Mishra *et al. Energy, Sustainability and Society* (2024) 14:28
https://doi.org/10.1186/s13705-024-00447-2

Energy, Sustainability and Society

RESEARCH

Open Access

Experimental assessment and optimization of the performance of a biodiesel engine using response surface methodology

Prasheet Mishra[1,2], Taraprasad Mohapatra[3], Sudhansu S. Sahoo[4*], Biranchi N. Padhi[1], Nimay Chandra Giri[5], Ahmed Emara[6,7*] and Kareem M. AboRas[8*]

Abstract

Background Biodiesel is a renewable and ecofriendly fuel for internal combustion engines. However, fuel standards need to be adapted for efficiency and commercial use. This paper deals with a novel process of its production using a purification step that counters the high costs of production and experimental analysis using multiresponse optimization.

Methods Soybean oil was chosen as a biodiesel of 5%, 10%, and 15% blend with common diesel fuel and is experimentally tested in a variable compression ratio compression ignition engine. The biodiesel is blended with common diesel fuel to run the engine without any modification in its setup, which also solves most of the operational problems. The functional relationship between the input parameters and the performance characteristics of the engine is evaluated by statistical response surface methodology using the Box–Behnken design model, which generates a design of experiment resulting in an optimum experimental run that reduces the overall cost of the experimental investigation. Uncertainty analysis is done to minimize the gap between the results considering the errors of each piece of equipment. Validation of the results is also carried out.

Results The analysis of variance is used to measure the acceptability of the model and the competency of the model to predict output performance. The optimum value of input parameters which are obtained are 4.5 kg for the load, the compression ratio of 18, and B05 for the fuel blend, which results in maximum performance of brake power of 3 kW, minimum fuel consumption and emissions of CO and NO_x, which are 0.39 kg/kWh, 0.01%, and 50 ppm.

Conclusions Cost analysis reveals that biodiesel produced from the novel process of transesterification is reasonable as compared with the conventional process. It is also environmentally more sustainable, which cannot be ignored. This technique can be used in future research for cost-effective production fields such as combustion parameters and biofuels produced from waste, which need to be explored.

Keywords Biodiesel, Compression–ignition engine, Multiresponse optimization, Response surface methodology, Transesterification process, Variable compression ratio

*Correspondence:
Sudhansu S. Sahoo
sudhansu@outr.ac.in; sahoo.sudhansu@gmail.com
Ahmed Emara
a.emara@ubt.edu.sa
Kareem M. AboRas
kareem.aboras@alexu.edu.eg
Full list of author information is available at the end of the article

Background

Energy is the backbone of all the countries to progress toward development of all types. Due to rapid urbanization and modernization, the energy demand has gone up by a large margin [1]. The transportation sector is one of the major consumers of energy as well as a major polluter of the environment [2, 3]. The demand of fuel is increasing but the sources are getting depleted and they are not renewable in nature. Now, development is not only considering industrialization and urbanization but also environmental sustainability. Biodiesel is one of the promising answers as it is a renewable energy source that is cleaner burning than diesel, specifically with CO emissions. It also helps in progressing toward the net zero emission target as the use of biodiesel reduces carbon emissions. Along with the environmental benefits, biodiesel produced from waste oil or from inedible oil, using wasteland to produce biodiesel focuses on the cost-effective aspect of it.

Biodiesel has already found its application in various parts of the globe and extensive research is being carried out on the mode of production and its use as an alternate fuel in various percentage blends in a compression–ignition (CI) engine [4, 5].

Biodiesel produced from waste cooking oil using a heterogeneous catalyst produced better emission characteristics as compared with a homogeneous catalyst [6]. Two primary ways of preparing biodiesel are pyrolysis and transesterification. Due to some limitations in the pyrolysis method such as the removal of oxygen during thermal cracking and the production process being a little costly [7], the transesterification process is usually followed for biodiesel production [8]. The transesterification process requires several steps for purification of the biodiesel, which increases its cost of production by almost to 1.63 US dollars per kg of biodiesel [9]. Also, there is a requirement for more space and various kinds of resources to produce biodiesel. This leads to its supply restriction, creating issues with food production [10, 11]. With the production of biodiesel, glycerine is also produced as a byproduct. Some methods have been used to avoid the production of glycerine: one of the researchers produced biodiesels from a nonedible oil in a jacketed packed bed bioreactor using an immobilized biocatalyst. They have no harmful byproducts and also have a good biodiesel conversion rate of more than 85% [12]. So, it is important to get the biodiesel but along with that, the cost of production should also be considered. Generally, biodiesel produces less energy as compared with fossil fuel if taken in the same quantity [13]. Oil, having a higher yield of biodiesel, is more desirable. Parameters such as flow rate, energy consumption rate, and purity are the factors that are responsible and have to be looked upon while selecting a particular type of oil for the production of biodiesel, and researchers have used optimization techniques to select the biodiesel [14]. The biodiesel produced is tested in some multifuel, variable compression ratios of internal combustion engines to find out the performance in terms of mechanical parameters and to study the emission analysis. Twenty percent blends of biodiesel can run in the engine without modifying it and the biodiesel showed similar trends in performance as diesel fuel, making a promising fuel in the near future [15]. The biodiesel is also tested for its stability by getting the properties of biodiesel and then the blends also. Some research work concluded that the B20 blend of biodiesel is found to be the optimum among all the blends [16]. Fuel oil as biodiesel is tested by taking various loads and it was found that the brake-specific energy consumption increases as compared with diesel fuel but the emission of CO and NO_x decreases [17]. The use of straight Simarouba oil as an alternate fuel in the Direct Injection (DI) compression ignition engine has been investigated, where performance analysis and emission analysis are carried out as well as the effect of hydrogen. The tydro-treated Simarouba oil showed enhanced brake power by 23% at full load but an increase in NO_x and a slight increase in smoke emission. The CO and Hydrocarbon (HC) emissions were reduced. This oil has 0.06% of free fatty acid and sustainability of half a year [18]. A few researchers took castor oil and made biodiesel through transesterification and used it in different blends and found that there is no significant difference between the performance parameters of biodiesel-fueled engines and only diesel-fueled engines [19]. Biodiesel from pure and used canola oil is taken and used as fuel with a maximum blend percentage of 20% in a direct-injection diesel engine. The performance was found to be almost similar to that of a diesel engine. The emission of CO was less. The NO_x emission of the 5% blend was less but it increased significantly with a higher blend percentage [20]. *Pangium edule* is a nonedible oil, which has not been used so extensively until now. It has good biodiesel conversion properties and testing the performance parameters of the CI engine can be done using this nonedible oil, which has got scope for the future [21]. Argemone biodiesel is also one of the biodiesels that is tested in research diesel engine to find out the performance and emission by varying the injection parameters with various blends until B20 [22–24].

Biodiesel is considered a renewable energy source as it is obtained from crops, crop residues, and animal wastes. It reduces mostly the emissions of CO and HC but increases the NO_x emissions. Jatropha seeds and fish wastes are used to produce biodiesel, as well as Karanja. This was tested in the CI engine and it was found that the CO emission and hydrocarbon emission were low as compared to the diesel fuel whereas NO_x emissions were found to be higher in the biodiesel-fueled engine [25, 26]. In a comparative study of diesel and biodiesel-fueled diesel engines, the NO_x emission was high in the biodiesel-fueled engine as the speed and load increased [27]. NO_x emission is found to be higher with higher loads whereas the soot emission decreases using waste cooking oil as biodiesel along with gasoline [28]. NO_x emission has been the most detrimental when biodiesel is used in blends with common diesel fuel. Some researchers have found that lowering the injection pressure and retarding the ignition has resulted in lower emission of NO_x [29]. By using different injection techniques, the NO_x has also been reduced especially using the technology of split injection compression ignition (SICI) [30]. The influence of fuel injection pressure with ternary fuel on the emission, combustion, and performance characteristics of a four-stroke diesel engine has been studied recently [31]. Using pongamia methyl ester with n-butanol blends with diesel gives reduced NO_x emission [32].

The use of optimization techniques in the engine performance analysis will give us the optimum condition of performance of a diesel engine. This will also reduce the time taken as well as the overall cost of the experiment as it reduces the number of experiments performed, giving out the optimum number of runs of experiments to be performed. There are various kinds of optimization techniques available. Researchers investigated the performance and emission of biodiesel engines by using the Taguchi method of optimization. This method gave them the optimum result conditions as per the factors taken [33]. Optimized results are obtained from the experimental setup using the biodiesel-fueled diesel engine using the response surface methodology (RSM) [34]. Even the use of blends has gone up to adding some additives such as Solketal in the biodiesel blends making it a ternary blend and using the RSM technique to come up with a robust model predicting enhanced performance and emission [35]. Varying the injection time also plays a vital role in affecting the performance of the engine. Injection time with load can be varied and, with the use of the RSM model, you can predict the optimum parameter of injection time and load, which will give you the optimum output response [36, 37].

From an extensive literature survey, it was found that biodiesel is a promising alternative to fossil fuel used in the diesel engine, with the only challenge remaining its cost of production. The availability of soybean oil and the production of soyabean biodiesel with sodium hydroxide as a catalyst with proper temperature range and agitation speed yields more than 92% of biodiesel is a major motivation, along with the availability of the research engine setup, to proceed with this work. The major contribution of this study consists of providing (1) a novel single-step purification process of transesterification reaction that has been used to produce biodiesel from an edible source and (2) an investigation of optimum multiple responses of the test engine such as brake power (BP), specific fuel consumption (SFC), CO, and NO_x emission carried out using the RSM technique. This technique helps to reduce the number of experimental runs and the overall cost. Additionally, the results are also validated with the related literature. A typical transesterification reaction to produce biodiesel is given in Fig. 1. This approach will support industry people and researchers to use the novel technique of biodiesel production, which can cut down the cost in a reasonable margin and simultaneously choose optimum parameters for better usability of biodiesel in conventional engines.

Methods

Biodiesel production

The feedstock in this work is soyabean oil, which chemically remains in triglycerides form. The transesterification process is used to convert this triglyceride into diglycerides and lastly glycerol form. The chemical equation is given in Fig. 1 [38]. The materials required for these reactions are soyabean oil (feedstock) and freshly prepared sodium hydroxide–methanol solution, and these are stored over anhydrous sodium sulfate solution before use for 10 h. The operating conditions are; 3:1 to 15:1 methanol to oil molar ratio, the sodium hydroxide catalyst varies between 0.1% and 1.5% with respect to oil,

$$
\begin{array}{ccccccc}
CH_2-O-COR & & & & R-COOCH_3 & + & CH_2OH \\
| & & & & + & & | \\
CH-O-COR^1 & + & CH_3OH & \rightarrow & R^1COOCH_3 & & CHOH \\
| & & & & + & & | \\
CH_2-O-COR^{11} & & & & R^{11}COOCH_3 & + & CH_2OH \\
\text{(Triglycerides)} & & \text{(Methanol)} & & \text{(Fatty Acid Methyl Ester)} & & \text{(Glycerol)}
\end{array}
$$

Fig. 1 Transesterification reaction to produce biodiesel. Source [38]

Table 1 Technical specifications of the research engine

Parameters	Description
Make	Kirloskar oil engines
Model	TV1
Type	Research diesel engine
Displacement (cm^3)	661.5
Max. engine power (KW)	3.5
Max. engine torque (Nm)	22.3
Bore x stroke (mm)	87.5 × 110
Compression ratio	12:1–18:1
Injection pressure	24×10^6 N/m^2
Max speed (rpm)	1500
Cylinder bore (mm)	87.5
Stroke (min)	110
Connecting rod length (mm)	234
Stroke type	4 Stroke
Number of cylinders	1
Speed type	Constant
Cooling type	Water
Fuel	Diesel
Swept volume (cm^3)	661.5

with reaction time and temperature range varying from 5 to 45 min and 30 to 70 °C, respectively. The biodiesel is produced in batches. In each batch, 100 g of soybean is taken into a sonication vessel where the reaction will be taking place. Initially, it is preheated to 50 °C below the operating temperature which is 60–650 °C. The sodium hydroxide–methanol mixture is added to the vessel at a very slow rate so that the desired temperature is not disturbed. The sonication speed varies in a range from 200–600 rpm. This facilitates more than 90% biodiesel yield. After the end of the reaction, the fatty acid methyl ester (FAME) produced is gravity separated from the glycerol. The deep brown glycerol is instantly heavily separated and settles down. The upper portion constitutes the fatty acid methyl ester (FAME), which looks light yellow, and the analysis results are presented in Table 1 and the FAME prepared is shown in Fig. 2d. Then purification of the FAME is done.

