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Optimization of Oxygen Enrichment in a CI Engine using Tallow Oil Biodiesel: A Response Surface Methodology Approach

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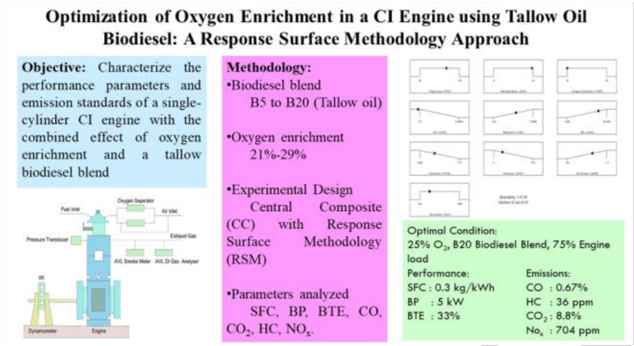
Graphical abstract



Abstract

The growing need for sustainable energy solutions has driven significant interest in biodiesel as a suitable replacement for fossil fuels. This research aims to characterize the performance parameters and emission standards of a single-cylinder CI engine with the combined effect of oxygen enrichment and a biodiesel blend. Tallow oil derived from animal fats is used as a source of biodiesel because of its renewable properties, cost-effectiveness, and green energy applications. The response surface methodology (RSM) optimizes engine parameters for enhanced efficiency and reduced emissions. Oxygen enrichment is done at various oxygen concentrations of 21-29%, and the tallow oil biodiesel blend of B5 to B20 is used. The central composite (CC) design was used to design experimentation and enable the development of regression models that predict engine responses. Performance factors such as specific fuel consumption (SFC), brake power (BP), brake thermal efficiency (BTE), and emission characteristics such as carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), and nitrogen oxides (NO_x) are the factors analyzed. The analysis found that 25% oxygen enrichment with a B20 biodiesel blend and a 75% engine load condition provides a desirability of 0.719, and the desirable parameters obtained are 0.3 kg/kWh of SFC, brake power of 5 kW, and the brake thermal Efficiency as 33%. When we come to emissions, it is found that the CO emission of 0.67%, the HC emission of 36 ppm, the CO_2 emission of 8.8%, and the NOx emission of 704 ppm. This result shows the optimum condition for the operation of the diesel engine.

Keywords: oxygen enrichment, biodiesel, optimization, response surface methodology, tallow oil, emission

1. Introduction

High demand for fossil fuels and the faster development of electrical systems, make it mandatory to improve the operation output of IC engines to retain their usage (Leach *et al.* 2020). There is extensive research on alternative fuels that are sustainable, renewable, and eco-friendly (Stančin *et al.* 2020). Biodiesel emerged as an effective substitute among various renewable energy sources. Renewable resources such as waste cooking oil, vegetable oil, and animal fats are the major source of biodiesel (Mahapatra *et al.* 2021; Suzihaque *et al.* 2022). Fuel properties influence the engine performance and emission to major extent (Kishore *et al.* 2024; Alawa and Chakma 2022). Biodiesel provides several advantages such as being biodegradable, reducing harmful emissions, and having less sulfur content (Aljaafari *et al.* 2022; Sarma *et al.* 2023).

Tallow oil biodiesel is derived from animal fats. About 9000 metric tons of tallow and animal fat for biodiesel production in India are available every year (Nachtergaele *et al.* 2022). Tallow oil is typically low-cost compared to edible oils and also minimizes wastage. Biodiesel also possesses better ignition characteristics and smoother engine operation due to a higher cetane number (Leach *et al.* 2020). Fine atomization of biodiesel is needed to control its higher viscosity and density (Malik *et al.* 2024; Alawa and Chakma *et al.* 2023; Botla *et al.* 2024; Ellappan, and Rajendran *et al.* 2020).

Biodiesel in a diesel engine facilitates better combustion performance because the higher cetane number of biodiesel improves the fuel ignition quality and combustion timing leads to more efficient energy release, smoother engine operation, and discharge minimization (Divyachandrika *et al.* 2024; Kumar *et al.* 2024; Krishna and Murugan *et al.* 2024). It exhibits good lubricating properties, which can reduce wear on the engine (Lv *et al.* 2024; Rex *et al.* 2024). A higher cetane number of Biodiesel improves combustion, reduces ignition delay, and produces smoother engine operation (Hemanandh *et al.* 2025; Modi *et al.* 2024; Miron *et al.* 2021). The use of Biodiesel reduces particulate matter and carbon monoxide emissions. Compared with diesel, Biodiesel is more eco-friendly than diesel because it is made from renewable resources (Deepanraj *et al.* 2022; Sharma *et al.* 2020).

Oxygen in the mixture plays a significant role in efficiency improvement and emission control. Oxygen in biodiesel is very minimal and not enough for oxygen enrichment. By enriching the air-fuel mixture with additional oxygen, the combustion process can be enhanced in several ways (Senthilkumar *et al.* 2023). Adding oxygen allows for more complete fuel combustion, increasing power output. Oxygen Enrichment is instrumental in high-performance applications such as racing cars or aircraft, where maximum power is desired (Xu *et al.* 2021; Costa Ricós *et al.* 2024). Oxygen enrichment can enhance fuel efficiency by promoting a more efficient and complete combustion process (Shi *et al.* 2020). Complete fuel combustion leads to less fuel wastage, improved mileage, and reduced fuel consumption. Oxygen enrichment can help reduce harmful exhaust emissions (Chen *et al.* 2019). When the combustion process is optimized, there is a reduction in unburned hydrocarbons (HC), carbon monoxide (CO), and other pollutants emitted from the engine (Fayyazbakhsh *et al.* 2022; Kumar 2020).

