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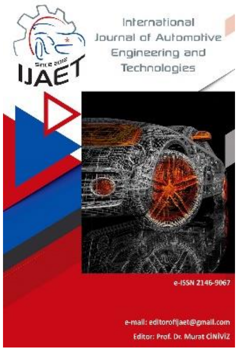

Original Research Article

Application of RSM for prediction and optimization of performance and emissions of diesel engine fuelled with butanol-diesel blends

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ABSTRACT

This work investigated the impacts of butanol-diesel fuel blends used in a turbocharged six-cylinder heavy-duty diesel engine on engine performance and exhaust emission parameters. It evaluated their optimization by using response surface methodology. The engine's operational factors, such as engine speed and the proportion of butanol-diesel fuel blend, have been optimized to attain optimal engine performance and exhaust emissions. The model was designed by Central Composite Design using Minitab software (trial version) and confirmed by the experimental results. According to RSM, the optimum blend ratio of butanol-diesel fuel and engine speed were 5% and 1721.4 rpm, respectively. Optimum desirability is found as 0.6260 with a butanol-diesel fuel blend of 5% and 1721.4 rpm engine speed for the heavy-duty diesel engine. The responses obtained under optimal conditions were determined as 821.19 Nm for torque, 158.1 kW for power, 895.7 ppm for NO_x, 104.05 ppm for CO, and 21.14 ppm for HC, respectively. The values for the R^2 coefficient determination were 99.02%, 99.98%, 99.67%, 99.97%, and 99.95%, respectively.

Keywords: Butanol; performance; emissions; RSM; prediction; optimization.

1. Introduction

The widespread utilization of diesel engines in automobiles, transportation, industry, and agriculture stems from their exceptional fuel efficiency and durability. Conversely, the use of fossil fuels is also increasing, providing the main fuel source for engines [1]. It is commonly acknowledged that the main causes of global climate change are emissions from the burning of fossil fuels, such as carbon monoxide (CO), carbon dioxide (CO2), particulate matter (PM), and nitrogen oxides (NOx) [2,3]. Researchers are compelled to explore clean, sustainable, and economically viable energy sources for engine applications due to the prominent issues of climate change and the energy crisis [4]. Many researchers have conducted studies on oxygenated fuels because of several advantages [5-10]. It has been demonstrated that using diesel fuel blends with alcohols such as methanol, ethanol, and butanol enhances engine performance, improves engine combustion, and decreases exhaust pollution emissions [1, 11].

Due to its superior fuel properties over lower carbon alcohols like methanol and ethanol, N-butanol generated from lignocellulosic residual feedstocks is now recognized as a promising and sustainable green energy alternative for diesel engines [8]. Compared to other alcohols, butanol provides several advantages as an alternative fuel for diesel engines because of its high cetane number, high heating value, high miscibility, and low vapor pressure. As a result, butanol research has been more well-known recently. Research on butanol-diesel blends and diesel engines has shown that reducing exhaust emissions can be done without a major impact on engine performance [12, 13]. Zhu et al. [14] examined how fuel mixes containing diesel and n-butanol affected particulate matter (PM) emissions using a pilot-main injection technique. Three different mixtures, diesel, D80B20, and D50B50, were made, and tests were carried out experimentally with two different injection pressures (40 MPa, 60 MPa) and two different load levels (~30%, ~60%). Consequently, n-butanol is a viable additive for diesel engines since it can lower PM and NOx emissions while influencing the soot particles' functional groups, degree of disorder, and oxidative reactivity. Yılmaz et. al. [15] have found that all N-butanol blends such as DBu5, DBu20, and DBu35 reduce both NOx emissions and total PAH emissions when compared to diesel fuel. Doğan [16] used a modified single-cylinder, four-stroke, naturally aspirated, water-cooled HS DI CI engine to study the influence of n-butanol/diesel fuel blends (at volumetric ratios of 5%, 10%, 15%, and 20%) on engine performance and exhaust emissions. The results of the study showed that while hydrocarbon emissions increased, nitrogen oxide, soot, and carbon monoxide emissions decreased as the amount of n-butanol in the fuel blends increased.

Different optimization methodologies are employed to utilize test results for modeling and analyzing the system [17]. ANN, RSM, Taguchi, and genetic algorithms are a few of the most popular artificial intelligence-based computer programs for optimization [18]. Response Surface Methodology (RSM) is a statistical and mathematical technique that is widely applied in many industries, including manufacturing, chemistry, and engineering [19, 20]. One of the most important advantages of RSM is that it saves money and time by reducing the number of experiments [21, 22]. RSM techniques have been utilized in numerous studies in internal combustion engine applications [22-25]. Dubey et al. [26] looked into the possibility of using waste soybean cooking oil (WSCO) biodiesel in place of conventional fuel for diesel engines used in agriculture. Response surface methodology (RSM) was used in the study, which varied the EGR rates of mixes of WSCO biodiesel-diesel fuel. Ghanbari et al. [27] examined the impact of alumina nanoparticle concentration and engine speed in combination on the emissions and performance of a four-stroke, six-cylinder diesel engine. Alumina nanoparticles were added in different ratios to diesel-biodiesel fuel blends to form mixtures. Response surface methodology (RSM) was used to analyses the way various variables interacted with the diesel engine's performance and emissions.

