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Research Article

Optimization of biodiesel production from jatropha oil and its impact on engine performance and emissions using response surface methodology

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ABSTRACT

This study aims to improve biodiesel production by assessing the effects of biodiesel-diesel fuel blends on engine performance and emissions using response surface methodology (RSM). The biodiesel was produced by the transesterification process. Here we see how the molar ratio (A), catalyst quantity (B), reaction temperature (C), and reaction time (D) affect the biodiesel conversion rate. During optimization, a Box-Behnken design (BBD) based on RSM was employed. Ideal conditions for achieving a biodiesel yield of 98.2069% were a B of 0.811601 wt%, a C of 75.8837°C, a D of 98.2069 min, and A of 7:1. Adjusting parameters like engine speed and biodiesel fuel mix ratio enhanced engine behavior and condensed exhaust emissions. The trials were structured utilizing the central composite design (CCD) technique grounded on RSM. The optimum operating criteria for the engine were evaluated to be a biodiesel ratio of 12.5845% and speed of engine is 2011.24 rpm. Under these conditions, the power output was 50.0817kW, torque was 254.757 Nm, smoke opacity was 6.48966%, CO emissions were 270.009 ppm, and NOx emissions were 819.573 ppm. These findings indicate that appropriate adjustments in biodiesel-diesel blends and engine parameters can significantly enhance engine performance and reduce exhaust emissions, providing insights into more efficient and environmentally friendly fuel utilization.

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INTRODUCTION

Energy consumption on a worldwide scale is mostly supported by petroleum fuels. Researchers are investigating renewable energy options because of the exhaustion of fossil fuel reserves [1]. A renewable alternative fuel, biodiesel is made from used cooking oils, plant oils, and animal fats [2]. This fuel has more cetane numbers and is renewable, biodegradable, and non-toxic than diesel fuel, and it burns more efficiently and with less pollution in the exhaust [3, 4]. Diesel engines can run on it alone or mix it with diesel fuel for added efficiency [5]. Jatropha oils are edible and environmentally beneficial as they are recyclable and more cost-effective than vegetable-based oils. Utilizing waste oil has benefits in terms of economics, environmental impact, and waste management [6, 7]. Various methods are utilized in biodiesel generation. The transesterification method is the more cost-effective production approach [8, 9]. The effect of process factors on biodiesel conversion rate has been the subject of sev-

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eral studies [10]. Jatropha typically results in lower emissions of particulate matter and sulfur dioxide, which contribute to improved air quality and reduced acid rain. It can be cultivated on marginal lands, potentially reducing competition with food crops. Assessing the biodiesel production is crucial for determining the fuel quantity. Several factors influence the biodiesel productivity, including speed, molar ratio of alcohol, time, temperature for reaction, and catalyst quantity [11]. Currently, the manufacture of biodiesel has gotten more expensive due to the existing technology. Various mathematical tools are receiving increased attention to address this issue. Mathematical models provide valuable insights for analyzing and predicting processes. They are utilized to optimize input parameters in order to improve process outputs [12, 13]. The response surface methodology is an effective statistical tool for optimizing biodiesel production process factors [14]. Statistically correct results can be obtained with less experimental runs using RSM, which is its main advantage [15]. With RSM, the best possible value for the response variable can be determined. The use of RSM has allowed several studies to fine-tune process factors in biodiesel manufacture. Experts have studied the effect of process factors on low-temperature algal oil biodiesel conversion [16]. RSM and ANN was used to examine the transesterification of algae oil. Relative Standard Deviation (RSD) values for ANN and RSM models were 0.999651 and0.9657, correspondingly. Researchers [17, 18] identified the ideal conditions for the transesterification process of sandbox seed oil. The production of biodiesel required the use of two catalysts: potassium hydroxide and calcined snail shell. Optimization was carried out using the RSM approach. The selected input parameters included time, temperature, and catalyst quantity. Many experts have studied biodiesel's impact on diesel engine efficiency and pollution levels in great detail. Several authors used the RSM to look at how different fuel mixtures and biodiesel affected performance and emissions [19]. The ideal operating parameters for a single-cylinder diesel engine that runs on a mixture of diesel and grape seed biodiesel at various volume ratios (5, 10, and 15%) were determined by researchers [20] using RSM. Exhaust gas temperature (EGT), smoke, NOx, CO, and HC were defined as responses, whereas injection pressure, engine load, biodiesel blend ratio, and brake-specific fuel consumption (BSFC) were chosen as independent factors. Through the application of response surface approaches, an engine that utilized a diesel fuel mixture with mahua oil methyl ester was fine-tuned in terms of both efficiency and emission levels [21]. The effects of various blend-to-torque load ratios on brake thermal efficiency (BTE), smoke opacity, brake specific fuel consumption (BSFC), hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NOx) emissions were studied. Using the BBD technique in RSM, this study seeks to determine the best process parameters for biodiesel production from Jatropha Oil. By optimizing engine variables such as blend ratio and engine speed, CCD based on RSM can increase engine power and torque values while reducing exhaust pollutants. The objective of this study is to evaluate the factors influencing biodiesel productivity and optimize the production process using mathematical models and response surface methodology (RSM). By assessing the impact of variables such as speed, molar ratio of alcohol, reaction time, temperature, and catalyst quantity, the study aims to enhance the efficiency and reduce the costs associated with biodiesel manufacturing. The novelty of this study lies in its application of response surface methodology (RSM) to optimize biodiesel production by systematically evaluating key influencing factors such as speed, molar ratio of alcohol, reaction time, temperature, and catalyst quantity. By leveraging advanced mathematical models, this approach aims to reduce production costs and improve efficiency, providing statistically accurate results with fewer experimental runs. This innovative use of RSM offers a comprehensive and cost-effective solution to enhance biodiesel manufacturing processes.Table1 gives the comparison between the current study with different literatures.

EXPERIMENTAL METHODOLOGY

Process of producing biodiesel

This analysis used Jatropha Oil obtained from households to produce biodiesel. This study used Jatropha Oil obtained from local households to produce biodiesel. Potassium hydroxide (KOH) was chosen as the catalyst and methanol (CH3OH) as the alcohol. Figure 1 displays the biodiesel manufacturing diagram.