The conventional way of purification is water washing and vacuum distillation. This process requires a huge amount of water which is treated too, resulting in a high cost of production of biodiesel. Also, due to continuous washing, there is also a partial loss of biodiesel content. Hence, a novel process of purification is adopted to reduce the cost of the production process.

The FAME is treated with dilute sulfuric acid, which nullifies the alkali content of the product. It is then washed with a counter-current water supply that removes the unreacted alcohol and residual glycerol. After this process, it is dried. It is then treated with silica gel under ultrasonication for 15–20 min. Now, the biodiesel is ready using a single-step purification process, which is the novelty of the work.

To test the biodiesel (FAME) in the compression ignition engine, it is blended to a certain percentage. According to the literature, the ignition characteristics are impacted by blends more than 20% without changing the other engine parameters. Blends of 5%, 10%, and 15% are taken which are denoted as B05, B10, and B15, respectively. The blends B05, B10, and B15 are prepared by taking 950 ml of common diesel fuel (CDF) and 50 ml of soyabean FAME (biodiesel), 900 ml of CDF with 100 ml of soyabean FAME, and 850 ml of CDF with 150 ml of soyabean FAME.

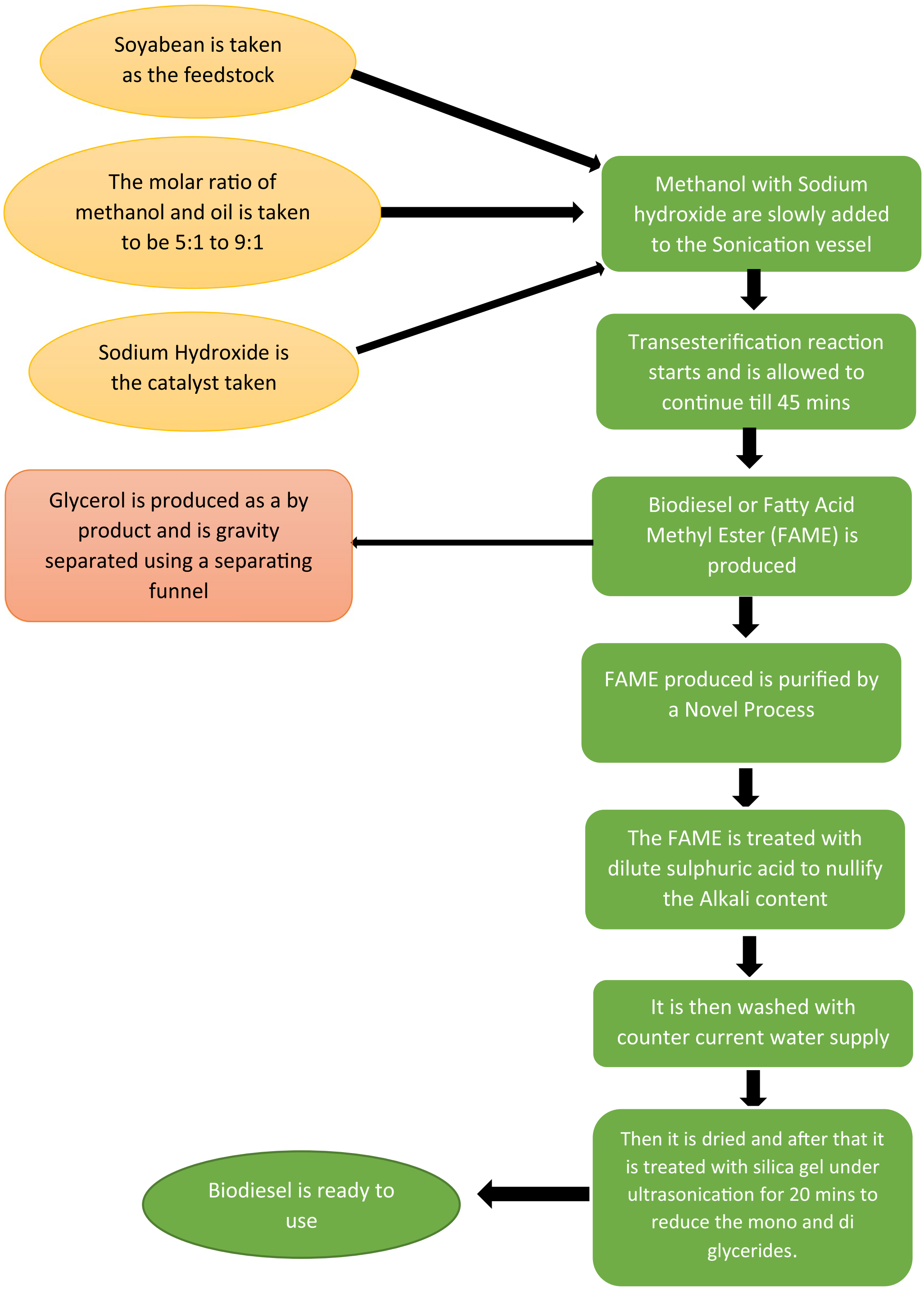
Experimental setup

For the current experimental study, a single-cylinder, four-stroke, variable compression ratio (VCR) research engine of Kirloskar is used. Major essential components of the said engine and measuring instruments used in experiments are illustrated in Fig. 2a. The detailed technical specifications and the engine setup specifications are presented in Table 1.

Uncertainty analysis

Uncertainty analysis is important for experimental research as the instruments used to measure various entities are prone to errors occurring naturally due to the condition of instruments, laboratories, calibration of instruments, environmental conditions, and measurement of readings (Table 2).

Thus, to reduce the probabilities of errors in different equipment while conducting experiments or to find out the uncertainties in the final value of various parameters measured by their respective instruments, a mathematical expression given in Eq. 1 [48], named the propagation of errors is used, which is as follows:



(a)

Fig. 2 **a** Line diagram of the variable compression ratio compression ignition engine. **b** Transesterification reaction with the novel purification step, **c** sonication vessel, **d** biodiesel (FLAME) prepared

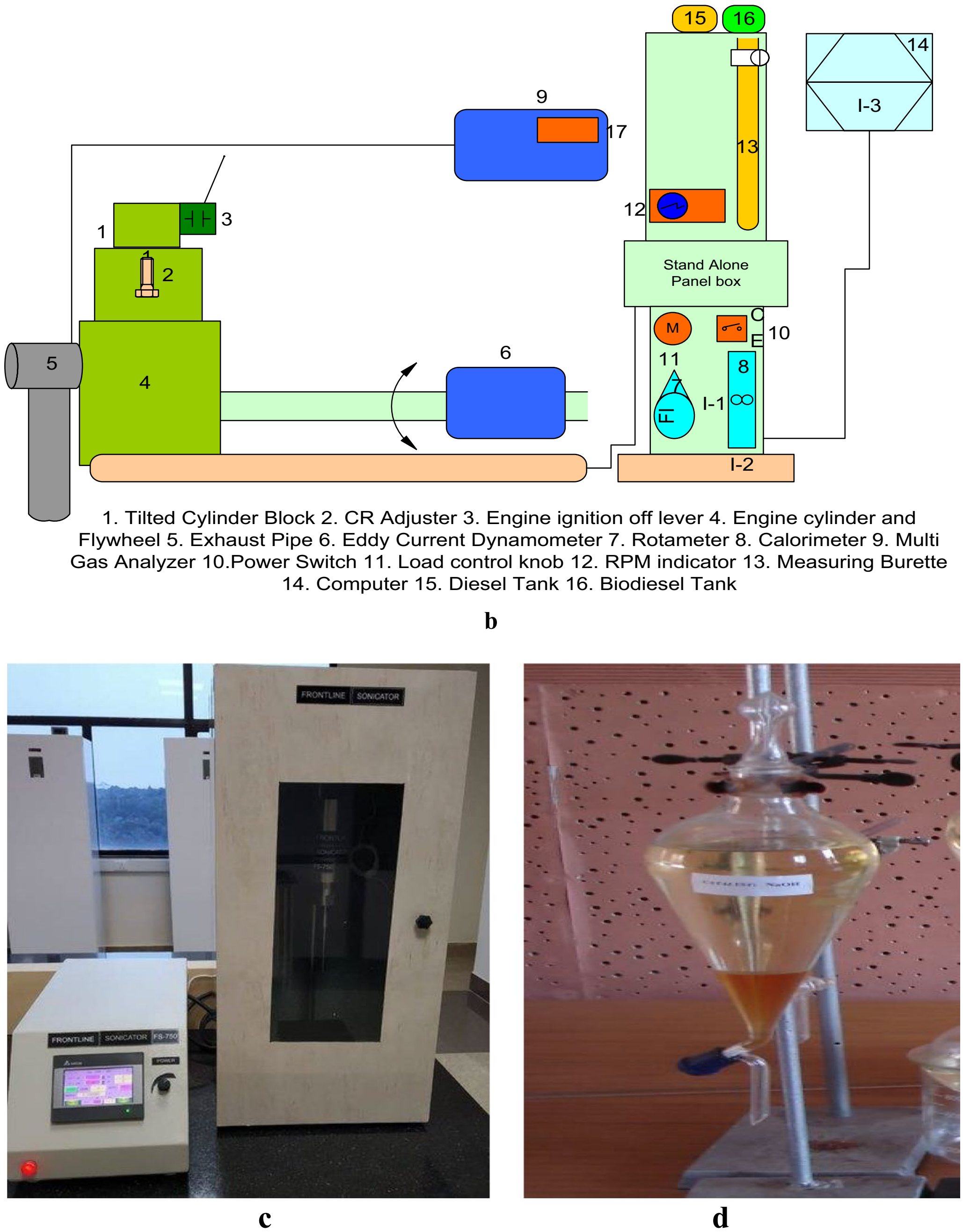


Fig. 2 continued

Table 2 List of instruments and their uncertainty analysis

Instrument	Measured Entity	Range	Units	Accuracy	% Uncertainties
Temperature indicator	Temperature	0–1200	°C	±1°C	0.1
Torque indicator	Torque	0–100	N-m	±0.1	0.2
Pressure sensor	Pressure	0–100	bar	±1	0.1
Fuel flow indicator	Mass flow rate	0–99	kg/h	±0.02	0.12
Gas analyzer	CO	0–100	%	±0.03	0.1
	NO_x	0–10000	ppm	±25	0.01
Calculated results					
BP	–	–	kW	–	0.1
SFC	–	–	kg/kWh	–	3.1

$$\begin{aligned} &\text{Total percentage uncertainties} \\ &= \sqrt{\left\{\begin{array}{l}(\mathrm{BP})^2+(\mathrm{SFC})^2+(\mathrm{CO})^2+(\mathrm{NO}_x)^2+(\mathrm{Temp.Ind})^2+(\mathrm{TorqueInd})^2 \\ +(\mathrm{Pressure\ \ sensor})^2+(\mathrm{fluidflow.Ind})^2\end{array}\right\}} \\ &= \sqrt{\{(0.1)^2+(3.1)^2+(0.1)^2+(0.01)^2+(0.1)^2+(0.2)^2+(0.1)^2+(0.12)^2\}} \\ &= \pm 3.1 \end{aligned} \tag{1}$$

Fig. 2a shows the line diagram of the variable compression ratio compression ignition engine. This is connected to the eddy current dynamometer for loading. There is a data acquisition system interfaced with a computer. There are instruments on the interface such as piezoelectric sensors, rotameters, calorimeters, and more to measure the inline cylinder pressure, fuel pressure, cooling water, water flow, airflow, fuel flow, temperature, and load measurement. The set up was supplied by the Kirloskar company.