The literature has revealed a lack of comprehensive studies on the optimization of butanol-diesel fuel blends' impacts on engine performance and exhaust emissions in heavy-duty diesel engines. This study aims to minimize exhaust emissions while optimizing engine performance values. This will be achieved by applying the RSM technique to optimize the butanol ratio and engine speed.

2. Material and Method

2.1. Test fuels

Blends of butanol and diesel were utilized as fuel in the experimental testing. Diesel fuel was blended at 5, 10, and 15% volumetric rates to create the fuel mixes. Before the start of the experiments, the engine underwent a 15-minute operation using diesel fuel to reach the operating temperature Table 1 lists the properties of the fuels used for the experiments.

2.2. Engine set up

A six-cylinder, four-stroke diesel engine with an air-cooling turbocharger was used for the experiments. Engine performance and emission values have been evaluated by running the engine at different speeds using butanol and diesel fuel mixtures. When butanol was used as a fuel additive in diesel engines, the torque, power, and exhaust emissions (NOx, CO, and HC) of butanol-diesel fuel blends were measured. Figure 1 shows a schematic representation of the test setup. Technical specifications of the engine are given in Table 2.

2.3. RSM (Response surface methodology)

RSM mathematical modelling is employed to attain a heavy-duty diesel engine's optimum engine performance and exhaust emissions. RSM is computer-based software used for modelling and optimizing, which has been successfully tested in various fields and has no limitations on its application [28, 29]. RSM methods are frequently employed to effectively run the engine by optimizing the preferred output and operational parameters [30]. Using the least necessary experiments, the engine's performance and exhaust emissions were assessed across a range of input parameter variations.

Table 1. Properties of fuel

Fuel Properties	Diesel	Butanol
Heating value (kJ/kg)	45144	33100
A/F Ratio (-)	15	11.2
Density (kg/m^3) at 20°C	0.835	0.810
Cetane Number	61	~25
Kinematic Viscosity (mm/s^2) at 40°C	2.75	2.25
Carbon/Total Mass Ratio (%)	86	64.8
Oxygen/Total Mass Ratio (%)	-	21.6
Molar mass (g/mol)	174	74.12

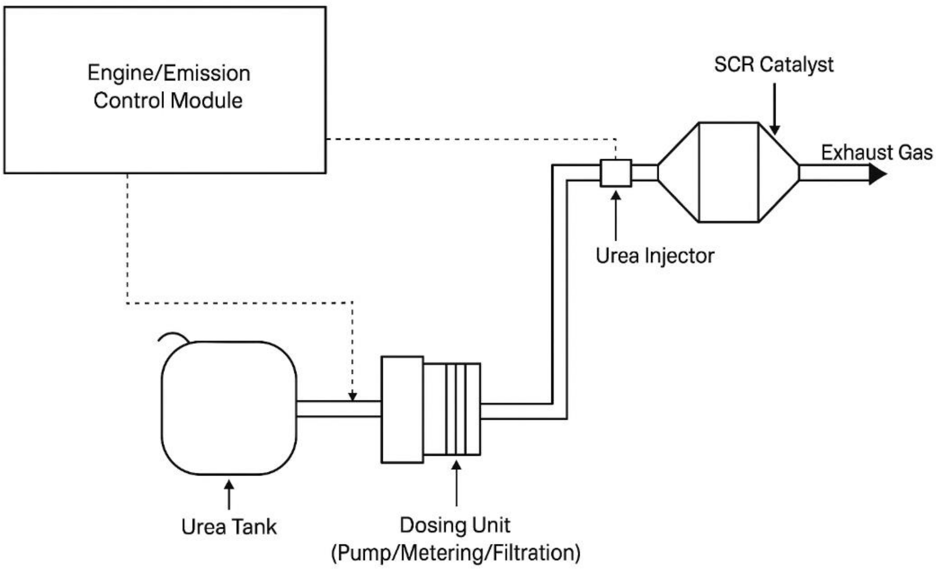


Figure 1. Schematic diagram of engine setup

Table 2. Specifications of engine

Brand	Cummins
Model	ISBE4+250B
Type	Electronic control system
Cylinder	6
Bore/Stroke	107/124 mm
Compression Ratio	17.3
Weight	485 kg
Aftertreatment	SCR
Peak Torque/ Speed (r/min)	1200-1800
Rated Speed	2500 rpm
Displacement	6700cc
Power	184 kW@2500 rpm
Torque	1020Nm @1500 rpm
Oil Cooler	Turbocharger & aftercooled