There are several methods to achieve oxygen enrichment in engines. In some engines, oxygen enrichment can be achieved by adjusting the air/fuel ratio to provide a slightly leaner mixture than the stoichiometric ratio, allowing more oxygen in the combustion zone (Abidin *et al.* 2020). Turbocharging and Supercharging increase the air entering the engine by compressing the intake air. This results in higher oxygen levels and allows more fuel to be burned, increasing power output (Chen *et al.* 2023). Oxygen Injection in some engines employs oxygen injection systems that introduce additional oxygen directly into the intake air or combustion chamber. This method ensures a higher oxygen concentration, resulting in improved combustion efficiency (Kapusuz *et al.* 2023). It's worth noting that oxygen enrichment should be applied within safe limits to prevent engine damage. Careful monitoring and control of the air-fuel mixture and engine parameters are essential to ensure reliable operation and avoid potential issues such as detonation or overheating. Engine oxygen enrichment offers improved power output, fuel efficiency, and reduced emissions (Vera *et al.* 2023). It is a technique utilized in various applications where engine performance and efficiency are crucial factors.

Response Surface Methodology (RSM) has emerged as a commanding statistical tool for the optimization of complex processes involving multiple input variables (Moradzadeh et al. 2024). RSM combines experimental design, mathematical modeling, and statistical analysis to explore the association between input parameters and output responses to identify the optimal operating conditions (Jain *et al.* 2023). The central composite (CC) design is a widely used RSM technique for efficient experimentation (Shajahan *et al.* 2024; Padma *et al.* 2024).

2. Experimental Procedure

A vertical-mounted single-cylinder diesel engine with water-cooling technology was utilized for this experiment. The experimental setup is depicted in **Figure 1**, with the engine specifications detailed in **Table 1**. An electrical loading method was employed, and exhaust gas temperature was monitored using a K-type thermocouple. The test rig included a data acquisition system for measuring the engine's combustion parameters. Exhaust emissions, including HC, CO, and NOx, were analyzed using an AVL Digas 444 N exhaust gas analyzer. To enhance the oxygen enrichment process, an additional pure oxygen inlet line was integrated into the air intake system.

Table 1. Engine Setup Specification

Engine Model	Kirloskar TV-1
Engine Type	Diesel
Type of Cylinder	Vertical Cylinder
Cooling Type	Liquid Cooling
Ignition Type	Compression-Ignition
Number of Cylinders	Single
Working Cycle	4 Stroke
Compression Ratio	17.5:1
Power	5.2 kW/ 7 HP
Nominal Engine Speed	1500 rpm
Bore / Stroke	87.5 mm/ 110 mm
Temperature Sensor	RTD, Type K Thermocouple
Load Sensor	Strain Gauge type load cell

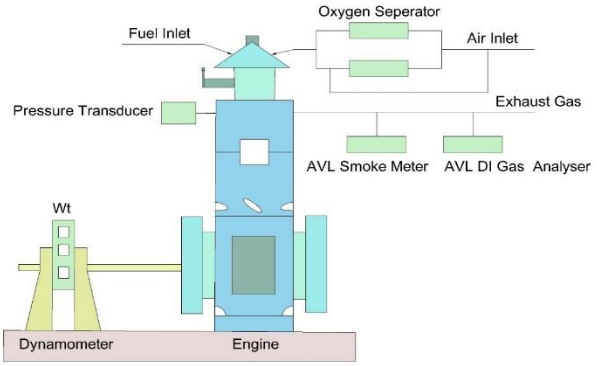


Figure 1. Kirloskar TV-1 Engine Test Setup

The fuel used here is the B5, B10, B15, and B20 Biodiesel blend of 5%, 10%, 15%, and 20% Tallow oil biodiesel along with the diesel fuel. This biodiesel used here is produced through the transesterification of tallow oil with methanol in the presence of a potassium hydroxide catalyst. The physical and chemical factors of the blends were determined using ASTM standards to ensure compliance with fuel specifications.

Tallow oil biodiesel is used as a biofuel because of its 14 MT of Tallow available globally (Biodiesel Technologies, Animal Tallow). It has a higher cetane number, cleaner and more efficient burning in diesel engines. Biodiesel was prepared using a transesterification process as per the biodiesel standard of ASTM D6751. Transesterification is widely used to convert triglycerides into methyl or ethyl esters and glycerol. The process involves the purification of tallow oil from impurities, water, and free fatty acids. Sodium hydroxide is used as the strong base catalyst by forming methoxide when mixing it with methanol. This highly reactive methoxide is mixed with purified tallow oil at a temperature of around 40–65°C. The triglycerides in the tallow oil react with methoxide to form methyl esters and glycerol as a byproduct. The reaction timing is basically about 1-2 hours at a high temperature or 2-4 hours at a low temperature. After settling, the biodiesel top layer is separated from the glycerol bottom layer. The final derived biodiesel is tested for its ASTM D6751 standard. The properties of tallow biodiesel and diesel are illustrated in **Table 2**.

