



Optimization of diesel engine performance and emissions with biodiesel-diesel blends and EGR using response surface methodology (RSM)

Ashish Dubey^{a,*}, Ravi Shankar Prasad^a, Jitendra Kumar Singh^b, Ashish Nayyar^c

^a Department of Mechanical Engineering, JK Lakshmi Pat University, Jaipur, 302026, India

^b Department of Chemical Engineering, JK Lakshmi Pat University, Jaipur, 302026, India

^c Department of Mechanical Engineering, Swami Keshvanand Institute of Technology, India

ARTICLE INFO

Keywords:

Waste cooking soybean oil biodiesel
EGR
RSM
Desirability approach
Exhaust emissions

ABSTRACT

The rising price of conventional liquid fuels and increasing pollution drive research into alternate bio-fuels. In the present study, waste cooking soybean oil (WSCO) was collected from local restaurants and food processing industries. The 92% biodiesel yield was obtained by using a homogeneous transesterification process. A detailed experimental and analytical study of the engine performance and emissions with binary fuel blends of WSCO biodiesel and ultra-low sulfur diesel (ULSD) has been performed using response surface methodology. Binary blends were prepared by adding 20–35 v.% of WSCO to ULSD; experiments were carried out at 0–15% EGR. To analyze the effects of input variables on BSFC, BTE, smoke, NO_x, CO, and HC, regression models were developed and confirmed to be statistically significant. The binary blend of B35 with 15% EGR (B35EGR15) showed the maximum desirability (0.928). The model's adequacy was validated by a confirmation test with an error in prediction below 6%. For blend B35EGR15, BSFC was increased by 6.61% and BTE was reduced by 5.30% for B35EGR15 as compared to ULSD (ULSD at 0% EGR). Smoke and NO_x emissions were decreased by 19.09% and 59.04%, while CO and HC emissions were increased by 17.54% and 11.76%, as compared to ULSD (ULSD at 0% EGR). The economic analysis showed that the operation cost was reduced by 23.34% for B35EGR15 as compared to ULSD (ULSD at 0% EGR). The B35EGR15 blend can be used in existing diesel engines with no engine modifications.

1. Introduction

Global energy demand is rising as a result of industrialization and urbanization (Ulusoy et al., 2018). The transportation (Chuah et al., 2021) and power generation sectors are mainly dependent upon fossil fuels, leads to the depletion of fossil reserves (Yadav et al., 2017). Furthermore, the combustible products produced during the operation of an IC engine degrade the natural environment (Chuah et al., 2016). Biofuels (especially biodiesel) may be a possible solution to these problems (Aydın, 2020). Biofuel has several advantages including renewable energy source, biodegradable, low operating cost, and reducing emission levels (Subramaniam et al., 2020). Waste cooking oil is a promising candidate for biodiesel production due to its low cost (Chuah et al., 2017) and ease of availability (Avinash and Murugesan, 2017). The use of WCO generates positive environmental impacts (Sahar et al., 2018). Many investigations have reported that biodiesel-diesel blends lower the exhaust emissions, except for the NO_x emissions. Chuah et al. (2015) investigated performance and emission parameters

using WCO biodiesel blends (10–50 v.%) at different engine speeds (from 1000 to 2000 rpm). The results showed that BSFC (2.1–9.0%) and exhaust gas temperature (1.0–6.8%) increased, while brake power (1.6–6.7%), torque (0.6–5.2%), and BTE (1.9–8.4%) were reduced with the biodiesel blend ratio. Carbon dioxide (8.7–38.5%) and nitrogen oxide (4.7–19.0%) emissions increased, while CO (3.3–26.3%) decreased with the biodiesel blend ratio. Singh and Sandhu (2020) observed improvement in BTE and BSFC with a reduction in exhaust emissions (excluding NO_x emissions) using argemone biodiesel-diesel blends. Serac et al. (2020) found that soybean biodiesel-diesel blends reduced CO, HC, and smoke emissions while increasing NO_x emissions. Similar results were reported by Joy et al. (2018), who found that neat palm kernel oil biodiesel-octanol blends reduced CO, HC, and smoke emissions while increasing NO_x emissions.

The EGR technique is a simple, less costly, and effective method to reduce NO_x emissions (Palash et al., 2013). Balasubramanian et al. (2021) reported the performance and emissions of a twin-cylinder diesel engine using WCO biodiesel (20–100%) blended diesel fuel. B20 was best suited for a reduction in HC, CO, and smoke emissions. Further, B20

* Corresponding author.

E-mail address: ashishdubey@jklpu.edu.in (A. Dubey).

<https://doi.org/10.1016/j.clet.2022.100509>

Received 25 February 2022; Received in revised form 22 April 2022; Accepted 8 May 2022

Available online 11 May 2022

2666-7908/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Nomenclature

WSCO biodiesel	Waste soybean cooking oil biodiesel
EGR	Exhaust gas recirculation
ULSD	Ultra low sulfur diesel
ULSDEGR0	Ultra low sulfur diesel without EGR
B20EGR0	20 v.% WSCO biodiesel +80 v.% ULSD without EGR
B35EGR15	35 v.% WSCO biodiesel +65 v.% ULSD at 15% EGR
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
CO	Carbon monoxide
NO _x	Nitrogen oxides
HC	Hydrocarbon
RSM	Response surface methodology

