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# Optimization of Gasoline–Jatropha Bioethanol Blends and Engine Speeds for Enhanced Performance and Emission Reduction in Spark Ignition Engines

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**ABSTRACT**

This study focused on optimizing the performance and emission characteristics of a spark ignition (SI) engine fueled with gasoline–Jatropha bioethanol blends. The objective was to determine the optimal blend ratio and engine speed combination that maximizes engine efficiency while minimizing harmful exhaust emissions, with the broader goal of establishing Jatropha-based bioethanol as a viable renewable additive to gasoline. The research methodology involved the production of high-purity Jatropha bioethanol via fermentation and distillation, followed by the preparation of various gasoline blends (B0–B30). Engine testing was conducted on a SI engine test bench operating across a speed range of 1800 RPM up to 3300 RPM. The experimental design utilized a Central Composite Design (CCD) to systematically investigate the effects of two key factors, blending ratio and engine speed, on performance and emissions. The experimental data were subsequently analyzed using Response Surface Methodology (RSM) to establish factor relationships and identify the optimal operating point. The analysis revealed that the optimal performance occurred at a 16% Jatropha bioethanol blend and 3300 rpm. Under these conditions, the engine efficiency metrics were significantly improved, with the brake power increasing to 1.31 kW (+22.7%) at 4Nm load, the brake specific fuel consumption (BSFC) reduced to 256 g/kWh (−33.7%), and the brake thermal efficiency (BTE) enhanced to 33% (+43.5%). The volumetric efficiency also improved to 40% (+5.3%), indicating superior air-fuel mixing. In terms of emissions, the concentrations of hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides (NOx) were reduced to 0.0019% (−29.6%), 0.018% (−40%), and 0.0671% (−9.9%), respectively. The only increase was in carbon dioxide ($CO_2$), which rose slightly to 1.24% (+18.4%) less harmful gases, reflecting more complete combustion due to the oxygenated nature of bioethanol. In conclusion, the optimization results demonstrate that a moderate Jatropha bioethanol blend enhances both fueling efficiency and combustion cleanliness of SI engines, positioning Jatropha-based bioethanol as a viable, performance-improving, and emission-reducing renewable additive for small-scale automotive applications.

Keywords: Performance, Emissions, Spark Ignition Engine, Bioethanol, Response Surface Methodology (RSM), Optimization

## 1.0 INTRODUCTION

The global transportation sector faces unprecedented challenges in reducing greenhouse gas emissions while meeting growing energy demands, making the development of sustainable alternative fuels a critical priority (Ibarra Vega & Redondo, 2024). In this context, bioethanol has emerged as one of the most promising renewable fuel additives for spark ignition (SI) engines, offering both environmental benefits and performance enhancements when appropriately blended with conventional gasoline (Karmakar et al., 2024; Deshpande et al., 2024). The integration of bioethanol into existing fuel infrastructure represents a practical pathway toward decarbonizing transportation while maintaining compatibility with current engine technologies (Syarifudin *et al.,* 2025).

Recent comprehensive reviews have demonstrated that ethanol-gasoline blends consistently improve combustion characteristics in SI engines, primarily due to ethanol's higher-octane rating, oxygenated nature, and favorable thermodynamic properties (Deshpande *et al.,* 2024). Studies have reported significant improvements in brake thermal efficiency, enhanced in-cylinder pressure development, and reduced emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) when using moderate ethanol blend ratios (Deshpande *et al.,* 2024; Saikia & Dutta, 2024). However, the optimization of blend ratios and operating conditions remains a complex challenge requiring systematic investigation to maximize benefits while minimizing potential drawbacks such as increased nitrogen oxides (NOx) formation under certain operating regimes (Tiwari *et al.,* 2025).

The selection of appropriate feedstock for bioethanol production is crucial for ensuring both sustainability and economic viability. While first-generation feedstocks like corn and sugarcane have dominated commercial bioethanol production, there is growing interest in non-food biomass sources that do not compete with food security (Karmakar et al., 2024). Jatropha curcas L. has gained considerable attention as a promising second-generation feedstock due to its ability to grow on marginal lands, high oil content, and minimal competition with food crops (Rajendran et al., 2024). Although Jatropha has been extensively studied for biodiesel production in compression ignition engines, its potential for bioethanol production and subsequent use in SI engines remains relatively underexplored (Ashok *et al.,* 2022).

Recent experimental investigations have highlighted the technical feasibility of Jatropha-derived biofuels in various engine applications. Studies on Jatropha biodiesel blends have demonstrated improved brake thermal efficiency and reduced brake specific fuel consumption at optimal blend ratios, typically around 25% by volume (Rajendran et al., 2024). Furthermore, advanced combustion strategies incorporating Jatropha-based fuels, such as reactivity-controlled compression ignition (RCCI), have shown promising results when optimized using multi-objective response surface methodology approaches (Ashok Aggarwal *et al.,* 2022). However, these studies have also identified emission tradeoffs, particularly increases in NOx emissions at conditions that maximize thermal efficiency, indicating the need for comprehensive multi-objective optimization (Rajendran *et al.,* 2024).

The application of statistical optimization techniques, particularly Response Surface Methodology (RSM) coupled with Central Composite Design (CCD), has become increasingly prevalent in biofuel research for identifying optimal operating conditions (Mishra et al., 2024; Samuel et al., 2024). These methodologies enable systematic investigation of multiple factors simultaneously while minimizing experimental effort and providing robust statistical models for prediction and optimization (Ashok Aggarwal et al., 2022). Recent studies have successfully applied RSM-based approaches to optimize various aspects of biofuel production and utilization, including biodiesel synthesis from multi-oil feedstocks and engine performance optimization with alternative fuel blends (Mishra *et al.,* 2024).

Contemporary research on ethanol-gasoline blends has consistently demonstrated performance improvements across various feedstock sources. Investigations using mangrove bioethanol, waste-derived ethanol, and other non-conventional sources have reported enhanced brake thermal efficiency, improved combustion completeness, and reduced CO and HC emissions (Karmakar *et al.,* 2024). Numerical analyses have further validated these experimental findings, showing that ethanol addition promotes more complete combustion and higher in-cylinder pressures, leading to improved thermal efficiency (Saikia & Dutta, 2024). However, the specific effects of Jatropha-derived bioethanol in gasoline blends for SI engines remain inadequately characterized in the literature.

The optimization of engine operating parameters in conjunction with fuel blend ratios represents a critical research gap that requires systematic investigation. While individual studies have examined either blend optimization or engine parameter optimization, few have simultaneously considered both factors in a comprehensive experimental design (Deshpande et al., 2024). Recent advances in multi-objective optimization techniques, including genetic algorithms and machine learning approaches, have demonstrated their potential for identifying optimal combinations of fuel properties and engine operating conditions (Tiwari et al., 2025; Sonawane *et al.,* 2025). These methodologies offer promising avenues for developing robust optimization frameworks that can balance performance improvements with emission reductions.