Table 3. Independent parameters and their corresponding levels

Symbol	Parameter	Unit	Level		
			-1	0	+1
A	Butanol ratio	%	5	10	15
B	Engine speed	rpm	1400	1800	2200

Table 4. Engine performance tests comparison between predicted and experimental values

			Experimental		RSM	
No	A: Butanol ratio (%)	B: Engine speed (rpm)	Torque (Nm)	Power (kW)	Torque (Nm)	Power (kW)
1	5	1400	848.15	136.02	853.79	135.84
2	10	1800	798.42	160.45	799.22	160.37
3	10	1800	798.42	160.45	799.22	160.37
4	10	1400	847.15	134.21	845.30	134.35
5	10	1800	798.42	160.45	799.22	160.37
6	5	2200	715.69	172.41	721.49	172.16
7	10	1800	798.42	160.45	799.22	160.37
8	10	1800	798.42	160.45	799.22	160.37
9	10	2200	712.54	170.15	710.38	170.43
10	15	2200	702.44	168.15	698.81	168.13
11	5	1500	820.45	161.54	809.02	161.98
12	15	1400	840.15	132.25	836.36	132.29
13	15	1800	781.54	158.21	788.96	158.19

Table 5. Exhaust emission tests comparison between predicted and experimental values

			Experimental			RSM		
No	A:Butanol ratio (%)	B: Engine speed (rpm)	NOx (ppm)	CO (ppm)	HC (ppm)	NOx (ppm)	CO (ppm)	HC (ppm)
1	5	1400	1034	108	13.81	1031.99	107.54	13.73
2	10	1800	845	130	22.93	841.66	128.97	22.90
3	10	1800	845	130	22.93	841.66	128.97	22.90
4	10	1400	998	105	14.08	1006.53	103.92	14.06
5	10	1800	845	130	22.93	841.66	128.97	22.90
6	5	2200	725	534	26.87	723.15	529.87	26.70
7	10	1800	845	130	22.93	841.66	128.97	22.90
8	10	1800	845	130	22.93	841.66	128.97	22.90
9	10	2200	694	508	27.02	702.20	514.25	27.18
10	15	2200	687	502	27.48	680.65	499.87	27.49
11	5	1500	861	134	22.25	864.86	138.59	22.50
12	15	1400	987	100	14.12	980.49	101.54	14.22
13	15	1800	805	120	23.25	817.86	120.59	23.14

In this research, data analysis was conducted utilizing the trial version of Minitab software, with the central composite design (CCD) being favored to construct a second-degree model [31]. In this particular model, the independent parameters selected were the ratio of butanol and engine speed, while torque, power, and exhaust emissions (NOx, CO, HC) were considered dependent variables. Table 3 provides a list of independent parameters and their corresponding levels. Figure 2 illustrates the procedures for RSM optimization.

13 empirical trials were carried out on the system to gather responses. The first stage of

RSM involves establishing an appropriate correlation between input and output parameters. For this correlation, a second-order equation model is applied, as shown in Eq. 1. [32].

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i=1}^{k} \sum_{i<j}^{k} \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

Y is response, β0 is the constant coefficient, Xi are the main factors, βii, βij, are the linear, quadratic, and interaction between the variables i and j coefficients respectively, ε is the residual.

The obtained experimental and predicted values of engine performance (torque, power) and exhaust emissions (NOx, CO, HC) are listed in Table 4 and Table 5, respectively. The experimental quadratic polynomial models presented below were utilized to predict engine performance and exhaust emissions by fitting the experimental results.