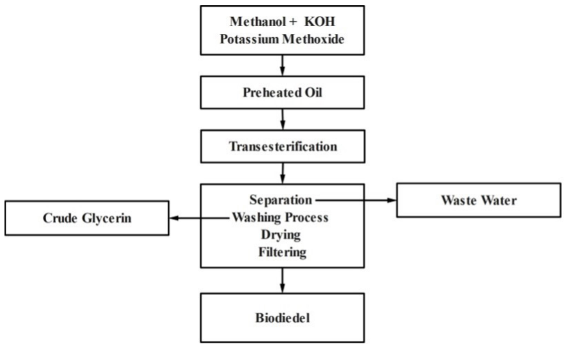

Figure 1. Schematic diagram illustrating the biodiesel production method

Preparing fuel blends for engine testing

Biodiesel produced from Jatropha Oil under ideal conditions was blended with pure diesel at varying volume ratio (0, 30, and 60%). Table 2 displays the apparatus utilized for assessing the fuel characteristics. The transesterification process of Jatropha biodiesel involves converting Jatropha oil into biodiesel by reacting it with methanol in the presence of a catalyst, typically sodium hydroxide or potassium hydroxide.

Engine testing unit

This engine delivers a power output of 89 kW at 3200 rpm and generates a torque of 295 Nm at 1800 rpm. Weighing 325 kg, the engine is equipped with a water-cooled oil cooler, enhancing its performance and durability.

Fuel blends were experimentally tested on a Mitsubishi Canter 4D34-2A type diesel engine with a hydraulic dynamometer to study their effects. Table 3 provides details on the engine unit utilized in studies, whereas Figure 2 shows a schematic representation of the experimental testing unit. While the MRU OpTrans 1600 uses absorption photometry to evaluate smoke opacity levels, the TESTO 350-S flue gas analyzer analyzes NOx and CO emissions. The results and their associated uncertainty are shown in Table 4.

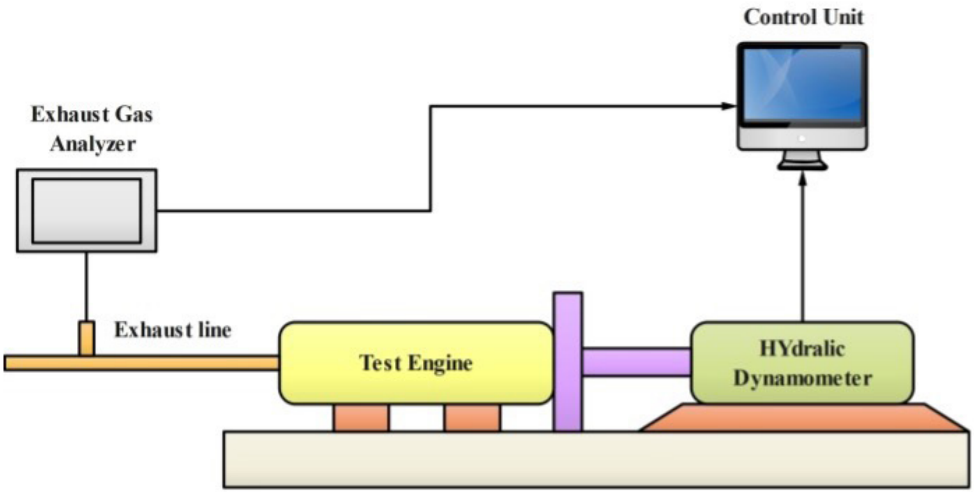

Figure 2. Diagram illustrating the experimental testing unit

Table 1. Comparison of comparison between the current study with recent literature

Authors	Title	Comments
H. Farouk, S. M. Zahraee, A. E. Atabani, M. N. Mohd Jaafar, F. H. Alhassan	Optimization of the esterification process of crude jatropha oil (CJO) containing high levels of free fatty acids: a Malaysian case study	Focuses on optimizing the esterification process for crude jatropha oil with high FFA using RSM in a Malaysian context.
K.-T. Liu, S. Gao, T.-W. Chung, C.-M. Huang, Y.-S. Lin	Effect of process conditions on the removal of phospholipids from Jatropha curcas oil during the degumming process	Investigates the impact of process conditions on phospholipid removal from Jatropha curcas oil during degumming, utilizing RSM.
A. Singh, S. Sinha, A. K. Choudhary	Optimization of Operating Parameters of Diesel Engine Powered with Jatropha Oil Diesel Blend by Employing Response Surface Methodology	Employs RSM to optimize operating parameters of a diesel engine powered by Jatropha oil-diesel blend.
M. Athar et al.	Biodiesel production by single-step acid-catalysed transesterification of Jatropha oil under microwave heating with modelling and optimisation using response surface methodology	Models and optimizes biodiesel production from Jatropha oil via single-step acid-catalyzed transesterification under microwave heating using RSM.
A. Ashok, S. K. Gugulothu, R. V Reddy, H. Ravi	Box-Behnken Response Surface Methodology Based Multi-Objective Optimization on Reactivity Controlled Compression Ignition Engine Characteristics Powered With Ternary Fuel	Uses Box-Behnken RSM for multi-objective optimization of a Reactivity Controlled Compression Ignition engine using ternary fuel.

Table 2. Fuel characteristics measuring devices

S. No	Properties	Units	Range	Accuracy
1	Viscosity@45°C	cSt	4.96	±0.01
2	Density @15°C	g/cm3	895.2	±0.001
3	Higher heating value	kJ/kg	39.871	0.001K
4	Cloud point	°C	0	±1
5	Pour point	°C	+5	±1
6	Cold filter plugging point	°C	+2	–

Table 3. Characteristics of the experimental engine unit

Manufacturer/series type	**Mitsubishi canter 4D3A-2A**
Engine type	Diesel engine with direct fuel injection and glow plug
Stroke	115 mm
Power	89 kW@3200 rpm
Bore	104 mm
Displacement	3907 cc
Torque	295 Nm at 1800 rpm
Weight	325 kg
Oil cooler	Water cooled

Table 4. Measurement accuracy and result uncertainty

Parameter	**Units**	**Accuracy**
Speed	rpm	±2
NOx	ppm	±1
CO	ppm	±10
Brake power	%	±2
Torque	%	±2
Smoke	%	±1
Calculated result		Uncertainty

RSM

In order to maximize the results, the RSM is a mathematical technique that is used to simulate and analyze scenarios impacted by various variables. RSM is a powerful tool for optimizing processes, understanding variable interactions, reducing experimentation efforts, and improving process efficiency and robustness. Equation (1) shows that the RSM model predicts the response surface using a quadratic polynomial equation [22], [23].

$$Y = \beta_0 + \sum_{i=1}^{n}\beta_i x_i + \sum_{i=1}^{n}\beta_{ii} x_i^2 + \sum_{i>j}^{n}\sum_{j}^{n}\beta_{ij} x_i x_j + e \quad (1)$$

Y projected output result

n number of components

b0 constant

bi linear

bii quadratic

bij interaction coefficients

xj are xi independent parameters

e error.

