Optimization of Bio-Additive Formulation Using Subang Citronellal, Clove, And Patchouli: Evaluation of Density, Power Output, And CO_2–O_2 Emissions

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Abstract.

This research examined the potential of essential oil–based bio-additives derived from citronella, clove, and patchouli to enhance the physicochemical properties, engine performance, and emission characteristics of Pertalite fuel. The study utilized Response Surface Methodology (RSM) with a Central Composite Design (CCD) to assess additive concentrations between 0.1 and 0.3 mL per liter of Pertalite. Findings indicated that these low-level additions did not significantly affect density, which remained similar to pure Pertalite. Likewise, power output and exhaust emissions (CO2 and O2) showed no notable improvements. Statistical evaluation using Design Expert® revealed all regression models were non-significant ($p > 0.05$), and optimization attempts failed to identify a valid optimum, with desirability values below 0.5. The minimal impact is attributed to the very low additive dosage, insufficient to influence atomization, combustion, or emission reduction. Additionally, gasoline's non-polar nature limits sensitivity to parameters such as pH, while operational variations during engine testing (temperature, RPM, and load) may have masked minor effects. In summary, essential oil bio-additives at concentrations below 0.03% by volume are ineffective for measurable improvements. Future studies should investigate higher concentrations, purification of active compounds, improved blending techniques, and stricter engine testing protocols. The contribution of oxygenated compounds to combustion enhancement also merits further exploration.

Keywords: *Bio-additive; Essential Oils; Fuel; Optimization and RSM (Response Surface Methodology).*

I. INTRODUCTION

The growth of two-wheeled vehicles globally and nationally continues to show an increasing trend each year. Global motorcycle sales reached more than 87 million units in 2023, with Southeast Asia as the largest contributor. Indonesia, one of the countries with the highest motorcycle population, recorded over 6 million new units distributed in 2023. This condition reflects the high dependence of society on motorcycles as the primary mode of transportation [1][2][3].The increasing number of vehicles directly affects air quality, particularly through exhaust emissions such as carbon monoxide (CO_2) and Oxygen (O_2). These compounds are major pollutants that contribute to declining air quality and increasing public health risks. Therefore, solutions are required that are not only technical but also environmentally sustainable [4].Essential-oil-based bio-additives represent a promising approach to addressing these issues. The active compounds in essential oils—eugenol, citronellal, and patchoulol—play a role in enhancing combustion performance and reducing exhaust emissions.

Previous studies have shown that mixing G88 gasoline with 0.1% citronella oil and 0.1% clove oil (known as BA2) can reduce average fuel consumption by 18.54%, with higher thermal efficiency despite lower volumetric efficiency. The resulting emissions also remained below Indonesia's regulatory limits for motor vehicle emissions [5][6][7].The potential for developing bio-additives is increasingly relevant considering that Indonesia—particularly regions such as Subang Regency—has abundant essential oil production. Recent data indicate that citronella production reaches approximately 795 tons from 190 hectares of land, while clove production is around 292 tons per year. Patchouli oil is also a major commodity with broad utilization potential. However, no optimal bio-additive formulation has yet been developed that systematically combines these three essential oils based on a scientific optimization approach. Therefore, this study aims to optimize a bio-additive formulation made from clove, citronella, and patchouli essential oils through a programming-based approach using Design Expert® software. Proper modeling enables an optimal experimental design [8].The main objective is to obtain a formulation capable of significantly reducing fuel consumption and CO_2–O_2 emissions, while maintaining combustion efficiency and practical applicability for gasoline-powered motorcycles in Indonesia.

II. METHODS

Tools and Materials

The tools used in this study included a fractional distillation apparatus, Gas Chromatography–Mass Spectrometry (GC-MS) to analyze key compounds in patchouli, citronella, and clove essential oils. Isolation of compounds was carried out using fractional distillation. Physical test involved the use of a picnometer and analytic scale. The blending of bio-additives with fuel was conducted manually for thirty seconds. Performance testing on two-wheeled vehicles utilized a dynamometer for measuring power and gas analyzer for measuring CO_2 and O_2 emission.Materials used in this study included patchouli, citronella, and clove essential oils; pertalite gasoline; density calibration standards; and engine lubricant oil.