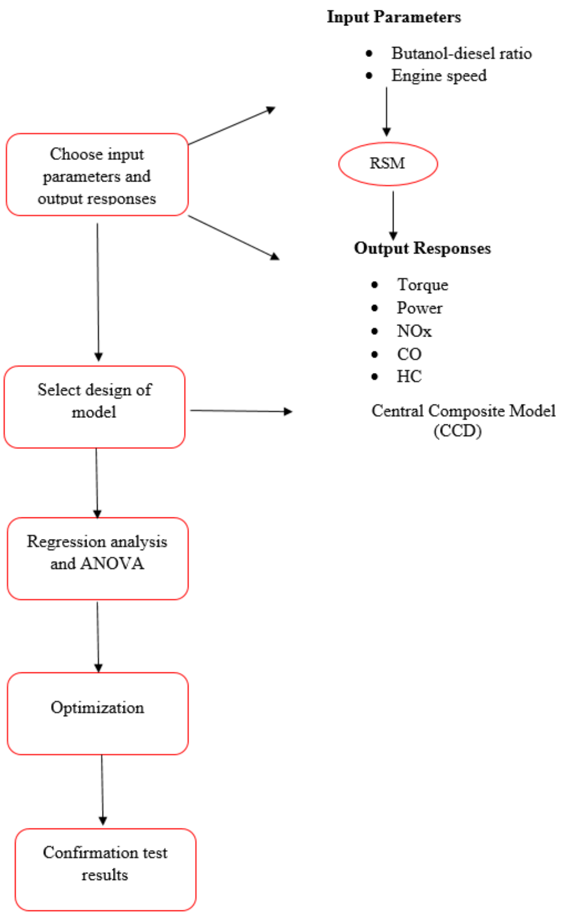


Figure 2. RSM flowchart

2.4. Desirability

Harrington introduced the desirability function as a method for optimizing multiple responses, and it has since been extensively employed to optimize multiple responses simultaneously [33]. Every response was converted into a dimensionless desirability value (d), which varies between d = 0, implying the response was entirely unacceptable, and d = 1, implying the response was more favourable [34]. It's essential to either maximize, minimize, or keep a constant value for the response variable being optimized to ensure the accuracy of comparisons made with measurement outcomes. As a result, researchers establish the "response target" when developing the RSM model [35].

3. Results and Discussions

3.1 RSM model

Numerical evidence about the probability value is obtained through variance analysis (ANOVA) [36]. Using variance analysis (ANOVA), the significant values between the input variables and responses have been obtained. The fact that the R^2 values gathered from RSM for all responses are greater than 0.95 indicates that these results are statistically meaningful. In ANOVA results, the p-value holds significant importance. Generally, a p-value of 0.05 or less is considered significant. Models with p-values exceeding 0.05 are typically deemed insignificant. A factor is considered to have had a significant impact on the model if its p-value is less than 0.05 [37]. Table 6 and Table 7 demonstrate the stability of the model analyzed using ANOVA, respectively. According to the tables, it is observed that the model's p-values are less than 0.0001. In Response Surface Methodology (RSM), the primary indicators for assessing a model are the R^2 and adjusted R^2 values. R^2 values approaching 1 indicate strong significance, highlighting the model's explanatory power and goodness of fit [38]. Table 8 gives the R^2, adj. R^2 and Pred. R^2 values for the model, respectively. The R^2 values for Torque, Power, NO_x, CO, and HC are respectively 99.02%, 99.98%, 99.67%, 99.97%, and 99.95%. Importantly, the fact that all models have R^2 values exceeding 0.9 indicates a strong fit of the regression model to the data. Table 9 gives the regression equations acquired from the model for each response.

Table 6. Variance Analysis for torque and power

	Torque		Power		
Source	F-value	P-value	F-value	P-value	
Model	141.94	0.000	7271.38	0.000	Significant
A-Butanol ratio (%)	14.56	0.007	357.82	0.000	
B-Engine speed (rpm)	659.03	0.000	32478.93	0.000	
AB	0.17	0.0060	1.00	0.351	
A^2	0.00	0.954	3.71	0.095	
B^2	20.47	0.001	2925.35	0.000	

Table 7. Variance analysis for Exhaust emissions (NO_x, CO, HC)

	NO_x		CO		HC		
Source	F-value	P-value	F-value	P-value	F-value	P-value	
Model	428.57	0.000	5504.41	0.000	2593.44	0.000	Significant
A-Butanol ratio (%)	49.73	0.000	37.33	0.000	28.85	0.001	
B-Engine speed (rpm)	2085.14	1	19400.75	0.000	12123.26	0.000	
AB	0.30	0.599	11.06	0.013	1.06	0.338	
A^2	0	0.954	0.08	0.783	0.90	0.374	
B^2	6.69	0.036	6883.19	0.000	676.16	0.000	

Table 8. Model Evaluation

Model	**Torque**	**Power**	**NO_x**	**CO**	**HC**
R^2	99.02%	99.98%	99.67%	99.97%	99.95%
Adj. R^2	98.33%	99.97%	99.44%	99.96%	99.91%
Pred. R^2	90.32%	99.84%	97.64%	99.78%	99.48%

Table 9. Regression Equations for responses

Regression Equations
Torque = $677.2 - 0.64A + 0.391B - 0.009A^2 - 0.000134B^2 - 0.00066AB$
Power = $-80.84 - 0.041A + 0.22524B - 0.01137A^2 - 0.000050B^2 - 0.000061AB$
$NO_x = 1850-6.49 A-0.678B-0.012A^2 + 0.000079B^2 + 0.00112AB$
CO = $2819.6 + 3.10A – 3.5098B + 0.0248A^2 + 0.001126B^2 – 0.003000 AB$
HC = $-53.16 + 0 0633A + 0.06740B – 0.00334A^2 – 0.000014 B^2 + 0.000038AB$

The engine performance (power, torque) and exhaust emissions (NO_x, CO, and HC) of a heavy-duty diesel engine running on butanol-diesel fuel mixes were compared between experimental and predicted values to assess the success of the RSM model. As seen in Figure 3, all response distributions are along or close to a straight line. The quality of model fit is assessed by the coefficient of determination (R^2). The analysis of the regression equation by ANOVA showed that the R^2 value was 0.9887. The adjusted R^2 and predicted R^2 values were 0.9767 and 0.9461 respectively. There is a reasonable agreement between the predicted R^2 and adjusted R^2 values because the difference is less than 0.2. Therefore, this model could be used in the theoretical prediction of the pomegranate seed oil biodiesel production process.