Current sustainability assessments emphasize the importance of considering life-cycle impacts and circularity principles in biofuel development (Karmakar et al., 2024). System dynamics frameworks have been applied to evaluate the long-term viability of bioethanol supply chains, highlighting the need to balance environmental benefits with water usage, land requirements, and socioeconomic impacts (Ibarra Vega & Redondo, 2024). This holistic approach to biofuel assessment underscores the importance of developing optimization strategies that consider not only engine performance but also broader sustainability metrics.

Despite the growing body of research on bioethanol-gasoline blends, several critical knowledge gaps remain. First, there is limited experimental data on the direct use of Jatropha-derived bioethanol in SI engines, with most Jatropha research focusing on biodiesel applications (Ashok Aggarwal et al., 2022). Second, systematic optimization studies that simultaneously consider blend ratio and engine operating parameters using robust statistical methodologies are scarce (Mishra et al., 2024). Third, comprehensive emission characterization of Jatropha bioethanol blends, particularly regarding the tradeoffs between different pollutant species, requires further investigation (Rajendran *et al.,* 2024).

The present study addresses these research gaps by investigating the optimization of gasoline-Jatropha bioethanol blend ratios and engine speeds for enhanced performance and emission reduction in spark ignition engines. The research employs a systematic experimental approach using Central Composite Design to evaluate the combined effects of blend ratio and engine speed on multiple performance and emission parameters. The findings contribute to the growing body of knowledge on sustainable transportation fuels while providing practical insights for the implementation of Jatropha-based bioethanol in small-scale automotive applications.

## 2.0 METHOD

### *2.1 MATERIALS*

The experimental work required a diverse set of materials and equipment, which can be grouped into three functional categories: Fuels and Reactor Components, Fuel Processing and Analytical Tools, and Engine Testing Equipment. The primary feedstocks were Jatropha fruit, used to synthesize bioethanol, and conventional gasoline, which served as the reference fuel and blending agent. Fuel processing utilized basic laboratory supplies, including various beakers, volumetric flasks, measuring cylinders, and auxiliary items like a spatula, stirrer, funnel, and filter/chess cloth, along with a grinding machine for initial feedstock preparation. Thermal and separation processes were executed using an oven, hot plate, and simple distillation apparatus. For detailed fuel characterization, precision instruments such as an automatic weighing balance, thermometer, pH meter, and a Refractometer (Karl Kolb) were employed. Finally, the core of the research relied on the Test bed TD110-115, a specialized apparatus essential for conducting the engine performance and emissions experiments.

### *2.2 Physicochemical Properties of the Produced Jatropha Bioethanol*

The physicochemical properties of the produced Jatropha bioethanol demonstrate its suitability as a fuel additive. It has a bioethanol concentration of 93.20% and a pH of 6.85. The fuel exhibits excellent dryness and purity profiles, with a moisture content of 0.95% and an ash content of 0.05%. It has a volatile matter content of 99.2% and a Calorific Value of 27.2 MJ/kg, confirming its high flammability, clean-burning potential, and sufficient energy content for effective engine performance.

### *2.3 Engine Testing and Optimization*

#### 2.3.1 Experimental setup

Engine performance and emissions were evaluated using a spark-ignition engine mounted on a TD110-115 test bed. Fuel blends were prepared with bioethanol concentrations ranging from 0% (B0, pure gasoline) to 30% (B30) by volume. The engine was tested across a speed range of 1800-3300 RPM. Data collection occurred after the engine reached stable operating conditions, with repeated measurements taken to ensure reliability.

#### *2.3.2 Performance Metrics*

The engine performance parameters were calculated using equations 1 to 5.

**a.** Brake Power (BP):

$$BP = \frac{2\pi NT}{60} \quad \text{... (1)}$$

**b.** Thermal Efficiency (η):

$$\eta = \frac{\text{Useful work output (BP)}}{\text{Fuel energy input}} \times 100 \quad \text{... (2)}$$

**c.** Volumetric Efficiency (VE):

$$VE = \frac{\text{Actual air intake}}{\text{Theoretical air intake}} \times 100 \quad \text{... (3)}$$

**d.** Brake Specific Fuel Consumption (BSFC):

$$BSFC = \frac{\dot{m}_f}{BP} \quad \text{... (4)}$$

***e.*** *Calorific Value (CV) was determined using a bomb calorimeter:*

$$CV = \frac{(m_w + m_e)C_{pw}(T_2 - T_1) + TC - m_{fuse}CV_1}{m_f} \quad \text{... (5)}$$

#### *2.3.3 Experimental Design and Optimization*

The study employed a Central Composite Design (CCD) methodology to systematically investigate the quadratic effects and interactions between the two primary factors: blending ratio and engine speed. This design matrix targeted key responses including PB, BSFC, BTE, VE, and exhaust emissions (HC, NOx, CO, and CO2). Response Surface Methodology (RSM), complemented by Analysis of Variance (ANOVA), was utilized for statistical data analysis and the subsequent identification of the globally optimal blending ratio and engine speed combination

## 3.0 RESULT AND DISCUSSION

- **Optimizing the blends using response surface methodology (RSM)**

The optimization of a spark ignition engine fueled with Gasoline–Jatropha bioethanol blends was carried out to identify the best combination of blending ratio and engine speed for improved performance and reduced emissions. Statistical analysis revealed that both the blending ratio and engine speed significantly influenced carbon dioxide ($CO_2$) emissions, and their interaction effect was also found to be highly significant. This implies that the combined adjustment of these two factors had a greater impact on the emission outcomes than the individual parameter variations. The regression model achieved an $R^2$ value of 83.23%, confirming that the model adequately described the variation in $CO_2$ emissions.

The RSM analysis provides the influence of blending ratio and engine speed on $CO_2$ emissions from the spark-ignition engine fueled with Gasoline–Jatropha bioethanol blends. The coded regression coefficients in table 1, indicated that both the blending ratio (Coef = 0.1565, p = 0.032) and engine speed (Coef = –0.1807, p = 0.035) exerted statistically significant effects on $CO_2$ emissions at the 95% confidence level. The quadratic effect of blending ratio (%²) was also significant (p = 0.049), suggesting that $CO_2$ emissions followed a curved trend rather than a purely linear relationship. Importantly, the two-way interaction between blending ratio and engine speed showed the strongest statistical significance (p = 0.014), showing the interdependent nature of these variables in determining emission outcomes.

Table 1: Coded Coefficients

| Term | Coef | SE Coef | T-Value | P-Value | VIF |
|---|---|---|---|---|---|
| Constant | 0.8789 | 0.0715 | 12.30 | 0.000 | |
| Blending Ratio (%) | 0.1565 | 0.0586 | 2.67 | 0.032 | 1.48 |
| Engine Speed (rpm) | -0.1807 | 0.0693 | -2.61 | 0.035 | 1.55 |
| Blending Ratio (%)*Blending Ratio (%) | 0.1911 | 0.0804 | 2.38 | 0.049 | 1.07 |
| Engine Speed (rpm)*Engine Speed (rpm) | 0.0397 | 0.0930 | 0.43 | 0.683 | 1.50 |
| Blending Ratio (%)*Engine Speed (rpm) | 0.2955 | 0.0910 | 3.25 | 0.014 | 1.64 |

Table 2 shows Model Summary. The model summary indicated that the developed regression model explained 83.23% of the total variation in $CO_2$ emissions ($R^2$ = 83.23%). However, the adjusted $R^2$ (71.24%) reflected some reduction due to the inclusion of non-significant terms, while the predicted $R^2$ (0.00%) suggested limited predictive accuracy outside the experimental data points. This discrepancy was further supported by the significant lack-of-fit (p = 0.018), implying that although the model captured the experimental trends well, its predictive ability may require further refinement through additional data points or alternative modeling techniques.