with 10% EGR reduced NO_x by a satisfactory level, keeping other emissions within acceptable limits. Nanthagopal et al. (2019) studied the influence of EGR (at 30%) on DI engines fuelled with neat WCO methyl ester (B100). The results showed that BSFC, smoke, and brake specific UBHC increased by 10.52%, 11.76%, and 50%. BTE and NO_x levels were reduced by 18% and 58.9%. Mahalingam et al. (2018) investigated engine performance and emissions using pentanol-biodiesel blends at EGR rates (0–20%) and found an increment in BSFC, CO, HC, and smoke emissions as the EGR rate increased. By increasing the EGR rate, NO_x and BTE were reduced. Ayhan et al. (2020) employed the Taguchi method to optimize the corn oil methyl ester-diesel blends (B0–B50) and EGR (0–20%). The observations showed that the NO_x emission is minimal using B0, 20% EGR, 40% engine load, and 2400 rpm. Shaik et al. (2020) carried out experiments with 20 v.% mango seed methyl ester (MSME20) blend with a diesel at different compression ratios (18:1, 20:1, and 22:1) and EGR (5 and 10%). The observations showed that at compression ratio (22:1) and EGR (5%), the BSFC, NO_x, HC, and CO emissions were reduced by 1.15%, 40.5%, 12.8%, and 20%. But the smoke increased by 6%. Bhaskar et al. (2013) examined the influence of EGR on engine performance and emissions of CI engine powered by fish oil methyl ester (FOME). It was reported that the addition of EGR increased specific energy consumption and decreased BTE. NO_x emissions were proportionally reduced with a percentage of EGR rate whereas soot emissions increased. Dhana Raju and Kishore (2019) studied the combined effects of EGR (10–30%) and a blend of 20 v.% tamarind seed methyl ester (TSME20) on the performance and emissions of a diesel engine. The experimental assessment revealed that the blend of TSME20 with 20% EGR reduced NO_x by 52.69%. Chaichan (2018) investigated the engine performance and emission characteristics with dual fuel mode (20 v.% gaseous hydrogen and 80 v.% biodiesel) and 30% cooled EGR. It was reported that dual fuel mode operation increased BTE and NO_x while lowering CO, HC, and PM emissions. Further, the use of EGR reduced NO_x with a tolerable performance and emissions. Damodharan et al. (2018) carried out experiments using neat waste plastic oil (WPO) with varying injection timing (21°–25°CA bTDC) and EGR (10–30%). At 25°CA bTDC of injection timing and 10% EGR, the 5.1% improvement in BTE and a 46% and 38% reduction in smoke and NO_x emissions. De Pours et al. (2017) investigated the performance of n-Hexanol-diesel blends (10–30 v.%) at various injection timings and EGR. The 30% n-Hexanol-diesel blend at 30% EGR was very effective in smoke reduction by 35.9%.

Optimization methods reduce the number of experiments, develop mathematical optimization models, and predict responses. Simsek and Uslu (2020b) recommend using RSM to improve engine performance and emissions. Ozgur (2021) applied the RSM technique to WCO biodiesel-diesel blends for engine performance and emissions. The optimum WCO biodiesel blend (9.17 v.%) showed the best responses. Khanjani and Sobati (2021) evaluated the influence of waste fish oil

(WFO) biodiesel (3, 5, and 7 v.%), water (3, 5, and 7 v.%), and surfactant (1, 1.5, and 2 v.%) on engine performance and emissions using RSM. The optimum values were identified as 3 v.% WFO-biodiesel, 6.13 v.% water, and 1 v.% surfactant. It was observed that CO, HC, and NO_x were reduced by 42.86%, 34.02%, and 25.53%. Murugapopathi and Vasudevan (2021) applied RSM for analysis of engine performance and emissions using rubber seed oil (RSO) biodiesel (0–20 v.%) with varying operating parameters. At optimum RSO biodiesel (20 v.%), BTE improved while CO, HC, and NO_x were reduced compared to diesel. Simsek and Uslu (2020b) investigated biodiesel-diesel blends (0–100 v.%) to maximize BTE and minimize exhaust gas temperature (EGT), NO_x, smoke, and CO₂. The RSM model revealed that the optimum responses of BTE (20.54%), EGT (199.88 °C), smoke (0.26%), NO_x (558.4 ppm), and CO₂ (4.52%) were found using 25.79 v.% RSO-biodiesel-diesel blends.

In the present study, WSCO-ULSD blends and EGR were used in various ratios. Performance and exhaust emissions of WSCO-ULSD blends were investigated on a stationary, agriculture-based, CI engine at different concentrations of fuel blend, loads, and EGR rates using the RSM technique. This has not been reported in the available literature. The RSM was used to identify the optimum WSCO-ULSD blend at a suitable EGR rate. The optimization criteria were set to maximize the BTE and minimize the BSFC, smoke, NO_x, CO, and HC using the desirability approach. The results were validated via a confirmation test. An economic assessment of engine operation has also been done for the optimal value of input variables.

2. Experimental setup, materials and methods

2.1. Experimental setup

In the present experimental investigations, an EGR coupled, single-cylinder, four-stroke, diesel engine coupled with an eddy current dynamometer was chosen. The specifications of the test setup are given in Table 1. The engine test setup is schematically represented in Fig. 1.

2.2. Measurement of emissions

The smoke in the exhaust is measured by a smoke meter made by AVL (Austria, Model: 437C). The exhaust emissions such as NO_x, CO, and HC were determined by using an exhaust gas analyzer (AVL India, Model: 444N). Table 2 illustrates the experimental ranges and resolution of emission data.

2.3. Uncertainty in measurement

The possibility of error/uncertainty during experiments is owing to operational parameters, equipment calibration, measuring instrument precision, human mistakes, and experiment design (Moffat, 1988). Table 2 illustrates the results of determining the uncertainty of various parameters.

Table 1
Specifications of test setup and equipment used.