EXPERIMENTAL DESIGN

A Box Benchmen Design in RSM was used to simulate biodiesel synthesis using four variables. Using different values for the following four input parameters. The 29 experiments were carried out to predict biodiesel yield. The trial input factors are listed in Table 5.

Table 5. Input factors and its levels

Factors Code	Units	Levels		
		+1	0	+2
A	**molar ratio**	**4**	**6**	**8**
B	**wt%**	**0.6**	**0.8**	**1.0**
C	**°C**	**50**	**60**	**70**
D	**min**	**60**	**80**	**100**

The engine trials were planned and improved with the help of a CCD. In order to predict and optimize engine outputs at three levels (1, 0, 1), we used two independent factors: blending ratio and speed of the engine.

Table 6. Parameters and levels in engine experimentation

Parameters	Symbol	Units	Levels		
			+1	0	1
Blend	**X**	**%**	**0**	**30**	**60**
Engine speed	**Y**	**rpm**	**1450**	**1850**	**2250**

Table 6 shows the levels of the input parameters. There are a total of 13 experimental runs in the CCD. The number of experimented trials were determined using Equation (2).

$$N = 2^k + 2 * k + NC$$

The number of centre points is indicated by NC, while the no of independent factors is represented by the variable k [24].

RESULTS AND DISCUSSIONS

Optimizing using RSM

The BBD experimental design utilized four independent variables (process parameters) to determine the highest biodiesel yield, as displayed in Table 7. Equation (3) illustrates the coded-component numerical model that links the results to the in depending factors [25], [26].

Biodiesel Yield (Y) = +97.76 +0.3258 A +0.2325 B +1.40 C -0.4025 D +0.3125AB +0.4275 AC +0.1125 AD +0.3425 BC -0.2975 BD -0.1975 CD -3.95 A2 -2.64 B2 -1.31 C2 -1.68 (3)

Table 7. Experimental input and its results of Jatropha Oil biodiesel by BBD

S. No	A	B	C	D	Experimented yield	Theoretical yield	Error
	molar ratio	wt%	°C	min	wt%	wt%	%
1	6	0.8	60	80	98.15	97.76	0.4
2	6	0.6	70	80	94.49	94.64	0.16
3	6	0.8	60	80	98.2	97.76	0.45
4	6	0.8	60	80	98.16	97.76	0.41
5	4	0.8	60	100	92.03	91.29	0.81
6	4	1	60	80	92.16	90.76	1.53
7	6	0.8	50	60	94.05	93.59	0.49
8	4	0.8	70	80	92.53	93.15	0.67
9	8	0.8	60	100	92.8	92.17	0.68
10	6	0.8	50	100	93.27	93.18	0.1
11	8	0.6	60	80	90.97	90.95	0.02
12	8	0.8	50	80	91.62	91.01	0.67
13	8	0.8	70	80	94.5	94.66	0.17
14	6	1	60	100	92.36	92.97	0.66
15	6	0.6	50	80	92.77	92.53	0.26
16	4	0.8	60	60	92.28	92.32	0.04
17	6	0.8	70	60	97.9	96.78	1.15
18	4	0.8	50	80	91.26	91.21	0.05

19	6	1	60	60	94.17	94.37	0.21
20	6	1	70	80	95.83	95.79	0.04
21	8	0.8	60	60	92.5	92.75	0.27
22	6	0.6	60	100	93.1	93.10	0
23	8	1	60	80	92.18	92.04	0.15
24	6	0.8	60	80	98.16	97.76	0.41
25	6	0.8	70	100	96.38	95.58	0.83
26	6	0.6	60	60	93.77	93.31	0.49
27	6	0.8	60	80	97.14	97.76	0.64
28	4	0.6	60	80	91.7	90.92	0.85
29	6	1	50	80	92.64	92.31	0.36

Table 8. Design of CCD and engine response experiments

Run	Input Factors		Power(kW)		Torque (Nm)	
	X (%)	Y (rpm)	Experiment	Predicted	Experiment	Predicted
1	0	2250	55	54.68	259.78	260.15
2	30	2250	52.43	52.82	241.68	241.11
3	30	1850	46.6	46.72	247.71	246.8
4	60	1450	40.14	40.29	240.34	239.59
5	60	1850	43.39	43.3	235.01	235.56
6	30	1850	47.34	46.72	247.04	246.8
7	60	2250	49.52	49.46	229.19	229.39
8	30	1450	43.8	43.76	249.02	250.34
Run	Input Factors		Power(kW)		Torque (Nm)	
	X (%)	Y (rpm)	Experiment	Predicted	Experiment	Predicted
9	30	1850	47.02	46.72	247.07	246.8
10	30	1850	46.64	46.72	245.81	246.8
11	0	1450	45.83	45.72	268.99	268.41
12	30	1850	46.35	46.72	247.11	246.8
13	0	1850	48.2	48.63	265.15	265.35

Run	Smoke Opacity (%)		CO (ppm)		NOx (ppm)	
	Experimented	Theoretical	Experimented	Theoretical	Experimented	Theoretical
1	7.5	7.56	301	295.64	673	665.24
2	7.3	7.23	266	262.81	790	788.41
3	6.5	6.57	236	244.31	960	960.08
4	10.2	10.16	196	192.97	1263	1254.91
5	6.2	6.23	214	211.47	1086	1083.24
6	6.3	6.57	244	244.31	956	960.08
7	7	7.01	228	229.97	907	911.58
8	10.6	10.63	226	225.81	1127	1131.74
9	6.5	6.57	241	244.31	955	960.08
10	6.7	6.57	244	244.31	956	960.08
11	11.2	11.21	262	258.64	1010	1008.58
12	6.8	6.57	246	244.31	964	960.08
13	7.1	7.03	272	277.14	834	836.91