Table 2: Model Summary

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.136442 | 83.23% | 71.24% | 0.00% |

Table 3 presents the Analysis of VarianceThe ANOVA results reinforced these findings, showing that both blending ratio (F = 7.13, p = 0.032) and engine speed (F = 6.80, p = 0.035) were significant linear factors influencing $CO_2$ emissions. The quadratic term of blending ratio also contributed significantly (F = 5.65, p = 0.049), whereas the quadratic term of engine speed was not statistically significant (p = 0.683). The strong interaction effect between blending ratio and speed (F = 10.54, p = 0.014) suggested that the lowest $CO_2$ emissions could be achieved only when both variables were jointly optimized.

Table 3: Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 5 | 0.646580 | 0.129316 | 6.95 | 0.012 |
| Linear | 2 | 0.181916 | 0.090958 | 4.89 | 0.047 |
| Blending Ratio (%) | 1 | 0.132779 | 0.132779 | 7.13 | 0.032 |
| Engine Speed (rpm) | 1 | 0.126683 | 0.126683 | 6.80 | 0.035 |
| Square | 2 | 0.108195 | 0.054097 | 2.91 | 0.121 |
| Blending Ratio (%) *Blending Ratio (%) | 1 | 0.105090 | 0.105090 | 5.65 | 0.049 |
| Engine Speed (rpm)*Engine Speed (rpm) | 1 | 0.003384 | 0.003384 | 0.18 | 0.683 |
| 2-Way Interaction | 1 | 0.196131 | 0.196131 | 10.54 | 0.014 |
| Blending Ratio (%)*Engine Speed (rpm) | 1 | 0.196131 | 0.196131 | 10.54 | 0.014 |
| Error | 7 | 0.130315 | 0.018616 | | |
| Lack-of-Fit | 2 | 0.103974 | 0.051987 | 9.87 | 0.018 |
| Pure Error | 5 | 0.026341 | 0.005268 | | |
| Total | 12 | 0.776895 | | | |

**Regression Equation in Uncoded Units**

Equation 10 represents the regression equation in uncoded units. The regression model developed for carbon dioxide ($CO_2$) emissions revealed that both blending ratio and engine speed significantly influence emission levels. The negative coefficient of the linear blending ratio term (-0.0820) indicates that increasing the proportion of Jatropha bioethanol in the blend reduces $CO_2$ emissions. However, the positive quadratic term (+0.000849) shows a nonlinear trend, suggesting that very high blending levels may cause a reversal, slightly increasing emissions beyond a certain point. Similarly, the linear effect of engine speed (-0.000994) demonstrates that higher speeds generally reduce $CO_2$ emissions, while the quadratic speed term is negligible, confirming a largely linear relationship.

$$CO_2(\%) = 2.991 - 0.0820\ \text{Blending Ratio (\%)} - 0.000994\ \text{Engine Speed (rpm)} + 0.000849\ \text{Blending Ratio (\%)}*\text{Blending Ratio (\%)} + 0.000000\ \text{Engine Speed (rpm)}*\text{Engine Speed (rpm)} + 0.000026\ \text{Blending Ratio (\%)}*\text{Engine Speed (rpm)} \quad \ldots (10)$$

In addition, the interaction between blending ratio and engine speed, represented by the positive coefficient (+0.000026), highlights that their combined effect plays a critical role in determining $CO_2$ emissions. This means that the impact of blending cannot be fully understood without considering engine speed, and vice versa, thereby reinforcing the need for simultaneous optimization of these variables.

Table 4 presents fits and diagnostics for unusual observations. Diagnostic analysis further revealed an unusual observation at data point 7, where the measured $CO_2$ (0.8700) was lower than the predicted value (1.0993). The residual of -0.2293 and a standardized residual of -2.35 suggest that this observation is an outlier. This deviation could be attributed to experimental uncertainties, variability in combustion dynamics, or operating fluctuations at that specific condition.

Table 4: Fits and Diagnostics for Unusual Observations

| **Obs** | **$CO_2$ (%)** | **Fit** | **Resid** | **Std Resid** | |
|---|---|---|---|---|---|
| 7 | 0.8700 | 1.0993 | -0.2293 | -2.35 | R |

*R Large residual*

Despite this, the overall regression model provides a reliable predictive framework for analyzing $CO_2$ emissions in spark-ignition engines fueled with gasoline–Jatropha bioethanol blends.

Figure 1 illustrates the variation in CO (%) emissions as a function of blending ratio and engine speed. CO emissions are heavily influenced by combustion completeness. Emissions are highest (≈0.04% by volume) at low ethanol ratios (0−10% ) and lower engine speeds (≈2000 rpm) due to incomplete combustion in gasoline-rich mixtures. As the ethanol blending ratio increases toward 20−30% and engine speed increases toward 3500 rpm, CO emissions fall significantly to their lowest (≈0.01% ). This reduction is a synergistic effect: the ethanol's oxygen content promotes complete oxidation, while higher engine speed enhances the turbulence and mixing necessary for efficient burning.

