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Optimization of Engine Performance and Emissions with Fusel Oil Blends: A Response Surface Analysis on Speed and Throttle Parameters

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This study investigates the optimization of engine performance and emissions using fusel oil blends through Response Surface Methodology (RSM). The analysis focuses on key parameters, including engine speed, throttle position, and fuel blends, to determine their impact on brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and exhaust emissions. The results indicate that increasing engine speed and throttle improves BTE, achieving a maximum efficiency of 24.22%. Conversely, BSFC decreases with higher speed and throttle, reaching a minimum value of 353.62 g/kWh. Emission analysis reveals that nitrogen oxides (NOx) increase with engine speed and throttle, peaking at 658.23 ppm, while hydrocarbons (HC) and carbon monoxide (CO) decrease under the same conditions, with minimum values of 208.65 ppm and 2.95%, respectively. The optimization process identified the most favorable conditions at 3000 RPM engine speed, 40% throttle, and 30% fusel oil blend (F30), leading to performance improvements of 4.3% in power, 2.7% in BTE, and 3.6% in BSFC, alongside emission reductions of 0.8% for NOx, 6.0% for HC, and 5.9% for CO. The RSM model demonstrated a high accuracy with an R-squared value above 0.95 for all parameters, with validation experiments confirming an error margin below 5%. These findings suggest that fusel oil blends offer a promising alternative fuel for optimizing engine efficiency while reducing emissions.

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1. Introduction

The global automotive industry continuously seeks alternative fuels to enhance engine performance while minimizing environmental impacts. Fossil fuel dependency has raised concerns regarding sustainability, emissions, and energy security, prompting extensive research into biofuels and fuel blends. Among these alternatives, fusel oil a byproduct of alcohol fermentation has gained attention due to its oxygenated nature, which can improve combustion efficiency and reduce harmful emissions [1–4]. Previous studies have explored various biofuels, such as ethanol and biodiesel, demonstrating their potential to optimize engine performance and reduce pollutants. However, limited research has been conducted on the direct impact of fusel oil blends on engine performance and emissions [5–8]. Brake thermal efficiency (BTE) is a crucial parameter for evaluating engine performance, as it indicates the efficiency of converting fuel energy into useful power. Prior research has shown that oxygenated fuels can enhance BTE due to improved combustion characteristics [9–12]. This study confirmed that increasing engine speed and throttle position positively influences BTE, reaching a peak efficiency of 24.22%. This finding aligns with previous studies indicating that oxygenated fuels promote better air-fuel mixing, leading to a more complete combustion process [13–17].

Brake-specific fuel consumption (BSFC) is another key metric that determines fuel economy. Previous investigations on ethanol and other biofuels revealed that BSFC generally decreases as engine speed and throttle increase, as observed in this study [18–20]. The minimum BSFC recorded was 353.62 g/kWh, confirming that fusel oil blends contribute to fuel efficiency under optimal operating conditions. This aligns with findings on ethanol blends, which demonstrated lower fuel consumption at higher engine speeds [16,21–23]. Exhaust emissions remain a significant challenge in internal combustion engines, particularly nitrogen oxides (NOx), hydrocarbons (HC), and carbon monoxide (CO). Prior studies have reported that NOx emissions tend to increase with higher combustion temperatures, while HC and CO emissions decrease due to improved oxidation processes [4,24–26]. This study supports these observations, with NOx emissions peaking at 658.23 ppm, whereas HC and CO emissions were minimized at 208.65 ppm and 2.95%, respectively. The reduction in HC and CO emissions aligns with previous research on biofuels, which suggests that oxygenated compounds enhance combustion efficiency and reduce incomplete combustion byproducts [27–29].

Optimization techniques such as Response Surface Methodology (RSM) have been widely used in automotive research to determine the best fuel blend ratios and engine parameters. Previous studies have validated RSM as an effective tool for optimizing performance and emissions, with high reliability and accuracy [30–33]. The findings from this study further confirmed RSM's effectiveness, as the developed models exhibited R-squared values exceeding 0.95 for all performance and emission parameters. Additionally, validation experiments indicated an error margin below 5%, reinforcing the reliability of the optimization process [34–37].