The engine behaviour and emission testing as well as reaction condition optimization were designed using the Design Expert 13 tool. Engine experimental matrix with both theoretical and experimented data is indicates in Table 8 using the CCD model. Real engine performance parameters are computed using equations (4) and (5). Eqs. (6 - 8) are utilized to calculate real engine exhaust emission parameters.

$$\text{Power} = +46.720 - 2.66\ X + 4.53\ Y + 0.0525\ XY - 0.7524\ X^2 + 1.57\ Y^2 \quad (4)$$

$$\text{Torque} = +246.80 - 14.90\ X - 4.62\ Y - 0.4850\ XY + 3.66\ X^2 - 1.07\ Y^2 \quad (5)$$

$$\text{Smoke OpXcity} = +6.57 - 0.4000\ X - 1.70\ Y + 0.1250\ XY + 0.0586\ X^2 + 2.36\ Y^2 \quad (6)$$

$$\text{CO} = +242.21 - 32.83\ X + 18.50\ Y - 1.75\ XY + 0.7759\ X^2 + 3.78\ Y^2 \quad (7)$$

$$\text{NOx} = +957.79 + 123.17\ X - 171.67\ Y - 4.75\ XY + 3.22\ X^2 + 1.72\ Y^2 \quad (8)$$

The significance of the experiments and the model can be evaluated using ANOVA. Table 9 displays the ANOVA results for biodiesel production. The table displays that the F-value for biodiesel production was 27.22, indicating the model's relevance. P-values below 0.0500 indicate that the model terms are statistically significant. C, A2, B2, C2, and D2 are important model terms in this criterion. A lack of fit value of 1.64 indicates that the lack of fit is not serious. A lack of fit that is not considerable is beneficial for the model's fit. An R2 value of 0.9646 was found by analyzing the regression equation using ANOVA. Predictions for R2 and adjusted R2 were 0.8250 and 0.9291. The anticipated R2 and adjusted R2 values show a close agreement since the difference between them is less than 0.2.

Table 9. ANOVA for biodiesel production

Source	SS	df	MS	F-value	p-value	
Model	157.80	14	11.27	27.22	< 0.0001	significance
A-A	1.27	1	1.27	3.08	0.1013	
B-B	0.6487	1	0.6487	1.57	0.2313	
C-C	23.44	1	23.44	56.59	< 0.0001	
D-D	1.94	1	1.94	4.69	0.0480	
AB	0.3906	1	0.3906	0.9432	0.3479	
AC	0.7310	1	0.7310	1.77	0.2052	
AD	0.0506	1	0.0506	0.1222	0.7318	
BC	0.4692	1	0.4692	1.13	0.3051	
BD	0.3540	1	0.3540	0.8548	0.3708	
CD	0.1560	1	0.1560	0.3767	0.5492	
A^2	101.24	1	101.24	244.45	< 0.0001	
B^2	45.31	1	45.31	109.42	< 0.0001	
C^2	11.06	1	11.06	26.70	0.0001	
D^2	18.27	1	18.27	44.11	< 0.0001	
Residual	5.80	14	0.4141			
Lack of Fit	4.66	10	0.4663	1.64	0.3342	Non- significance
Pure Error	1.14	4	0.2838			
Cor Total	163.60	28				

Table 10. Results on ANOVA on torque and power

Source	Power			Torque		
	SS	F-value	P-value	SS	F-value	P-value
Model	172.56	215.58	< 0.0001	1497.62	379.29	< 0.0001
A-X	42.56	265.85	< 0.0001	1331.46	1686.06	< 0.0001
B-Y	123.13	769.10	< 0.0001	127.88	161.94	< 0.0001
XY	0.0110	0.0689	0.8005	0.9409	1.19	0.3112
X^2	1.56	9.77	0.0167	36.99	46.84	0.0002
Y^2	6.79	42.39	0.0003	3.16	4.01	0.0854
Residual	1.12			5.53		
LOF	0.5130	1.13	0.4383	3.60	2.49	0.1990
Pure Error	0.6076			1.93		
Cor Total	173.68			1503.14		

Table 11. ANOVA for nitrogen oxides, carbon monoxide and smoke opacity

Source	Smoke opacity			CO			NOx		
	SS	F-value	P-value	SS	F-value	P-value	SS	F-value	P-value
Model	**36.69**	**302.28**	**< 0.0001**	**8589.13**	**107.72**	**< 0.0001**	**2.680E+05**	**3207.51**	**< 0.0001**
A-X	**0.9600**	**39.55**	**0.0004**	**6468.17**	**405.58**	**< 0.0001**	**91020.17**	**5447.12**	**< 0.0001**
B-Y	**17.34**	**714.36**	**< 0.0001**	**2053.50**	**128.76**	**< 0.0001**	**1.768E+05**	**10581.63**	**< 0.0001**
XY	**0.0625**	**2.57**	**0.1526**	**12.25**	**0.7681**	**0.4099**	**90.25**	**5.40**	**0.0531**
X^2	**0.0095**	**0.3910**	**0.5516**	**1.66**	**0.1042**	**0.7562**	**28.71**	**1.72**	**0.2313**
Y^2	**15.36**	**632.99**	**< 0.0001**	**39.38**	**2.47**	**0.1601**	**8.21**	**0.4913**	**0.5060**
Residual	**0.1699**			**111.64**			**116.97**		
Lack of Fit	**0.0179**	**0.1571**	**0.9198**	**50.84**	**1.11**	**0.4417**	**60.17**	**1.41**	**0.3623**
Pure Error	**0.1520**			**60.80**			**56.80**		
Cor Total	**36.86**			**8700.77**			**2.681E+05**		

Tables 10 and 11 display the results of the analysis of variance (ANOVA) for the torque, power, smoke, CO, and NOx regression models. With p-values less than 0.05, the model terms are considered statistically significant according to the ANOVA analysis. Results showed that the R2 values for CO, power, smoke, NOx, and torque were 0.9872, 0.9935, 0.9954, 0.9996, and0.9963, respectively. There was an evaluation of adjusted R2 values of 0.9889 for power, 0.9937 for torque, 0.9780 for smoke, 0.9826 for CO, and 0.9993 for NOx. The planned and actual values of biodiesel production are strongly correlated, as seen in Figure 3. An accurate depiction of the biodiesel production experimental data is given by the model.