Response surface methodology

In recent research, optimization carried out for CI engine performance is common. Out of numerous optimization techniques, response surface methodology (RSM) is potent and widely used in several engineering applications. RSM is a statistical approach mostly used in the formulation of a mathematical model establishing the exact correlation between input variables and output performance given in Eqs. 2 and 3 [47, 48]. This is done as:

$$Y = f(X_1, X_2, X_3.........) \pm \in \tag{2}$$

where output performance, Y, is functionally dependent (polynomial function, f) on variables $X_1, X_2, X_3.........X_k$ with evaluated experimental error $\in$, as follows:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i}^{k} \sum_{j}^{k} \beta_{ij} X_i X_j + \in \tag{3}$$

wheres β_0, β_i, β_{ii}, β_{ij} are coefficients of the second-order model.

Here, in the RSM, the resulting data are fitted to a varying order model and the coefficient of β is defined. The model equation is best fitted with a least-square technique for minimum error. The model fittingness is checked by analysis of variance (ANOVA). RSM uses both first and second-order designs. But central composite and Box–Behnken design mostly use the second-order design.

The Box–Behnken design is chosen in the current work as it is reasonable and takes fewer experiment test runs than other designs.

In Box–Behnken design, the total number of test runs to be performed is given by the equation:

$N = 2k(k-1) + Cp$, where k is the number of factors and Cp is the number of central points.

Three-factor levels $(-1, 0, +1)$ with equal intervals are suitable for the Box–Behnken design.

Results and discussion

In this study, the performance of a CI engine is experimentally investigated concerning different input parameters namely load, compression ratio, and fuel blend. Multiple output responses have been tried in this work to obtain optimized performance in maximizing the brake power and minimizing the specific fuel consumption, CO emission, and NO_x emission. The fuel properties as analyzed by the gas layer chromatography are presented in Table 3

Statistical analysis

Here, the performance analysis of a CI engine fueled with biodiesel blends is carried out using the statistical RSM model concerning three parameters: load, compression ratio, and type of fuel, keeping the injection pressure and speed of the engine constant. Detailed information about RSM analysis is provided in the flow chart in Fig. 3.

From the extensive literature survey, the following parameters have been selected as the key input parameters for the current study, as the performance of the CI engine is effectively represented by these parameters [39, 40].

Experimental data are used to estimate the optimum value of input parameters and the interaction between them for optimization analysis by RSM. Table 4 presents the value of the input variables in actual and coded modes. The ranges of these input parameters are:

- Load (L): ($2 \leq L \leq 7$)
- Compression ratio (CR): ($14 \leq$ CR ≤ 18)
- Type of fuel blends: ($5 \leq B \leq 15$)

To explore the true relationship between input parameters and output response, the design of the experiment (DOE) is produced by the RSM Box–Behnken design as presented in Table 5. A total of 15 test runs have been conducted and the output responses recorded are presented in Table 5.

An ANOVA test was performed, which justifies that the formulated model will predict the output responses with higher accuracy. Different parameters such as the R^2-value and R^2-adjusted are calculated to test the competence of the mathematical model. The model significance is tested by the P-value and F-value. With the help of analytical software, regression equations and the associated coefficient are evaluated. The analysis results are recorded in Tables 6 and 7.

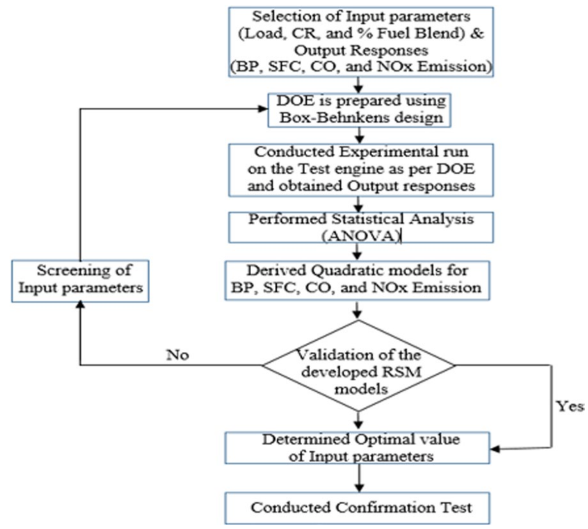


Fig. 3 Response surface methodology flow chart

In Tables 8 and 9, the R^2 value for the brake power (BP), specific fuel consumption (SFC), CO emission, and NO_x emission is high (99.98%, 99.93%, 99.99%, and 99.65%, respectively), which indicates a good model fit suitably used to calculate BP, SFC, CO emission and NO_x emission. The predicted R^2 value for the brake power is 99.70%, which is logically concurrent with the adjusted R^2 value of 99.94%. Similarly, the predicted R^2 values of 99.54%, 99.93%, and 94.52% are in logical agreement with the adjusted R^2 values of SFC, CO emission, and NO_x emissions of 99.81%, 99.99%, and 99.01%, respectively.

Appropriate precision measures the signal-to-noise (S/N) ratio with a desirability of more than 4. Suitable precision for BP, SFC, CO, and NO_x emissions are 174.382, 77.871, 273.819, and 37.132, respectively, which indicate adequate signal, and the model can be used to predict the result of all the four responses mentioned.

In every statistical analysis, whether the entity of a model or the model itself is substantial or not is confirmed by the P-value or F-value of an ANOVA test.

Table 3 Fuel properties

FAME	Density at 15 °C in g/cc	Calorific value in kJ/kg	Viscosity at 40 °C (cst)
B100	0.89	37,400	4.43
B05	0.828	41,520	2.89
B10	0.832	41,390	3.1
B15	0.836	41,120	3.8

Table 4 Coded and actual values of input variables

Factor	Name	Units	Type	Actual values	
				Minimum	Maximum
A	Load	kg	Numeric	2	7
B	Comp. ratio		Numeric	14	18
C	Fuel blends	%	Numeric	5	15

Table 5 Design layout and output responses

Std.	Run	Input variables output responses						
		A: Load kg	B: Comp. ratio	C: Fuel blends %	BP kW	SFC kg/kWh	CO emission %	NO_x emission ppm
8	1	7	16	15	2	0.41	0.0104	280
1	2	2	14	10	0.55	0.82	0.021	92
11	3	4.5	14	15	1.13	0.52	0.0108	127
2	4	7	14	10	1.5	0.39	0.0205	215
9	5	4.5	14	5	1.73	0.52	0.03	129
14	6	4.5	16	10	1.16	0.53	0.0206	148
13	7	4.5	16	10	1.17	0.52	0.0207	150
7	8	2	16	15	0.55	0.86	0.0108	90
4	9	7	18	10	2.1	0.41	0.0202	270
6	10	7	16	5	2.76	0.38	0.03	218
15	11	4.5	16	10	1.16	0.51	0.0206	146
12	12	4.5	18	15	1.15	0.59	0.0103	212
5	13	2	16	5	1.63	0.84	0.03	91
10	14	4.5	18	5	2.32	0.54	0.03	130
3	15	2	18	10	0.5	0.87	0.0204	92

Table 6 ANOVA for response surface quadratic model—brake power

Source	Sum of squares	*df*	Mean square	*F*-value	*P*-value	
Model	6.26	9	0.696	2802.62	< 0.0001	Significant
A: Load	3.29	1	3.29	13,246.76	< 0.0001	
B: Compression Ratio	0.1682	1	0.1682	677.32	< 0.0001	
C: Fuel blends	1.63	1	1.63	6559.78	< 0.0001	
AB	0.1056	1	0.1056	425.34	< 0.0001	
AC	0.0256	1	0.0256	103.09	0.0002	
BC	0.0812	1	0.0812	327.08	< 0.0001	
A^2	0.0212	1	0.0212	85.5	0.0002	
B^2	0.0217	1	0.0217	87.39	0.0002	
C^2	0.9078	1	0.9078	3655.39	< 0.0001	
Residual	0.0012	5	0.0002			
Lack of fit	0.0012	3	0.0004	11.75	0.0794	Not significant
Pure error	0.0001	2	0			
Cor total	6.27	14				

R^2 = 99.98%, adjusted R^2 = 99.94%, "Cor" is 'Corrected total sum of squares'

The *P*-value throws light on the probability of getting to the extreme of the sample value to become equal or more than what is observed in the actual. In general, the researcher decides on the significance level or the confidence interval for any kind of statistical analysis. Hence for the current work, a 5% error has been considered with a 95% confidence level and 0.05 level of significance (α). The significance of the model is tested by comparing the significance level (α) with the *P*-value. If the *P*-value of any term of the model is < 0.05, then it is considered significant. The models that are considered insignificant have less impact on the output responses as compared with the significant models. An *F*-value similar to the *p*-value can be taken into consideration for finding whether the model is significant or insignificant. In an ANOVA test, the *F*-value is found from the "F-distribution" from the ratio of mean squares as mentioned below in Eq. 4:

$$F\text{-stat} = \frac{\text{Mean Square Treatment(MST)}}{\text{Mean Square Error(MSE)}} \quad (4)$$

Table 7 ANOVA for response surface quadratic model-specific fuel consumption

Source	Sum of squares	*df*	Mean square	*F*-value	*P*-value	
Model	0.4412	9	0.049	817.02	< 0.0001	Significant
A: Load	0.405	1	0.405	6750	< 0.0001	
B: Comp. ratio	0.0032	1	0.0032	53.33	0.0008	
C: Fuel blends	0.0012	1	0.0012	20.83	0.006	
AB	0.0002	1	0.0002	3.75	0.1106	
AC	0	1	0	0.4167	0.5471	
BC	0.0006	1	0.0006	10.42	0.0233	
A^2	0.0307	1	0.0307	512.4	< 0.0001	
B^2	0.0005	1	0.0005	7.79	0.0384	
C^2	0.0005	1	0.0005	7.79	0.0384	
Residual	0.0003	5	0.0001			
Lack of fit	0.0001	3	0	0.3333	0.8075	Not significant
Pure error	0.0002	2	0.0001			
Cor total	0.4415	14				

R^2 = 99.93%, adjusted R^2 = 99.81%, "Cor" is 'Corrected total sum of squares'

Table 8 ANOVA for response surface quadratic model—CO emission

Source	Sum of squares	*df*	Mean square	*F*-value	*P*-value	
Model	0.0008	9	0.0001	10,716.38	< 0.0001	Significant
A: Load	1.51E−07	1	1.51E−07	19.31	0.0071	
B: Comp. ratio	2.45E−07	1	2.45E−07	31.28	0.0025	
C: Fuel blends	0.0008	1	0.0008	96,339.73	< 0.0001	
AB	2.25E−08	1	2.25E−08	2.87	0.1509	
AC	4.00E−08	1	4.00E−08	5.11	0.0734	
BC	6.25E−08	1	6.25E−08	7.98	0.0369	
A^2	6.41E−09	1	6.41E−09	0.8183	0.4071	
B^2	1.64E−08	1	1.64E−08	2.09	0.2074	
C^2	3.14E−07	1	3.14E−07	40.1	0.0014	
Residual	3.92E−08	5	7.83E−09			
Lack of fit	3.25E−08	3	1.08E−08	3.25	0.2441	Not significant
Pure error	6.67E−09	2	3.33E−09			
Cor total	0.0008	14				

R^2 = 99.99%, adjusted R^2 = 99.99%, "Cor" is 'Corrected total sum of squares'

where MST is the group variance and MSE is the sample variance (error).