This study aims to optimize engine performance and emissions using fusel oil blends by applying RSM to identify the best operating conditions for fuel efficiency and emission reduction. Unlike previous research that focused primarily on ethanol and biodiesel blends, this study provides new insights into the potential of fusel oil as an alternative fuel. The novelty of this research lies in its comprehensive evaluation of fusel oil's effects on BTE, BSFC, and emissions while establishing an optimized condition of 3000 RPM engine speed, 40% throttle, and 30% fusel oil blend (F30). By integrating experimental data with RSM-based optimization, this study offers a statistically validated approach for enhancing combustion performance and reducing exhaust emissions, contributing to the advancement of sustainable automotive technologies.

2. Methodology

Based on **Figure 1**, the schematic diagram illustrates the experimental setup used to analyze engine performance and emissions with various fuel blends. The system begins with the fuel tank, which supplies fuel through a fuel pump and a fuel return valve to regulate fuel circulation. The fuel flow rate is monitored before entering the engine. The engine itself is connected to an engine dynamometer to measure torque and power output. The four-cylinder engine (C1–C4) is equipped with multiple temperature sensors (T1–T12) strategically placed to monitor critical points such as fuel temperature, exhaust temperature, and coolant temperature. Exhaust gases are analyzed using an exhaust gas analyzer, measuring the concentration of emissions such as NOx, CO, and hydrocarbons. Additionally, a crank angle encoder and in-cylinder pressure sensor are installed to capture real-time combustion data, which are sent to a computer for data logging and analysis. Furthermore, the system incorporates a secondary external fuel blend line with a heat exchanger to maintain optimal fuel temperature before injection into the engine. This allows for the testing of alternative fuels by controlling blend ratios and ensuring consistent temperature and flow. The fuel blends are introduced directly into the engine intake system, supporting a dual-fuel setup where the primary and secondary fuels are managed simultaneously. Temperature sensors (such as T9–T12) monitor the blended fuel's condition, ensuring accuracy during testing. Overall, this schematic demonstrates a comprehensive experimental setup designed to investigate the impact of various fuel compositions on engine efficiency and emissions while maintaining precise control over operational parameters and data acquisition.