Research Procedure

This research consisted of several systematic and structured stages. It began with an in-depth literature review and problem formulation to determine the urgency of the study and identify research gaps. A state-of-the-art analysis was then conducted to define the novelty level and scientific contribution of the research.The experimental design employed Response Surface Methodology (RSM) with a Central Composite Design (CCD) approach using Design Expert®. The primary factors studied were the concentrations of essential-oil bio-additives (patchouli, citronella, and clove) blended into the fuel. The main responses were fuel consumption efficiency and reduction of exhaust gas emissions from two-wheeled engines.

Table 1. Independent Variables and Concentration Levels in the Study

Code	Variable	Main Active Component	Concentration Levels (per 1000 mL Pertalite)	Unit	Active Component Range (%)
X1	Citronella Oil	Citronellal	0.1 · 0.2 · 0.3	mL/1000 mL	30–45%
X2	Clove Oil	Eugenol	0.1 · 0.2 · 0.3	mL/1000 mL	70–90%
X3	Patchouli Oil	Patchouli Alcohol	0.1 · 0.2 · 0.3	mL/1000 mL	30–45%

Table 2. Factors and Variable Levels in the Experimental Design

Factor	Symbol	Level –α	Level –1	Center Point (0)	Level +1	Level +α
Citronella Oil	X1	Determined by software	0.1	0.2	0.3	Determined by software
Clove Oil	X2	Determined by software	0.1	0.2	0.3	Determined by software
Patchouli Oil	X3	Determined by software	0.1	0.2	0.3	Determined by software

The total number of treatment variations was determined using the initial factorial design and the Central Composite Design (CCD). In Design Expert®, each concentration variable in the initial factorial design includes five observation points (−α, −1, 0, +1, +α). The center point in this study corresponds to the ratio of citronella oil, patchouli oil, clove oil, and Pertalite at 0.2 : 0.2 : 0.2 : 1000 mL.

The subsequent stages include:

1. Preparation of tools and materials, including characterization using GC–MS to confirm the initial levels of key compounds: patchouli alcohol, citronellal, and eugenol in the essential oils.
2. Isolation of key compounds through fractional distillation to purify the major active components.
3. Physicochemical characterization of the isolated compounds, including viscosity, density, pH, flash point, refractive index, and surface tension.
4. Mixing of bio-additive compounds into gasoline using a magnetic stirrer according to the concentration variations determined in the CCD design.
5. Vehicle performance testing on a two-wheeled engine test bench (dynamometer) to measure power, torque, as well as emission testing using a gas analyzer.
6. Data analysis using Design Expert® to model variable interactions, identify the optimal combination, and generate response surface plots and model equations.

III. RESULT AND DISCUSSION

1. Physical Property (Density)

Density measurements across all treatment variations indicated that adding bio-additives derived from citronella, clove, and patchouli at concentrations of 0.1–0.3 mL per 1000 mL of Pertalite did not result in any significant changes in fuel density. The recorded values remained very close to those of pure Pertalite. ANOVA analysis using Design Expert® confirmed that the regression model was statistically non-significant ($p > 0.05$), whether considering individual factors (X1, X2, X3), their interactions (X1X2, X1X3, X2X3), or quadratic effects. The minimal variability observed suggests that such a small volumetric fraction of bio-additive was insufficient to alter the bulk properties of the fuel.From a chemical standpoint, this outcome is expected because essential oils generally exhibit densities similar to light hydrocarbons and possess good miscibility with gasoline.