It is also required to find out the *F*-critical value before the test from the *F*-distribution table by using the relation as mentioned below inequation 5:

$$F\text{ - crit} = F_{(\alpha)(k-1,N-k)} \quad (5)$$

where α is the significance level, k is the sample number, and N is the data value number. For a model to be significant, *F*-stat must be greater than *F*-crit (*F*-stat > *F*-crit). In this work, *F*-crit = 1 is allocated by the analytical software (*Design Expert 11, Stat-Ease,Inc.Pdf*, n.d.) [34]. Therefore, all model terms are tested by taking the *F*-crit value as 1. The *F*-value for the model representing BP is 2802.62, which is > 1 and the probability value is < 0.0001, i.e., < 0.05, which implies that the model is substantial to calculate the BP effectively. Similarly, for SFC, CO emission, and NO_x emission, the *F*-values for the respective models are 817.02, 10,716.38, and 156.12, which are all > 1, and the probability value for all three factors are < 0.0001, i.e., < 0.05, which implies that the models are substantial for calculating the SFC, CO, and NO_x emission effectively.

Table 9 ANOVA for response surface quadratic model—NO_x emission

Source	Sum of squares	*df*	Mean square	*F*-value	*P*-value	
Model	57,680.08	9	6408.9	156.12	< 0.0001	Significant
A: Load	47,740.5	1	47,740.5	1162.98	< 0.0001	
B: Comp. ratio	2485.13	1	2485.13	60.54	0.0006	
C: Fuel blends	2485.13	1	2485.13	60.54	0.0006	
AB	756.25	1	756.25	18.42	0.0078	
AC	992.25	1	992.25	24.17	0.0044	
BC	1764	1	1764	42.97	0.0012	
A^2	1440.23	1	1440.23	35.08	0.002	
B^2	0.9231	1	0.9231	0.0225	0.8867	
C^2	14.77	1	14.77	0.3598	0.5748	
Residual	205.25	5	41.05			
Lack of fit	197.25	3	65.75	16.44	0.0579	Not significant
Pure error	8	2	4			
Cor total	57,885.33	14				

R^2 = 99.65%, adjusted R^2 = 99.01%, "Cor" is 'Corrected total sum of squares'

ANOVA analysis

To evaluate the significance of the statistical model developed from the input variables and the output responses of the models, an analysis of variance (ANOVA) is carried out as presented in Table 6.

The above plots are obtained as shown in Figs. 4 and 5 by analyzing the data using ANOVA in the analytical software. They are the predicted versus the actual value plots for the performance parameters BP, SFC, CO, and NO_x emission. These graphs generally estimate the model's capability to predict the real problem. It is detected from these plots between predicted and actual values that the performance data are almost normally distributed with an acceptable range of errors, though smaller deviations are observed.

The generalized relationship between the test design parameters and the model output response is given in Eqs. 6,7,8, 9,10, and 11 [47, 48].

In coded units:

$$L,\ \text{CR},\ \text{and}\ B = a.A + b.B + c.C + d.AB + e.AC + f.BC + g.A^2 + h.B^2 + i.C^2 \tag{6}$$

In uncoded units:

$$L,\ \text{CR},\ \text{and}\ B = \text{a.load} + \text{b.Comp.Ratio} + \text{c.fuelblends} + \text{d.load} * \text{Comp.Ratio} + \text{e.load} * \text{fuelblends} + \text{f.Comp.Ratio} * \text{fuelblends} + \text{g.load}^2 + \text{h.Comp.Ratio}^2 + \text{i.fuelblends}^2 \tag{7}$$

Table 10 represents the coefficient of Eqs. 6 and 7 for the performance parameters BP, SFC, CO, and NO_x emission. These equations consist of significant and insignificant terms. The insignificant model has been omitted from Eq. 5 and 6 regarding their *P*-values > 0.1 and the new equations are represented in Eqs. 8, 9, 10, and 11.

Performance parameters:

$$\begin{aligned}\text{BP} = &-2.57805 - 0.436700\text{load} + 0.682083\text{Comp.Ratio} - 0.287717\text{fuelblends} \\ &- 0.032500\text{load} * \text{Comp.Ratio} + 0.006400\text{load} * \text{fuelblends} - 0.014250\text{Comp.Ratio} \\ &* \text{fuelblends} + 0.012133\text{load}^2 - 0.019167\text{Comp.Ratio}^2 + 0.019833\text{fuelblends}^2\end{aligned} \tag{8}$$

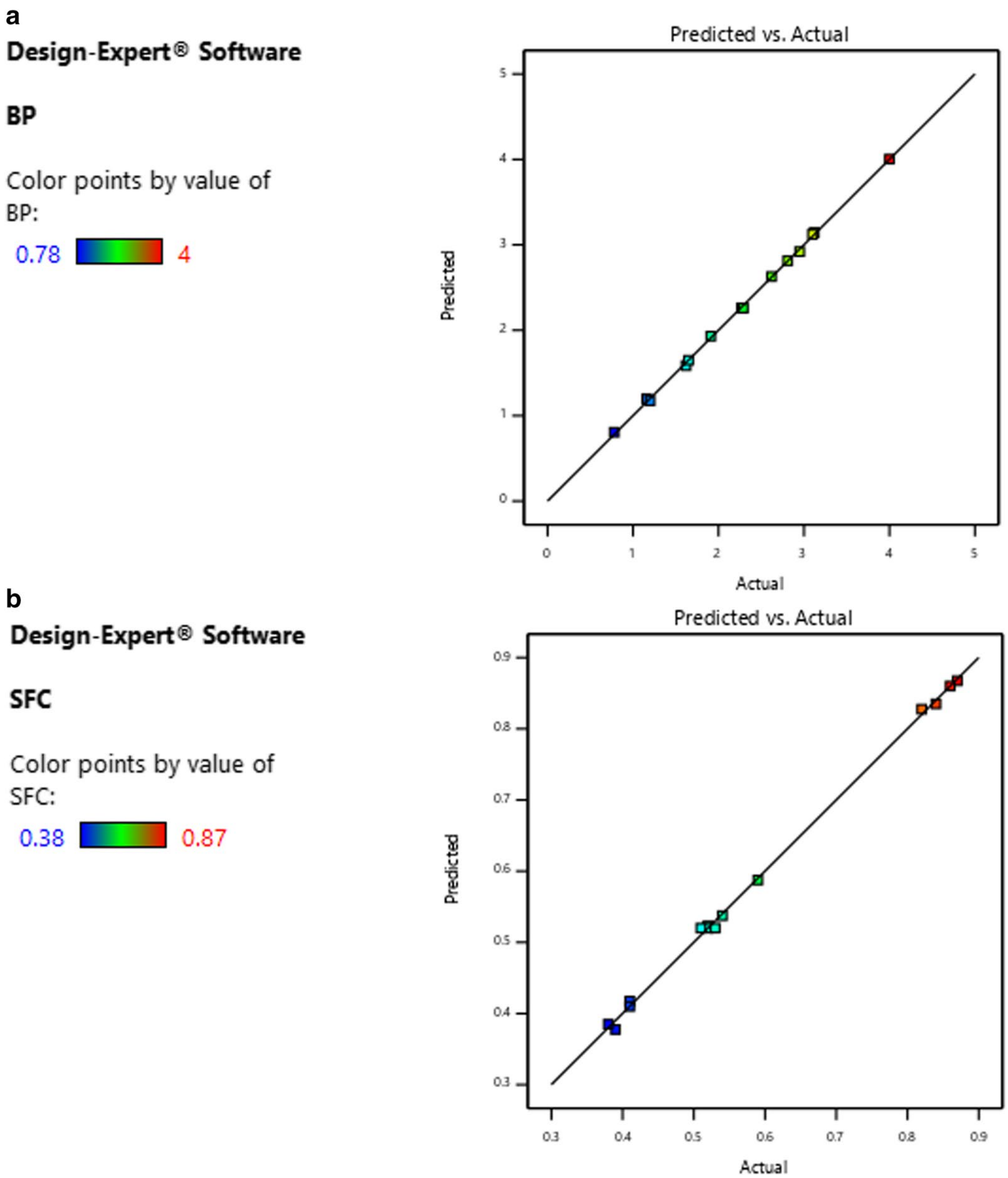


Fig. 4 **a** Predicted versus actual values for BP, **b** Predicted vs. actual values for SFC.

$$\begin{aligned} \text{SFC} =& 1.90165 - 0.199400\text{load} \\ & - 0.085750\text{Comp.Ratio} \\ & - 0.027400\text{fuelblends} \\ & - 0.001500\text{load} * \text{Comp.Ratio} \\ & + 0.000200\text{load} * \text{fuelblends} \\ & + 0.001250\text{Comp.Ratio} * \text{fuelblends} \\ & + 0.014600\text{load}^2 + 0.002813\text{Comp.Ratio}^2 \\ & + 0.000450\text{fuelblends}^2 \end{aligned} \tag{9}$$

Emission parameters:

$$\begin{aligned} CO =& 0.034858 - 0.000155\text{load} \\ & + 0.000503\text{Comp.Ratio} \\ & - 0.001473\text{fuelblends} \\ & + 0.000015\text{load} * \text{Comp.Ratio} \\ & - 8.00000E - 06\text{load} * \text{fuelblends} \\ & - 0.000013\text{Comp.Ratio} * \text{fuelblends} \\ & - 6.66667E - 06\text{load}^2 \\ & - 0.000017\text{Comp.Ratio}^2 \\ & - 0.000012\text{fuelblends}^2 \end{aligned} \tag{10}$$