Table 2. Properties of Tallow Oil Biodiesel and Diesel

Properties	Units	Diesel	Tallow Biodiesel
Chemical Formula		$C_{12}H_{24}$	$C_{18}H_{36}O_2$
Cetane Number		50	57.5
Flash Point	^0C	60	122
Density	g/cm^3	0.85	0.87
Specific heat capacity	J/kg K	2100	1780
Calorific value	MJ/kg	45	38.5
Kinematic viscosity	mm^2/s	2.98	5.42
Carbon Content	%	86.7	76.1
Hydrogen Content	%	12.8	12.7
Oxygen Content	%	0.0	11.2

For oxygen enrichment, instead of using a separate oxygen cylinder, a double-column pressure swing adsorption test setup is installed, and zeolite 5A is used as the adsorbing material. When air is allowed to passes through the adsorbing material, it adsorbs the nitrogen present in the air and provides a pure oxygen supply. An oxygen meter is used to measure the quantity of oxygen present in the incoming air to the engine. Oxygen concentration is maintained at 23-29%, respectively, and is used for testing. The oxygen concentration is restricted below 30% because, when the oxygen presence exceeds this condition, an uncontrolled combustion and detonation take place. Another concern in biodiesel usage is the increase in kinematic viscosity, with B20 biodiesel blend the kinematic viscosity is increased to 3.47 mm^2/s which reduces the combustion but higher cetane number of the biodiesel in turn improves the combustion and nullifies the negative effect.

The central composite (CC) design of RSM was used to design the experiments. Oxygen concentration of 21% to 29% and the biodiesel blending ratio of B5 to B20 are used with the engine load of 0 to 100% with 18kg for full load condition as the input variables for optimization. The test engine was stabilized to its operating temperature before each test. For analyzing the optimal operating condition of the engine parameters such as SFC, BTE, BP, NO_x, CO, HC, and CO_2 were measured.

Analyzing the experimental data using RSM to develop regression models for engine performance and emission parameters. Design Expert software is used to develop quadratic models. Analysis of variance (ANOVA) was carried out to evaluate the significance of input parameters. A combination of oxygen concentration, biodiesel blend, and engine load are used in the optimization to identify the Maximum performance and minimum emissions of the engine.

3. Results

The results obtained from the experimental and optimization outputs are discussed. The obtained results are influenced by oxygen concentration, biodiesel blend, and engine load. The obtained results are analyzed using the regression models and the optimized conditions for operation are identified. The input and output parameters used for optimization are tabulated in **Table 3**.

Table 3. Optimization parameter for design matrix

Run	Factor 1 A: Engine Load (%)	Factor 2 B: Bio-diesel Blend (%)	Factor 3 C: Oxygen Concentration (%)	Response 1 SFC (Kg/kWh)	Response 2 Brake Power (kW)	Response 3 BTE (%)	Response 4 CO Emission (%)	Response 5 HC Emission (PPM)	Response 6 CO_2 Emission (%)	Response 7 NO_x Emission (PPM)
1	25.00	0.00	29.00	0.47	1.78	20.65	0.03	29.00	3.81	547.00
2	62.50	10.00	27.00	0.34	4.43	30.07	0.08	40.80	7.99	781.50
3	25.00	10.00	27.00	0.47	1.74	21.41	0.07	46.20	4.80	322.00
4	100.00	20.00	25.00	0.31	6.87	34.60	1.77	76.00	11.70	682.00
5	100.00	10.00	27.00	0.34	7.17	33.80	1.29	87.50	11.40	895.00
6	62.50	10.00	27.00	0.33	4.39	30.59	0.08	39.40	7.97	780.20
7	25.00	20.00	25.00	0.42	1.72	22.09	0.06	25.41	4.60	381.00
8	62.50	20.00	27.00	0.36	3.82	29.73	0.25	30.74	7.40	796.00
9	62.50	10.00	25.00	0.30	3.55	29.19	0.03	26.00	7.30	652.00
10	62.50	0.00	27.00	0.32	3.54	28.58	0.00	20.48	6.80	1340.00
11	62.50	10.00	27.00	0.33	4.39	29.98	0.08	39.40	7.97	780.20
12	100.00	0.00	29.00	0.33	7.45	32.51	0.53	51.74	10.30	1864.00
13	25.00	20.00	29.00	0.48	1.85	21.91	0.05	27.00	4.45	366.00
14	62.50	10.00	27.00	0.33	4.34	30.93	0.03	38.35	7.92	780.15
15	25.00	0.00	25.00	0.41	1.65	20.82	0.03	21.00	3.94	548.00
16	62.50	10.00	27.00	0.31	4.37	30.96	0.06	39.38	7.95	780.18
17	100.00	20.00	29.00	0.34	7.75	34.49	1.61	77.00	11.70	708.00
18	62.50	10.00	29.00	0.35	3.90	28.99	0.04	36.00	7.10	756.00
19	62.50	10.00	27.00	0.34	3.48	30.60	0.08	40.19	8.13	795.80
20	100.00	0.00	25.00	0.30	6.60	33.12	0.70	42.00	10.70	1785.00

The input factors in the experimental design include engine load, biodiesel blend ratio, and oxygen concentration. Engine load values are varied within the range of 25% to 100% load. A mean load of 62.5% was considered a representative value because no load conditions produce results that deviate significantly from typical engine performance. Biodiesel blend ratios were selected within the range of B0 (pure diesel) to B20 (20% biodiesel blend). This fuel blend ratio provides the balance between improving fuel combustion characteristics and also reduces fuel viscosity and reduced calorific value.