At concentrations below 0.03%, their contribution to overall fuel density is negligible. The three-dimensional response surface plot in Figure 1 illustrates this trend, showing an almost flat surface with no pronounced peaks or valleys, which confirms the absence of significant density variation across the tested factor ranges.Recent literature supports these findings. Reviews on essential oils as fuel additives highlight that while certain components of citronella, clove, and patchouli oils can improve combustion characteristics, their effect on density is minimal unless applied at substantially higher concentrations. Similarly, studies in biodiesel research emphasize that additive impact on density strongly depends on dosage and molecular structure, with sub-percent levels rarely producing measurable changes. These observations reinforce that the lack of significant density variation in this experiment is consistent with the chemical nature of essential oils and the very low concentrations applied.

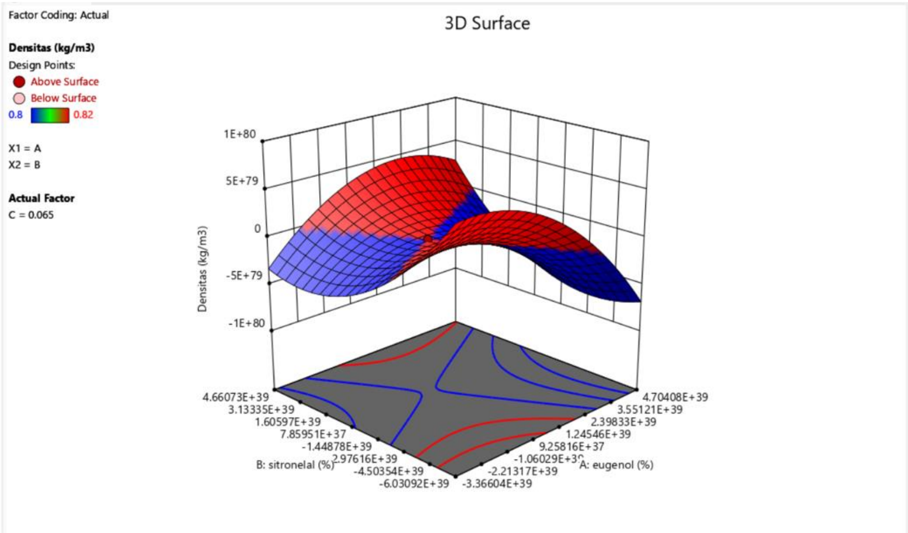

Fig 1. Three-dimensional response surface plot (3D surface plot) showing the effect of eugenol (A) and citronellal (B) on fuel density under constant factor C conditions.

2. Performance Test (Power)

Power measurements across all treatment variations indicated that the addition of bio-additives derived from citronella, clove, and patchouli at concentrations of 0.1–0.3 mL per 1000 mL of Pertalite did not produce any significant improvement in engine performance. The recorded power values remained very close to those obtained with pure Pertalite. ANOVA analysis using Design Expert® confirmed that the regression model was statistically non-significant ($p > 0.05$), whether considering individual factors (X1, X2, X3), their interactions (X1X2, X1X3, X2X3), or quadratic effects. The minimal variability observed suggests that such a small volumetric fraction of bio-additive was insufficient to influence combustion efficiency or energy release.From a chemical perspective, this outcome is expected because essential oils, although containing oxygenated compounds that can enhance combustion, were applied at concentrations below 0.03%, which is too low to meaningfully affect fuel properties or engine power output.

The three-dimensional response surface plot in Figure 1 illustrates this trend, showing an almost flat surface with no significant peaks or valleys, confirming the absence of notable power variation across the tested factor ranges.Recent literature supports these findings. Studies on essential oils as fuel additives indicate that while certain components of citronella, clove, and patchouli oils can improve combustion quality and stability, their effect on power is negligible unless applied at substantially higher concentrations. Similarly, biodiesel research emphasizes that additive effectiveness depends strongly on dosage and molecular structure, with sub-percent levels rarely producing measurable changes. These observations reinforce that the lack of significant power variation in this experiment is consistent with the chemical nature of essential oils and the very low concentrations applied.