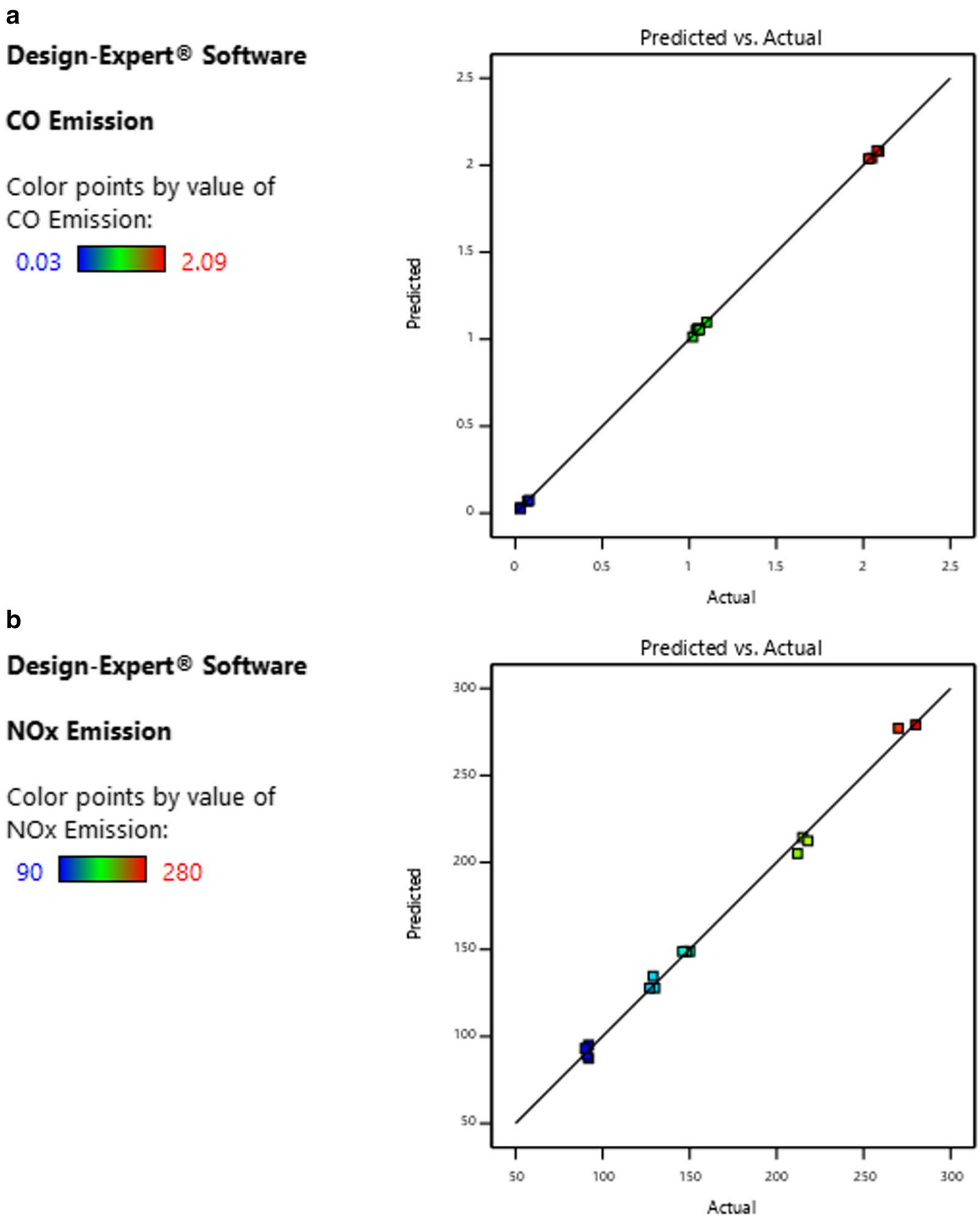


Fig. 5 **a** Predicted versus actual values for CO, **b** Predicted versus actual values for NO_x.

$$NO_x = 463.39000 - 54.14000 load - 20.56250 Comp.Ratio - 37.34500 fuelblends + 2.75000 load * Comp.Ratio + 1.26000 load * fuelblends + 2.10000 Comp.Ratio * fuelblends + 3.16000 load^2 - 0.125000 Comp.Ratio^2 + 0.080000 fuelblends^2 \quad (11)$$

Validation of the response surface model

Figure 6 depicts the differences between measured and predicted responses. From Fig. 6 the results of the comparison prove that the RSM models will adequately predict the values of the output responses (BP, SFC, CO emission, and NO_x emission) and thus validated.

In Fig. 7a, keeping the blends of fuel constant, the effect of compression ratio and load on the brake power is achieved. It is observed from the figure that, with an increase in the load, the brake power increases. There is no significant change in the brake power observed by varying the compression ratio. As brake power is directly related to the torque produced inside of the cylinder of the engine, for more load there will be more torque and

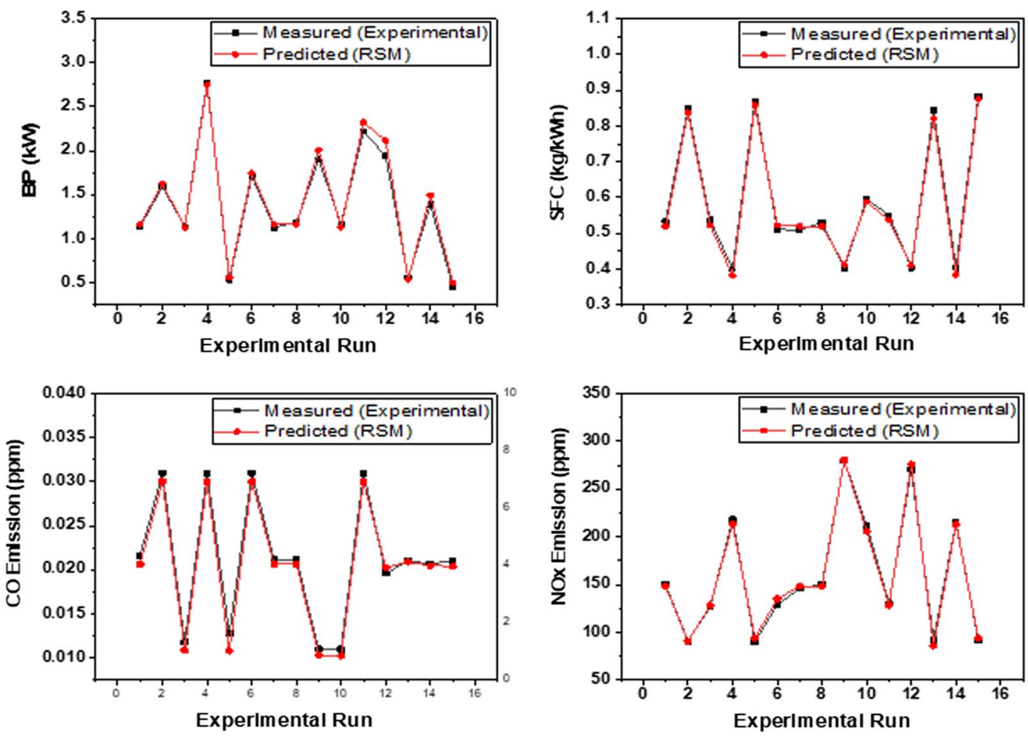


Fig. 6 Comparison between measured and predicted values of the output responses **a** for BP, **b** for SFC, **c** for CO emission, and **d** for NO_x emission

hence that increases the brake power. With the increase in the compression ratio, the BP seems to be increasing and reaches the maximum value at a higher compression ratio and load. So, it can be said that the change in the compression ratio gives a small change in the brake power but for the variation in the load, the change in the brake power is positive and significant. Figure 7b shows the effect of compression ratio and load on the specific fuel consumption, keeping the blends of fuel factors constant. It is observed from the plot that the SFC decreases with an increase in the load. With the change in the compression ratio, there is not much change in the SFC. Specific fuel consumption largely depends on the load concerning its mathematical representation.

In Fig. 7c, the blends of the fuel factor are kept constant and the effect of compression ratio and the load on the CO emission is achieved. There is no significant change observed in the CO emission by varying the compression ratio and the load in the engine. The reason might be due to the use of the blends of the fuel the oxygen content increases, which reacts with CO formed during the combustion and gets converted to CO_2 and which results in a constant value or no increase in the CO emission at varying load and compression ratio. Figure 7d shows the effect of compression ratio and load on the NO_x emission keeping the factor blends of fuel constant. The NO_x emission increases with an increase in the load. There is a very small increase in the NO_x emission with the increase in the compression ratio. This might be due to the use of biodiesel as fuel in the CI engine, which takes more time in combustion and this will lead to more formation of NO_x. It is observed in the plot that, at higher load and higher compression ratio, the NO_x emission is maximum, that is because, at a very high temperature, the NO_x formation is more as the combination of nitrogen and oxygen at high temperature as responsible for the formation of its oxides [41].

Table 10 Estimated regression coefficients

Factor	Coefficient estimate			
	BP	SFC	CO emission	NO_x emission
Intercept	1.16	0.52	0.0206	148
A: Load	0.6412	−0.225	−0.0001	77.25
B: Comp. ratio	0.145	0.02	−0.0002	17.62
C: Fuel blends	−0.4513	0.0125	0.0125	17.63
AB	0.1625	−0.0075	0.0001	13.75
AC	0.08	0.0025	−0.0001	15.75
BC	−0.1425	0.0125	−0.0001	21
A^2	0.0758	0.0912	0	19.75
B^2	−0.0767	0.0113	−0.0001	− 0.5
C^2	0.4958	0.0112	−0.0003	2

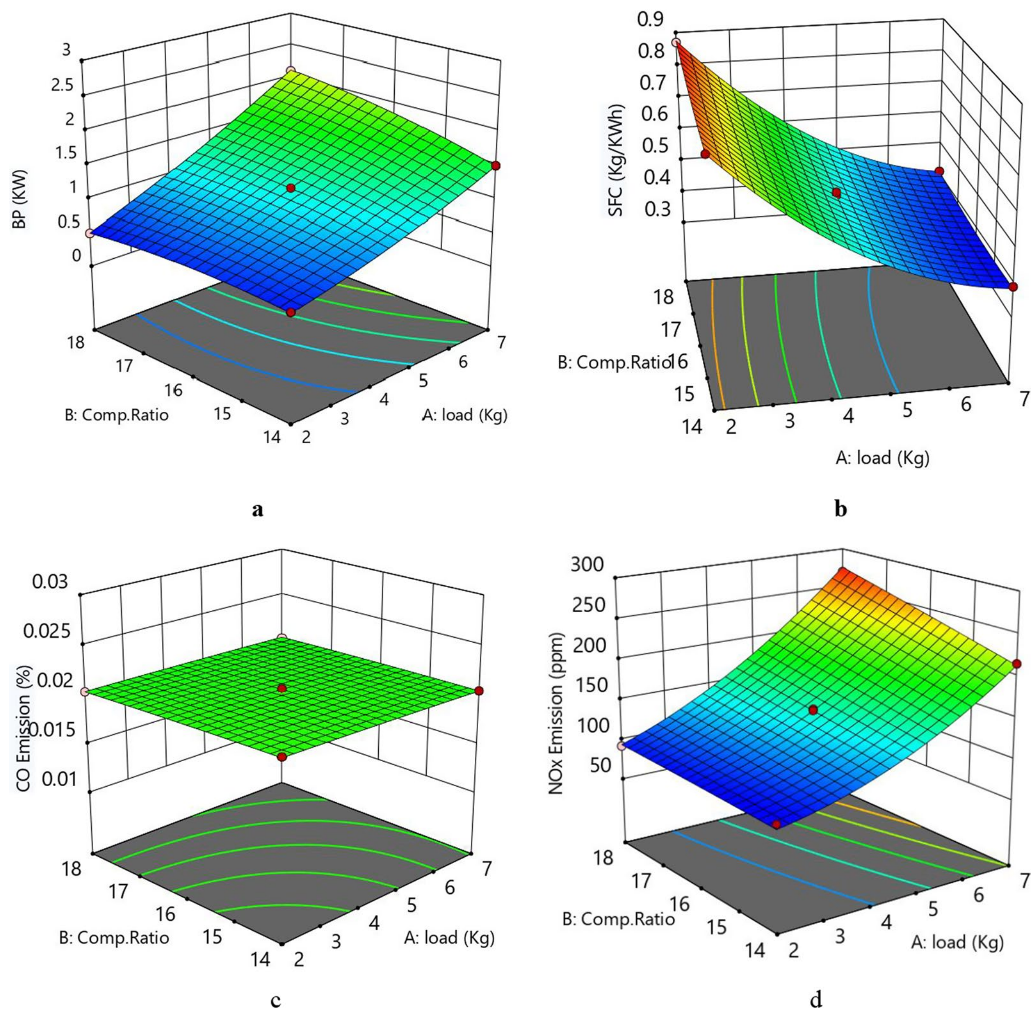


Fig. 7 Three-dimensional surface plots between **a** compression ratio and load for BP, **b** compression ratio and load for SFC, **c** compression ratio and load for CO, **d** compression ratio and load for NO_x emission