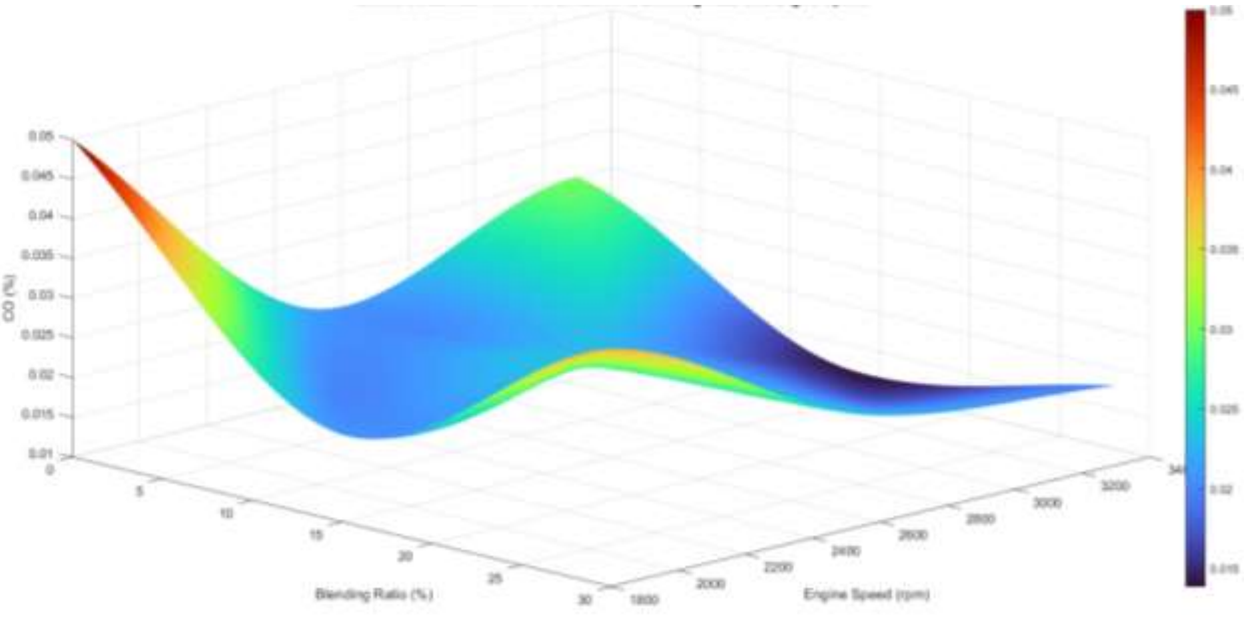


*Figure 1: illustrates the variation in CO (%) emissions as a function of blending ratio and engine speed.*

Figure 2 shows the variation in volumetric efficiency as a function of ethanol blending ratio and engine speed. Volumetric efficiency, the engine's breathing ability, is dominated by speed-related flow dynamics. Efficiency is at its maximum (≈44%) at lower engine speeds (2000−2500 rpm) and lower ethanol blend ratios (0−10%), where the time available for cylinder filling is optimal. Efficiency progressively decreases toward 40−41% as the engine speed increases to 3500 rpm, due to increasing intake flow restrictions. The ethanol blending ratio has a minor effect, causing only a slight fluctuation in efficiency, as its primary influence is through the intake charge cooling effect.

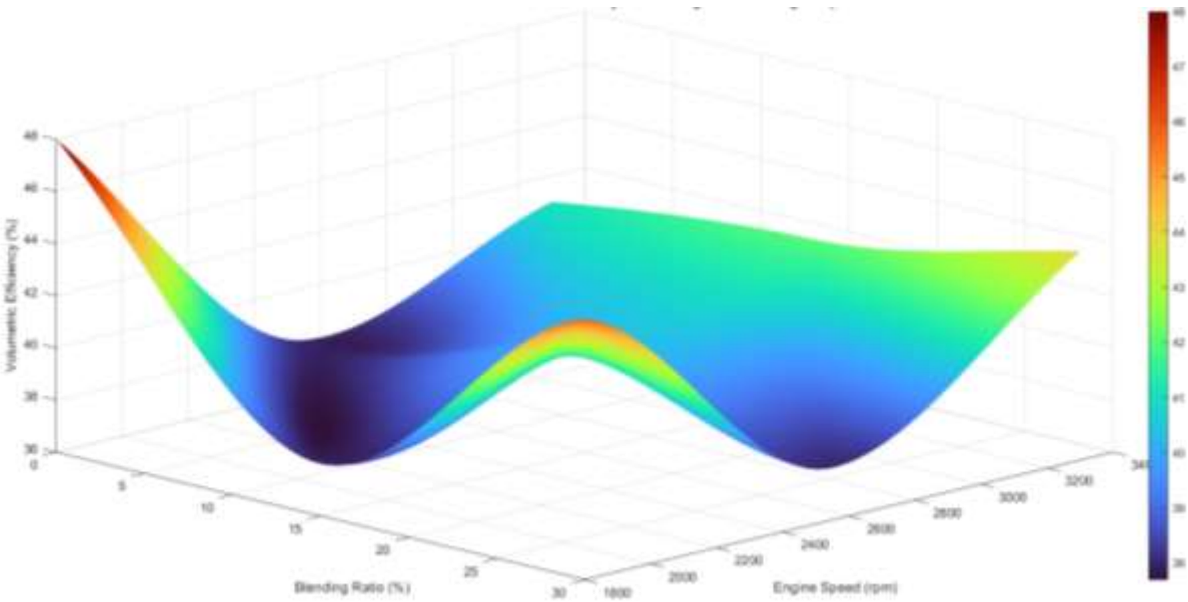


*Figure 2: variation in volumetric efficiency as a function of ethanol blending ratio and engine speed.*

Figure 3 shows the variation in Brake Thermal Efficiency as a function of ethanol blending ratio and engine speed. Brake Thermal Efficiency, the fuel energy conversion rate, peaks in the intermediate range of both factors. The maximum BTE (≈35% ) is observed at intermediate engine speeds (2500−3000 rpm) combined with mid-range ethanol blending ratios (10−20% ). This optimal zone provides the best balance between reduced heat loss (due to moderate speed) and improved combustion efficiency (due to the oxygen from the Jatropha bioethanol). Efficiency is lower at both the extreme low speed and extreme low blending ratios.

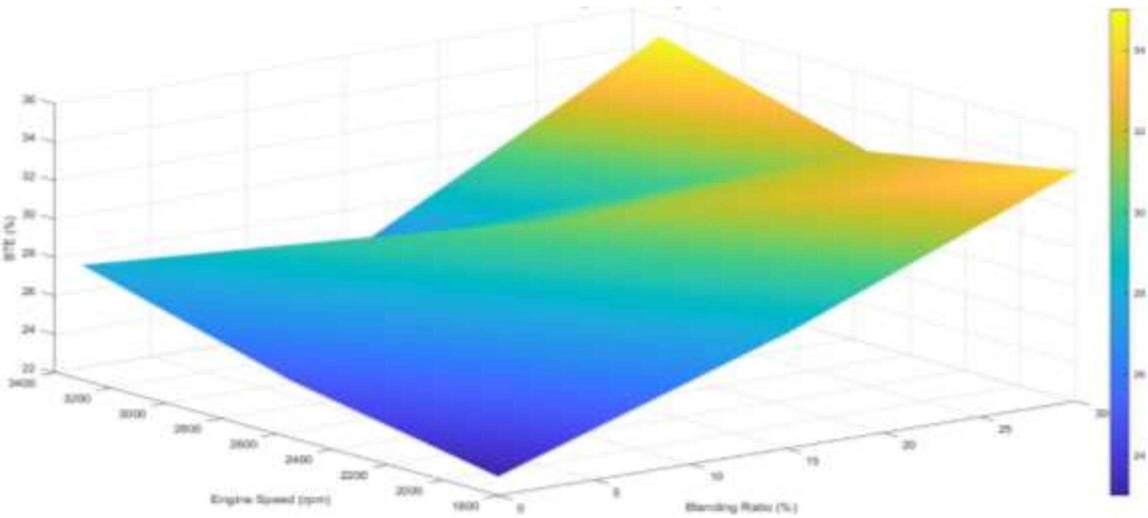


*Figure 3: variation in Brake Thermal Efficiency as a function of ethanol blending ratio and engine speed*

Figure 4 presents the variation in Brake Specific Fuel Consumption (BSFC), as a function of ethanol blending ratio and engine speed. Brake Specific Fuel Consumption (BSFC), an inverse measure of fuel economy, mirrors the BTE pattern. The minimum BSFC (≈250 g/kWh), indicating peak fuel economy, occurs at mid-range engine speeds (2500−3000 rpm) and mid-range ethanol blending ratios (15−25% ). This condition corresponds to the point of maximum efficiency. Conversely, BSFC is highest (≈350 g/kWh) at lower engine speeds (≈2000 rpm), where thermal efficiency is lowest. The lower BSFC in the optimal blend range helps to offset the reduced energy content of the Jatropha bioethanol.