Oxygen enrichment promotes improved biodiesel fuel combustion, which tends to burn slowly with the influence of biodiesel density and viscosity. For the oxygen enrichment Zeolite Pressure swing adsorption method is used. The oxygen enrichment is varied between 21% to 29% to provide the optimum results. If the oxygen concentration is increased beyond 29% uncontrolled combustion takes place and the excess temperature rise in the cylinder damages the engine as well as increase the NO_x emission drastically.

The regression equation with the coded factors derived from a RSM study is provided is each of the results. Where A, B, and C are coded variables representing the engine load, biodiesel blend and oxygen concentration respectively. In this the individual variable represents the linear effect, cross product represents the interaction effect and square terms of the variable represents the quadratic effect.

3.1. Specific Fuel Consumption

Figure 2 depicts the analysis of Specific Fuel Consumption (SFC) concerning engine load, bio-diesel blend, and oxygen enrichment. Specific fuel consumption decreases with increased oxygen enrichment and increases with a higher biodiesel ratio due to lower energy content. The figure shows a close correlation in the predicted and actual values indicating a high standard of accuracy and reliability of the RSM model. The F-value of 49.47 indicates the significance and 0.01% chance of changes due to noise. There is no significant lack of fit with the F-value of 1.93. The fit statistics show that the adjusted R^2 value is 0.9583 and the predicted R^2 should be 0.9040. The difference in R^2 values is about 0.05 which is within the range. The final equation of the coded factors is given as

$$SFC = 0.3336 - 0.0638\,A + 0.0071\,B + 0.0232\,C - 0.0006\,AB$$
$$-0.0076\,AC + 0.0002\,BC + 0.0623\,A^2 - 0.0004\,B^2 - 0.0124\,C^2$$

3.2. Brake Power

Higher engine loads result in higher braking power output since more fuel is utilized to generate power. The increase in biodiesel ratio causes a minor loss in brake power. Oxygen enrichment increases brake performance. **Figure 3** shows that the real and anticipated values are closely related, and the prediction accuracy is quite high. The

70.05 suggests that the significant model. The F-value of lack of fit is 0.74 indicates that it is not significant. The fit statistics reveal that the R^2 values for adjusted and predicted are 0.9703 and 0.9601, respectively. The coded factor equation is written as

$$\text{Brake Power} = 4.08 + 2.71\,A + 0.0990\,B + 0.0249\,C + 0.0536\,AB + 0.1836\,AC + 0.0049\,BC + 0.6090\,A^2 - 0.1630\,B^2 - 0.1236\,C^2$$

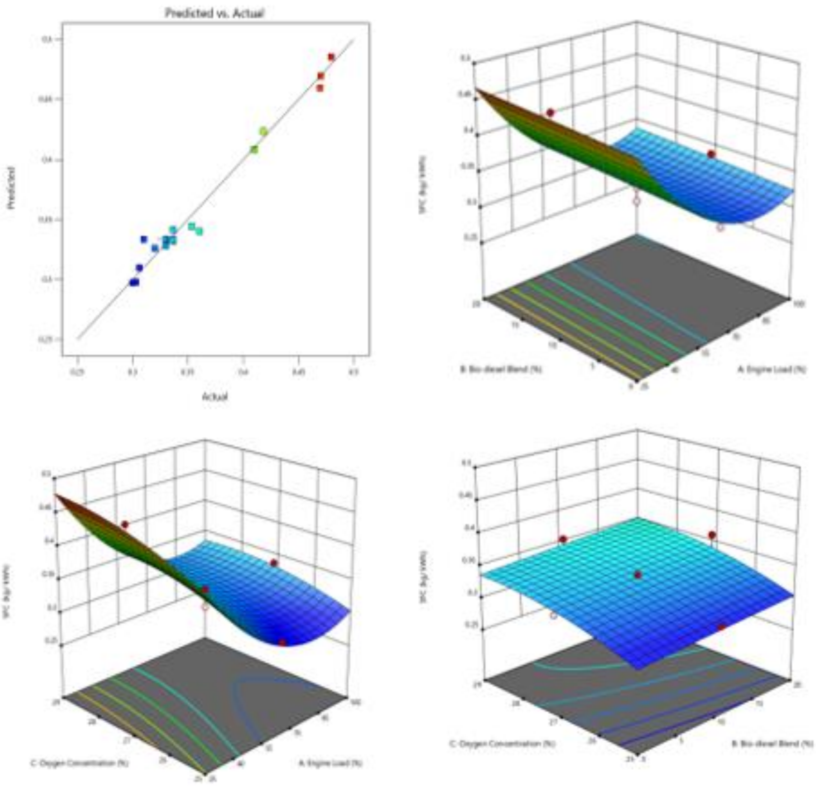


Figure 2. Response Surface Comparison for Specific Fuel Consumption.