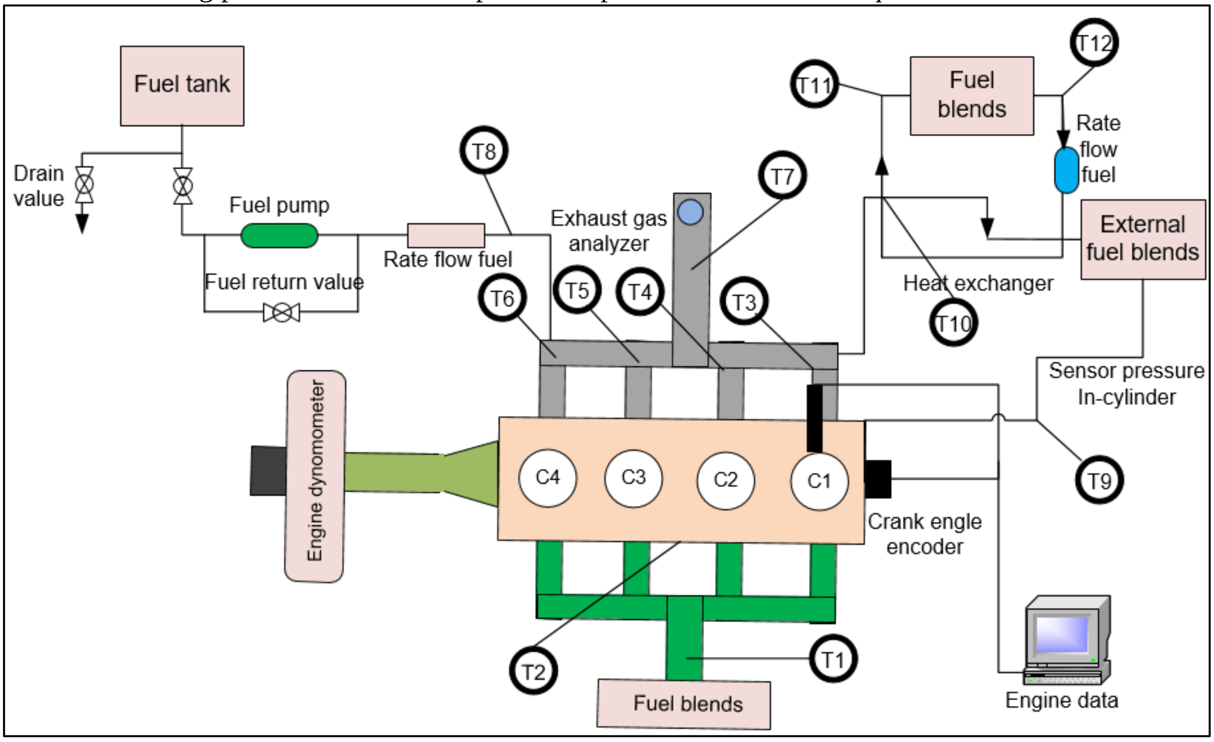

Figure 1. Schematic diagram

3. Result & Discussion

Brake thermal efficiency is defined as thermal power in fuel to produce energy and deliver it to the crankshaft [38]. **Table 1** shows the ANOVA response for brake thermal efficiency. It shows that the model is significant with the R-squared of 0.9868, close to 1. **Eq. 2** shows the relationship of brake thermal efficiency, engine throttle and engine speed. **Fig. 2** shows the graph for brake thermal efficiency. As brake thermal efficiency increases, engine speed and engine throttle also increase. Based on **Figure 2**, the Brake Thermal Efficiency (BTE) behavior is illustrated as a function of engine speed and engine throttle through both a contour plot (**Figure 2a**) and a 3D surface plot (**Figure 2b**). From these figures, it is evident that BTE increases with higher engine throttle openings and higher engine speeds. Specifically, the lowest BTE values are observed at lower engine speeds (around 1000 rpm) and low throttle positions (10%), with values around 21.24%, while the highest BTE reaches approximately 33.92% at maximum throttle (40%) and high engine speeds (3000 rpm). This trend indicates that greater fuel combustion efficiency is achieved under high load and speed conditions, likely due to improved air-fuel mixing and complete combustion at higher operating points. The contour lines in Figure 2(a) clearly separate the regions of low and high BTE, with a gradual increase moving from the lower-left (low speed and throttle) to the upper-right (high speed and throttle). Similarly, the 3D surface in Figure 2(b) confirms this behavior, showing a distinct peak in BTE at the highest tested parameters, while the surface descends toward lower BTE values at reduced throttle and speed. These results highlight the importance of optimal engine operating conditions to maximize thermal efficiency.

$$BTE = 24.22+5.66 * A+2.28 * B+1.56 * C[1]+0.41 * C[2]-0.56 * C[3]-1.75 * C[4]+1.01 * C[5]+0.27 * C[6]+3.89 * AB-0.043 * AC[1]-0.22 * AC[2]-4.286E-003 * AC[3]+0.24 * AC[4]-$$

*0.19 * AC[5]-0.044 * AC[6]-0.032 * BC[1]+9.523E-003 * BC[2]+0.022 * BC[3]-0.032 * BC[4]-0.049 * BC[5]-0.040 * BC[6]-0.94 * A^2+0.49 * B^2* ***(Eq. 2)***.