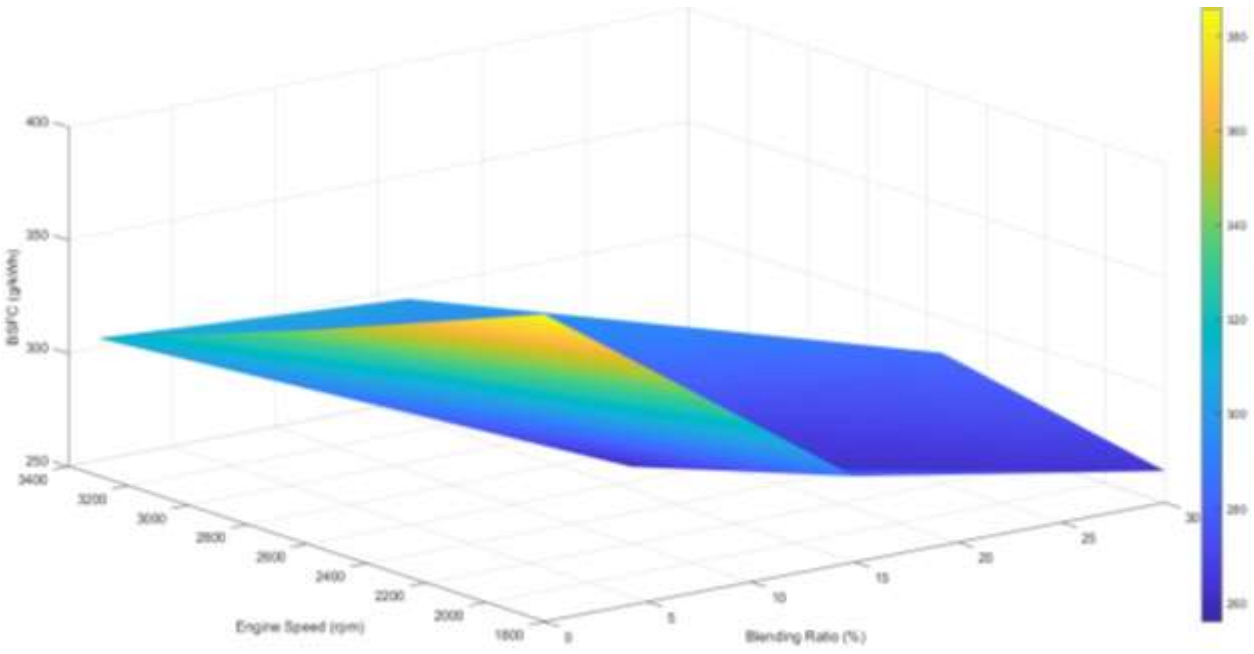


*Figure 4: variation in Brake Specific Fuel Consumption (BSFC), as a function of ethanol blending ratio and engine speed*

Figure 5 presents the variation in Brake Power as a function of ethanol blending ratio and engine speed. Brake Power shows a strong, almost linear dependence on engine speed. Power output is at its maximum (≈1.6 kW) at the highest engine speed tested (3500 rpm), particularly at lower ethanol blending ratios (0−10% ). Power is at its minimum (≈0.8−1.0 kW) at the lowest speed (2000 rpm). The ethanol blending ratio has a relatively minimal effect, resulting in only a slight reduction in power as the ratio increases, primarily due to the lower energy density of the bioethanol.

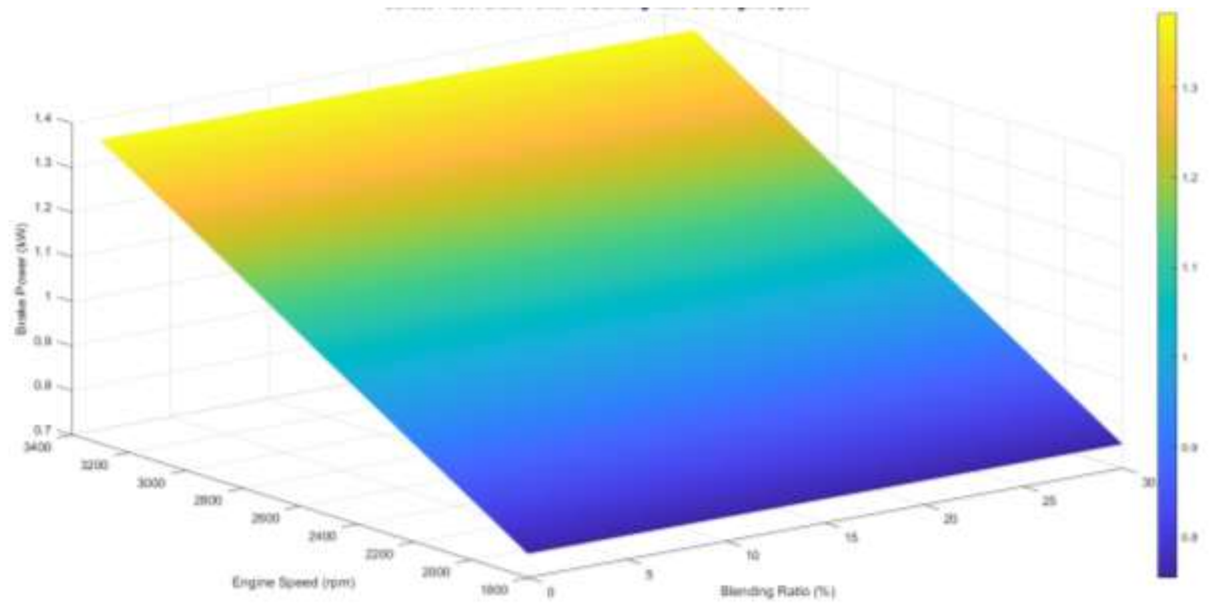


*Figure 5: variation in Brake Power as a function of ethanol blending ratio and engine speed*

Figure 6 illustrates the variation in NOx (%) emissions as a function of blending ratio and engine speed. NOx emissions, pollutants formed at high temperatures, display a reverse trend to CO and HC. Emissions are at their lowest (≈0.06% by volume) at lower engine speeds and lower ethanol blending ratios (0−10% ). As the engine speed increases to 3500 rpm and the ethanol blend ratio rises toward 20−30%, NOx emissions increase to their maximum (≈0.08% ). This increase is directly attributed to the higher in-cylinder temperatures and greater oxygen availability induced by both the faster combustion at higher speeds and the oxygen content of the Jatropha bioethanol.

