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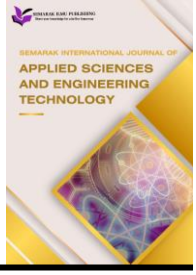

Optimizing Combustion Pressure in Single-cylinder Diesel Engine with Response Surface Methodology (RSM) Using Blended Plastic Oil and Palm Oil Biodiesel

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ABSTRACT

Fossil fuels are both non-renewable and unsustainable. With decreasing diesel resources and increasing plastic waste concerns, exploring environmentally friendly alternative fuels—plastic fuel—is crucial. This study investigates the influences of blended fuel derived from polypropylene plastic waste and palm oil biodiesel (B100, PO10, and PO25 blends) on the peak pressure in single-cylinder diesel engines. The engine load (10, 55, and 100%), engine speed (2000, 2500, and 3000 rev/min), and fuel mixtures of biodiesel: plastic oil (100%: 0%, 90%: 10%, and 75%: 25%) were selected as the independent variables in a Central Composite Design (CCD) experimental plan. Analysis of variance (ANOVA) was performed to explore the influences of independent variables, and desirability analysis was used to determine the optimal setup for maximum peak pressure. Results revealed that the peak pressure increases with engine speed for B100. However, for P010 and P025, the peak pressure peaked at 2500 rev/ min and then bottomed out at 3000 rev/ min. Furthermore, peak pressure increases with engine load for all fuel mixtures. Based on desirability analysis, maximum peak pressure (80.5 bar) can be achieved with an engine speed of 2500 rev/ min, engine load of 100%, and fuel type of P010. Moreover, PO10 could perform better than D100 while using less diesel. It is envisaged that blended plastic oil and palm oil biodiesel could be viable alternative fuels that reduce not only diesel usage but also plastic waste.

1. Introduction

The fuel reserves have been significantly depleted for the past few decades, whereas the demand for diesel has kept increasing in tandem [1,2]. The diesel engine is the most efficient and economical for moving heavy loads and generating electricity. However, diesel engines heavily pollute the environment worldwide and cause many harmful effects: cancer, cardiovascular, and bronchial problems [3]. New diesel sources, such as biodiesel and plastic fuel, could mitigate this problem.

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Biodiesel, derived from renewable sources like palm oil, offers a promising alternative to diesel due to its renewability, lower sulfur content, lower aromatic content, and biodegradability [4]. Furthermore, biodiesel is environmentally friendly and has a higher lubricity than conventional diesel fuel [5]. However, the cost of preparing biodiesel is high [6], and the sources for its production have been widely used in food production [7]; therefore, exploring other options is crucial.

Plastics are used in various industries—automobiles, manufacturing, and household—leading to the exponential rise in plastic waste generation[8]. This plastic waste crisis is a significant concern for the whole world and needs innovative and sustainable waste management. A new pyrolysis technology could convert plastic waste into fuel and solve fuel resource depletion, environmental pollution, and plastic waste management [9]. However, to date, no one has investigated the optimal blend of plastic, biodiesel, and conventional diesel for maximum diesel engine performance (peak pressure). Therefore, this study explores the influences of blended fuel derived from polypropylene plastic waste and palm oil biodiesel (B100, PO10, and PO25 blends) on peak pressure—as a substitute for conventional diesel—in single-cylinder diesel engines. The present work employs a Central Composite Design (CCD) experimental plan in Response Surface Methodology (RSM) to evaluate the effects of engine speed, load, and fuel blends on peak pressure. The desirability analysis was then used to determine the optimal engine speed, load, and fuel blend that produces the highest peak pressure for maximum engine performance. The findings from this comprehensive investigation are expected to contribute significantly to the knowledge base on alternative fuels, paving the way for developing environmentally sustainable ones. The results will complement the recent research gap on plastic fuel that contributes to less efficient fuel consumption and low peak combustion pressure.