Pareto chart and regression equation were created for each response. The Pareto chart displays the absolute magnitudes of the standardized impacts arranged from the most significant to the least significant. Additionally, it includes the vertical dashed red line established by the model to highlight the statistically significant effects. If the bar graph representing selected variables lies to the right of this line, it signifies effectiveness; conversely, if it falls to the left, it denotes ineffectiveness. Figure 4 demonstrates the Pareto charts of responses respectively. According to Figure 4 the impact of engine speed seems to be more significant for all responses.

3.2. Effects of input parameters on torque and power

Figure 5 displays the effects of engine operating variables on torque and power, respectively. These variables are the butanol ratio and engine speed. As can be seen from Figure 5, increasing the amount of butanol in diesel fuel results in decreases in torque and power values which may be due to butanol having a lower calorific value than diesel fuel [39]. 3D surface and contour plot of power is shown in Figure 6. Power increases as engine

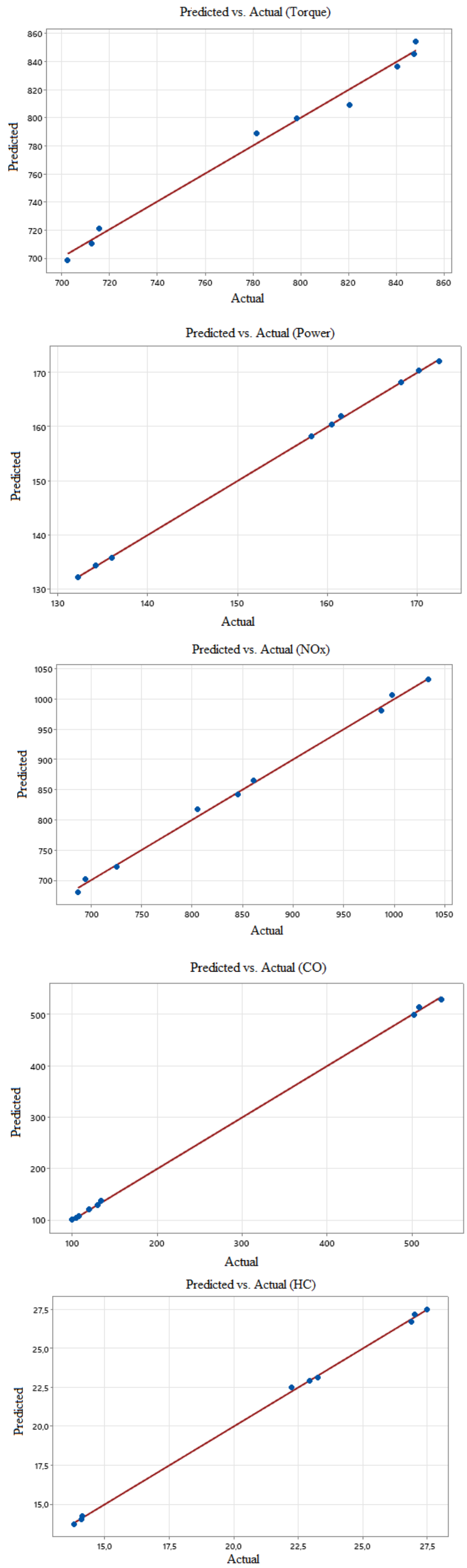


Figure 3. Comparison of predicted and experimental values of all responses

speed increases. The maximum engine power was obtained as 172.41 kW at 2200 rpm engine speed in a 5% butanol-diesel fuel mixture. A decrease in engine power is observed as the ratio of butanol in the fuel mixtures increases. Butanol has a lower calorific value compared to diesel fuel. As the proportion of butanol in the butanol-diesel fuel blends increases, a decrease in engine power has been observed due to the lower energy content of these mixtures [40].

