation and application of clove oil followed the recommendations of Kadarohman et al. (2012) [7] and Bhangwar et al. (2024) [8], emphasizing the effects of oxygenated fuel chemistry and antioxidants on combustion stability.

3. RESULT AND ANALYSIS

3.1. Overview of Experimental Setup

The overall configuration of the test system is shown in **Fig. 2**, where the motorcycle engine, dynamometer, and gas analysis systems are connected in an integrated setup. The blower and fan were used to simulate road airflow, ensuring consistent engine cooling and exhaust sampling. The experimental layout follows the procedures outlined in Suryati et al. [10] and Sunaryo et al. [9], guaranteeing accurate measurement of performance and emission parameters.

3.2. Torque and Brake Power Analysis

Fig. 3 and **Fig. 4** present the measured torque and brake power for Pertalite (P0), Pertalite + 0.5% clove oil (P0.5), Pertalite + 1% clove oil (P1) and (P2) pertalite + 2% clove oil across various engine speeds (3000–6000 rpm). The P2 blend exhibited a 4.62% increase in maximum torque (10.61 Nm) at 6000 rpm compared to pure Pertalite, while brake power improved by approximately 6.34% (8.99 kW) (Fig. 4). This increase is most pronounced at medium-range speeds, according to optimal air-fuel mixing and efficient fire propagation, for the torque results can be seen in **Fig 3** and power in **Fig 4**.

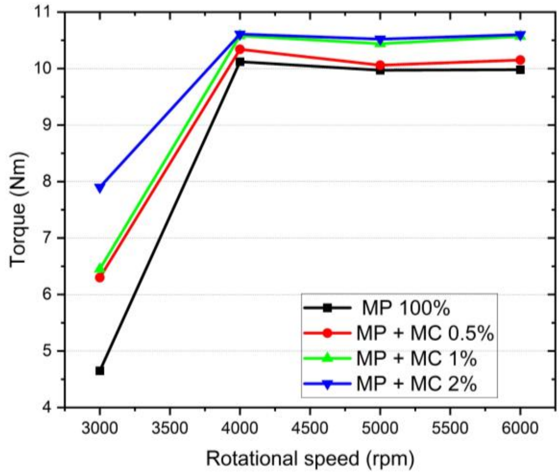


Fig 3. Torque and power vs. engine speed (P0, P0.5, P1 and P2)

At higher speeds (>6000 rpm), the torque for P2 slightly decreased, which can be attributed to an overly lean mixture and delayed combustion. High oxygen content has been documented by Kadarohman et al. (2012) [7] and Bhangwar et al. (2024) [8], who reported that excessive oxygenation in fuel can alter flame speed and increase ignition delay.

These results suggest that clove oil, at the optimal mixing ratio (approximately 2%), enhances engine output by improving atomization and combustion completeness, consistent with the oxygenated bio-additive behaviour reported in Fuel and Frontiers in Energy Research journals.

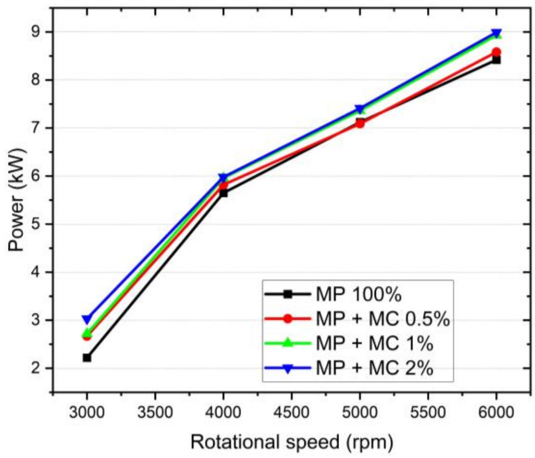
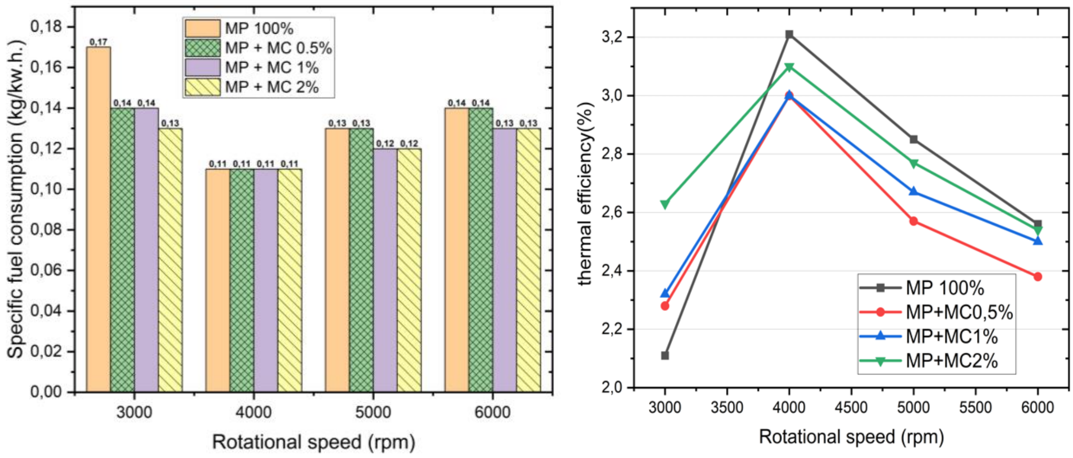