Item	Specification
Engine	
Make	Kirloskar-TV1
Type	Single cylinder, 4 stroke, VCR engine
Bore × stroke (mm)	87.5 × 110
Compression ratio	19:1
Rated power (kW)	3.75
Rated speed (rpm)	1500
Injection type	Direct injection
Intake system	Naturally aspirates
Injection pressure (bar)	210
Injection timing (°CA BTDC)	23

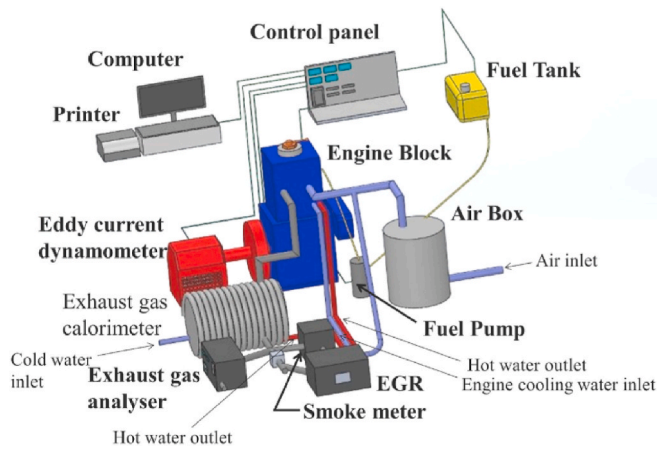


Fig. 1. Layout of the engine setup.

Table 2

Range, resolution and % uncertainties of instruments.

Measured parameter	Experimental range	Resolution	Uncertainty (%)
BSFC	0.22–0.53 kg/kW.h	–	±0.114
BTE	12.58–31.82%	–	±0.114
Smoke	11.36–31.7 %HSU	0.1%	±0.05
NO _x	15–132 ppm	1 ppm v.	±3
CO	0.061–0.091%	0.001%	±3
HC	18–24 ppm	1 ppm v.	±5

Overall uncertainty of measurements ($\delta U_{\text{overall}}$) can be written as (Huang et al., 2015):

$$(\delta U_{\text{overall}}) = \sqrt{(\delta U_{\text{BSFC}})^2 + (\delta U_{\text{BTE}})^2 + (\delta U_{\text{Smoke}})^2 + (\delta U_{\text{NO}_x})^2 + (\delta U_{\text{CO}})^2 + (\delta U_{\text{HC}})^2} \quad (1)$$

$$(\delta U_{\text{overall}}) = \sqrt{(0.114)^2 + (0.114)^2 + (0.05)^2 + (3)^2 + (3)^2 + (5)^2} = 6.56\%$$

2.4. EGR application

An external EGR system was installed to applying 0%, 5%, 10%, and 15% EGR flow rates in this investigation. Exhaust gas recirculation is a technique for reducing NO_x levels by some amount of engine exhaust being fed into the engine's inlet manifold to mix with the fresh air. The specific heat of the mixture inside the combustion chamber rises during this process, while the oxygen level drops. The quantity of exhaust gas was measured using an orifice meter. An EGR valve was used to adjust the EGR rate, and the percentage of the EGR amount was calculated using eq. (2) (Balasubramanian et al., 2021).

$$\text{EGR (\%)} = \frac{(\text{CO}_2)_{\text{int}} - (\text{CO}_2)_{\text{atm}}}{(\text{CO}_2)_{\text{out}} - (\text{CO}_2)_{\text{atm}}} \quad (2)$$

where (CO₂)_{int} and (CO₂)_{out} are concentration of CO₂ at the inlet and the outlet.

2.5. Fuel preparation

2.5.1. Biodiesel production

The WSCO has been collected from the local restaurants in Jaipur, Rajasthan, India. This WSCO is converted into biodiesel by the transesterification process. The transesterification process was completed at a methanol to oil molar ratio of 5:1, a reaction temperature of 60 °C, a reaction time of 80 min, and a KOH catalyst concentration of 0.75 wt%. Upon the completion of transesterification, biodiesel and glycerol were obtained. Further, the biodiesel was separated and washed using distilled water; the water contents were eliminated by the low amount of heating. A 92% biodiesel yield was achieved (Dubey et al., 2020). The

physicochemical properties of biodiesel were obtained as per ASTM6271-D standards and are illustrated in Table 3.

2.5.2. Preparation of fuel blends

The ULSD was purchased from the local BPCL fueling station and has properties as per IS 1460:2005 (fifth revision). The bio-oxygenated fuel blends were prepared by blending different proportions of WSCO biodiesel into ULSD.

2.6. Test methodology

The investigations were executed at 1500 rpm speed and under different engine loading conditions (25%, 50%, 75%, and 100%). The engine operating characteristics of a low concentration of biodiesel blends show approximately similar trends to diesel fuel to allow attention to higher blend ratios for the investigation. The different rates of the EGR enabled the NO_x formation to be minimized.

2.7. Experimental design

For experimental design, optimization, and validation, Design-Expert® software (version 13) by Stat-Ease, Inc., USA was used. The input variables with their levels are shown in Table 4. All input variables are taken as numeric factors. The load (25–100%), WSCO biodiesel ratio (20–35 v.%), and EGR (0–15%) were selected for the objective of maximizing BTE and minimizing BSFC, smoke, NO_x, CO, and HC.

2.7.1. Response surface methodology

RSM is a statistical method used to develop quadratic/cubic prediction models for the input variables and their response variables (Bokhari et al., 2017). RSM assists in finding the influence of input variables on response variables, reducing the number of experiments and optimizing the response variables (Ganapathy et al., 2011). The RSM flowchart for this investigation is presented in Fig. 2.

$$Y = \beta_0 + \sum_{i=1}^n \beta_i x_i + \sum_{i=1}^n \beta_{ii} x_i^2 + \sum_{i>j}^n \sum_j \beta_{ij} x_i x_j + e \quad (3)$$

where Y– response variable, n– number of factors, β_0 , β_i , β_{ii} and β_{ij} – regression coefficients, x_i and x_j – independent factors and e– error.

2.7.2. Desirability

The desirability is a scale-free value of the estimated response. It combines multiple responses into a single dimensionless metric. The nature of each response's goal might be maximized, minimized, in range, equal to, or target, and defines the desirability function. The present study involves the maximization and minimization of BTE and

Table 3

The physicochemical properties of ULSD and WSCO biodiesel.