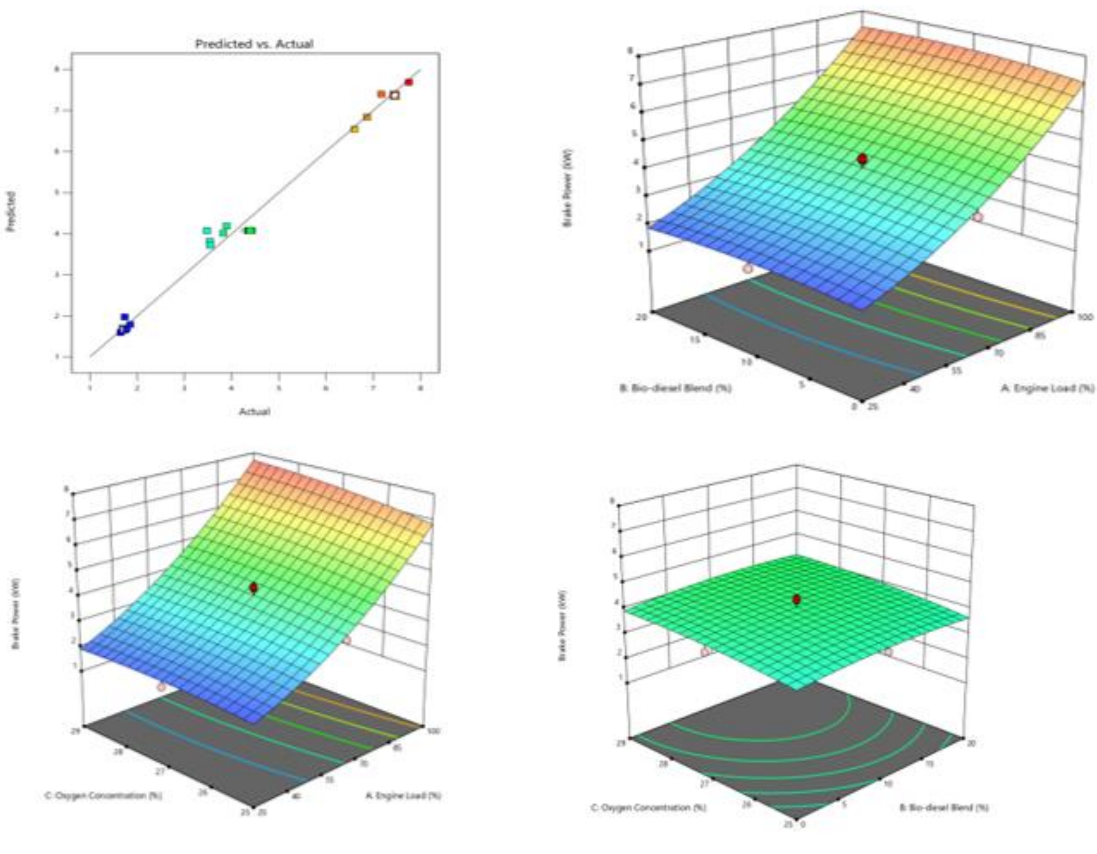


Figure 3. Response Surface Comparison for Brake Power

3.3. Brake Thermal Efficiency

As the combustion rate increases, the brake thermal efficiency improves. Biodiesel also has an impact on the thermal efficiency. **Figure 4** demonstrates that the anticipated and real values are almost identical. Thus, the procedure is significant. There is only 0.01% chance owing to noise will occur with the F-value of 111.31, which makes the model significant. Similarly the P-values of less than 0.0500 suggest significance of the model. The Lack of Fit F-value of 3.81 indicates that it is not significant. The fit data reveal that the adjusted R^2 value is 0.9812 and the anticipated R^2 value is 0.9627, which are quite similar with a difference of less than 0.2. The code factor equation for the BTE is given as

$$BTE = 30.13 + 6.16\,A + 0.7138\,B - 0.1264\,C + 0.1165\,AB - 0.0460\,AC + 0.0615\,BC - 1.93\,A^{2} - 0.3790\,B^{2} - 0.4439\,C^{2}$$