2. Methodology

2.1 Preparation of Fuel

The study employed a scientific approach, delving into the technical aspects of polypropylene as a fuel and exploring broader implications for waste management and environmentally friendly energy alternatives. The research involved blending plastic fuel with palm oil biodiesel using the splash blending method to create an alternative fuel for diesel engines. This bending method ensures a consistent and stable mixture, optimizing the advantages of both components. The resulting blend will undergo combustion and performance tests to evaluate its viability as an alternative fuel option for diesel engines, as shown in Table 1. This innovative technique emphasizes a commitment to sustainability by merging the benefits of plastic recycling with the renewable qualities of biodiesel, offering a forward-thinking solution to address energy needs while minimizing environmental impact.

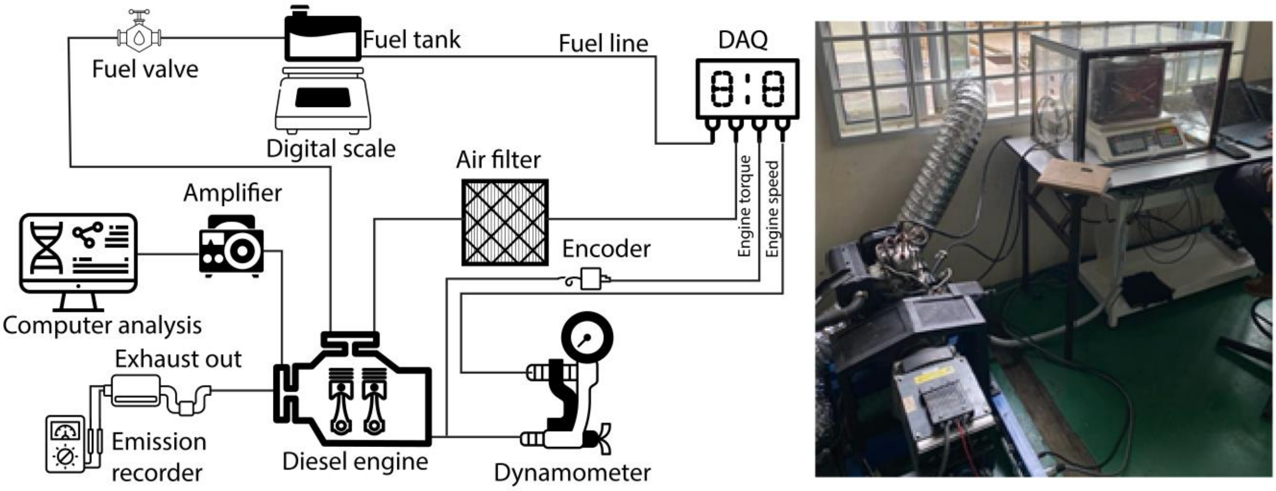
Table 1
Blended ratio for plastic fuel percentage (PO), biodiesel percentage (B), and diesel percentage (D)

PO (%)	B (%)	D (%)
10	90	0
25	75	0
0	100	0

To ensure the quality of the mixed fuel, a stability test was conducted using the gravity method [10]. The mixed fuels were left undisturbed for three days using this method, and any appearance, odor, or density changes were recorded. In this study, no layer formation and consistent densities suggest that the mixtures are consistent and suitable for experimental purposes.

2.2 Experimental Test

Figure 1 shows the experimental setup for the cylinder combustion test process in schematic and actual photographs. The blended samples were kept in the fuel tank, and the consumptions were continuously monitored with a digital scale. The single-cylinder engine (Yanmar L48N, Japan) was attached to the eddy current dynamometer to vary the engine load according to the desired design value. The fuel scale, engine pick-up sensor, air intake temperature, and encoder were connected to the data acquisition for monitoring and recording. The peak pressure was obtained from a pressure sensor connected to the combustion analysis system (sensitivity 0.8 mV/psi, accuracy ± 0.1%).