Property	ULSD (Nayyar et al., 2019)	WSCO biodiesel (Dubey et al., 2020)
Density (kg/m ³) at 20 °C	829	881
Flash point (°C)	68	190
Boiling point (°C)	180–360	–
Lower heating value (MJ/kg)	43	37.45
Specific gravity	0.829	–
Latent heat of vaporization (kJ/kg)	250	40.5
Auto-ignition temperature (°C)	315	–
Cetane number	55.5	52
Viscosity (cST) at 40 °C	3.2	5.35
Oxygen content (wt.%)	0	10.97
Carbon content (wt.%)	87.0	77.10
Hydrogen content (wt.%)	12.6	11.81

Table 4
Factors and levels for WSCO biodiesel.

Parameter	Coded values	Levels			
		1	2	3	4
Load (%)	A	25	50	75	100
WSCO biodiesel (v.%)	B	20	25	30	35
EGR (%)	C	0	5	10	15

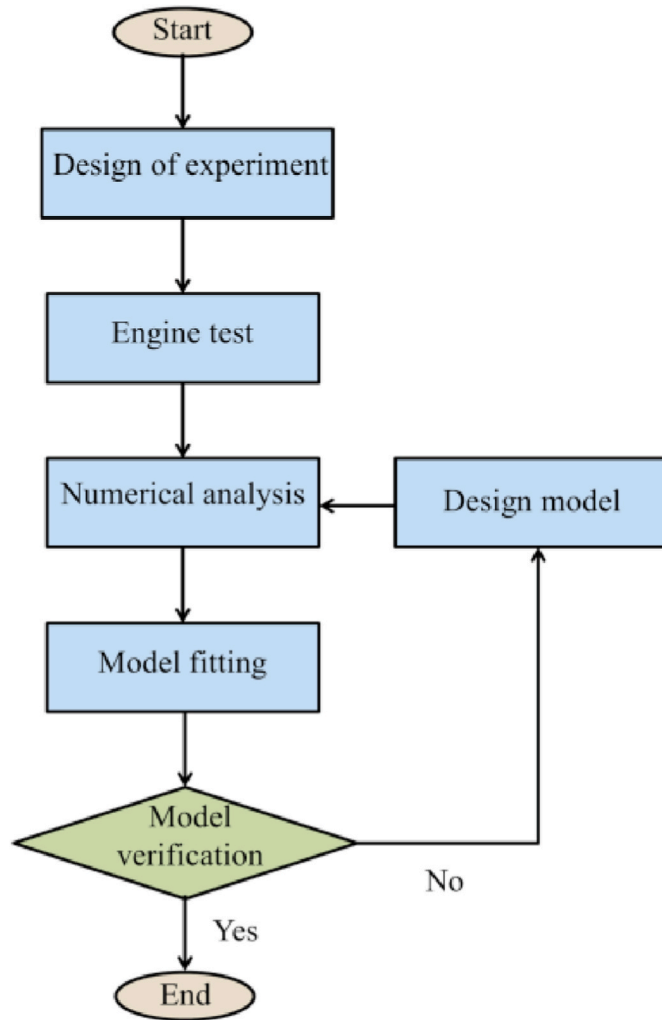


Fig. 2. RSM flowchart.

BSFC, smoke, NO_x, CO, and HC emissions. Eqs. (4) and (5) give the desirability (d_i) for maximizing and minimizing the response (Krishnamoorthy et al., 2018).

$$\begin{aligned}
 &\text{For maximize,} \\
 &d_i = 0, \text{ when } Y_i < \text{Low}_i \\
 &d_i = \left(\frac{Y_i - \text{Low}_i}{T_i - \text{Low}_i} \right)^{wt_i}, \text{ when } \text{Low}_i \leq Y_i \leq T_i \\
 &d_i = 1, \text{ when } Y_i > T_i \\
 &\text{For minimize,} \\
 &d_i = 1, \text{ when } Y_i < T_i \\
 &d_i = \left(\frac{\text{High}_i - Y_i}{\text{High}_i - T_i} \right)^{wt_i}, \text{ when } T_i \leq Y_i \leq \text{High}_i \\
 &d_i = 0, \text{ when } Y_i > \text{High}_i
 \end{aligned} \quad (4)$$

where i— response, Y— value of the response, Low and High— lower and upper limits of the response, T— target value of the response, and wt_i— weight with an assigned value of 1. The overall desirability (D) is calculated by the geometric mean of the sole desirability of each response given by eq. (6) (Krishnamoorthy et al., 2018). The confirmation test is then conducted using the desirability approach to validate the optimal solution.

$$D = \left(\prod_{i=1}^n d_i^{r_i} \right)^{1/\sum r_i} \quad (6)$$

3. Results and discussion

3.1. Model analysis and evaluation for WSCO biodiesel blend with EGR

Figs. 3–5 show the fair accuracy of the models and a robust correlation between the predictions and actual results of the models. Table 5 illustrates the experimental design matrix along with the observed data.

3.1.1. ANOVA for WSCO biodiesel blend with EGR

Tables 6 and 7 present the ANOVA for response surface quadratic and 2FI models of BSFC, BTE, smoke, NO_x, CO, and HC emissions. ANOVA analysis was used in this study with a significance level of = 0.05 (at a 95% confidence level).

The p-value is the most crucial parameter in the ANOVA analysis. The maximum p-value for a model should be 0.05, and models with p-values higher than 0.05 are considered irrelevant (Datta Bharadwaz et al., 2016). When the p-value is less than 0.05, it indicates that the factor has a significant impact on the model being developed (Awad et al., 2017). In Tables 6 and 7, linear and second-order coefficients of BSFC, BTE, smoke, NO_x, CO, and HC are significant. As can be seen, the interaction coefficients of BSFC, BTE, smoke, NO_x, CO, and HC are significant except for the interaction parameter of AC for the smoke. In Table 8, the other diagnostic parameters for evaluating the developed model of response variables are illustrated. For BSFC, the R² value is 0.9979. Its closeness to 1 indicates the accuracy as well as adequacy of the model. The difference between the Adj. R² value (0.9969) and the Pred. R² value (0.9952) is less than 0.2, showing the reasonable agreement between them. The value of adequate precision is 79.436. This shows the rigor of the model. The polynomial regression equation for BSFC is presented by equation 7 in Table 9.