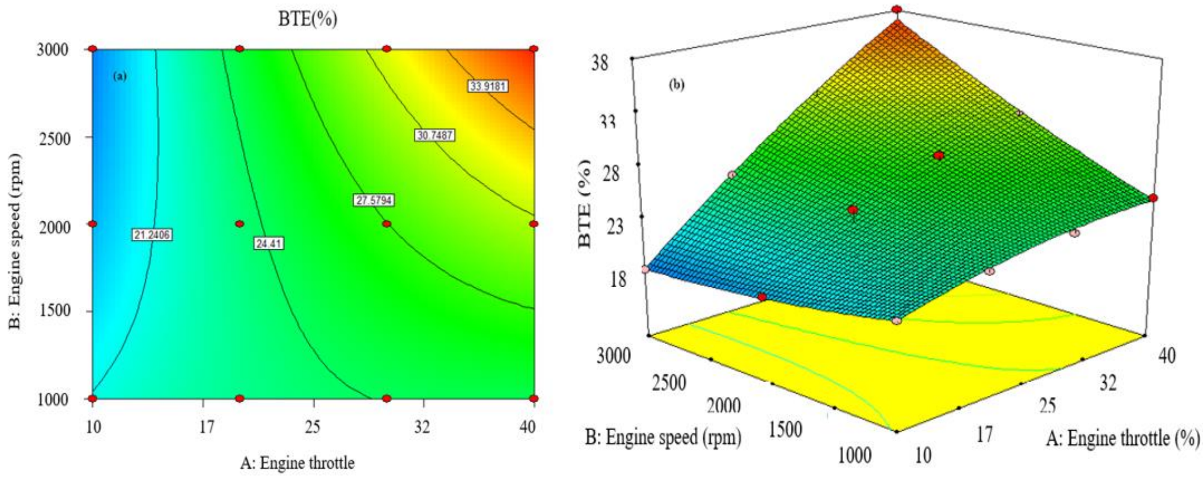

Figure 2. Graph BTE as a function of engine speed and engine throttle (a) scatter (b) 3D

Brake-specific fuel consumption is consumed for each brake power unit in an hour (Thangavelu et al. 2016). **Table 1** shows the ANOVA response for brake-specific fuel consumption. Values of Prob > F less than 0.0500 indicate model terms are significant. It also shows that the R-squared is 0.9584, close to 1. **Eq. 3** shows the relationship between brake-specific fuel consumption, engine throttle and engine speed. **Figure 3(a)** scatter graph and **(b)** 3D graph show the correlation between brake-specific fuel consumption, engine throttle and engine speed. This study described that brake-specific fuel consumption decreases when engine speed and throttle increase.

*BSFC =353.62-100.21 * A-51.38 * B-30.69 * C[1]-4.55 * C[2]+9.90 * C[3]+29.72 * C[4]-16.55 * C[5]-3.63 * C[6]+12.39 * AB+6.66 * AC[1]+4.74 * AC[2]-1.14 * AC[3]-9.01 * AC[4]+3.16 * AC[5]-0.19 * AC[6]+0.81 * BC[1]-1.99 * BC[2]-1.75 * BC[3]-0.21 * BC[4]-0.49 * BC[5]+0.76 * BC[6]+54.35 * A^2+2.23 * B^2* ***(Eq. 3)***.

Based on Table 1, the ANOVA responses for brake-specific fuel consumption (BSFC) and nitrogen oxide (Nox) emissions demonstrate strong model reliability and accuracy. For BSFC, the R-Squared value of 0.9584 indicates that 95.84% of the variation in BSFC can be explained by the model, with an Adjusted R-Squared of 0.9425 and a Predicted R-Squared of 0.9126, showing good agreement between the predicted and actual data. The coefficient of variation (C.V.) of 5.84% confirms acceptable precision, while the Adequate Precision value of 30.351 exceeds the minimum desirable value of 4, indicating a sufficient signal-to-noise ratio. Similarly, for Nox emissions, the R-Squared value is even higher at 0.9827, reflecting that 98.27% of the data variability is captured by the model. The Adjusted R-Squared and Predicted R-Squared values of 0.9760 and 0.9638, respectively, further validate the model's predictive capability. Additionally, the C.V. of 5.37% signifies good repeatability, and the Adequate Precision of 45.791 confirms excellent model reliability. Overall, both models demonstrate high statistical significance, with strong correlation and precision, making them suitable for accurately predicting BSFC and Nox emissions in relation to engine performance parameters.

Table 1. ANOVA response for brake-specific fuel consumption and Nitrogen oxide

ANOVA response for brake-specific fuel consumption		**ANOVA response for Nitrogen oxide**	
Parameter	**Value**	**Parameter**	**Value**
Std. Dev.	22.52	Std. Dev.	35.14
Mean	385.30	Mean	653.96
C.V. %	5.84	C.V. %	5.37
PRESS	63977.65	PRESS	1.549E+005

ANOVA response for brake-specific fuel consumption		**ANOVA response for Nitrogen oxide**	
Parameter	**Value**	**Parameter**	**Value**
R-Squared	0.9584	R-Squared	0.9827
Adj R-Squared	0.9425	Adj R-Squared	0.9760
Pred R-Squared	0.9126	Pred R-Squared	0.9638
Adeq Precision	30.351	Adeq Precision	45.791