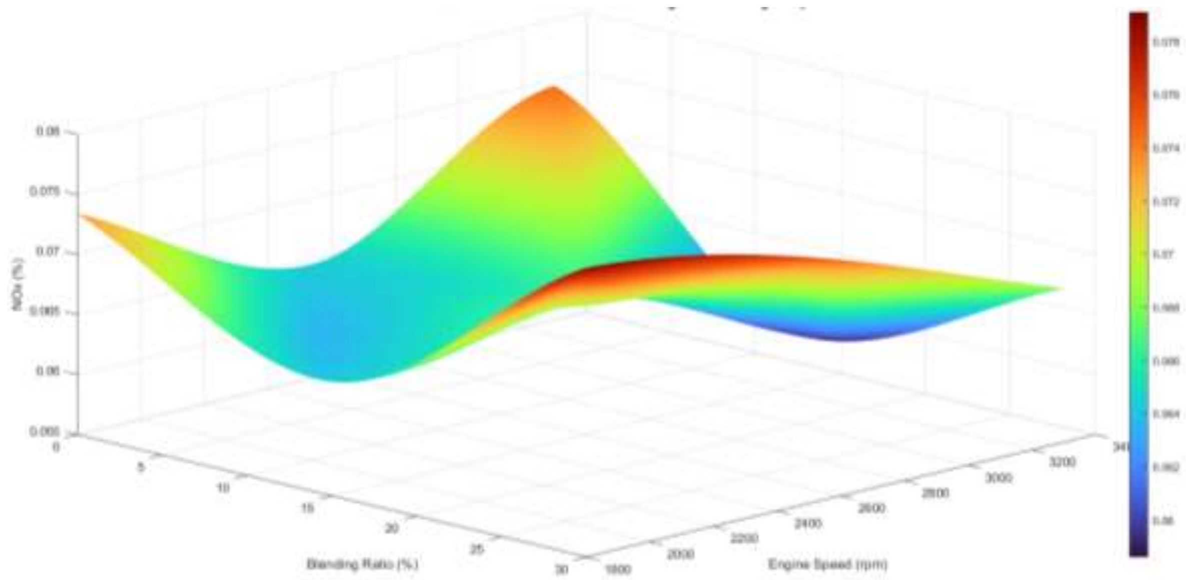


*Figure 6: variation in NOx (%) emissions as a function of blending ratio and engine speed.*

Figure 7 presents the variation in HC (%) emissions as a function of blending ratio and engine speed. Hydrocarbon (HC) emissions track closely with CO, indicating incomplete combustion. HC emissions are relatively high (about 0.0036% by volume) at lower ethanol ratios (0−10% ) and engine speeds (≈2000 rpm). As the ethanol blending ratio increases toward 20−30% and the engine speed increases to 3500 rpm, HC emissions decrease substantially to their lowest (≈0.0018% ). This beneficial effect is due to the improved fuel oxidation from the bioethanol's oxygen and the increased combustion completeness provided by enhanced turbulence at higher engine speeds.

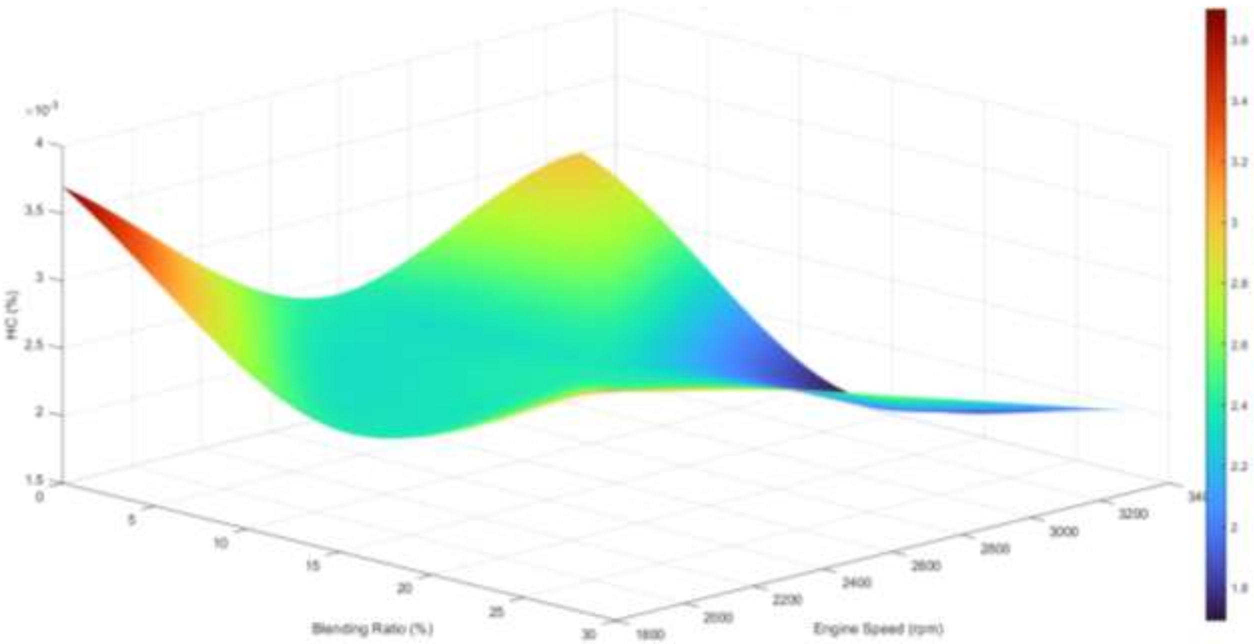


*Figure7: variation in HC (%) emissions as a function of blending ratio and engine speed.*

Figure 8 presents the variation in $CO_2$ (%) emissions as a function of blending ratio and engine speed. $CO_2$ emissions, the main product of complete combustion, reflect the engine's efficiency in fully oxidizing carbon. Emissions are lowest (0.5−0.75% by volume) at low blending ratios (0−10%) and moderate engine speeds (2000−2500 rpm). CO2 levels increase to their peak (≈1.25%) at the combination of higher ethanol blending ratios (≈30%) and higher engine speeds (≈3500 rpm). This trend confirms that both the oxygen in the Jatropha bioethanol and the greater turbulence at high speed promote the most complete combustion, maximizing the conversion of fuel carbon to $CO_2$.