Similarly, the summary of ANOVA (Tables 6 and 7) and model evaluation (Table 8) for BTE, smoke, NO_x, CO, and HC emissions showed the value of R², Adj. R², Pred. R², and adequate precision well suited within the mandate limits for accuracy and adequacy of the model for desired responses. The polynomial regression equations for BTE, smoke, NO_x, CO, and HC are presented by equations 8, 9, 10, 11, and 12 in Table 9.

3.2. Performance of engine using WSCO biodiesel blends with EGR

3.2.1. Brake specific fuel consumption and brake thermal efficiency

It is observed from Fig. 6 (a) and 6 (b) that BSFC increases with increasing WSCO biodiesel in blends and EGR rate. The probable reason for increasing BSFC with WSCO biodiesel is the interactive effects of blend viscosity, density, lower calorific value, and poor atomization. Mofijur et al. (2013) presented similar arguments and reported a higher BSFC for biodiesel blends. Asokan et al. (2019) reported the higher figures of BSFC for biodiesel-diesel blends due to the lower heating value of the blends. The addition of EGR increases the value of BSFC due to dilution of the fresh charge by recirculation of exhaust gas. This results in a reduction in-cylinder temperature. To produce the same energy for a particular load, a greater amount of fuel is required. A similar trend was reported in the literature (Nanthagopal et al., 2019). The BSFC of B35EGR15 is 4.74% higher than B20EGR0 at full load.

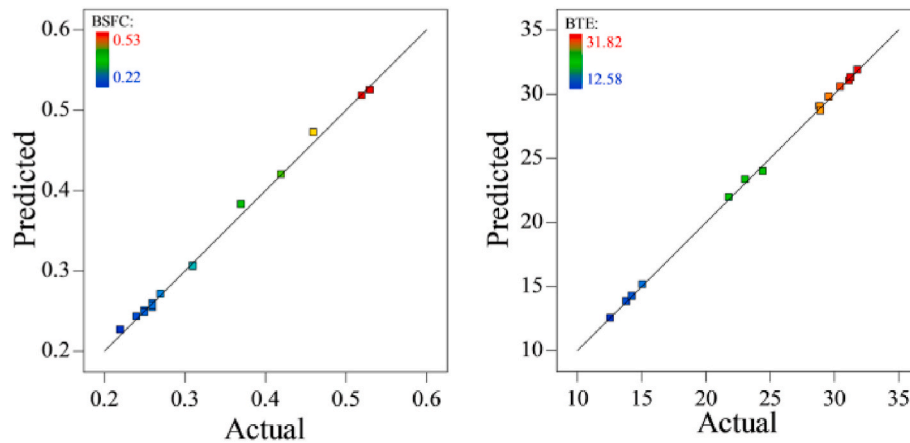


Fig. 3. Actual and predicted values for (a) BSFC and (b) BTE.

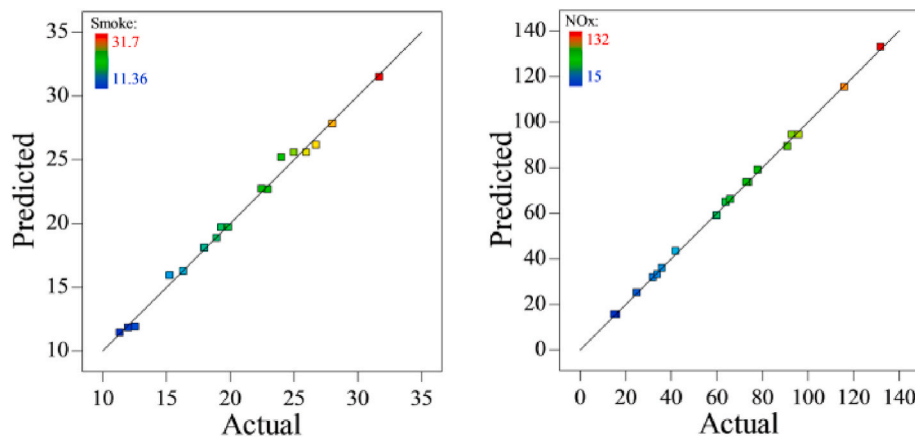


Fig. 4. Actual and predicted values for (a) smoke and (b) NO_x.

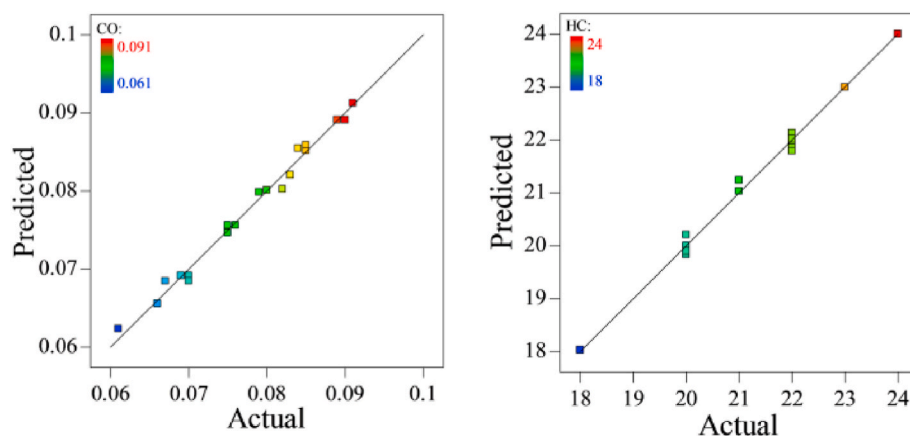


Fig. 5. Actual and predicted values for (a) CO and (b) HC.