Fig 4. Brake power comparison for P0, P0.5, P1 and P2

3.3. Specific Fuel Consumption and Thermal Efficiency

Trends in specific fuel consumption (SFC), brake thermal efficiency (BTE), and fuel consumption (FC) are illustrated in Figs. 5 and 6. Both parameters exhibit a similar relationship, as evident in the results obtained for specific fuel consumption (SFC) and thermal efficiency, as shown in **Fig. 5**.



(a) (b)

Fig 5. (a) Specific fuel consumption (SFC) and (b) Thermal efficiency

The P2 blend achieved the lowest SFC value of 0.13 kg/kWh, indicating a 7.14% reduction relative to the baseline fuel (P0), thermal efficiency increased from 2.11% (P0) to 2.63% (P2) at the lowest engine speed, but at the highest engine speed there was a slight decrease of 2.54% (P2) to 2.56% (P0), meanwhile, FC fuel consumption is not much different from other mixture variations. This trend indicates that moderate concentrations of clove oil enhance energy utilization efficiency by improving oxygen availability, thereby facilitating the more complete oxidation of hydrocarbons. Similar efficiency improvements were noted by Sunaryo et al. (2020) in gasoline–plastic oil mixtures and by Kadarohman et al. (2012) in eugenol-based diesel blends. The results for fuel consumption (FC) are presented in **Fig. 6**.

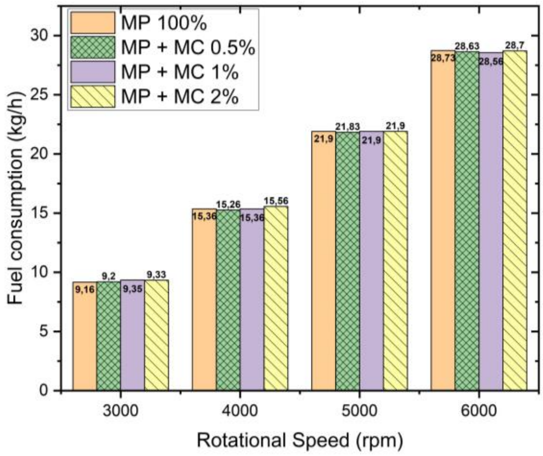


Fig 6. Fuel consumption (FC).

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

3.4. Exhaust Gas Emission Characteristics

The comparative emission performance for CO, CO_2, and HC is summarized in Fig. 5. CO emissions decreased significantly by 23.08% (P2) compared to P0. This reduction is directly related to the increased oxygen content in clove oil, which facilitates a more complete oxidation of carbon compounds during combustion. This pattern aligns with the results of Bhangwar et al. (2024), who reported up to 25% lower CO emissions in biodiesel-clove oil blends. For the results obtained on exhaust gas emissions, see **Fig. 7**.

HC emissions increase by 77.27% (P2) from the mixture (P0), confirming that the eugenol in clove oil has thicker physical properties than Pertalite, which blocks the combustion of the entire fuel. However, although HC levels are increasing, they are still well below the set threshold. CO_2 decreased by 25% (P2) compared to fuel use (P0). This decrease indicates that the process of burning fuel at modified test conditions becomes more efficient, resulting in a reduced amount of carbon being oxidized into CO_2.