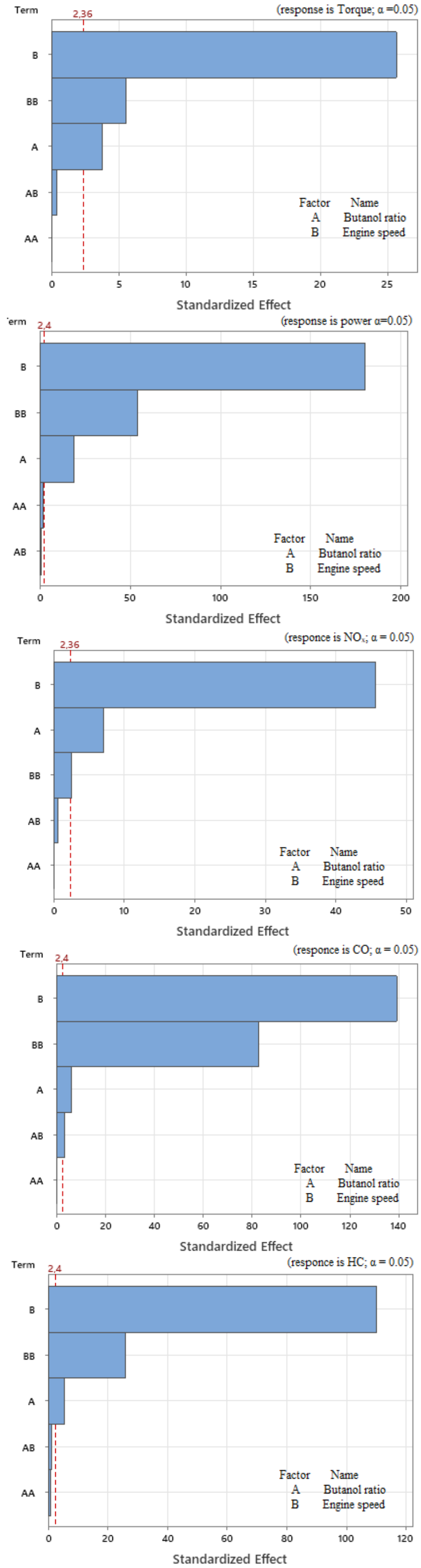
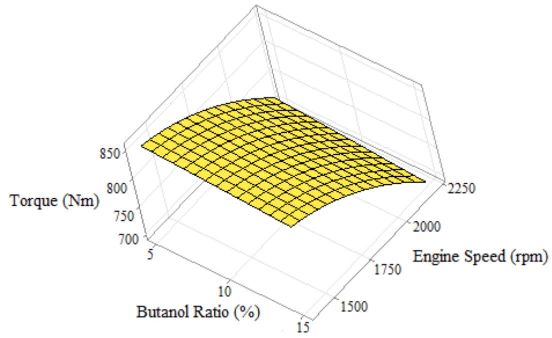
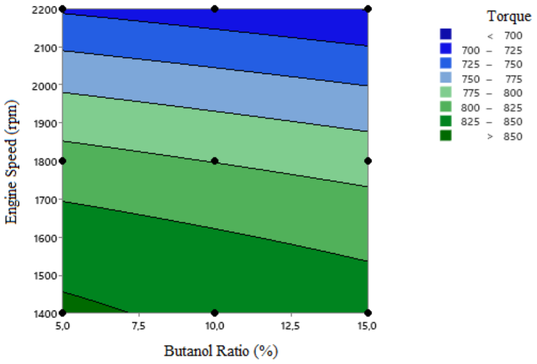


Figure 4. Pareto charts for all responses

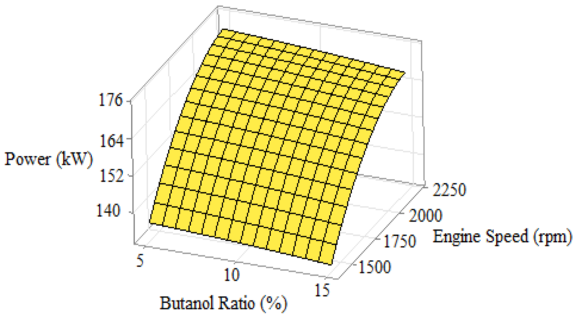


(a) 3D surface plot

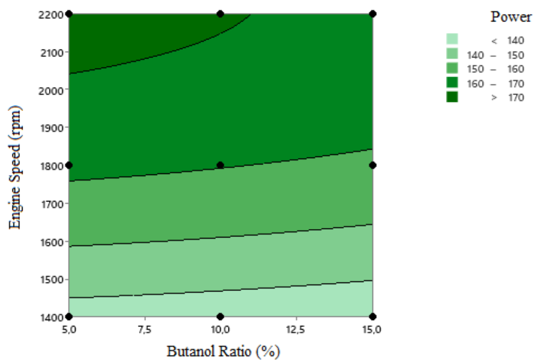


(b) Contour plot

Figure 5. (a) 3D surface plot and (b) Contour plot for Torque versus butanol ratio and engine speed