Fig. 7 (a) and 7 (b) show that the BTE gradually decreases with the increase of the WSCO biodiesel in blends and EGR rate. The reasons are the same as those for increasing BSFC (Mahalingam et al., 2018). Swaminathan et al. (2019) also observed a reduction in BTE using sunflower biodiesel-diethyl ether blends at 15% EGR due to the higher BSFC and poor spray characteristics. The reduction of BTE with EGR addition has been discussed in the literature (Bhaskar et al., 2013). At full load, the BTE of B35EGR15 is reduced by 1.5% when compared to B20EGR0.

3.3. Emissions of engine using WSCO biodiesel blends with EGR

3.3.1. Smoke emission

The 3D surface plots in Fig. 8 (a) show that the smoke decreased with increased WSCO biodiesel in blends. The reasons for smoke reduction are: (i) the absence of aromatic compounds and low sulfur content present in biodiesel; and (ii) the adequate amount of oxygen available in WSCO biodiesel for the combustion process. Simsek (2020) reported a reduction in smoke emissions with an increased percentage of biodiesel

Table 5

Experimental design matrix for WSCO biodiesel blends with EGR.

Run	Load (%)	WSCO biodiesel (v.%)	EGR (%)	BSFC (kg/kW.h)	BTE (%)	Smoke (HSU%)	NO _x (ppm)	CO (%)	HC (ppm)
1	25	30	5	0.46	13.82	12.57	34	0.08	22
2	50	20	5	0.31	24.45	18.94	47	0.091	22
3	25	25	0	0.42	15.08	13.02	36	0.085	21
4	75	20	0	0.22	29.58	24.47	96	0.083	20
5	100	20	0	0.261	31.82	30.04	137	0.066	20
6	75	25	5	0.25	28.86	22.96	78	0.079	21
7	100	35	15	0.27	30.48	22	66	0.07	20
8	75	35	0	0.26	28.94	21.3	93	0.067	18
9	50	30	15	0.37	21.8	14.99	32	0.085	23
10	100	30	5	0.263	31.27	26.74	116	0.061	20
11	25	35	10	0.53	12.58	11.36	25	0.075	22
12	25	20	15	0.52	14.26	13.33	20	0.09	24
13	100	20	15	0.264	31.16	28.7	79	0.075	22
14	100	20	15	0.264	31.16	28.7	78	0.075	22
15	25	20	15	0.52	14.26	13.33	21	0.089	24
16	25	35	10	0.53	12.58	11.36	25	0.076	22
17	75	20	10	0.26	28.89	24.02	65	0.084	22
18	100	35	15	0.27	30.48	22.98	66	0.069	20
19	75	35	0	0.26	28.94	21.87	96	0.07	18
20	50	30	0	0.31	23.08	17.27	64	0.082	20

Table 6

ANOVA table of BSFC and BTE.

BSFC				BTE		
Source	SS	F Value	p-value	SS	F Value	p-value
Model	0.244	1009.44	<0.0001	1066.475	4096.72	<0.0001
A	0.143	3556.02	<0.0001	831.108	19155.54	<0.0001
B	0.004	96.23	<0.0001	6.387	147.20	<0.0001
C	0.009	224.16	<0.0001	4.092	94.30	<0.0001
AB	0.0002	6.84	0.021	1.910	44.03	<0.0001
AC	0.005	132.82	<0.0001	0.289	6.67	0.022
A ²	0.018	456.80	<0.0001	38.483	886.96	<0.0001

blends. While the addition of EGR increases the amount of smoke, the reduction in oxygen availability due to EGR results in incomplete combustion of fuel and causes an increment in smoke. A comparable pattern has been reported in the literature (Shaik et al., 2020). The addition of WSCO biodiesel and EGR reduced the smoke significantly by 18.4% for B35EGR15 as compared to B20EGR0 at full load condition.

3.3.2. NO_x emission

Fig. 8 (b) shows that NO_x slightly increases with an increasing percentage of WSCO biodiesel. High fuel consumption of blends and shorter ignition delay are two factors that are associated with NO_x emissions. The proper oxidation of fuel occurs due to the adequate oxygen available in WSCO biodiesel. This increases the cylinder temperature and the shorter ignition delay allows less cooling time via heat transfer. The increased cylinder temperature results in increased NO_x emissions (Chauhan et al., 2012). The addition of EGR reduces the NO_x emissions.

Table 7ANOVA table of smoke, NO_x, CO, and HC emissions.

Smoke				NO _x			CO			HC		
Source	SS	F Value	p-value	SS	F Value	p-value	SS	F Value	p-value	SS	F Value	p-value
Model	790.24	474.745	<0.0001	21141.23	1568.867	<0.0001	0.001	142.94	<0.0001	52.33	330.07	<0.0001
A	586.26	2113.21	<0.0001	13905.67	9287.321	<0.0001	0.001	566.34	<0.0001	10.01	504.98	<0.0001
B	51.452	185.462	<0.0001	25.812	17.240	0.002	0.0005	336.12	<0.0001	10.35	522.29	<0.0001
C	20.150	72.631	<0.0001	3569.333	2383.886	<0.0001	0.0001	64.55	<0.0001	22.29	1124.53	<0.0001
AB	1.429	5.152	0.041	73.478	49.074	<0.0001	0.0000	20.43	0.0007	0.4	20.4	0.0009
AC	0.006	0.021	0.887	972.905	649.784	<0.0001	0.0001	47.24	<0.0001	0.33	16.8	0.0018
BC	3.531	12.727	0.003	44.705	29.857	0.0003	0.0000	14.47	0.0025	0.15	7.43	0.0198
A ²	–	–	–	245.310	163.838	<0.0001	0.0002	156.34	0.0025	–	–	–
B ²	–	–	–	76.011	50.766	<0.0001	–	–	–	1.15	58.25	<0.0001
C ²	–	–	–	7.771	5.190	0.0459	–	–	–	0.3	15.2	0.0025

Table 8

Model evaluation.