(a) (b)

Fig. 1. Experimental setup in (a) schematic and (b) photograph view

2.3 Response Surface Methodology and Desirability

Response surface methodology (RSM) employs mathematical and statistical techniques to estimate the effects of variables and identify optimal combinations. The prevalent model utilized in RSM is typically the polynomial model, derived from Taylor series expansion, and can be represented by the following equation:

$$\beta_0 + \sum_{i}^{k} \beta_i X_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \left(\beta_{ij} X_i^2\right) + \varepsilon \quad (1)$$

where *Y* is the response variable, X_i is the factors, *k* is the number of the factors, β_0, β_i and β_{ij} are constants, and ε is the statistical error.

The central composite design (CCD) was applied in this study because the CCD is the most commonly used second-order model in optimizing the response [11]. Three factors (engine load (%), engine speed (rev/ min), and fuel type) and three levels (−1, 0, 1) full factorial design were used in this study (Table 2). The face-centered design (α-value=1) was adopted, resulting in 52 runs. The response measured in this study was peak pressure (bar).

This study employed the desirability function in the Design Expert (Version 13, Stat-Ease Inc, Minneapolis, MN) statistical software to optimize the peak pressure response. The desirability function transforms all responses to the dimensionless value from 0 to 1. The most desired response is 1 and 0, which presents an unacceptable limit [12,13]. The desirability function can be expressed as:

$$d_i = 0, Y_i < Low_i$$
$$d_i = \left[\frac{Y_i - Low_i}{T_i - Low_i}\right]^{wt_i}, Low_i \leq Y_i \leq T_i \quad (2)$$
$$d_i = 1, Y_i > T_i$$

where d_i is the individual desirability, Y_i is the particular response, Low_i is the lower acceptable value, $High_i$ is the acceptable upper value, T_i is the target value, and wt_i is the weight for the target value.

Table 2
Factors and levels used for response surface test

Factor	Type	Low level (-1)	Middle level (0)	High level (+1)
Engine load (%)	Numeric	10	55	100
Engine speed (rev/ min)	Numeric	2000	2500	3000
Fuel type	Categoric	B100	P010	P025

3. Results and Discussion
3.1 Variation of In-Cylinder Pressure

The combustion pressure in an internal combustion engine is an indicator of the combustion process and its impact on engine performance. Figure 2 shows the 2000 rev/min condition for 100% engine load. PO25 blended is showing a significant increase in pressure. Plastic fuel lowers diesel oil's viscosity, improves fuel atomization, and reduces the auto-ignition temperature and ignition delay [14].

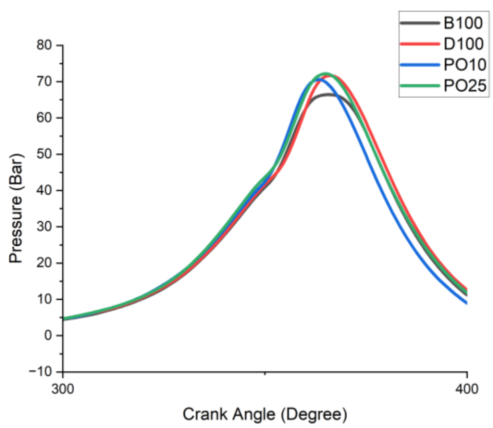


Fig. 2. Pressure trends at 2000 rev/ min

At medium speed (2500 rev/min) and 100% load, the PO25 blend ignited earlier combustion compared with other fuels, and the resemblance pressure value at the combustion peak is shown in Figure 3. The reason could be because the low viscosity PO25 produces good atomization of fuel mixture and therefore, produced earlier combustion.