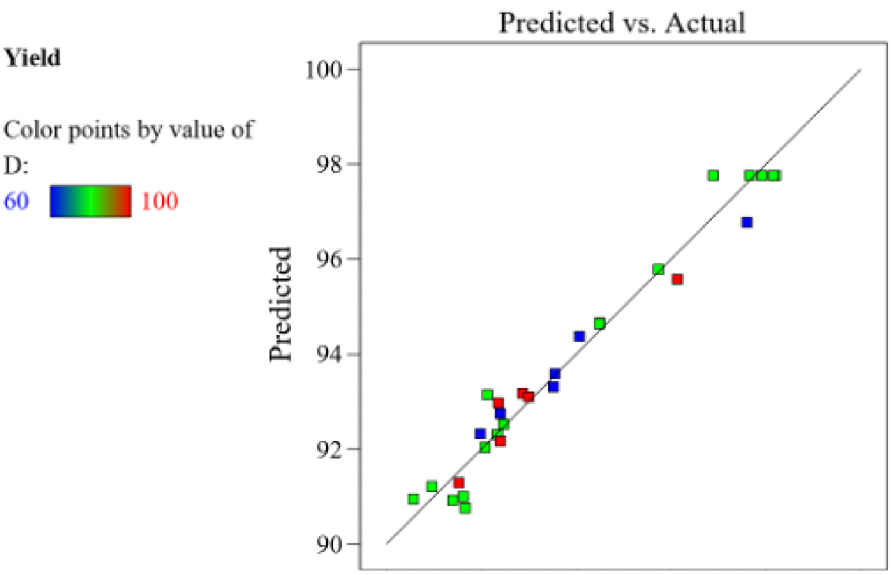

Figure 3. Predicted data and actual yield of Regression plot using RSM

Effects of reaction factors on the production of biodiesel

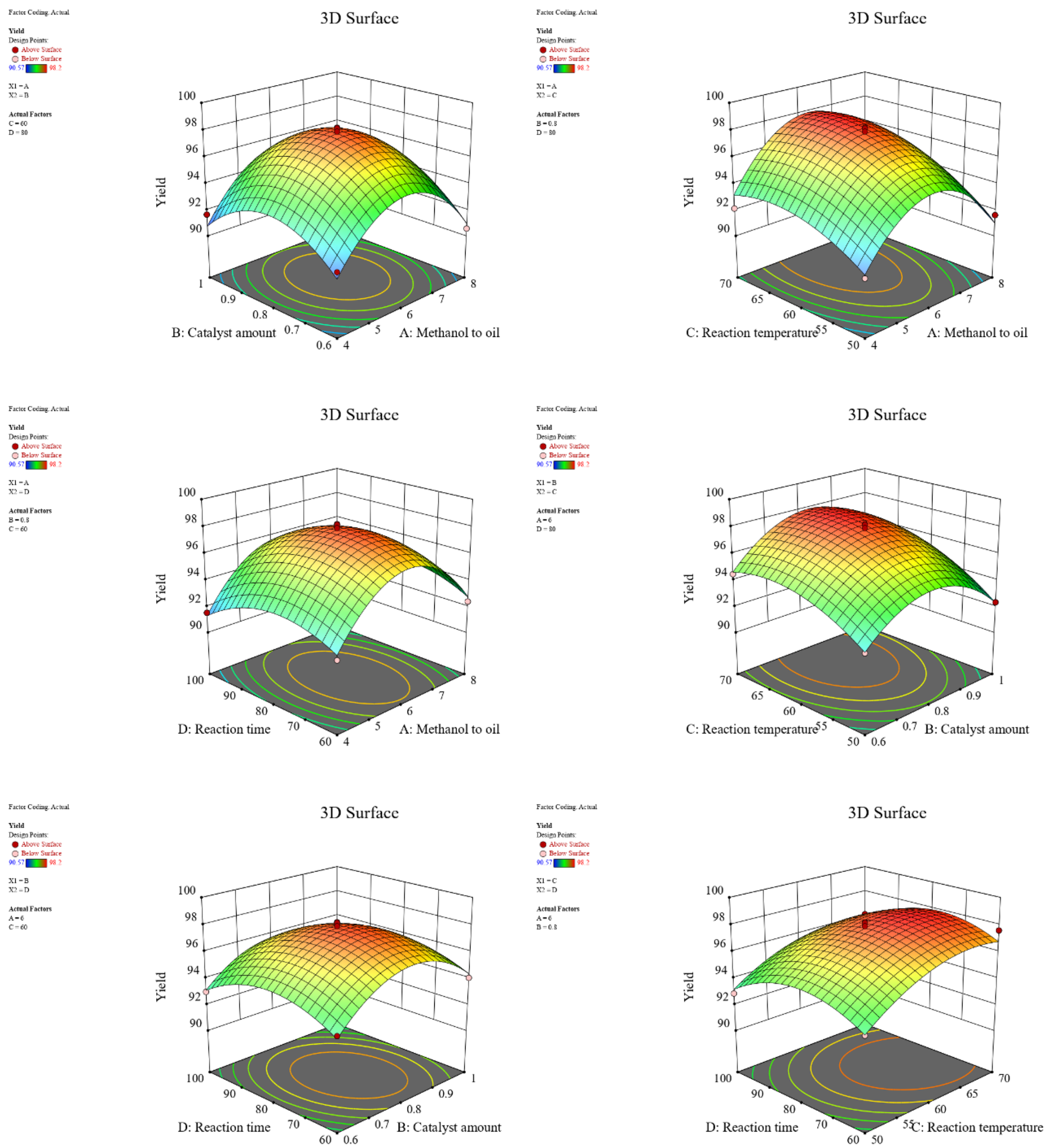

Figure 4. 3D RSM of biodiesel yield versus (a) AB, (b) AC, (c) AD, (d) BC, (e) BD, (f) CD.

Figure 4 shows that the effects of reaction factors on biodiesel productivity. The figures show 3D RSM demonstrating the correlation between biodiesel production and the combined effect of two factors variables.

Effects of factor A on biodiesel yield

The factor A of alcohol significantly impacts the biodiesel output [27]. Plots a–c shows how different catalyst quantities, reaction temperatures, and reaction times are affected by different molar ratios, which in turn affect biodiesel yield. How the catalyst concentration relates to the molar ratio. Biodiesel production rises as the alcohol quantity grows until it reaches its peak value. Excessive alcohol reduces biodiesel yield by increasing glycerol solubility in the biodiesel phase, making separation more challenging [28].