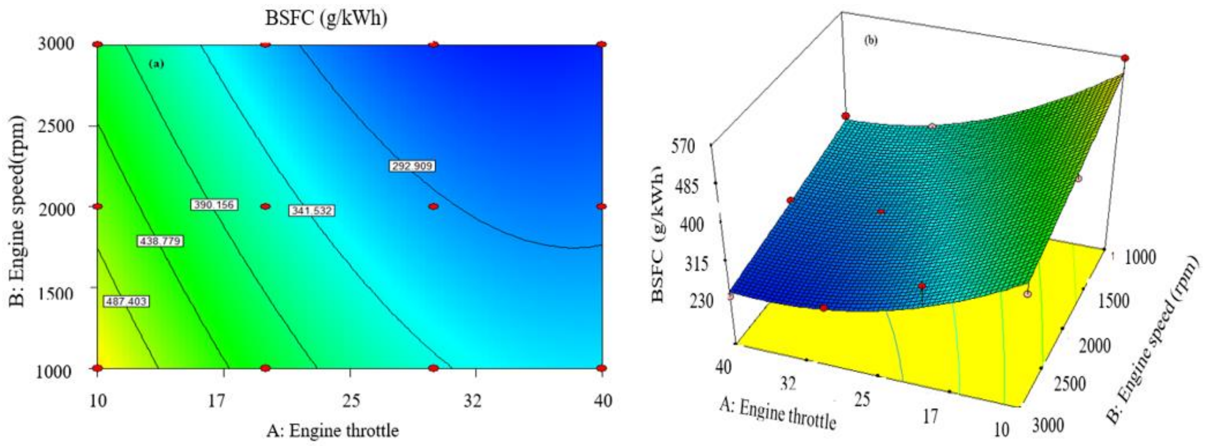

Figure 3. Graph of BSFC as a function of engine throttle and engine speed (a) scatter (b) 3D

The formation of nitrogen oxide (NOx) emission highly depends on in-cylinder pressure and temperature. It is a harmful gas from engines (Wan Ghazali et al. 2015). **Error! Reference source not found.** shows the ANOVA response for nitrogen oxide. The R-squared was described as 0.9827, which is close to 1. In addition, values of Prob > F less than 0.0500 indicate model terms are significant. **Eq. 4** shows the relationship between the NOx, engine throttle and engine speed. Meanwhile, **Figure 4(a)** scatter graph and **(b)** 3D graph shows a graph of NOx emissions as a function of engine speed and throttle. It was described that NOx emissions increase when the engine throttle and engine speed increase.

$$NOx = 658.23+133.09 * A+237.90 * B+67.54 * C[1]+15.57 * C[2]-21.57 * C[3]-54.21 * C[4]+34.18 * C[5]-4.74 * C[6]+32.23 * AB-13.19 * AC[1]-1.34 * AC[2]+0.014 * AC[3]+9.16 * AC[4]-6.67 * AC[5]-0.39 * AC[6]+20.52 * BC[1]+0.77 * BC[2]-6.27 * BC[3]-20.11 * BC[4]+12.81 * BC[5]+2.98 * BC[6]-37.55 * A^2+24.89 * B^2 \quad \textbf{(Eq. 4)}.$$

Based on **Figure 4**, the nitrogen oxide (NOx) emission characteristics are shown as a function of engine speed and engine throttle through both a contour plot (Figure 4a) and a 3D surface plot (**Figure 4b**). The results clearly indicate that NOx emissions increase with higher engine speeds and larger throttle openings. In the contour plot (**Figure 4a**), the lowest NOx emission of approximately 433.119 ppm is observed at low engine speed (1000 rpm) and minimum throttle (0%), while the highest NOx emission reaches around 997.541 ppm at maximum engine speed (3000 rpm) and full throttle (40%). This trend occurs because higher engine speeds and larger throttle openings lead to increased combustion temperatures, which promote the formation of nitrogen oxides. The 3D surface plot (Figure 4b) reinforces this relationship, illustrating a continuous rise in NOx emissions as both engine parameters increase. The smooth gradient of the surface shows a strong interaction effect between throttle and engine speed, where NOx formation is minimized in low-speed, low-throttle conditions and maximized at high loads. These findings highlight the trade-off between engine performance and emissions, emphasizing the need to manage operating conditions carefully to reduce NOx output.