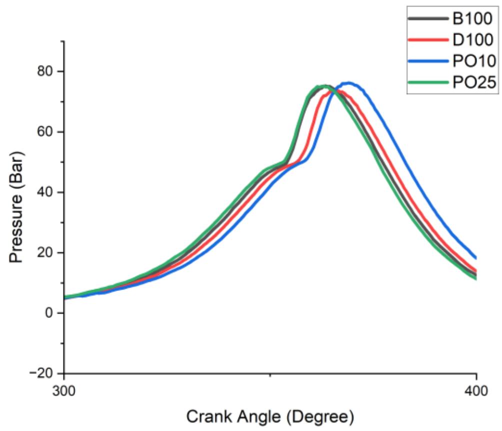


Fig. 3. Pressure trends at 2500 rev/ min

Figure 4 shows the indication of pressure at 3000 rev/min and 100% load. The B100 produces the highest peak pressure due to its high viscosity, cetane number, and calorific value at high speed and the high load of the internal combustion engine [15]. The plastic fuel mixtures (P025 and P010) produce 97.1% and 92.8% of the maximum peak pressure of B100, and therefore, it is evident that the plastic fuel could produce approximately similar performance compared with the conventional diesel and biodiesel.

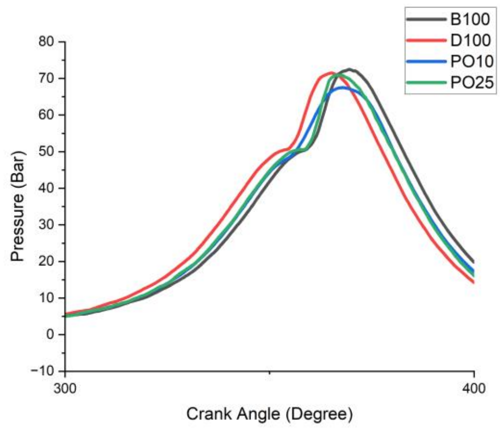


Fig. 4. Pressure trends at 3000 rev/ min

3.3 Analysis of RSM

The experimental results in Table 3 were exported to Design Expert software for analysis of variance (ANOVA) and optimization. The fit summary outputs revealed that the significant model for peak pressure was the "Design Model." The engine load (B) and fuel type (C), interaction between engine speed and fuel type (AC), engine speed squared (A^2), and interaction between engine speed squared and fuel type (A^2C) were found to be the most significant factors affecting the peak pressure ($p < 0.05$), whereas the other factors were insignificant (Table 4). The following regression equation, Eq. (3) explains the functional relationship between peak pressure and other factors in the coded unit.

$$Peak\ pressure = 63.3 - 0.62A + 11.61B - 7.72C1 - 1.65C2 + 5.92C3 - 1.17AB + 3.53AC1 - 0.7908AC2 - 2.65AC3 + 0.04BC1 + 1.66BC2 + 1.13BC3 - 2.18A^2 - 0.86B^2 + 1.25ABC1 - 0.56ABC2 + 0.65ABC3 + 6.23A^2C1 + 3.45A^2C2 - 10.15A^2C3 + 2.57B^2C1 - 1.83B^2C2 - 0.63B^2C3 \quad (3)$$

Table 3
Experimental results from the engine running tests

Run	A: Engine Speed rpm	B: Engine Load %	C: Type of Fuel	Peak Pressure (bar)
1	2000	10	B100	50.6857
2	2000	10	PO25	50.5455
3	2500	55	B100	55.7237
4	3000	100	B100	72.5053
5	2500	55	PO10	69.2551
6	2500	55	PO25	66.1025
7	3000	100	PO25	70.9778
8	3000	10	B0	47.7608
9	2500	55	PO10	69.2551
10	2500	55	PO25	66.1025
11	2500	55	B100	55.7237
12	2500	55	B0	60.7581
13	2000	55	PO10	62.0483
14	2500	55	PO25	66.1025
15	2500	55	PO25	66.1025
16	2500	100	B100	75.2237
17	3000	55	PO25	62.6873
18	2500	55	B0	60.7581
19	3000	55	B0	59.8545
20	2500	55	PO10	69.2551
21	2500	55	PO10	69.2551
22	2500	55	B0	60.7581
23	2500	55	B100	55.7237
24	2500	100	B0	73.7946
25	3000	55	PO10	51.5804
26	2500	55	PO25	66.1025
27	3000	10	PO25	57.4025
28	2000	100	PO10	73.0925
29	3000	10	PO10	38.8313
30	2000	100	B100	67.17
31	2000	100	B0	73.915
32	3000	55	B100	62.7951
33	2500	55	B0	60.7581
34	2000	55	B100	55.7237