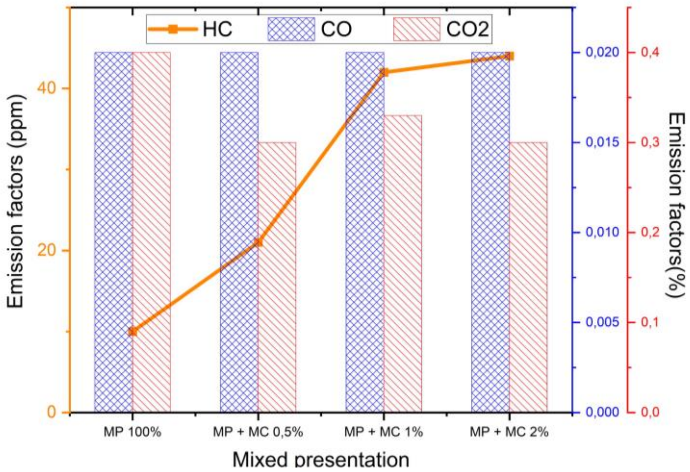


Fig 7. Emission profiles (CO, CO_2, and HC)

3.5. Characteristics of calorific values

The total calorific value in the clove oil mixture increased by 9.49% at (P0.5%) compared to (P0). The result of the calorific value is shown in **Fig. 8**.

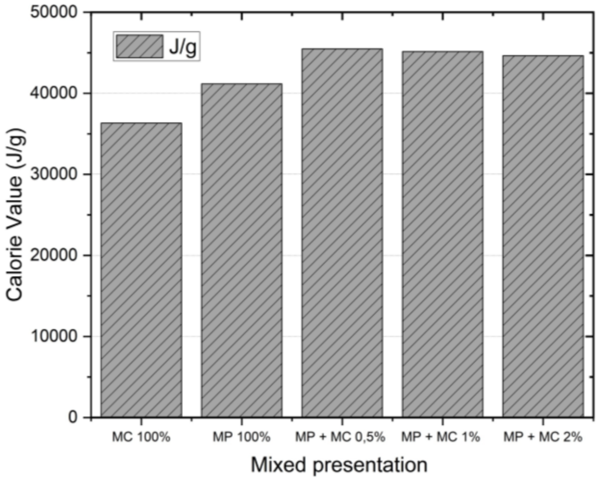


Fig 7. Summary chart of emission reduction impact

Fig. 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 Kadarohman et al. (2012) and Bhangwar et al. (2024), 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 2** provides a summary comparison between the present study and previous research relevant.

Table 1. Comparison of previous research

Study	Fuel/Additive	Observations	Alignment with present study
Kadarohman et al. (2012)	Diesel + clove oil/eugenol	Higher heat release, shorter ignition delay	Confirmed in enhanced torque and lower CO emission
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 confirms that mixing clove oil with Pertalite fuel improves the overall performance and emission profile of gasoline engines. The experimental results showed that the 2% clove oil (P2) mixture produced the most balanced results, resulting in a 4.62% increase in torque and 6.34% higher braking power compared to pure Pertalite. This increase occurs at medium engine speeds (3000–6000 rpm), where combustion stability is optimized. Specific fuel consumption decreased by about 7.14%, while thermal efficiency increased from 2.11% to 2.63% at 3000 rpm, indicating more efficient energy conversion and cleaner combustion processes. In terms of exhaust emissions, the addition of clove oil significantly reduces the presence of harmful pollutants. The concentration of carbon monoxide decreased by 23.08%, and hydrocarbons increased by 77.27%, while the concentration of carbon dioxide was lowered by 25%. Regarding the calorific value, the use of bio-additives can improve energy quality by 9.49%. The presence of residual oxygen in the exhaust confirms leaner combustion and reduces the fraction of fuel that does not burn. These results clearly demonstrate that clove oil acts as an effective oxygenated additive, enhancing fuel combustion, improving efficiency, and minimizing emissions. In conclusion, clove oil at a 2% blending ratio provides the optimal performance gain and emission reduction, making it a promising renewable additive for gasoline engines. Its application can support cleaner transportation fuels and contribute to compliance with stricter emission regulations, such as EURO 4. Further research is recommended to investigate long-term engine effects, oxidation stability, and the behavior of clove oil blends in electronic fuel injection systems.

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