	BSFC	BTE	Smoke	NO _x	CO	HC
SD	0.006	0.208	0.527	1.224	0.001	0.141
Mean	0.338	24.175	20.498	61.7	0.078	21.15
C.V. %	1.878	0.862	2.570	1.983	1.518	0.666
PRESS	0.001	1.097	6.986	63.282	0.004	0.741
R ²	0.998	0.999	0.995	0.999	0.995	0.996
Adj R ²	0.997	0.999	0.993	0.999	0.993	0.993
R ² _{pred}	0.995	0.998	0.991	0.997	0.991	0.986
AP	79.436	157.03	64.353	135.67	64.35	63.223

SD– Standard deviation, AP– Adequate precision.

Table 9

Equations of polynomial models in terms of coded factors for WSCO biodiesel blends.

Parameter	Equation
BSFC = 0.291–0.113 × A + 0.017 × B + 0.0295 × C – 0.005 × AB – 0.0269 × AC + 0.079 × A ²	(7)
BTE = 26.202 + 8.637 × A – 0.685 × B – 0.629 × C + 0.454 × AB + 0.198 × AC – 3.615 × A ²	(8)
Smoke = 20.036 + 7.251 × A – 1.974 × B + 1.267 × C – 0.390 × AB – 0.028 × AC – 0.597 × BC	(9)
NO _x = 58.118 + 38.085 × A + 1.410 × B – 19.779 × C – 3.001 × AB – 12.048 × AC – 2.171 × BC + 9.252 × A ² – 5.452 × B ² + 1.668 × C ²	(10)
CO = 0.083 – 0.008 × A – 0.006 × B + 0.0029 × C + 0.0017 × AB + 0.0029 × AC + 0.0014 × BC – 0.0086 × A ²	(11)
HC = 21.799 – 1.0102 × A – 0.892 × B + 1.419 × C – 0.221 × AB – 0.222 × AC + 0.123 × BC – 0.671 × B ² – 0.327 × C ²	(12)

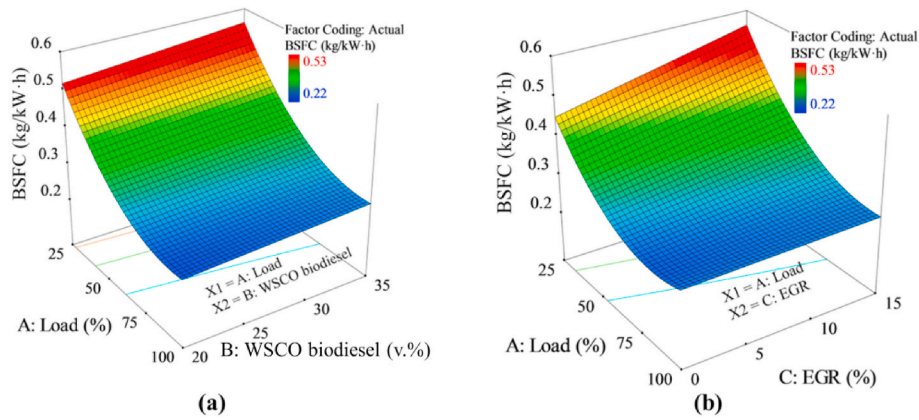


Fig. 6. (a) Interactive effects of load and WSCO biodiesel blends on BSFC
 Fig. 6(b). Interactive effects of load and EGR on BSFC.

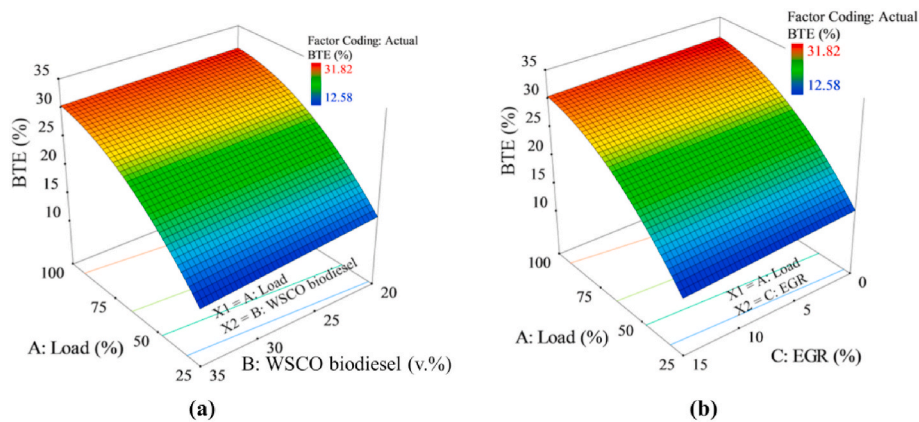


Fig. 7. (a) Interactive effects of load and WSCO biodiesel blends on BTE.
 Fig. 7 (b). Interactive effects of load and EGR on BTE.

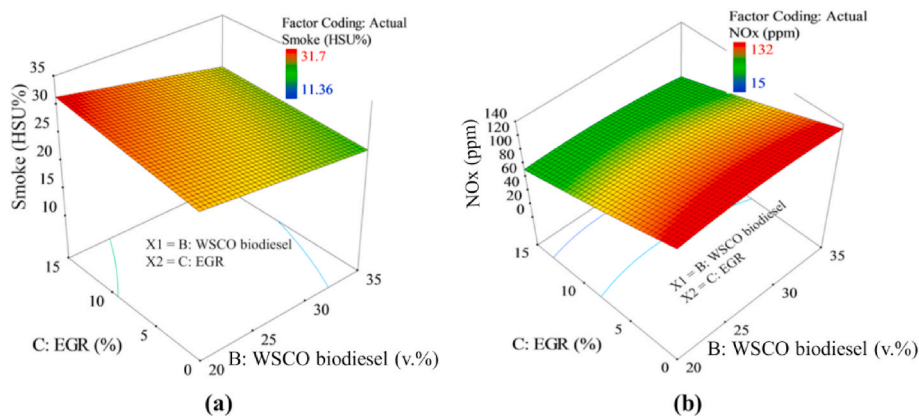


Fig. 8. Interactive effects of EGR and WSCO biodiesel blends on (a) smoke and (b) NO_x.