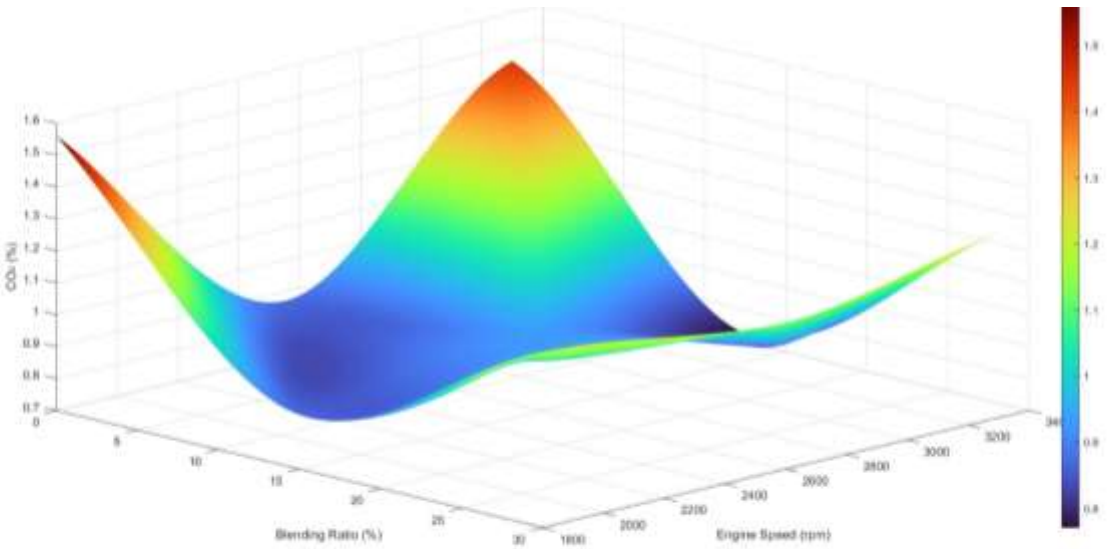


*Figure 8: variation in $CO_2$ (%) emissions as a function of blending ratio and engine speed*

**4.4.3. Response Optimization of Jatropha Bioethanol–Gasoline Blends for Performance and Emission Characteristics**

Figure 1 presents the Response Optimization Plot, which highlights the most desirable operating conditions for the Jatropha bioethanol–gasoline blends as determined through experimental modeling in Minitab. The optimal blending ratio was approximately 16.1% bioethanol at an engine speed of 3300 rpm, achieving a composite desirability value of 0.778, which signifies a good balance between performance and emission outcomes. At this point, the model predicted a substantial reduction in exhaust emissions, with $CO_2$ minimized to 0.771%, CO reduced to 0.0129%, NOx lowered to 0.0587%, and HC emissions minimized to 0.0017%. These results indicate a more complete combustion process and suggest that bioethanol addition enhances the environmental sustainability of the fuel blend.

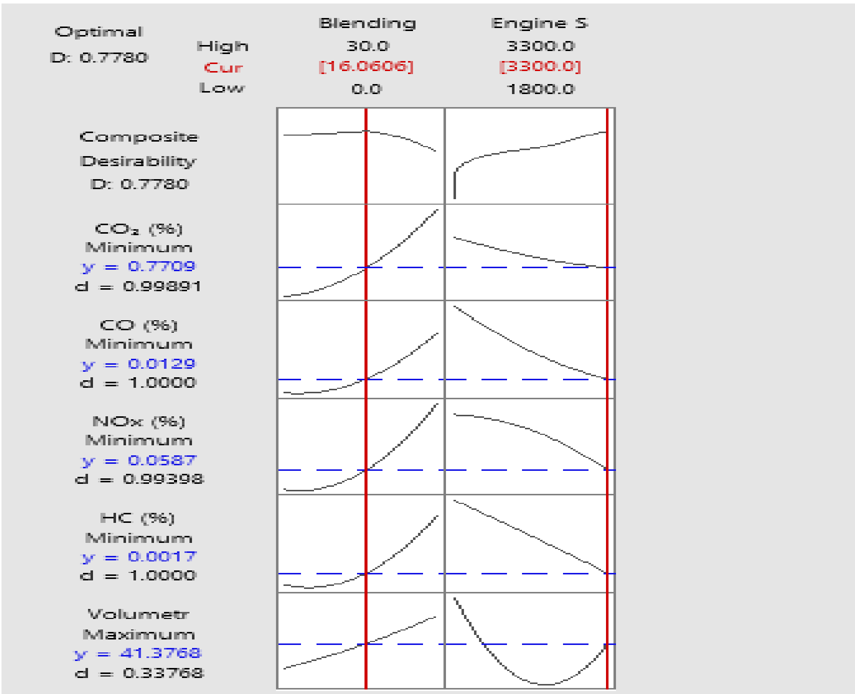


*Figure 9: Response Optimization Plot*

Beyond emission reduction, the optimized conditions also improved overall engine performance. The volumetric efficiency increased to 41.38%, while brake thermal efficiency (BTE) reached 28.75%, demonstrating better conversion of fuel energy into useful work. Fuel utilization efficiency was also enhanced, with a predicted brake-specific fuel consumption (BSFC) of 277.38 g/kWh, indicating reduced fuel demand for the same power output. Additionally, the brake power was maximized at 1.382 kW, confirming the positive impact of bioethanol blending on power generation compared to gasoline alone.

#### *4.4..4 Experimental Validation of Optimal Performance and Emission Characteristics at 16% Jatropha Bioethanol Blend and 3300 rpm Engine Speed*

Figure 10 represents the optimal engine performance and emission characteristics of gasoline-Jatropha Bioethanol Blend. The experimental validation at the optimal design point of 16% bioethanol blending ratio and an engine speed of 3300 rpm, confirmed the effectiveness of Jatropha bioethanol as a sustainable fuel additive in spark-ignition engines. The test yielded a brake power of 1.31 kW, which is consistent with the optimization prediction (1.38 kW), demonstrating only a slight variation that validates the model's reliability in estimating engine output. Similarly, the brake-specific fuel consumption (256 g/kWh) and brake

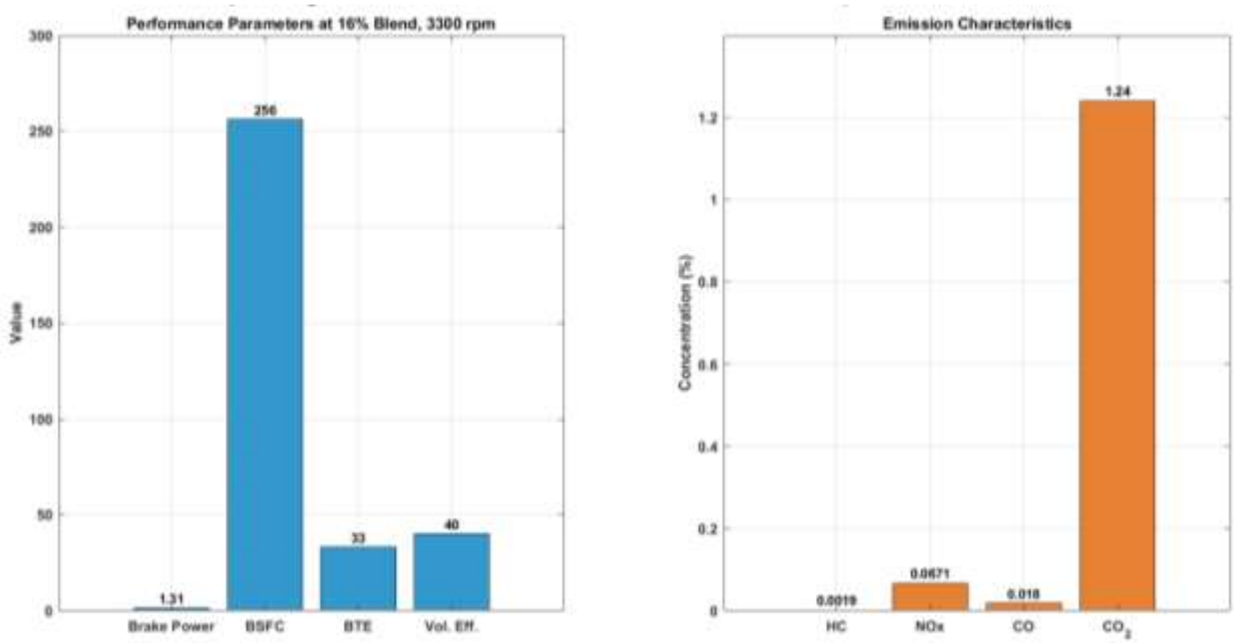


*Figure 10: Optimal Engine performance and Emission Characteristics of Gasoline-Jatropha Bioethanol Blend*