Effects of factor B on biodiesel yield

The amount of catalyst is a significant factor that affects biodiesel production by speeding up transesterification [29]. The greatest biodiesel production was achieved with a catalyst quantity of 0.8 weight percentage. The biodiesel yield reduced when the catalyst amount exceeded 0.8 wt%. Excessive catalyst will decrease biodiesel production due to saponification and hydrolysis issues.

Effects of factor C and factor D on the yield of biodiesel

This graph shows the impact of reaction temperature and duration on biodiesel production. An improved biodiesel production was seen in the alkali-catalyzed transesterification process when reaction temperatures were raised, as seen in the figure.

Optimizing and validating biodiesel yield

For each process variable, the ideal value was found using Regression Equation (3). Figure 5 shows the ideal parameters for making biodiesel. Based on the outcome of the RSM model, the optimal parameters are as follows: B of 0.811601 wt%, C of 75.8837°C, D of 98.2069 minutes, and A of 6.10935:1. The projected maximum biodiesel production under these ideal circumstances was 98.2069%. A yield of 97.762% was achieved in an experiment that used the optimum processing factors. The yield of Jatropha Oil methyl ester is 0.35% off from the ideal value, which is still within acceptable limits. The yield of Jatropha Oil methyl ester is 0.35% off from the ideal value, which is still within acceptable limits.

Engine performance analysis

Torque and Power

Fig 6 and 7 display the impact of engine functioning settings on braking torque and power. Figure 6 shows that at 2200 rpm, the braking power was maximal for all test fuels. The brake power ratings are negatively impacted by increasing concentrations of biodiesel blends. Torque readings taken at high engine speeds reveal a drop with increasing biodiesel blend percentage.

Exhaust emissions analysis

CO emission

Fig. 8 displays the effect of engine operating variables on CO emissions. The carbon monoxide emission value of fuel blends decreased as the biodiesel blend percentages increased. The oxygen concentration of biodiesel usually causes the decline since it makes combustion more difficult.