35	2000	10	B0	43.2621
36	2000	55	PO25	70.6358
37	3000	100	PO10	67.4853
38	2500	100	PO25	75.1729
39	2500	55	PO10	69.2551
40	3000	10	B100	55.7025
41	2500	10	PO10	59.1271
42	2000	10	PO10	42.3849
43	2500	55	B100	55.7237
44	2500	10	PO25	59.6598
45	2500	100	PO10	76.2024
46	3000	100	B0	71.5053
47	2000	100	PO25	74.1425
48	2500	55	B100	55.7237
49	2000	55	B0	70.4233
50	2500	55	B0	60.7581
51	2500	10	B100	38.6226
52	2500	10	B0	48.5715

The coefficient (R^2) was determined to verify the model's goodness of fit. The present model explained 93% of the variability in the peak pressure (R^2=0.93). The signal-to-noise ratio was more than 4, which suggests this model is adequate to navigate the design space (Adeq. Precision=17.5366). The peak pressures for different fuel types are shown in Figure 5 - Figure 7. When using B100 and P025, the peak pressure increases with engine speed and load. These trends are expected because an increase in engine load and speed produces higher power and higher peak pressures [16]. For P010, a similar trend was observed when increasing the engine load. However, when increasing the engine speed, the peak pressure reached the maximum value at 2500 rev/ min and bottomed out at a speed of 3000 rev/ min. Figure 8 shows the optimization result using the desirability analysis. Based on the figure, the optimal peak pressure can be achieved with an engine speed of 2500 rev/ min and a load of 100%.

Table 4
Resulting ANOVA table for reduced cubic model (response: peak pressure)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4501.76	23	195.73	16.88	< 0.0001	significant
A-Engine Speed	9.30	1	9.30	0.8022	0.3781	
B-Engine Load	3234.80	1	3234.80	278.96	< 0.0001	significant
C-Type of Fuel	367.31	3	122.44	10.56	< 0.0001	significant
AB	21.77	1	21.77	1.88	0.1815	
AC	120.51	3	40.17	3.46	0.0294	significant
BC	72.22	3	24.07	2.08	0.1260	
A^2	52.68	1	52.68	4.54	0.0420	significant
B^2	8.08	1	8.08	0.6972	0.4108	
ABC	16.35	3	5.45	0.4699	0.7057	
A^2C	425.12	3	141.71	12.22	< 0.0001	significant
B^2C	28.59	3	9.53	0.8218	0.4929	
Residual	324.68	28	11.60			
Lack of Fit	324.68	12	27.06			
Pure Error	0.0000	16	0.0000			
Cor Total	4826.44	51				
Std. Dev.	3.41	R^2	0.9327			
Mean	61.90	Adjusted R^2	0.8775			
C.V. %	5.50	Predicted R^2	0.3463			
		Adeq. Precision	17.5366			