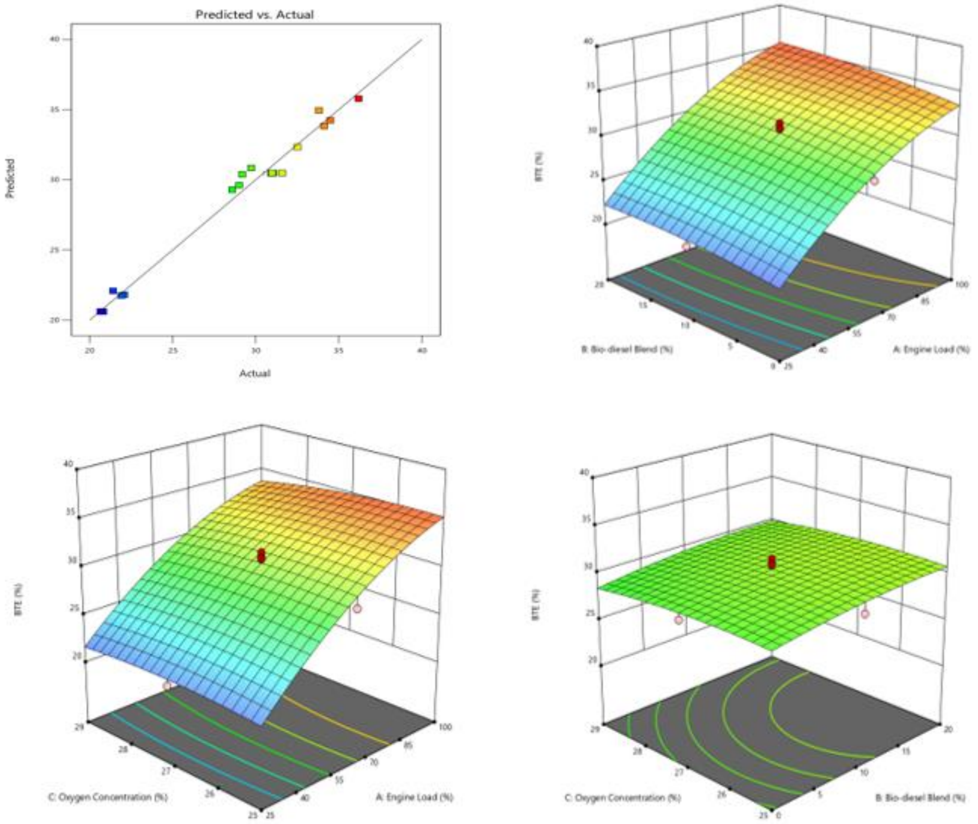


Figure 4. Response Surface Comparison for Brake Thermal Efficiency

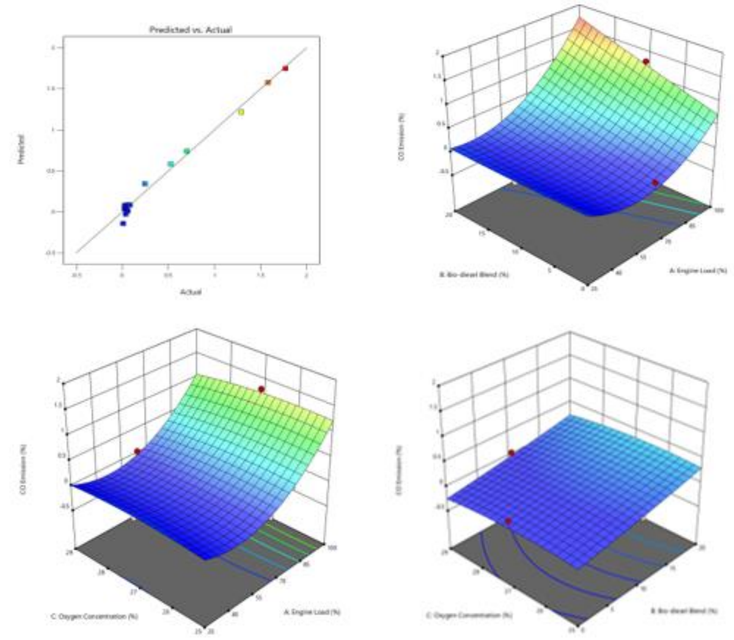


Figure 5. Response Surface Comparison for CO Emission

3.4. CO Emission

The increase in oxygen enrichment reduces the carbon monoxide emission. **Figure 5** shows the closer prediction about the actual values. The F-value of 114.78 indicates that significant model, with only a 0.01% probability of this occurring due to noise. P-values of less than 0.0500 suggest significant model. The Lack of Fit F-value of 24.03 indicates that the lack of fit is not substantial. The fit statistics of adjusted R^2 is 0.9818 and the predicted R^2 is 0.9315. It shows the difference in statistics is 0.05 which is less than 0.2. The coded factor equation is given as

$$\text{CO Emission} = 0.0839 + 0.5648\,A + 0.2421\,B - 0.0369\,C + 0.2586\,AB - 0.0441\,AC + 0.0031\,BC + 0.5698\,A^2 + 0.0183\,B^2 - 0.0737\,C^2$$