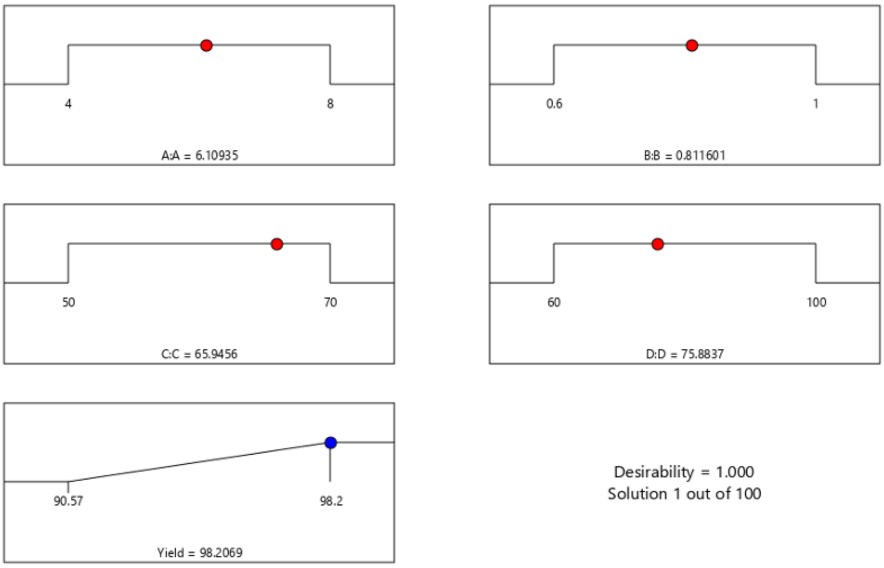

Figure 5. Optimized results of biodiesel yield

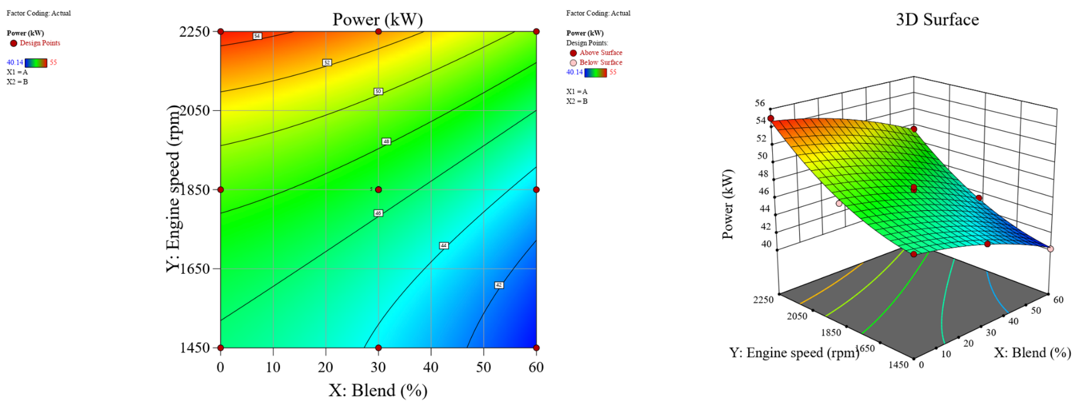

Figure 6. contour plot and 3 D RSM for power versus X and Y

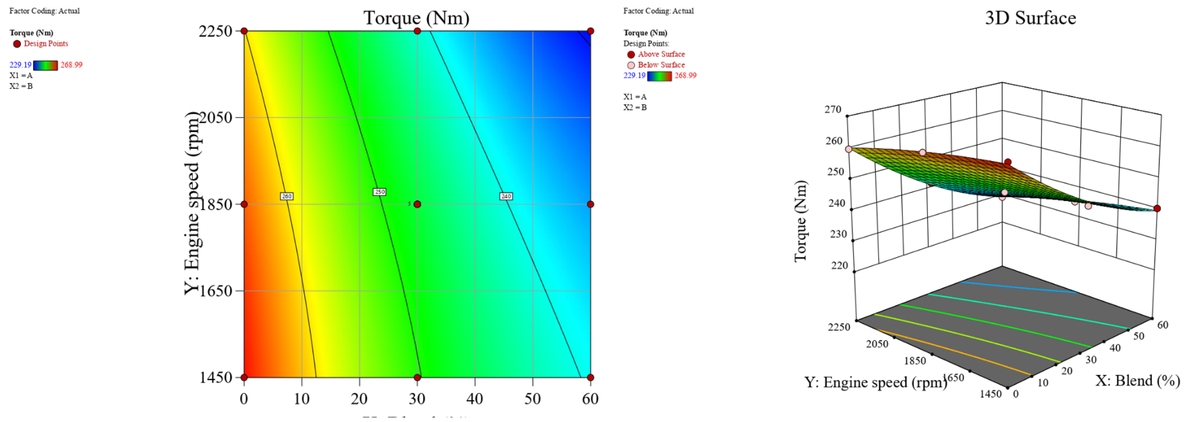

Figure 7. 2D and 3 D contour plot RSM for torque versus X and Y

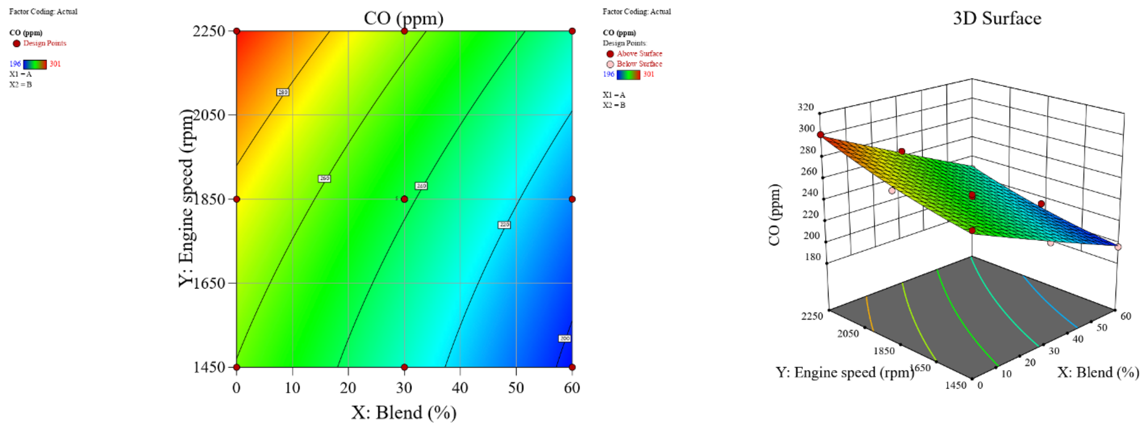

Figure 8. Contour plot and 3 D RSM for CO versus X and Y

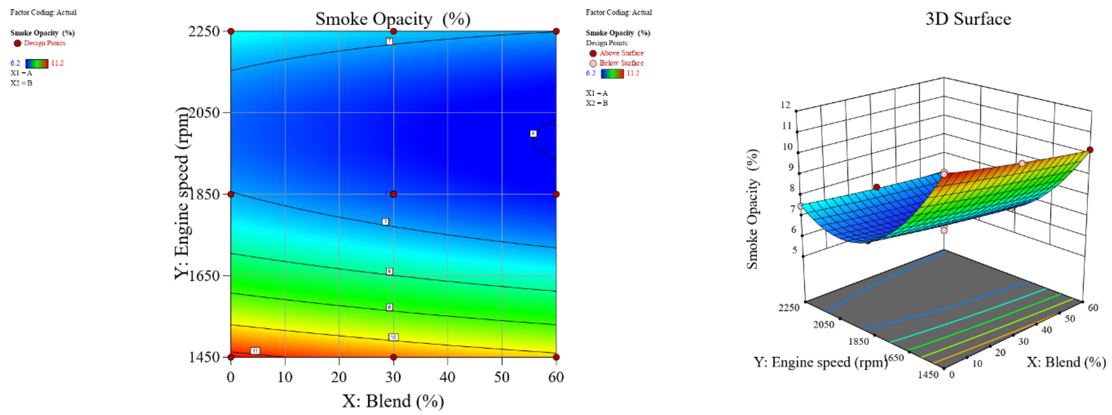

Figure 9. Contour plot and 3D RSM for smoke opacity versus X and Y

Smoke opacity

Fig. 9 displays a 2D contour plot and 3D RSM illustrating the changes in smoke opacity at various engine running settings. Biodiesel fuel mixtures have a lower smoke opacity value related to diesel fuel. This corresponds to the maximum oxygen content found in biodiesel, resulting in enhanced and complete fuel burning [30].

NOx emission

Figure 10 displays a 2D and 3D contour plot illustrating the combined effect of blending proportion and speed of engine on NOx releases. NOx emissions rise as the biodiesel blend ratios increased. NOx emissions are rising because biodiesel's higher oxygen content improves combustion, leading to increased combustion temperature and providing extra oxygen for NOx generation.

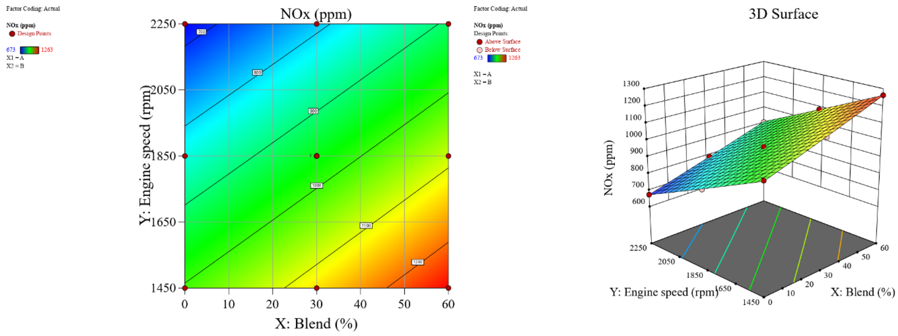

Figure 10. Contour plot and 3 D RSM for NOx versus X and Y.