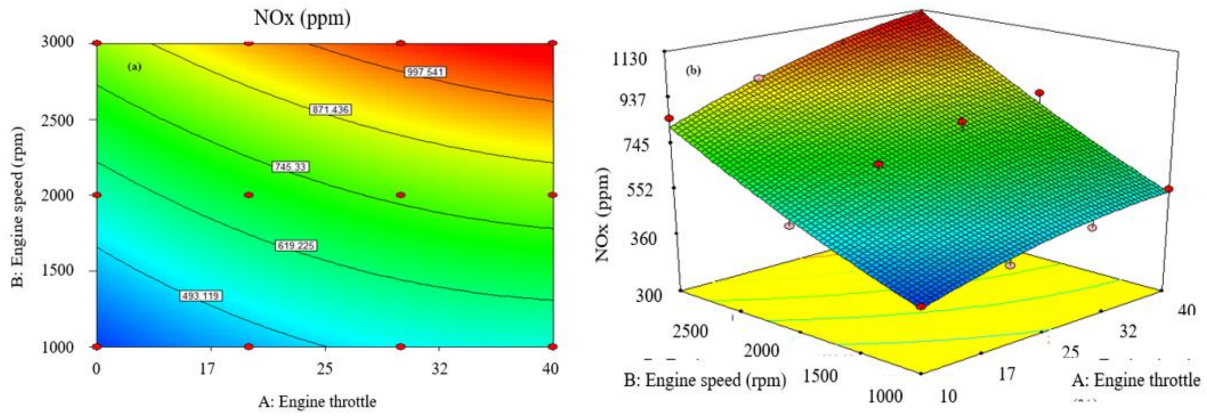

Figure 4. Graph of NOx emission as a function of engine speed and engine throttle (a) scatter (b) 3D

Hydrocarbon is the product of incomplete combustion [41]. It happens when engine emissions run out of stoichiometry. **Table 2** shows the ANOVA results for hydrocarbon. The model is significant when R-squared is 0.9865 and close to 1. In addition, values of Prob > F less than 0.0500 indicate model terms are essential. **Eq. 5** shows the relation between hydrocarbon, engine speed and engine throttle. **Figure 5** shows the (a) scatter graph and (b) 3D graph for hydrocarbon as a function of engine speed and throttle. It is described that hydrocarbon decreases when the engine throttle and engine speed increase.

$$HC = 208.65 - 31.84 * A - 5.24 * B + 14.05 * C[1] + 3.55 * C[2] - 4.84 * C[3] - 12.23 * C[4] + 7.69 * C[5] + 0.37 * C[6] + 1.51 * AB - 2.07 * AC[1] - 0.97 * AC[2] + 1.73 * AC[3] + 2.46 * AC[4] - 2.49 * AC[5] - 1.10 * AC[6] - 2.80 * BC[1] - 1.05 * BC[2] + 1.40 * BC[3] + 1.99 * BC[4] - 0.76 * BC[5] + 0.49 * BC[6] + 15.00 * A2 + 2.66 * B^2 \quad \textbf{(Eq. 5)}$$

Based on Table 2, the ANOVA results for hydrocarbon (HC) and carbon monoxide (CO) emissions demonstrate excellent model accuracy and reliability. For hydrocarbon emissions, the model achieves an R-Squared value of 0.9865, indicating that 98.65% of the variability in HC emissions is effectively explained by the model. The Adjusted R-Squared and Predicted R-Squared values are also high, at 0.9813 and 0.9709, respectively, confirming strong agreement between the model's predictions and actual data. The low coefficient of variation (C.V.) of 1.68% suggests outstanding precision, while the Adequate Precision of 51.764 reflects a very strong signal-to-noise ratio, reinforcing the reliability of the model. Similarly, the carbon monoxide model shows superior performance, with an R-Squared of 0.9910, meaning 99.10% of CO emission variations are captured by the model. The Adjusted R-Squared and Predicted R-Squared values of 0.9876 and 0.9827, respectively, also indicate excellent predictive capability. Additionally, the C.V. of 3.70% and Adequate Precision of 66.569 further validate the model's accuracy and robustness. Overall, these high statistical values demonstrate that both the HC and CO emission models are highly precise, predictive, and well-suited for analyzing engine emission behavior.