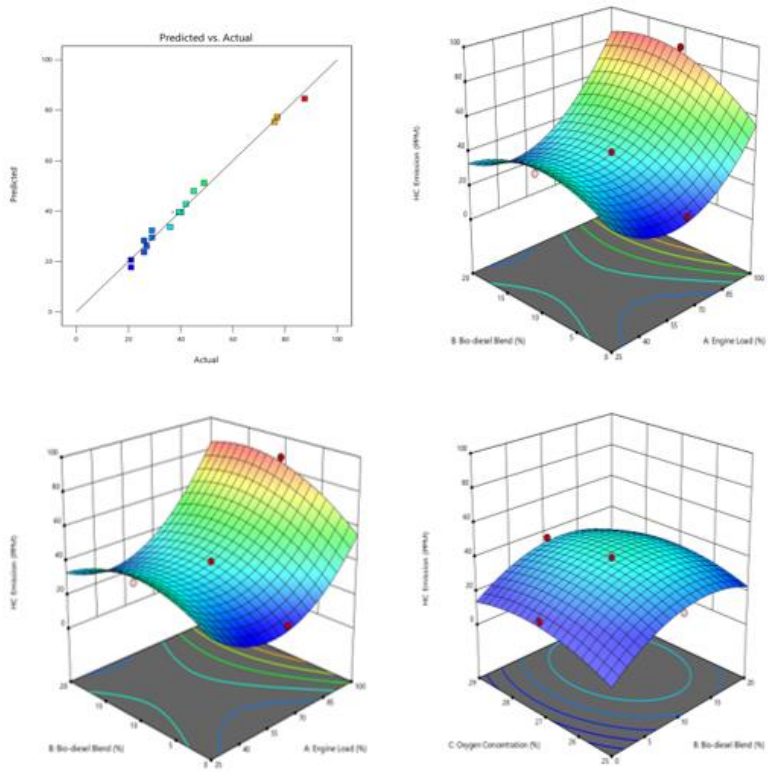


Figure 6. Response Surface Comparison for HC Emission

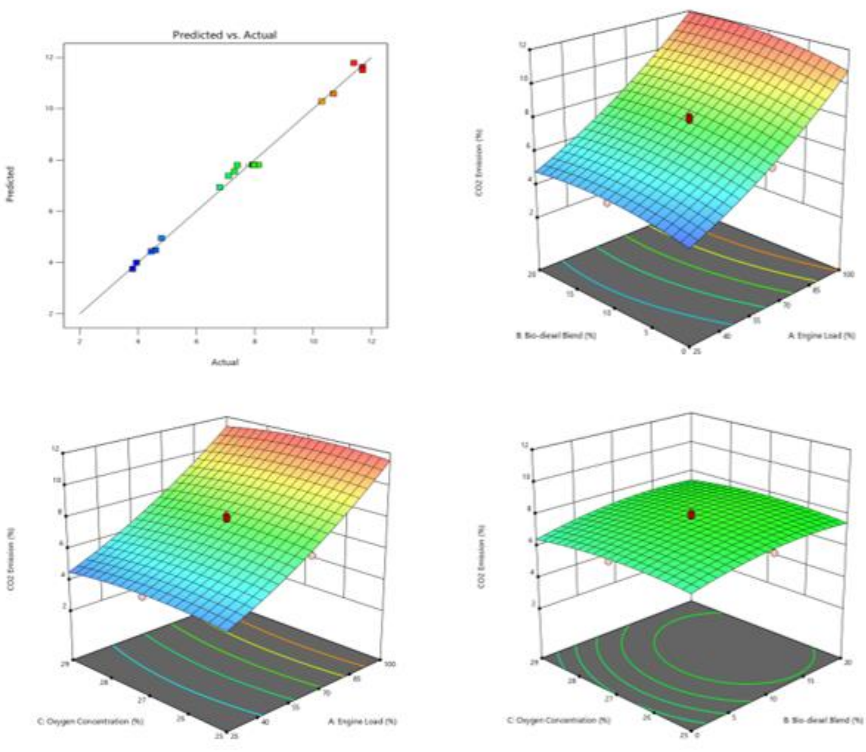


Figure 7. Response Surface Comparison for CO_2 Emission

3.5. HC Emission

Similar to CO nemission, oxygen enrichment causing complete combustion results in a reduction of Hydro carbon emission. **Figure 6** shows that there is a close response in the actual to that of predicted values and depicts the process as significant. The F-value of 115.70 indicates the significance. There is just a 0.01% chance that an F-value owing to noise. The F-value of 117.97 indicates non-significance of lack of fit. The fit statics difference has a difference of 0.06 which is less than 0.2. The code factor equation is given as

$$\text{HC Emission} = 39.51 + 18.35\,A + 7.30\,B + 2.70\,C + 7.37\,AB - 0.1250\,AC - 1.63\,BC + 26.79\,A^2 - 14.46\,B^2 - 8.46\,C^2$$

3.6. CO_2 Emission

With the increase of oxygen enrichment, CO_2 level increases. This is due to the increase in the combustion process which results in reducing CO and HC emissions and increases CO_2 formation. **Figure 7** illustrates a close connection between anticipated and actual values. The F-value of 171.16 and P-value of <0.0500 specifies that the model is significant. The F-value of 28.27 indicates that the Lack of Fit is not statistically significant. The adjusted R^2 value is 0.9877, whereas the predicted R^2 value is 0.9679. Based on the study, the difference in R^2 value is smaller than 0.2 for fit statistics. The coded factor equation for CO2 emissions is as follows

$$CO_2Emission = 7.81 + 3.42\,A + 0.43\,B - 0.088\,C + 0.1375\,AB - 0.0150\,AC + 0.0475\,BC + 0.5580\,A^2 - 0.4420\,B^2 - 0.3420\,C^2$$

3.7. NO_x Emission

With the increase in oxygen concentration, there is a steady rise in Nitrogen oxide emission. But biodiesel addition of the B20 blend provides a moderate increase in nitrogen oxide emission. **Figure 8** shows the close correlation between the actual and predicted and the process is significant. The Model F-value of 119.79 indicates that the model is significant. P-values of less than 0.0500 suggest that it is significant. The F-value of 145.96 indicates that the Lack of Fit is not significant. The difference in R^2 value is 0.06 which is less than 0.2 and the values are above 0.92. So the fit statics is significant. The final equation for NO_x emission is given as

$$NO_x\text{Emission} = 776.37 + 377\,A - 315.1\,B + 19.3\,C - 238.88\,AB + 15.12\,AC - 8.38\,BC - 157.91\,A^2 + 301.59\,B^2 - 62.41\,C^2$$