(a) 3D surface plot

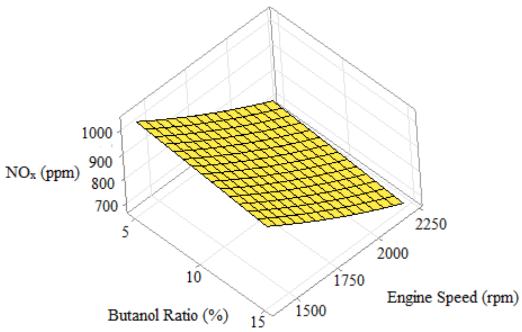


(b) Contour plot

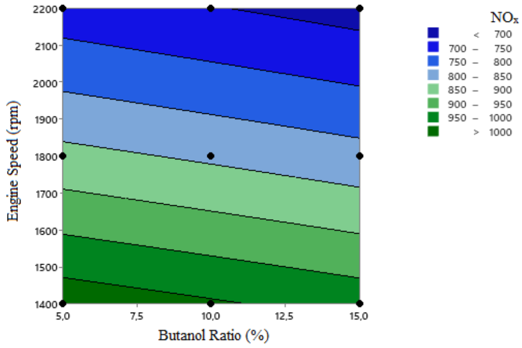
Figure 6. (a) 3D surface plot and (b) Contour plot for Power versus butanol ratio and engine speed

3.3. Effects of input parameters on NO_x, CO, HC

As depicted in Figure 7, increasing the proportion of butanol in fuel blends leads to a decrease in NO_x emissions. This reduction is primarily due to butanol's high latent heat of vaporization. The elevated latent heat of vaporization facilitates greater heat removal from the combustion chamber, thereby reducing the peak temperature during combustion [41]. Figure 8 clearly shows that adding butanol to the blend reduces CO emissions. This reduction is attributed to butanol's inherent oxygen content within its molecular structure. Diesel-butanol blends increase the oxygen content in the air-fuel mixture, which enhances CO oxidation and promotes more complete combustion, potentially lowering CO emissions [42]. The rise in HC emissions observed when alcohol is added to fuel blends may be linked to the higher latent heat of vaporization characteristic of alcohol blends. This higher latent heat causes slower evaporation, which in turn can result in a slower and less homogeneous fuel-air mixture [43].



(a) 3D surface plot

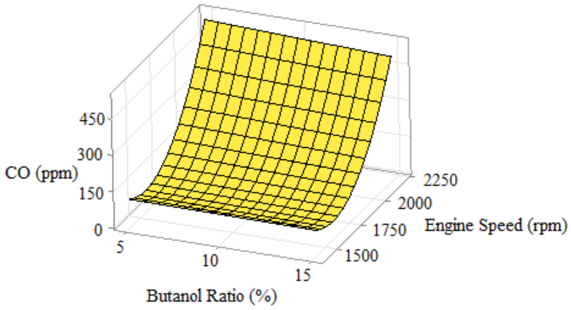


(b) Contour plot

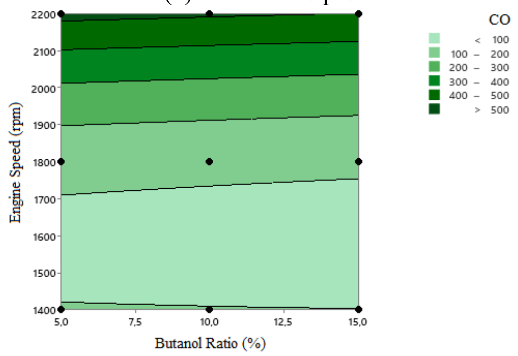
Figure 7. NO_x versus butanol ratio and engine speed in (a) 3D surface and (b) Contour plot

3.4. Optimization

The optimization of engine input parameters when using butanol as a fuel can be crucial for maximizing performance and minimizing emissions. RSM (Response Surface Methodology) is a statistical technique used for optimizing processes and finding the best combination of input variables to achieve desired outputs. When applied to engine optimization, RSM can help identify the finest engine input parameter settings for butanol-diesel fuel blends. The results of multi-purpose optimization obtained from RSM based on the principle of maximizing or minimizing output responses (Torque, Power, NOx, CO, HC).