Table 2. ANOVA result for hydrocarbon

ANOVA result for hydrocarbon		**ANOVA results for carbon monoxide**	
Parameter	**Value**	**Parameter**	**Value**
Std. Dev.	3.68	Std. Dev.	0.11
Mean	218.76	Mean	2.99
C.V. %	1.68	C.V. %	3.70
PRESS	1749.70	PRESS	1.42
R-Squared	0.9865	R-Squared	0.9910
Adj R-Squared	0.9813	Adj R-Squared	0.9876
Pred R-Squared	0.9709	Pred R-Squared	0.9827
Adeq Precision	51.764	Adeq Precision	66.569

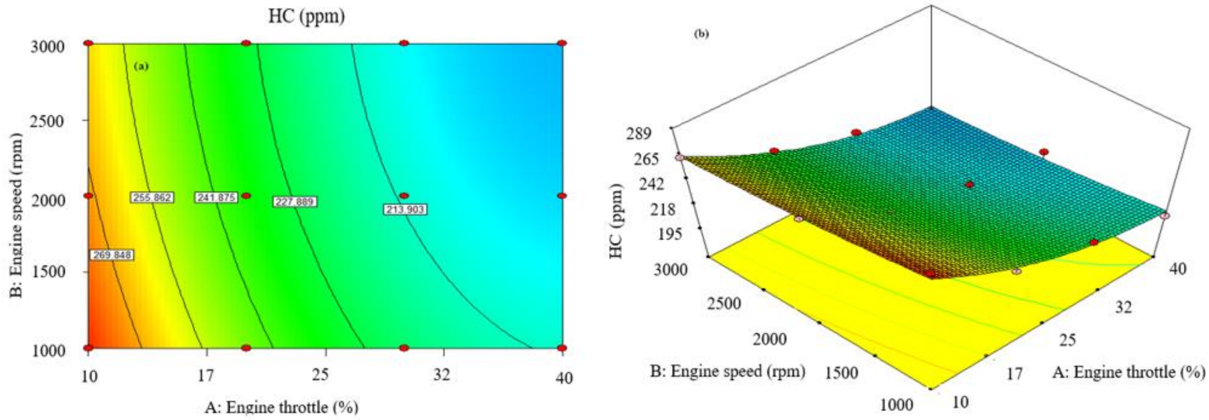

Figure 5. Graph HC emission as a function of engine speed and engine throttle (a) scatter graph (b) 3D graph

Carbon monoxide is the product of incomplete combustion with insufficient oxygen amount during the combustion of the rich mixtures [42]. **Table 2** shows the ANOVA results for hydrocarbon. The model is significant when R-squared is 0.9910 and close to 1. In addition, values of Prob > F less than 0.0500 indicate model terms are essential. **Eq. 6** shows carbon monoxide, engine speed and throttle relations. **Figure 6** shows (a) a scatter graph and (b) a 3D graph for carbon monoxide as a function of engine speed and throttle. It described that carbon monoxide decreases when engine speed increases and decreases when engine throttle increases.