Optimization and validation of engine results

The engine factors were optimized using Design Expert 13, and the outcomes are presented in Fig. 11. Reducing exhaust emissions while optimizing engine performance factors is the goal of this research. The findings indicate that the optimal anticipated values for torque, power, smoke opacity, NOx and CO are 254.757 Nm, 50.0817 kW, 6.48966%, 819.573 ppm and 270.009 ppm, respectively. These values are achieved with an engine speed of 2011.24 rpm and biodiesel blend of 12.5845%. Experimental testing was undertaken at the optimum input values to validate the optimized findings. Table 12 presents the test and predicted results. The validation findings indicate that the RSM model is highly effective for optimizing engine performance and emission values. Also Alcohols are promising alternative fuels to fossil-based gasoline. Ethanol and methanol are the alcohols that widely investigated for usability in internal combustion engines[31]. Moreover several opportunities exist for the future of fossil fuels, including technological advancements in CCS, the potential role of natural gas as a "bridge" fuel, and the use of fossil fuels in non-energy applications [32]. The engine performance of Jatropha biodiesel

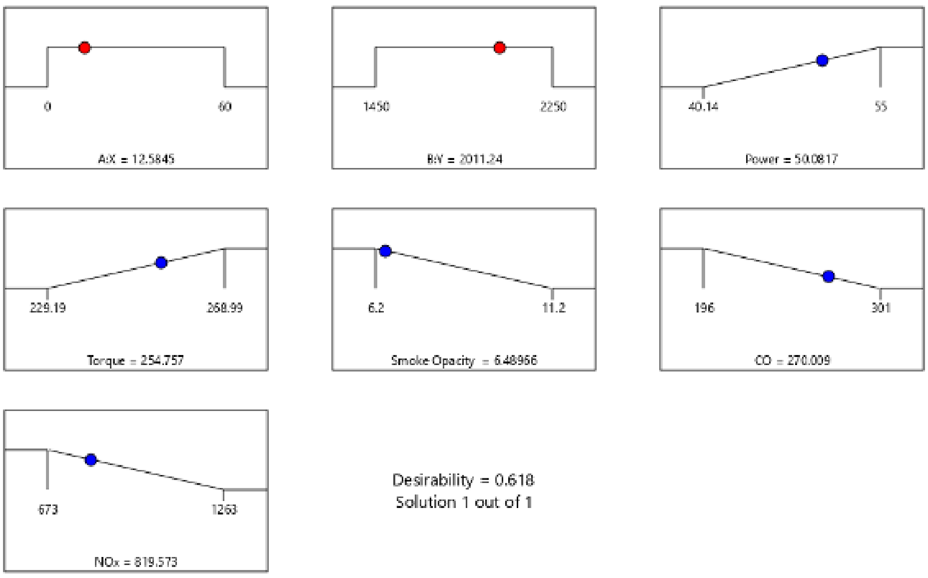

Figure 11. Optimization graph displaying torque, power, smoke opacity, NOx and CO

is equivalent to that of petroleum-based diesel [33].The oxygen content in biodiesel affects its combustion characteristics, often leading to a decrease in combustion efficiency due to incomplete combustion. 7:1 methanol/oil ratio and 0.9% catalyst when blended with petro-diesel (B20) gave the highest cetane number [34]. The analysis of variance showed that fuel type was the predominant operating factor influencing the grey relational grade which means fuel type was the most important parameter in the simultaneous optimization of exhaust emissions and engine performance higher output torque value, better thermal efficiency and durability [35,36].

Table 12. Checking for optimal performance and comparing emissions to prior studies

Factors	Predicted	Experimental	Error (%)
Blend (%)	12.5845	12.5845	–
Speed (rpm)	2011.24	2011.24	–
Load (%)	–	–	–
Injection pressure (bar)	–	–	–
Injection Timing bTDC	–	–	–
Torque (Nm)	254.757	253.59	0.46
Brake power (kW)	50.0817	49.13	1.92
BSFC (g/kWh)	–	–	–
BTE (%)	–	–	–
EGT (C)	–	–	–
NOx (ppm)	819.573	825.54	0.73
CO (ppm)	270.009	276	2.19
Smoke (%)	6.48966	6.71	3.34
UHC (ppm)	–	–	–

ECONOMIC ANALYSIS

The cost of Jatropha biodiesel production is influenced by factors such as seed procurement, oil extraction, transesterification, and purification processes. An economic analysis reveals that while initial setup and production costs can be high, optimizing these processes through methods like response surface methodology can enhance efficiency and reduce expenses. The parameters used to find economic costs for the design can be calculated mathematically energy sector could address the wastefulness associated with this particular waste stream [37,38].

CONCLUSIONS

➔This study used a transesterification procedure to create biodiesel from jatropha oil. To get the maximum biodiesel output, BBD was used. The adoption of CCD led to an increase in engine efficiency and a decrease in emissions. Here are the results:

➔The most important factors influencing biodiesel production, emission characteristics and engine performance can be identified with the use of statistical analysis. Its goal is to minimize the number of experiments needed to get the most reliable results.

➔The ideal settings for biodiesel generation were a 10935:1 molar ratio A, 0.811601 wt% B, 75.8837°C C, and 98.2069 min D. The projected maximum biodiesel production under these ideal conditions was 98.2069%. The experimental yield of 97.762% closely matches the projected yield of 98.2069% based on the results.

➔The optimization model for biodiesel had an R2 of 0.9596, whilst the corresponding values for torque, power, smoke opacity, NOx and CO were 99.63%, 99.35%, 99.54%, 99.96%, and 98.72% respectively.

➔With 50.0817 kW of power, 254.757 Nm of torque, 6.48966% of smoke opacity, 270.009 ppm of CO, and 819.573 ppm of NOx, respectively, these are the ideal values. These values are achieved with a biodiesel blend of 12.5845% at speed of engine of 2011.24 rpm.

➔Rendering to the validating test conducted under ideal conditions, the percentage of error between the optimal responses and the experimental results was less than 3%.

➔The results showed that the error rates for torque (0.46%), power (1.92%), smoke opacity (3.34%), NOx (0.73%), and

CO (2.19%).

➢The findings proved that RSM design is useful for optimizing biodiesel productivity processing variables and engine operating factors.

➢The successful application of RSM in this study suggests its potential for broader applications in optimizing other biofuel production processes, contributing to the development of more sustainable and efficient renewable energy sources.

NOMENCLATURE

ASTM	American Society for Testing and Materials
B20	20% Biodiesel Blend
B100	100% Biodiesel Blend
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
BSFC	Brake Specific fuel consumption
BTE	Brake Thermal Efficiency
RSM	Response Surface Methodology

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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