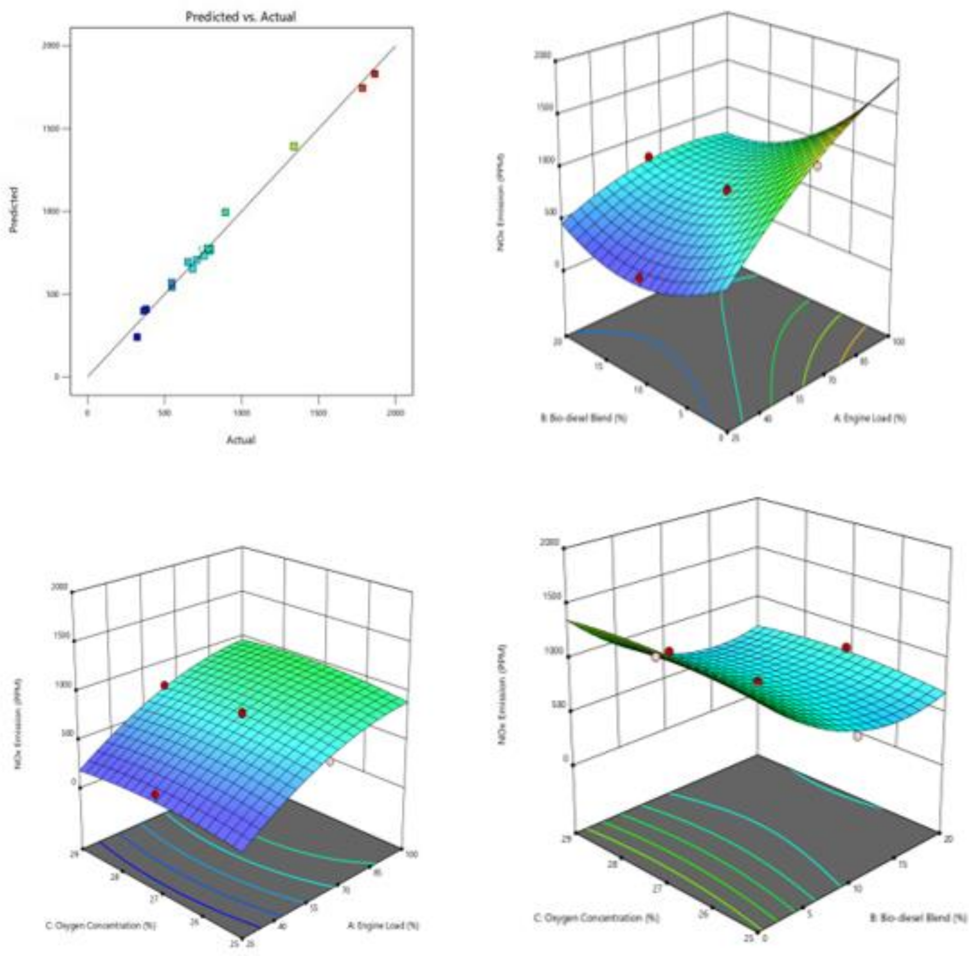


Figure 8. Response Surface Comparison for NO_x Emission

4. Discussion

Response surface methodology ramps plot as shown in **Figure 9** depicts that with the engine load condition of 75% and the Bio-diesel blend of B20 with the oxygen enrichment of 25% oxygen concentration will provide the desirability of 0.719 and the desirable parameters obtained are 0.3 kg/kWh of SFC, Brake Power of 5kW and the Brake Thermal Efficiency as 33%. When we come to emissions it is found that the CO emission of 0.67%, HC emission of 36ppm, CO_2 emission of 8.8%, and the NO_x emission of 704 ppm. This result shows the optimum condition for the operation of the diesel engine.

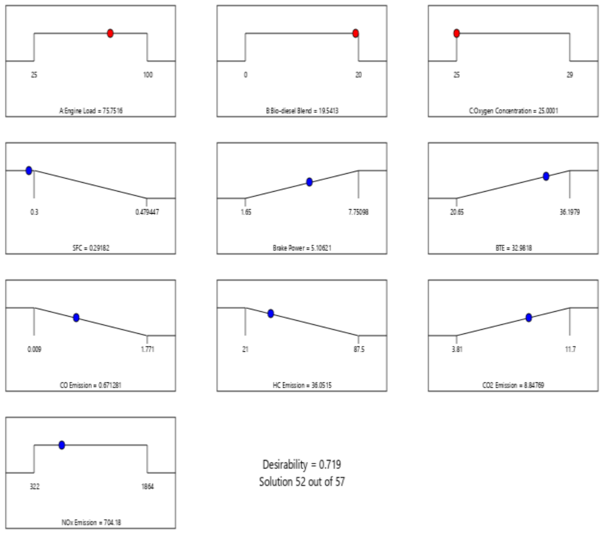


Figure 9. Response Surface Methodology Ramps Plot

5. Conclusion

The response surface methodology model provides a high level of accuracy with a strong association between the actual and predicted values for SFC, BP, and BTE. The higher R^2 values confirm that the model effectively represents the experimental results. Engine load has the most significant influence on brake power and specific fuel consumption. Increasing the engine load tends to improve the efficiency. Optimal engine load will give better performance. Lower biodiesel blends provide a good control over the fuel efficiency and engine performance. Because a higher biodiesel blend above B20 increases the specific fuel consumption as well as reduces the brake power. Oxygen enrichment improves the combustion process which results in the reduction of SFC and increases Brake power. The oxygen concentration of 25-27% was found to be optimal for improving engine performance when biodiesel is used. Because oxygen concentration beyond this range drastically improves the NO_x emission.

The study identified the following optimal conditions for achieving better results. With the 75% engine load, a Biodiesel blend of B20 and an oxygen concentration of 25% provides the best results and better performance characteristics of lower Specific fuel consumption, higher brake power, and improved efficiency. In the emission characteristics, there is a reduction in exhaust emission and the increase of NO_x emission occurs but at a controlled level. So, from the result it is resolved that Oxygen enrichment proved to be an effective strategy to overcome the limitations of biodiesel blends and enabling improved performance in CI engines.

The desirable parameters obtained are 0.3 kg/kWh of SFC, brake power of 5 kW, and the brake thermal efficiency as 33%. Emission parameters are the CO emission of 0.67%, the HC emission of 36 ppm, the CO2 emission of 8.8%, and the NOx emission of 704 ppm.

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