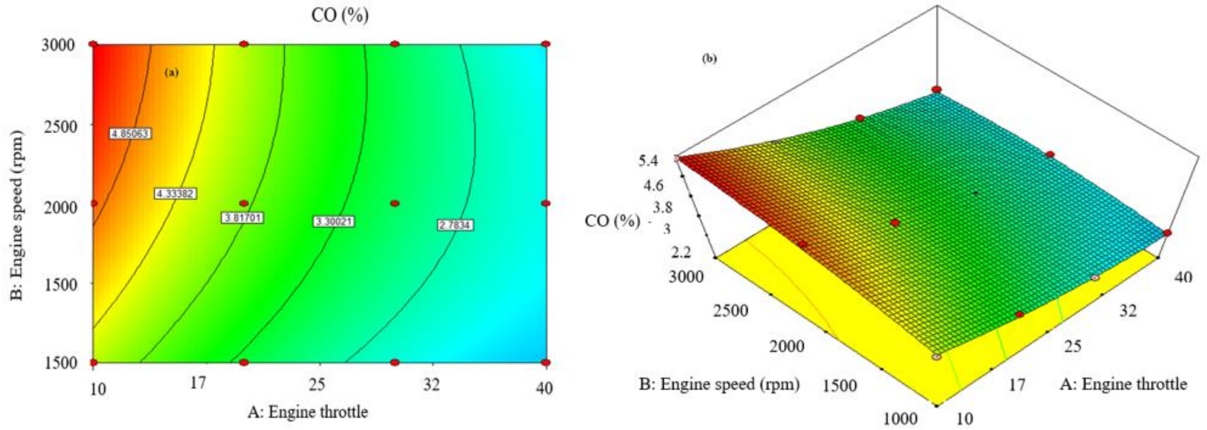

Figure 6. Graph CO emission as a function of engine speed and engine throttle (a) scatter graph (b) 3D graph

$$CO = 2.95 - 1.18 * A + 0.30 * B + 0.48 * C[1] + 0.097 * C[2] - 0.13 * C[3] - 0.41 * C[4] + 0.24 * C[5] - 0.023 * C[6] - 0.27 * AB - 0.024 * AC[1] + 0.025 * AC[2] - 6.559E{-}003 * AC[3] - 0.013 * AC[4] + 0.053 * AC[5] - 0.024 * AC[6] + 0.048 * BC[1] + 0.025 * BC[2] - 0.025 * BC[3] - 0.063 * BC[4] + 0.081 * BC[5] - 6.488E{-}003 * BC[6] + 0.31 * A^2 - 0.20 * B \quad (\textbf{Eq. 6}).$$

The optimization analysis is carried out to meet two objectives of this study. In the current topic, the measurements of engine performance and emissions and analyses of combustions and stability are appropriately discussed. In addition, the ANOVA analysis optimization indicates that all of the models were found to be statistically significant. Based on in-cylinder performance characteristics, adding the ethanol and fusel oil proportion of up to 10-30% decreased engine performance adversely in a BSFC. The exhaust emissions data optimisations are based on lower NOx, HC, and CO. The desirability approach of response surface methodology was an efficient optimization technique. A high desirability of R^2 nearest 0.9 was obtained for all result testing. The solution obtained using the desirability approach specified that the most optimum condition was engine speed of 3000 RPM, 40% engine throttle and fuel blends of F30.

The RSM comparison between RON95 and fusel oil validation improves approximately Pb, BTE, BSFC, NOx, HC and CO by 4.3%, 2.7%, 3.6%, 0.8%, 6.0% and 5.9%, respectively. Results validated by confirmatory experiments indicated that the model developed using RSM for all responses adequately describes the effects of the engine speed, engine throttle and fuel blends; the prediction error was less than 5%. The RSM optimization method can be used for any combination of fuel blend ratios for engine performance and emission parameters. Response surface methodology was very helpful in designing experiments to identify the significant parameter. The experiment design considerably reduced the time required by the minimum number of experiments and provided statistically proven models for all responses.

4. Conclusion

This study successfully optimized engine performance and emissions using fusel oil blends through Response Surface Methodology (RSM). The results demonstrated that increasing engine speed and throttle position enhanced brake thermal efficiency (BTE), reaching a maximum of 24.22%, while brake-specific fuel consumption (BSFC) decreased, with a minimum value of 353.62 g/kWh. Emission analysis showed that nitrogen oxide (NOx) increased with engine speed and throttle, peaking at 658.23 ppm, whereas hydrocarbon (HC) and carbon monoxide (CO) emissions decreased, with minimum values of 208.65 ppm and 2.95%, respectively. The optimization process identified the most effective operating conditions at 3000 RPM engine speed, 40% throttle, and 30% fusel oil blend (F30), leading to performance improvements of 4.3% in power, 2.7% in BTE, and 3.6% in BSFC, while reducing emissions by 0.8% for NOx, 6.0% for HC, and 5.9% for CO. The RSM model exhibited high reliability, with an R-squared value exceeding 0.95 for all parameters, and validation experiments confirmed an error margin below 5%. These findings suggest that fusel oil blends can be a viable alternative fuel, optimizing engine efficiency while reducing harmful emissions. Future research should explore higher fusel oil blend ratios and long-term engine performance impacts.

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