thermal efficiency (33%) recorded during validation closely align with the predicted values, indicating that the fuel blend supports more efficient energy conversion compared to gasoline alone. The volumetric efficiency of 40% also confirms enhanced combustion air–fuel mixing, in agreement with the optimization results.

From the emissions perspective, the validation showed notable reductions in pollutants. Hydrocarbon emissions were minimized to 0.0019%, and carbon monoxide (0.018%) was significantly lower than in pure gasoline runs, confirming the role of ethanol's inherent oxygen in promoting more complete combustion. Likewise, nitrogen oxides were limited to 0.0671%, while carbon dioxide was recorded at 1.24%, reflecting efficient combustion without excessive carbon release. These experimental outcomes are in strong agreement with the model predictions, even though minor deviations exist, which are expected due to uncontrolled environmental and operational factors.

The validation confirms that the optimization model is robust and reliable in predicting both engine performance and emissions. The results highlight that a 16% bioethanol–gasoline blend at 3300 rpm provides a practical balance between performance enhancement and emission reduction, demonstrating the viability of Jatropha bioethanol as sustainable fuel alternative.

## 4.0 CONCLUSION

This study demonstrates the successful optimization of a spark ignition engine using gasoline-Jatropha bioethanol blends, achieving significant improvements in both efficiency and environmental performance. The optimal condition was established at a 16% Jatropha bioethanol blend and 3300 RPM engine speed. This blend yielded notable enhancements, including a 43.5% increase in Brake Thermal Efficiency (BTE), a 33.7% reduction in Brake Specific Fuel Consumption (BSFC), and a 22.7% gain in power output. The oxygenated fuel nature led to cleaner combustion, resulting in substantial reductions in Carbon Monoxide (40%) and Hydrocarbons (29.6%). Although $CO_2$ emissions slightly increased which is less harmful, indicating more complete combustion, the findings confirm Jatropha-based bioethanol as a viable, performance-improving, and emission-reducing renewable fuel additive for small-scale spark ignition engines, offering a promising pathway toward sustainable transport solutions.

**REFERENCES**

Ashok Aggarwal, A., Gugulothu, S. K., Reddy, R. V., Gurel, A. E., & Deepanraj, B. (2022). Prediction-optimization of the influence of 1-pentanol/jatropha oil blends on RCCI engine characteristics using multi-objective response surface methodology. *Renewable Energy Focus*, *42*, 244-261. https://doi.org/10.1016/j.ref.2022.05.006

Deshpande, R. S., Tadamalle, A. P., Katikar, R. S., Biradar, A. K., Kadam, P., & Thipse, S. S. (2024). Engine performance and emission evaluation of gasoline-ethanol fuel blend in SI engines under various conditions of load and speed. *Journal of Mines, Metals and Fuels*, *72*(3), 112-125. https://doi.org/10.18311/jmmf/2024/45291

Deshpande, R., Kardekar, N., Ingle, P., Kadam, P., Biradar, A., & Thipse, S. (2024). A review on performance and emissions measurements of ethanol blends for gasoline engines. *Journal of Mines, Metals and Fuels*, *72*(4), 145-158. https://doi.org/10.18311/jmmf/2024/45419

Ibarra Vega, D., & Redondo, J. M. (2024). System dynamics and viability theory for sustainability assessment, application for bioethanol production in Colombia. *Revista de Investigación Agraria y Ambiental*, *15*(2), 87-104. https://doi.org/10.22490/21456453.6961

Karmakar, R., Singh, P., Kumar, A., Sharma, V., Patel, M., & Gupta, S. (2024). Circularity of biomass feedstock to produce ethanol and feasibility of ethanol-gasoline fuel blends in engine. *The Journal of Solid Waste Technology and Management*, *50*(4), 630-645. https://doi.org/10.5276/jswtm/iswmaw/503/2024.630

Mishra, P., Kumar, S., Sharma, R., Patel, N., Singh, M., & Gupta, A. (2024). Experimental assessment and optimization of the performance of a biodiesel engine using response surface methodology. *Energy, Sustainability and Society*, *14*, Article 23. https://doi.org/10.1186/s13705-024-00447-2

Rajendran, S., Duraisamy, B., Murugesan, E., Prakash, C., & Chandramauli, A. (2024). Environmental exhaust emissions reduction and performance improvement analysis of biodiesel operated diesel engine performance using operating parameters. *Global Nest Journal*, *26*(6), 1245-1258. https://doi.org/10.30955/gnj.06279

Saikia, P. J., & Dutta, P. P. (2024). Numerical analysis of the effect of ethanol-gasoline blends on a single-cylinder spark-ignition engine performance and emissions. *International Journal of Emerging Technology and Advanced Engineering*, *14*(23), 1-8. https://doi.org/10.46338/ijetae142324_01

Samuel, O. D., Patel, G. C. M., Thomas, L., Chandran, D., Paramasivam, P., & Enweremadu, C. C. (2024). RSM integrated GWO, driving training, and election-based algorithms for optimising ethylic biodiesel from ternary oil of neem, animal fat, and jatropha. *Scientific Reports*, *14*, Article 21170. https://doi.org/10.1038/s41598-024-72109-4

Sonawane, S., Sekhar, R., Warke, A., Patel, M., Kumar, V., & Singh, P. (2025). Experimental investigation and prediction of combustion parameters using machine learning in ethanol-gasoline blended engines. *Journal of Engineering and Technological Sciences*, *57*(1), 25-42. https://doi.org/10.5614/j.eng.technol.sci.2025.57.1.3

Syarifudin, S., Yohana, E., Muchammad, M., & Suhartana, S. (2025). Performance and emission characteristics of an engine fueled with mangrove bioethanol–gasoline blends. *Automotive Experiences*, *8*(1), 12-25. https://doi.org/10.31603/ae.13121

Tiwari, A., Soni, P. K., & Nayak, S. S. (2025). GA optimization for performance and emission characteristics of SI engine via ethanol-gasoline blend. In *Advances in Computational Intelligence and Robotics* (pp. 245-268). IGI Global. https://doi.org/10.4018/979-8-3693-7352-1.ch013