Figure 8a shows the effect of the factors blends of fuel and the load on the brake power of the engine. It is observed from the figure that the brake power increases by increasing the load. For the blends of fuel, at the lower blend, the BP has a higher value but that gradually decreases with an increase in the blend percentage. This may be due to, at the initial stage of lower blends of fuel, the biodiesel has considerably more oxygen content as compared with diesel fuel and improved lubricity so the combustion is better but with an increase in the blend percentage, the calorific value decreases, decreasing the heating effect and the power reduces. Figure 8b shows the effect of the same factor as mentioned above for the blends of the fuel and the load on the SFC. With the increase in the load, the SFC decreases and it almost has no change when the variations are done in the fuel blends. It gives a similar behavior as the common diesel fuel [42]. Figure 8c shows the effect of the factor fuel blends and load on CO emission. The CO emission decreases with the increase in the blend percentage of the fuel, while it almost has no change when it comes to varying the load of the engine. The variation due to the change in the fuel blends percentage might be due to an increase in the oxygen content while going from lower percentage blends to higher percentage blends, i.e., from B05 (50 ml of biodiesel and 950 ml of common diesel fuel) to B15 (150 ml of biodiesel with 850 ml of common diesel fuel). But the effect of this increase in the emission will not affect the environment more as the CO formed reacts with the oxygen to give CO_2. So, the amount of CO produced gets converted to CO_2. And CO_2 emission is reduced when biodiesel is used as fuel: the CO_2 emitted is consumed by the plants themselves from whom the biodiesel is prepared. Figure 8d gives us the effect of the factors of fuel blends and load on NO_x emission. The NO_x emission increases gradually with an increase in the fuel blend and

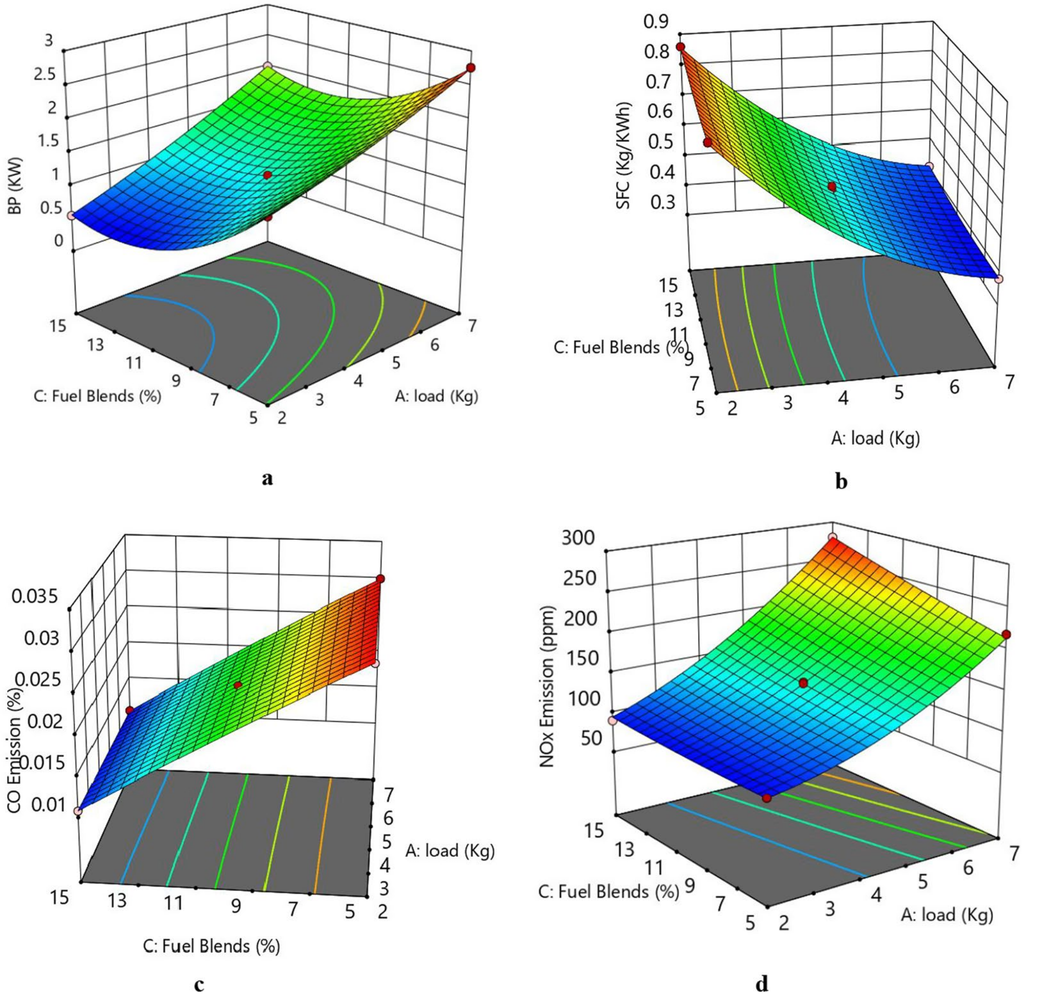


Fig. 8 Three-dimensional surface plots between fuel blends and load for BP, **b** fuel blends and load for SFC, **c** fuel blends and load for CO, and **d** fuel blends and load for NO_x emission

increases significantly with the increase in the load of the engine. The reason for this trend may be that, for a biodiesel blend, the percentage of oxygen present is more as compared with conventional diesel fuel and, at high temperatures, the formation of oxides of nitrogen will increase as the nitrogen becomes active at higher temperatures and reacts with oxygen to give nitrogen oxides.

Figure 9a, b, c, and d show the effect of the factors of fuel blends and compression ratio on the brake power, specific fuel consumption, CO emission, and NO_x emission. The compression ratio has no significant effect on all four responses whereas the blends of fuel have a significant effect on the brake power and emission of CO and NO_x. The reason for this is already been given in the explanation about Figs. 7 and 8

Load and blends of fuel play a crucial role in affecting the responses whereas compression ratio does not have such a significant effect on the responses. The results are compared and validated from extensive literature studies [12, 36, 43].

Multiresponses optimization using the "desirability function"

CI engine performance has got more than one quality response. Most of the time, these responses are naturally contradicting each other and hence need to be optimized. To obtain overall or multiple responses, optimized CI engine performance fueled with biodiesel, and the optimal input parameters are necessary to be traced out by the optimization technique. Out of the various methods applied for the solution of optimization of multiresponses, the desirability function is applied in this work to obtain optimum performance and emission responses in the CI engine. For a detailed

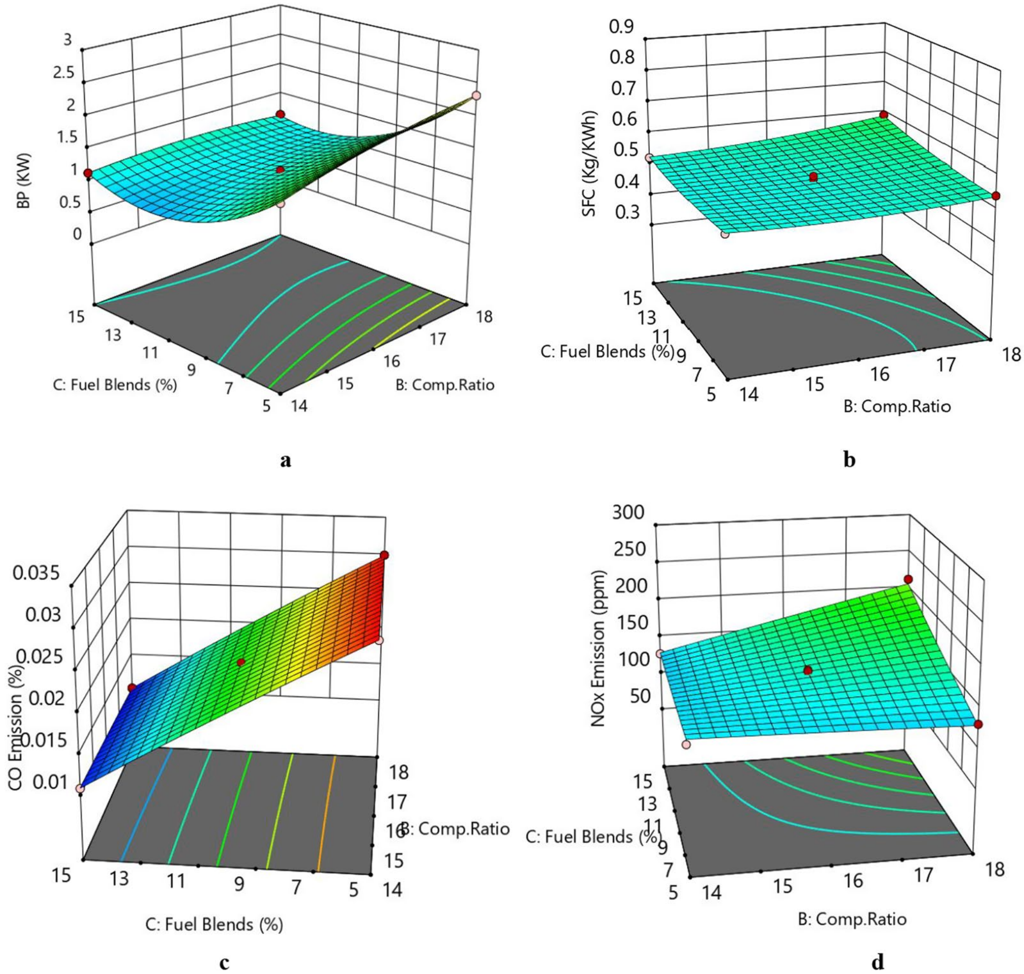


Fig. 9 Three-dimensional surface plots between **a** fuel blends and compression ratio for BP, **b** fuel blends and compression ratio for SFC, **c** fuel blends and compression ratio for CO, and **d** fuel blends and compression ratio for NO_x emission

optimization of multiple response analysis References [11, 44] may be referred to.

In the desirability approach, the values of all current output responses are given a number between 0 and 1, which is known as their desirability (di). Then, the geometric mean is used to combine individual desirability (di) to determine composite desirability (*D*) for a given objective. The highest *D*-value predicts the optimum condition of output performance, and in this work, the optimal input parameters are calculated for maximum BP as well as minimum SFC, CO emission, and NO_x emission using composite desirability (*D*). Figure 10 shows the outcome of the optimization analysis.

From Fig. 10 it is found that the maximum value for the brake power and minimum value for the specific fuel consumption, CO, and NO_x emission is predicted to be 2.359 kW, 0.525 kg/kWh, 0.029%, and 132.553 ppm, which results in the optimum performance and emission of the CI engine fueled with biodiesel blends with composite desirability, *D* of 0.904873. The high desirability value indicates that the performance and emission of the CI engine are well optimized. This predicted optimum response is the result of the optimum input parameters, i.e., a load of 4.63281 kg, near to 4.5 kg, compression ratio of 18, and fuel blend of B05.

Confirmation test

In the present study, a confirmation test was conducted and is presented in Table 11 for the test engine using three different test fuels for a load of 4.6 kg and a compression ratio of 18. These are the predicted optimal values of load and compression ratio determined from RSM using the desirability function approach. From Table 11, it is confirmed that SOYA B5 performs better as compared with other test fuels as predicted using the RSM technique.