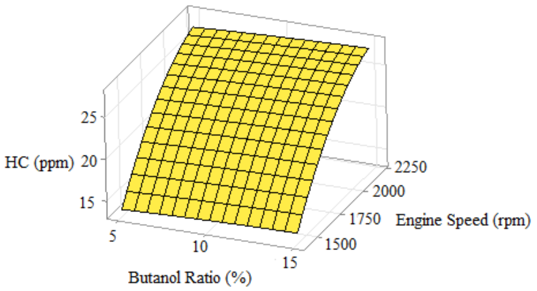


(a) 3D surface plot

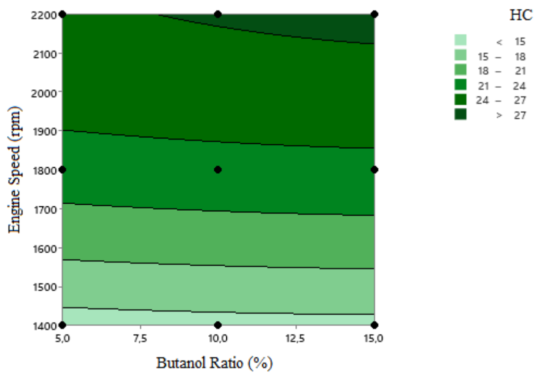


(b) Contour plot

Figure 8. CO versus butanol ratio and engine speed in (a) 3D surface and (b) Contour plot



(a) 3D surface plot



(b) Contour plot

Figure 9. HC versus butanol ratio and engine speed in (a) 3D surface and (b) Contour plot

Table 10 provides the goals set for each response, the lower and upper limits used, the weights, and the importance of the factors, which are optimization criteria. Figure 10 demonstrates the RSM optimizer outcomes. The optimum butanol ratio and engine speed were found as 5% and 1721.4 rpm, respectively.

Table 10. Details of RSM optimization

Response	Goal	Lower	Upper	Weight	Importance
Butanol Ratio (%)	In range	5	10	1	1
Engine Speed (rpm)	In range	1400	2200	1	1
Tork	Max.	702.44	848.15	1	1
Power	Max.	132.25	172.41	1	1
NOx	Min.	694	1034.00	1	1
CO	Min.	105	534.00	1	1
HC	Min.	13.81	27.48	1	1

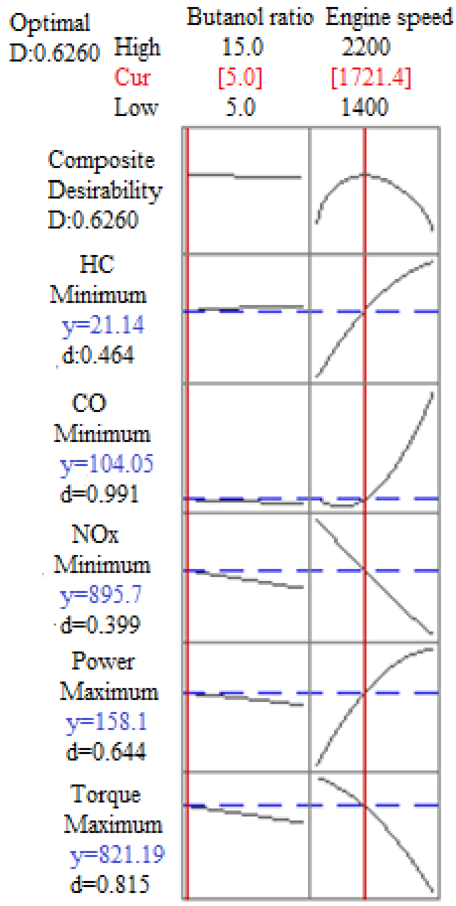


Figure 10. RSM Optimizer

4. Conclusion

In the current study, the effects of varying amounts of butanol additive and engine speed on the performance and emission characteristics of heavy-duty diesel engines have been investigated. The results obtained based on the RSM optimization approach by varying the engine speed and ratio of butanol at various levels are provided below:

- A strong agreement was observed between the experimental responses and the predictions made by the RSM.

- The regression analysis identified a robust relationship between the independent variables and the responses, effectively explaining this relationship. The coefficient of determination R^2 for torque, power, NO_x, CO, and HC was found to be 99.02%, 99.98%, 99.67%, 99.97%, and 99.95%, respectively, which indicates the success of the model.
- The experiments conducted using Minitab software determined the optimum conditions as a butanol ratio of 5% and an engine speed of 1721.4 rpm. At these optimum conditions, the torque, power, NO_x, CO, and HC emission values were determined as 821.19 rpm, 158.1 Nm, 895.7 ppm, 104.05 ppm, and 21.14 ppm, respectively.
- Pareto charts indicate that engine speed has a more significant effect on engine responses compared to butanol ratio.
- This study emphasizes the optimization of the effects of butanol-diesel fuel blends on performance and exhaust emissions in a turbocharged diesel engine using Response Surface Methodology (RSM). The study demonstrates how factors such as butanol ratio and engine speed can be optimized to improve engine performance and reduce environmental emissions. Furthermore, the high R^2 values and ANOVA results obtained support the reliability and validity of the model. This research provides an important scientific foundation for engine optimization and the use of environmentally friendly fuels.

Credit Authorship Contribution Statement

The author accepts full responsibility for the content of this article and has approved its submission.

Declaration of Competing Interests

The author declares that there are no competing interests.

5. References

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