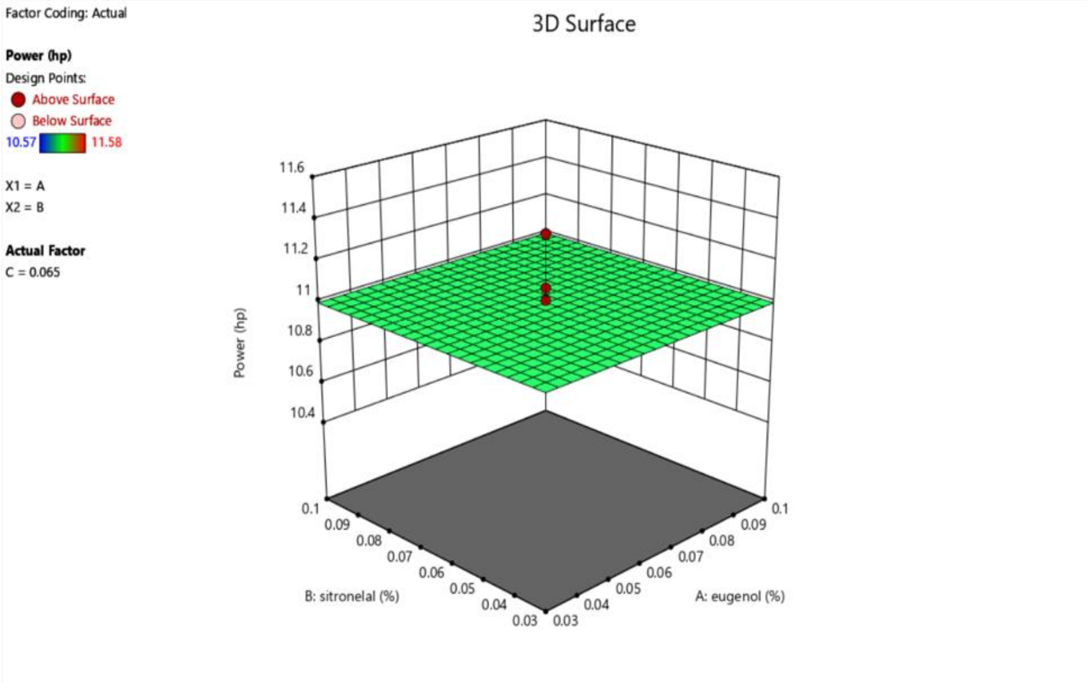

Fig 2. Three-dimensional response surface plot (3D surface plot) showing the effect of eugenol (A) and citronellal (B) on enigine power under constant factor C conditions.

3. Emissions Test (CO_2 and O_2)

a. CO_2 (Carbon Dioxide)

CO_2 emission measurements across all treatment variations revealed that incorporating bio-additives derived from citronella, clove, and patchouli at concentrations of 0.1–0.3 mL per 1000 mL of Pertalite did not lead to any significant reduction in exhaust CO_2 levels. The observed emission values remained close to those recorded for pure Pertalite. ANOVA analysis using Design Expert® confirmed that the regression model was statistically non-significant ($p > 0.05$), whether considering individual factors (X1, X2, X3), their interactions (X1X2, X1X3, X2X3), or quadratic effects. The low variability in the data suggests that such a small volumetric fraction of bio-additive was insufficient to influence combustion chemistry or carbon dioxide formation.From a chemical perspective, this result is expected because essential oils, while containing oxygenated compounds, were applied at concentrations below 0.03%, which is too low to meaningfully alter the stoichiometry or oxidation pathways during combustion.