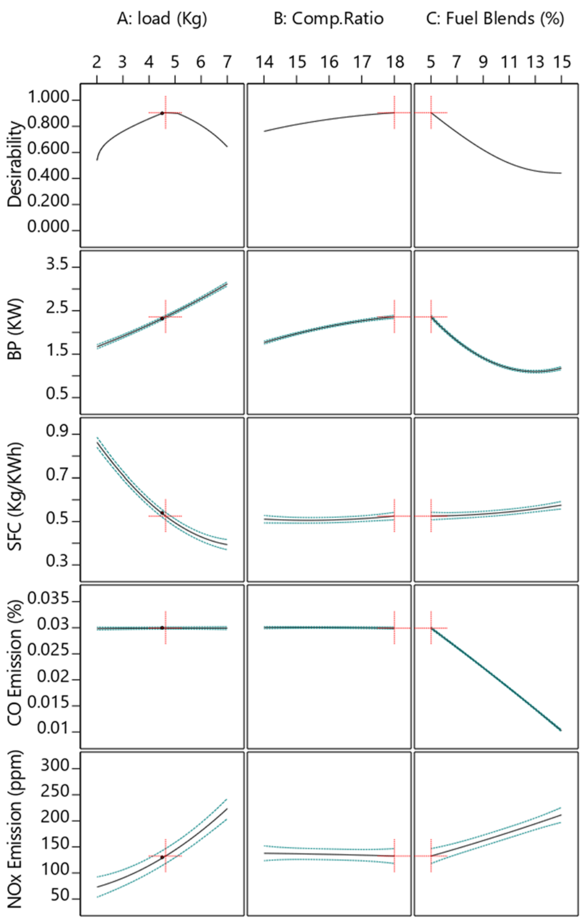


Fig.10 Multiresponse optimization using the "desirability function"

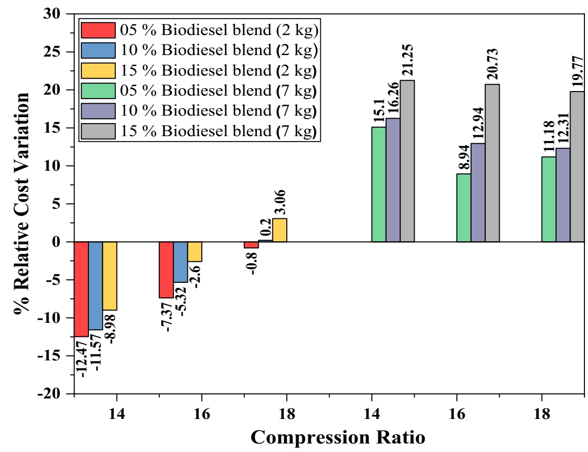


Fig. 11 Relative cost variation in % of the variable compression ratio engine

Economic analysis

An economic analysis was carried out in the variable compression ratio compression ignition engine using diesel fuel and soybean blend biodiesel. The economic analysis was done considering 1 L of biodiesel. The analysis result is plotted in Fig. 11 where % relative cost is compared with the compression ratio and load of the engine. The cost of the diesel fuel is taken as zero and it is on the reference line. The results show that there is a percentage increase in the cost with the increase in the load. Also, at higher loads and with increasing blends from B05 to B15, the cost % increases. However, with the increase in compression ratio, a decrease in the cost % is observed as specific fuel consumption decreases.

Through the extensive literature survey, it was found that the conventional process used to bear 60–80% of the overall cost of the production process. The total cost of production depends on factors such as (a) the cost of feedstock and raw materials, (b) the electricity cost for the mixing of alcohol and catalyst, (c) the electricity cost for the transesterification process, and (d) the electricity cost of counter-current water washing. All these factors add up to the total cost of the biodiesel production.

The water usage is reduced by 2 L for 1 L production of biodiesel [32, 45, 46]. Hence, the costs of 5%, 10%, and 15% blend of biodiesel amounted to Indian National Rupees (INR) 110.65, INR 125.11, and INR 139.55 respectively. Whereas in the novel method of biodiesel

Table 11 Conformation test

	Input parameters			Output response			
	Fuel type	Load in kg	CR	BP in kW	SFC kg/kWh	CO emission in %	NO_x emission in ppm
Experimented value (test engine)	SOYA B5	4.6	18	2.32	0.54	0.032	139
	SOYA B10	4.6	18	1.17	0.57	0.0208	177
	SOYA B15	4.6	18	1.15	0.59	0.0103	212
Optimum value (RSM model)	SOYA B5	4.6	18	2.36	0.525	0.03	132.55

production the cost of 5%, 10%, and 15% blend of biodiesel is INR 102.72, INR 109.24, and INR 115.76. The cost variation for the novel method for 5%, 10%, and 15% blends of biodiesel is found to be 70%.

The cost of biodiesel is also high at different blends, higher loads and a higher compression ratio. But the environment is a major concern globally and everyone is trying to bring down the emissions coming from engines. Biodiesel use can reduce carbon emissions. In the long run, the fossil fuel reserves are not replenishing and soon there will come a time when the demand for fossil fuels will be high but the supply will be less. At that time, the cost of diesel fuel will go up by a huge margin and, as researchers are trying to make biodiesel cost effective, by this time biodiesel will be more cost-effective than diesel fuel. Using biodiesel fuel in blends also makes the fossil fuel reserves last longer. Glycerol, the byproduct of biodiesel production can be applied in some way, which can make the biodiesel cost-effective, too. More work should be done on the cost-effectiveness aspect of biodiesel production.

Environmental sustainability

Biodiesel supports environmental sustainability in the following ways:

- The use of biodiesel reduces the emission of carbon monoxide (CO). The biodiesel has more content of oxygen which reacts with the CO produced and converts that to CO_2.
- Biodiesel is a low-carbon emission fuel and it reduces greenhouse gas emissions. Biodiesel used as fuel in internal combustion engines releases carbon dioxide (CO_2) but that is consumed by the plants, which are the feedstock for biodiesel production. So, the net emission of carbon to the environment is nullified. The hydrocarbon emissions are reduced too.
- Biodiesel production cost is the only factor to be countered to make it fully feasible for application. Still, the cost can be countered with proper use of the byproduct produced.
- Glycerol is the byproduct and if the same can be processed or can be worked upon to make it useful for some application, then it can be sold, which counters the cost of production.
- Seventy percent of the cost of biodiesel comes from the feedstock. Using waste oil or used oil to produce biodiesel will minimize this cost to a larger extent.
- Still, the majority of transportation is dependent on fossil fuels. The fossil fuel reserves are getting depleted slowly. A day will come when the demand will still be high for fossil fuel but the supply will be scant. This gap between the demand and supply will affect the cost of the fossil fuel. The cost will be almost the same as that biodiesel or might shoot up more than that biodiesel.

Conclusions

The biodiesel taken is produced in a novel technique in its purification phase, which addresses the major challenge of cutting the cost of biodiesel production. The soybean biodiesel in 5%, 10%, and 15% blends were taken and used as fuel in the VCR CI test engine. The three input parameters: load, compression ratio, and fuel blends were taken in three levels. The influence of these input factors on the performance characteristics, i.e., brake power, specific fuel consumption, CO, and NO_x emission was evaluated by the suitable RSM Box–Behnken design model. According to the design of the experiment (DOE) provided by the Box–Behnken design, 15 test runs have been conducted on the CI engine experimental setup. The accuracy of the model was checked by the ANOVA technique. The optimum condition of the input variables was evaluated by the multi-response optimization with the "desirability function" to get maximum brake power and minimum SFC, CO, and NO_x emission. From the results, it may be concluded that:

a. One of the major challenges faced by industrialists in producing biodiesel is its production cost. This paper has tried to consider this point and has come up with a novel process of purification that reduces the overall production cost of biodiesel as compared with the conventional biodiesel production technique.
b. The change in the compression ratio gives a small change in the brake power but for the variation in the load, the change in the brake power is positive and significant. With the increase in the load, the SFC decreases and it almost has no change when the fuel blends are varied. There is a very small increase in the NO_x emission with the increase in the compression ratio.
c. The compression ratio has no significant effect on all four responses, whereas the blends of fuel have a significant effect on the emission of CO and NO_x. Only there is a decrease in the CO emissions with the increase of fuel blends percentage.
d. The *P*-value > 0.05 in the ANOVA model suggests the intensity of the contribution of each input parameter to the output response. From the ANOVA analysis, it is observed that for brake power, the load and fuel blends have more contribution. Similarly, for the SFC the highest contribution is from the load, the CO emission fuel blend has the highest contribution, and

for the NO_x emission, load has the highest contribution.

e. The multiresponse optimization for the maximum value for brake power and minimum value for the SFC, CO, and NO_x emissions are 3 kW, 0.398978 kg/kWh, 0.01%, and 50 ppm, which has been done with the desirability function and which gave a very high desirability value, *D* of 0.904873.
f. The optimum input parameters that provide the optimum performance of the CI engine are 4.63281 kg of load, i.e., nearly 5 kg of load, and the compression ratio of 18 and B05 for the fuel blend.
g. As the experimental work is conducted on a constant-speed diesel engine, the results are suitable for stationary engines such as diesel generators as compared with an automotive engine that has variable speed.
h. From the economic analysis, it is found that biodiesel costs more than diesel fuel with higher loads. But biodiesel helps in the reduction of carbon emissions, which is the most important concern across the globe and it has a lot of other useful aspects that can be explored with future research work such as the usage of glycerol, which is a byproduct that can generate some revenue and which cuts down the overall production cost.
i. There has been little few work done on the factors affecting combustion. Also, other optimization techniques can be explored to make a more suitable model.

Acknowledgements
The authors gratefully acknowledge the Management of IIIT Bhubaneswar and School of Maritime Studies, Centurion University of Technology and Management, India for providing the facilities to carry out the research work in both the college campus and my homeland.

Author contributions
PM: Resources, Data collection, Methodology, Designing, Analysis, Visualization, Writing, Original draft preparation. TM: Conceptualization, Methodology, Software, Writing, Reviewing. SSS: Resources, Data collection, Methodology, Project administration. BNP: Reviewing, Editing, and Interpretation. NCG: Reviewing, Editing, Paper correction, and formatting. AE: Reviewing, Editing, Paper correction. KMA: Reviewing, Editing, Paper correction, and formatting.

Funding
This research received no external funding.

Data availability
Data will be made available on reasonable request.

Declarations

Consent to participate
The authors mutually agree that they participated in the preparation of the manuscript.

Informed consent
This article is about consent to renewable energy and agricultural research procedures ethics.

Competing interests
On behalf of all authors, the corresponding author states that there is no conflict of interest.

Author details
[1]Department of Mechanical Engineering, IIIT Bhubaneswar, Bhubaneswar, India. [2]School of Maritime Studies, Centurion University of Technology and Management, Jatni 752050, Odisha, India. [3]Department of Mechanical Engineering, C V Raman Global University, Bhubaneswar 752054, Odisha, India. [4]School of Mechanical Sciences, Odisha University of Technology and Research, Bhubaneswar 751029, Odisha, India. [5]Department of Electronics and Communication Engineering, Centurion University of Technology and Management, Jatni 752050, Odisha, India. [6]Electrical Engineering Department, University of Business and Technology, Ar Rawdah, 23435 Jeddah, Saudi Arabia. [7]Engineering Mathematics and Physics Department, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt. [8]Department of Electrical Power and Machines, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt.