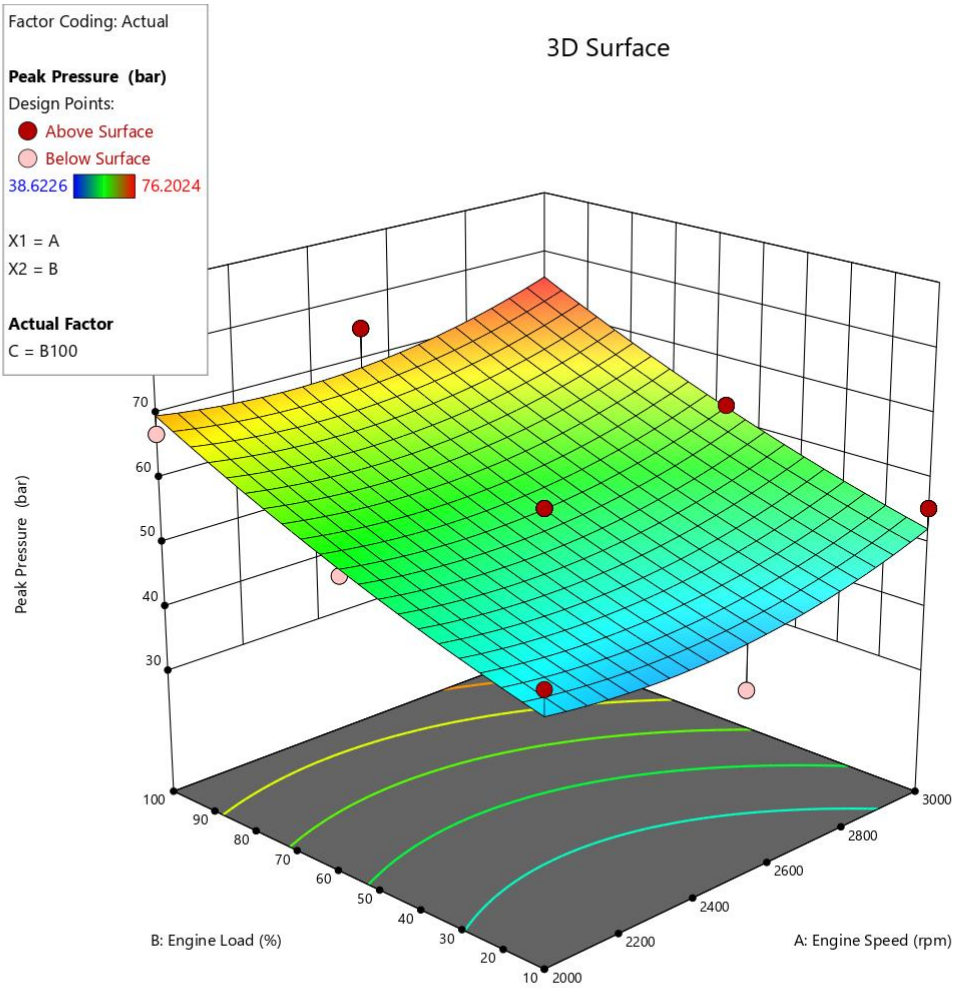


Fig. 5. 3D surface plot(A-B) for peak pressure using B100 fuel

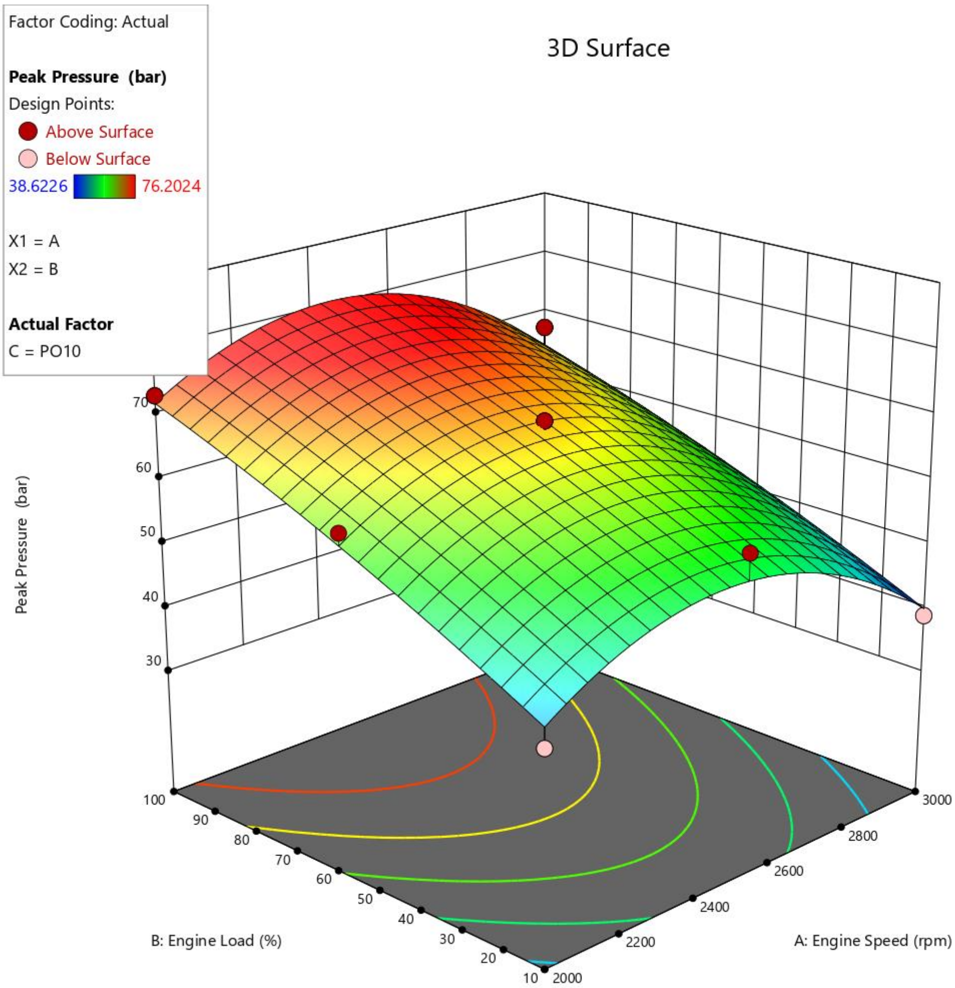


Fig. 6. 3D surface plot(A-B) for peak pressure using P010 fuel

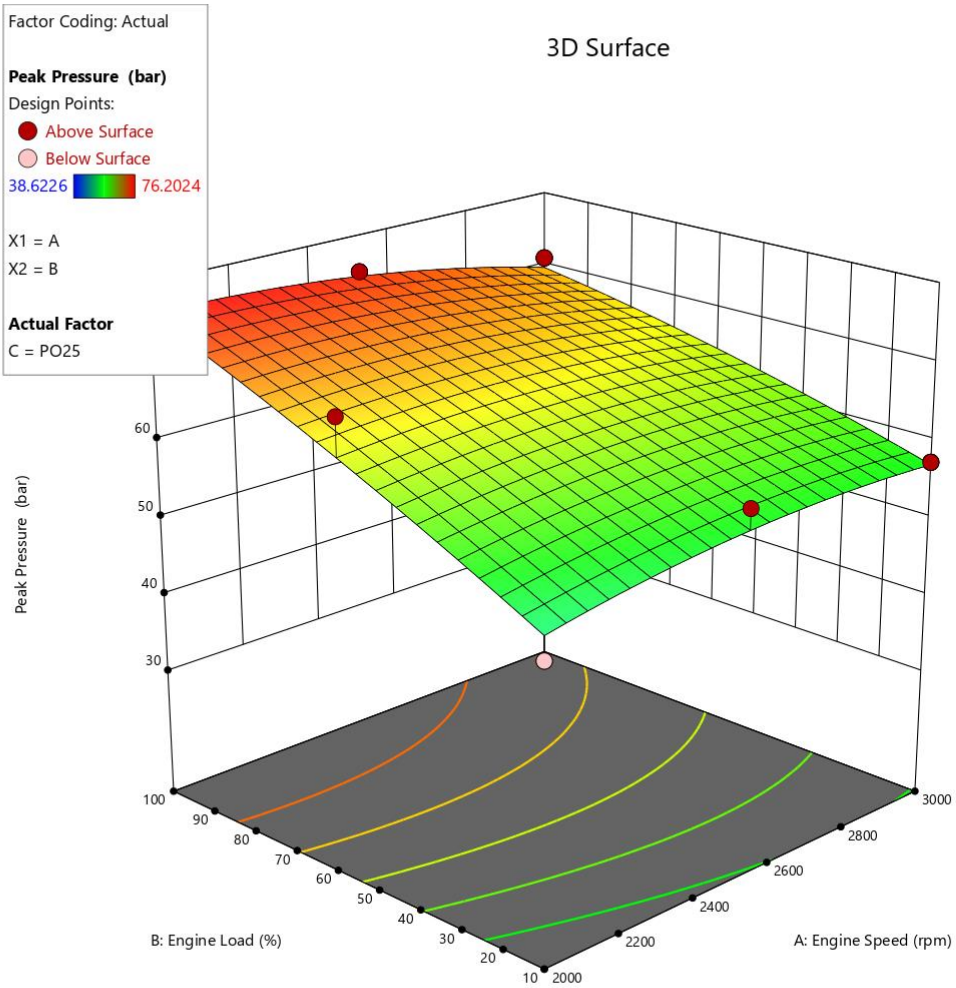


Fig. 7. 3D surface plot(A-B) for peak pressure using P025 fuel

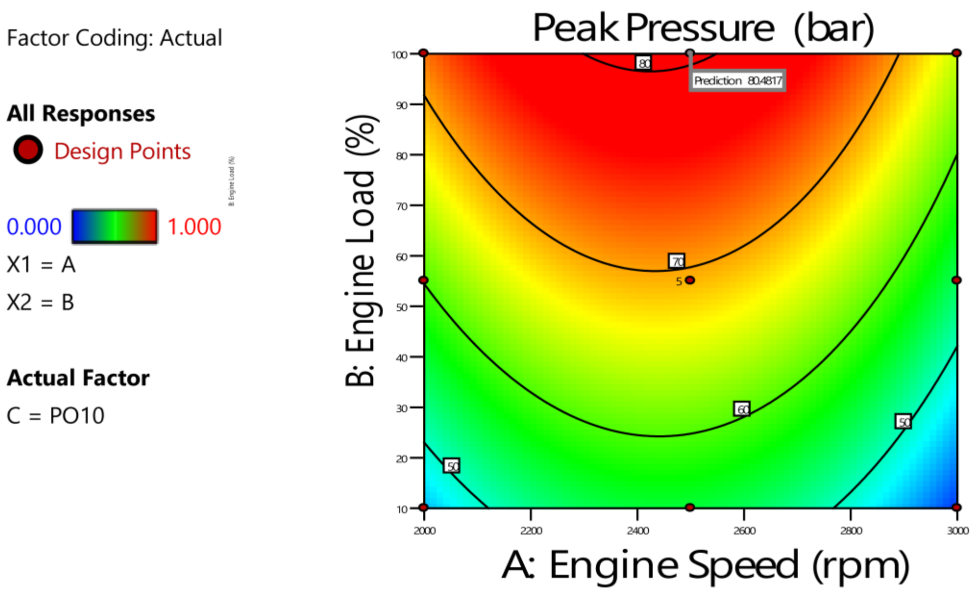


Fig. 8. Desirability analysis results

4. Conclusion

The present work proposes an engine speed of 2500 rev/ min and an engine load of 100% for maximum peak pressure. Furthermore, using the P010 fuel produces better performance in terms of peak pressure than other fuel types (P025 and B100). The essential conclusions from our study are summarized below:

- Peak pressure increases with the increase of engine speed and engine load.
- Engine load and speed significantly affect the peak pressure.
- P010 plastic fuel produces better performance than B100 and P025.
- Plastic fuel can be the future solution for waste management, depleted fuel reserves, and a green environment.

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