The three-dimensional response surface plot in Figure 1 illustrates this trend, showing a nearly flat surface with no significant peaks or valleys, confirming the absence of notable CO_2 emission changes across the tested factor ranges.Recent literature supports these findings. Reviews on essential oils as fuel additives indicate that while certain fractions of citronella, clove, and patchouli oils can improve combustion quality and reduce incomplete combustion products, their effect on CO_2 emissions is minimal unless applied at substantially higher concentrations. Similarly, biodiesel studies emphasize that additive effectiveness depends strongly on dosage and molecular structure, with sub-percent levels rarely producing measurable changes. These observations reinforce that the lack of significant CO_2 emission variation in this experiment is consistent with the chemical nature of essential oils and the very low concentrations applied.

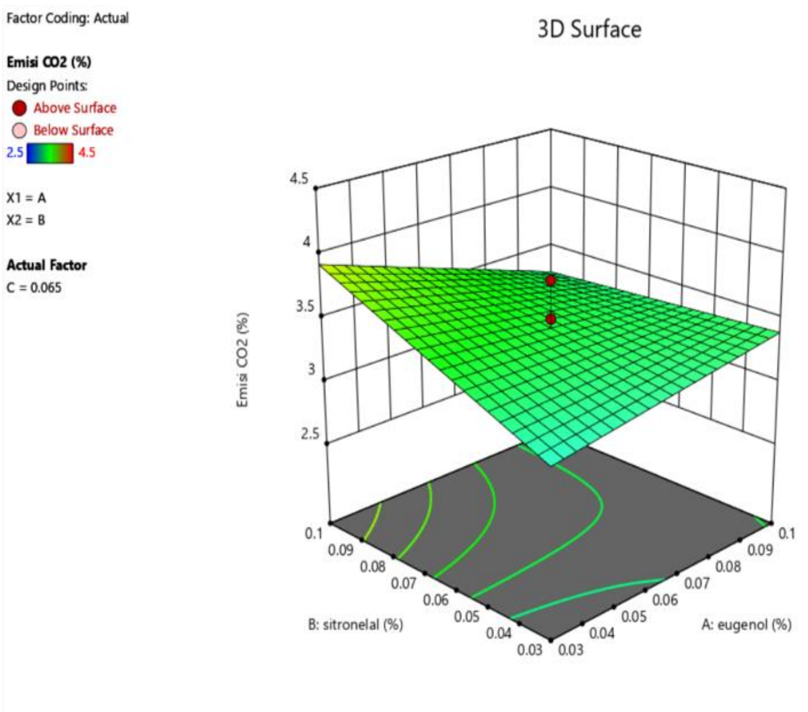

Fig 3. Three-dimensional response surface plot (3D surface plot) showing the effect of eugenol (A) and citronellal (B) on CO_2 emission under constant factor C conditions.

b. O_2 (Oxygen)

Analysis of oxygen (O_2) emission across all experimental treatments demonstrated that the incorporation of bio-additives derived from citronella, clove, and patchouli at concentrations ranging from 0.1 to 0.3 mL per 1000 mL of Pertalite did not result in any statistically significant variation in exhaust O_2 levels. The measured values remained comparable to those observed for unmodified Pertalite fuel. Analysis of variance (ANOVA) performed using Design Expert® confirmed that the regression model was non-significant ($p > 0.05$), regardless of whether individual factors (X_1, X_2, X_3), two-way interactions (X_1X_2, X_1X_3, X_2X_3), or quadratic effects were considered. The minimal variability observed indicates that such a low volumetric fraction of bio-additive was insufficient to influence combustion stoichiometry or oxygen utilization during the oxidation process.From a mechanistic perspective, this outcome is consistent with the chemical characteristics of essential oils.