Received: 13 February 2023 Accepted: 8 February 2024
Published online: 05 June 2024

References

1. Giri NC, Mohanty RC (2020) Accelerating India's energy sector to sustainable sources, potentials, and prospects. Indian J Nat Sci 10(58):18066–18076
2. Chauhan SK, Gangopadhyay S, Singh N (2009) Environmental aspects of biofuels in road transportation. Env Chem Lett 7(4):289–299. https://doi.org/10.1007/s10311-008-0185-7
3. Giri NC, Mohanty RC (2022) Agrivoltaic system: experimental analysis for enhancing land productivity and revenue of farmers. Energy Sustain Dev 70:54–61. https://doi.org/10.1016/j.esd.2022.07.003
4. Hassan MdK, Halder P, Pelkonen P, Pappinen A (2013) Rural households' preferences and attitude towards biomass fuels-results from a comprehensive field survey in Bangladesh. Energy Sustain Soc. https://doi.org/10.1186/2192-0567-3-24
5. Mukhopadhyay P, Chakraborty R, Singh S (2022) Triacetin additive in biodiesel to reduce air pollution: a review. Environ Chem Lett. https://doi.org/10.1007/s10311-021-01362-0
6. Srivastava RK, Shetti NP, Reddy KR, Aminabhavi TM (2020) Biofuels, biodiesel and biohydrogen production using bioprocesses. A review. Env Chem Lett 18(4):1049–1072. https://doi.org/10.1007/s10311-020-00999-7
7. Ma F, Hanna MA (1999) Biodiesel production: a review1Journal Series #12109, Agricultural Research Division, Institute of Agriculture and Natural Resources., University of Nebraska–Lincoln.1. Bio Tech 70(1):1–15. https://doi.org/10.1016/s0960-8524(99)00025-5
8. Sekar M, Kumar TRP, Kumar MSG, Vaníčková R, Marousek J (2021) Techno-economic review on short-term anthropogenic emissions of air pollutants and particulate matter. Fuel 305(1):121544. https://doi.org/10.1016/j.fuel.2021.121544
9. Petchsoongsakul N, Ngaosuwan K, Kiatkittipong W, Wongsawaeng D, Assabumrungrat S (2020) Different water removal methods for facilitating biodiesel production from low-cost waste cooking oil containing high water content in hybridized reactive distillation. Renew Engy 162:1906–1918. https://doi.org/10.1016/j.renene.2020.09.115
10. Kumar D, Das T, Giri BS, Verma B (2020) Optimization of biodiesel synthesis from nonedible oil using immobilized bio-support catalysts in jacketed packed bed bioreactor by response surface methodology. J Clean Prod. https://doi.org/10.1016/j.jclepro.2019.118700
11. Yadav AK, Dewangan A, Mallick A (2018) Synthesis and biodiesel study of biodiesel from kachnar seed oil. J Energy Eng. https://doi.org/10.1061/(ASCE)EY.1943-7897.0000565

12. Hajjari M, Tabatabaei M, Aghbashlo M, Ghanavati H (2017) A review on the prospoect of sustainable biodiesel production: a global scenario with an emphasis on waste-oil biodiesel utilization. Renew Sustain Energy Rev 72:445–464. https://doi.org/10.1016/j.rser.2017.01.034
13. Gonçalves PC, Monteiro LPC, Santos LS (2020) Multi-objective optimization of a biodiesel production process using process simulation. J Clean Prod 270:122322. https://doi.org/10.1016/j.jclepro.2020.122322
14. Goga G, Chauhan BS, Mahla SK, Cho HM (2019) Performance and emission characterisitics of diesel engine fueled with rice bran biodiesel and n-butanol. Energy Rep 5:78–83. https://doi.org/10.1016/j.egyr.2018.12.002
15. Kannan M, Sathish Babu R, Sathish S (2020) Experimental investigations on the performance and emission characteristics of CI engine fuelled with biodiesel from neem oil. Int J Ambient Energy. https://doi.org/10.1080/01430750.2020.1726812
16. Uzun BB, Kiliç M, Apaydin-Varol E, Pütün AE (2014) Optimization of biodiesel production and fuel properties of blends. Energy Sourc Part A: Rec Util Environ Effects 36(8):898–906. https://doi.org/10.1080/15567036.2010.549907
17. Akcay M, Ozer S (2019) Experimental investigation on performance and emission characteristics of a CI diesel engine fueled with fusel oil/diesel fuel blends. Energy Sources A Recov Util Environ Effect. https://doi.org/10.1080/15567036.2019.1689317
18. Das M, Sarkar M, Datta A, Santra AK (2018) An experimental study on the combustion, performance and emission characteristics of a diesel engine fuelled with diesel-castor oil biodiesel blends. Renew Energy 119:174–184. https://doi.org/10.1016/j.renene.2017.12.014
19. Verma A, Rawat K, Saify M, Singh A, Maheswari P (2020) Performance analysis of CI engine powered with simarouba glauca L biodiesel fuel. Adv Mat Eng Manuf Process 41–50. Lecture Notes on Multidisciplinary Industrial Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-15-4331-9_4
20. Roy MM, Wang W, Bujold J (2013) Biodiesel production and comparison of emissions of a DI diesel engine fueled by biodiesel-diesel and canola oil-diesel blends at high idling operations. Appl Energy 106:198–208. https://doi.org/10.1016/j.apenergy.2013.01.057
21. Atabani AE, Badruddin IA, Masjuki HH, Chong WT, Lee KT (2015) Pangium edule reinw: a promising non-edible oil feedstock for biodiesel production. Arab J Sci Eng 40(2):583–594. https://doi.org/10.1007/s13369-014-1452-5
22. Kathirvelu B, Subramanian S, Govindan N, Santhanam S (2017) Emission characteristics of biodiesel obtained from jatropha seeds and fish wastes in a diesel engine. Sustain Environ Res 27(6):283–290. https://doi.org/10.1016/j.serj.2017.06.004
23. Sharma A, Kumar P, Sandhu SS, Singh M (2023) Experimental investigation into the effects of Argemone biodiesel/diesel blends on cyclic variations in a multi-cylinder CRDI engine. Clean Energy. https://doi.org/10.1093/ce/zkac081
24. Singh M, Kumar P, Sandhu SS (2022) An investigation of optimum control of injection timing/injection pressure for a multicylinder common rail direct injection engine fueled with AB20 blend. Proc Inst Mech Engine Part E: J Process Mech Eng. https://doi.org/10.1177/09544089221146165
25. Kumar P, Singh M, Sandhu SS (2022) Wavelet analysis for cyclic combustion dynamics of a multi-cylinder CRDI diesel engine fuelled with a blending of argemone biodiesel-diesel oil. Chaos. https://doi.org/10.1063/5.0080910
26. Giri NC, Mohanty RC (2022) Design of agrivoltaic system to optimise land use for clean energy-food production: a socio-economic and environmental assessment. Clean Technol Environ Policy 24(1):2595–2606
27. Chen H, Xie B, Ma J, Chen Y (2018) NO_x emission of biodiesel compared to diesel: higher or lower? App Thermal Engg 137:584–593. https://doi.org/10.1016/j.applthermaleng.2018.04.022
28. Mirhashemi FS, Sadrnia H (2020) NO_x emissions of compression ignition engines fueled with various biodiesel blends: a review. J Energy Inst 93(1):129–151. https://doi.org/10.1016/j.joei.2019.04.003
29. Prabhahar M, Alharbi SA, Almoallim HS, Prakash S, Saravana Kumar M, Surendrababu K, Sendilvelan S, Bhaskar K, Maroušek J, Anderson A (2023) Trade-off characteristic between soot and oxides of nitrogen emission with pre-injected diesel and biodiesel in a SICI-CIDI engine. Fuel. https://doi.org/10.1016/j.fuel.2022.125624
30. Tabatabaei M, Aghbashlo M, Najafi B, Hosseinzadeh-Bandbafha H, Faizollahzadeh Ardabili S, Akbarian E, Khalife E, Mohammadi P, Rastegari H, Ghaziaskar HS (2019) Environmental impact assessment of the mechanical shaft work produced in a diesel engine running on diesel/biodiesel blends containing glycerol-derived triacetin. J Clean Prod 223:466–486. https://doi.org/10.1016/j.jclepro.2019.03.106
31. Agrawal T, Gautam R, Agrawal S, Singh V, Kumar M, Kumar S (2020) Optimization of engine performance parameters and exhaust emissions in compression ignition engine fueled with biodiesel-alcohol blends usin taguchi method, multiple regression and artificial neural network. Sustain Fut 2(6):100039. https://doi.org/10.1016/j.sftr.2020.100039
32. Atadashi IM, Aroua MK, Abdul AAR, Sulaiman NMN (2011) Refining technologies for the purification of crude biodiesel. Appl Energy 88:4239–4251. https://doi.org/10.1016/j.apenergy.2011.05.029
33. Singh A, Sinha S, Choudhary AK, Panchal H, Elkelawy M, Sadasivuni KK (2020) Optimization of performance and emission characteristics of CI engine fueled with Jatropha biodiesel produced using a heterogeneous catalyst (CaO). Fuel 280:118611. https://doi.org/10.1016/j.fuel.2020.118611
34. Design Expert 11, Stat-Ease,Inc.pdf. (n.d.)
35. Sharma P, Le MP, Chillar A, Said Z, Deepanraj B, Cao DN, Bandh SA, Hoang AT (2022) Using response surface methodology approach for optimizating performance and emission parameters of diesel engine powered with ternary blend of Solketal-biodiesel-diesel. Sustain Energy Tech Assess 52:102343. https://doi.org/10.1016/j.seta.2022.102343
36. Jain A, Bora BJ, Kumar R, Sharma P, Deka H (2023) Theoritical potential estimation and multi-objective optimization of Water Hyacinth (Eichhornia Crassipes) biodiesel powered diesel engine at variable injection timings. Renew Energy 206:514–530. https://doi.org/10.1016/j.renene.2023.02.033
37. Said Z, Sharma P, Bora BJ, Nguyen VN, Bui TAE, Nguyen DT, Dinh XT, Nguyen XP (2023) Modelling-optimization of performance and emission characteristics of dual-fuel engine powered with pilot diesel and agricultural-food waste-derived biogas. Hyd Eng 48(18):66761–66777. https://doi.org/10.1016/j.ijhydene.2022.07.150
38. Chozhavendhan S, Singh MVP, Fransila KRP, Devi GK (2020) A review on influencing parameters of biodiesel production and purification process. Curr Res Green Sustain Chem. https://doi.org/10.1016/j.crgsc.2020.04.002
39. Ganesan N, Shani I, Samuel OD, Enweremadu CC, Veza I, Chandran D (2022) Optimization and sustainability of gasohol/hydrogen blends for operative spark ignition engine utilization and green environment. Case Stud Ther Eng. https://doi.org/10.1016/j.csite.2022.102381
40. Singh TS, Rajak U, Samuel OD, Chaurasiya PK, Natarajan K, Verma TN, Nashine P (2021) Optimization of performance and emission parameters of direct injecton disel engine fulled with microalgae Spirulina (L.)—response surface methodology and full factorial method approach. Fuel 285(1):119103. https://doi.org/10.1016/j.fuel.2020.119103
41. Saravanan S, Kaliyanasunder R, Rajesh Kumar B, Lakshmi Narayana Rao G (2020) Effect of design parameters on performance and emissions of a CI engine operated with diesel-biodiesel- higher alcohol blends. Renew Energy 148:425–436. https://doi.org/10.1016/j.renene.2019.10.049
42. Ashok B, Nanthagopal K (2019) Eco friendly biofuels for CI engine applications. Adv Eco-Fuels Sustain Environ. https://doi.org/10.1016/b978-0-08-102728-8.00015-2
43. Enweremadu C, Samuel O, Rutto H (2022) Experimental studies and theoretical modelling of diesel engine running on biodiesel from South African and Canola oils. Environ Clim Technol 26:630–647. https://doi.org/10.2478/rtuect-2022-0048
44. Kumar S, Shukla SK (2018) Study of degradation of quality of soyabean biodiesel with storage time and its emissions on various loads. Mater Today Proc 5(11):23177–23192. https://doi.org/10.1016/j.matpr.2018.11.049
45. Rao KS, Ramakrishna A (2015) Cost estimation analysis of biodiesel production from waste chicken fat. Int J Appl Eng Res 10:8863–8870
46. Parida S, Misra S, Sahu DK (2011) Development of process technology to produce low cost biofuel 1- Minimization of operation parameters during preparation of biodiesel. World Renewable Energy Congress, Sweden, 72-78. https://doi.org/10.3384/ecp1105772
47. Das AK, Mohapatra T, Panda AK (2023) Multiple response optimization for performance and emission of a CI engine using waste plastic oil and

biogas in dual fuel mode operation. Sustain Energy Technol Assess 57: 103170. https://doi.org/10.1016/j.seta.2023.103170

48. Mishra SS, Mohapatra T, Sahoo SS (2023) Functional investigation, multiple response optimization, and economic analysis of a VCR CI engine fired with diesel, calophyllum inophyllum oil, and waste biomass-derived producer gas in multi-fuel mode. Arab J Sci Eng 48: 4003–4023. https://doi.org/10.1007/s13369-022-07349-5