Although these compounds contain oxygenated functional groups that could theoretically enhance combustion efficiency, the applied concentrations (<0.03% v/v) were far below the threshold required to induce measurable changes in exhaust gas composition. The three-dimensional response surface plot presented in Figure 1 corroborates these findings, exhibiting an almost planar surface without pronounced gradients, thereby confirming the absence of significant O_2 emission variation across the tested factor ranges.Current literature supports these observations. Studies on essential oils as fuel additives report that while certain fractions of citronella, clove, and patchouli oils can improve combustion quality and reduce incomplete oxidation products, their influence on oxygen emission remains negligible at sub-percent concentrations. Similarly, biodiesel research emphasizes that additive efficacy is strongly dependent on dosage and molecular structure, with very low concentrations rarely producing detectable effects. These findings collectively reinforce that the lack of significant O_2 emission variation in this study is attributable to the chemical nature of essential oils and the extremely low dosage employed.

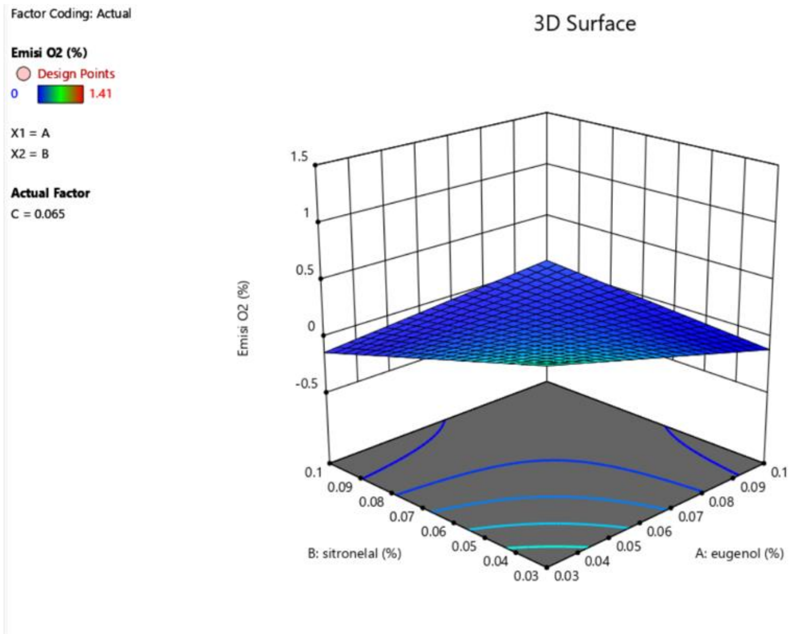

Fig 4. Three-dimensional response surface plot (3D surface plot) showing the effect of eugenol (A) and citronellal (B) on O_2 emission under constant factor C conditions.

Optimum Point

The optimization process conducted using Design Expert® did not yield a valid optimum point. The regression models generated were statistically non-significant ($p > 0.05$), preventing the software from constructing a representative response surface. Furthermore, the optimization desirability value remained below 0.5, indicating that none of the treatment combinations met the targeted improvements in density, power, or emission parameters.Consequently, the optimization attempt was deemed unsuccessful, and the bioadditive formulation based on citronellal, eugenol, and patchoulol at concentrations of 0.1–0.3 mL per 1000 mL of Pertalite cannot yet be recommended as an effective bioadditive.

IV. CONCLUSION

This study aimed to optimize the formulation of bio-additives based on essential oils of citronella, clove, and patchouli using the RSM–CCD method. However, the results indicated that the addition of bio-additives at concentrations of 0.1–0.3 mL per 1000 mL of Pertalite did not produce a significant effect on physical property (density), engine performance (power), or exhaust emissions (CO2 and O2).Statistical analysis using Design Expert® revealed that all resulting regression models were not significant ($p > 0.05$), thus preventing the optimization process. No optimum point was found that met the targets for performance improvement or emission reduction.Overall, the study concludes that the bio-additive dosage used was below the effective threshold, and therefore unable to produce measurable changes. Future research should consider increasing the bio-additive concentration, purifying active compounds to higher levels, applying more homogeneous mixing methods, conducting tests under stricter load and RPM variations, and analyzing oxygenated compounds to map the potential for improved combustion quality.

V. ACKNOWLEDGMENTS

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