The lower combustion temperature due to EGR is the possible reason for NO_x reduction (Dhana Raju and Kishore, 2019). Rajasekar et al. (2020) reported that the addition of EGR lowered the combustion temperature, resulting in a reduction in NO_x emissions. At full load, NO_x emissions from B35EGR15 are reduced by 50% when compared to B20EGR0.

3.3.3. CO and HC emissions

It can be observed from Fig. 9 (a) and 9 (b) that CO and HC emissions are reduced with WSCO biodiesel proportions. This could be due to two

factors: (i) the high Cetane number of the fuel blends improves combustion, resulting in a reduction in CO and HC emissions; and (ii) the ample amount of oxygen present in WCO biodiesel leads to complete combustion and engine exhaust excretes fewer CO and HC emissions (Simsek and Uslu, 2020a). With increased rate of EGR, the CO and HC emissions increase. The dilution of the fresh charge due to EGR reduces the oxygen availability for complete combustion. This reflects the higher CO and HC emissions (Nanthagopal et al., 2019). Bhowmick et al. (2019) have reported that the addition of EGR increases CO and HC

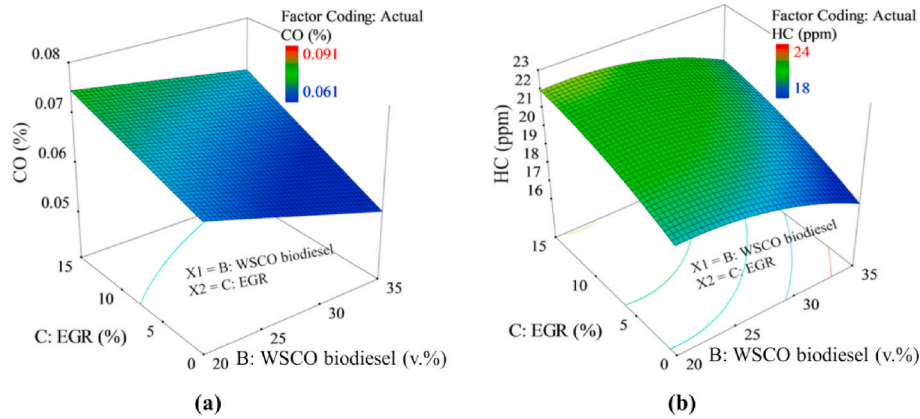


Fig. 9. Interactive effects of EGR and WSCO biodiesel blends on (a) CO and (b) HC.

emissions due to dilution of oxygen at the inlet. Damodharan et al. (2018) observed a similar trend in CO and HC emissions with EGR rates. It is observed that the combined effect of WSCO biodiesel and EGR increases the CO emissions of B35EGR15 by 4.5% as compared to B20EGR0 at full load condition. There is no impact on HC emissions.

3.4. Optimization

The aim of the optimization is to support assistance for WSCO blend and EGR rate selection. Table 9 shows optimization criteria for implementing to attain the maximum value of BTE with a minimum value of BSFC and emissions. Weights were allocated to accentuate the target value. The default weight value of “1” is assigned to the goal to change the shape of certain desired functions. Equal importance to all goals was given by selecting the importance value of “5”. The numerical optimization for the input variables and the response variables is shown in Table 10. The blend B35 (35 v.% of WSCO biodiesel) with 15% EGR is considered for optimum performance and emissions with the highest desirability of 0.9282. The desirability of all constraints for the most desirable solution post optimization through a bar graph is shown in Fig. 10.

3.5. Validation

The conformation test was conducted at an optimal value of 100% load, B35 blend, and 15% EGR. The percent errors of the selected solution are within the tolerance and confirm the accuracy of the prediction model as shown in Table 11. Fig. 11 shows the graphs of the predicted results.

Table 10
Optimization criteria.

Parameter	Goal	Limits		Weight
		Lower	Upper	
Load	In range	25	100	1
WSCO biodiesel	In range	20	35	1
EGR	In range	0	15	1
BSFC	Minimize	0.22	0.53	1
BTE	Maximize	12.58	31.82	1
Smoke	Minimize	11.36	31.7	1
NO _x	Minimize	15	132	1
CO	Minimize	0.061	0.091	1
HC	Minimize	18	24	1

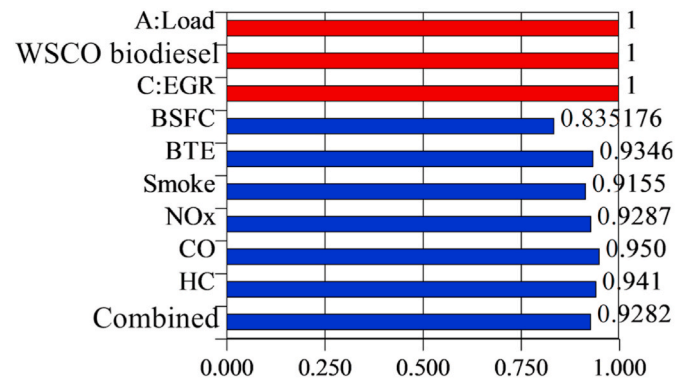


Fig. 10. Desirability of all constraints for the most desirable solution post optimization through a bar graph.

4. Comparison between B35EGR15 and ULSDEGR0

4.1. Performance and emission basis

Fig. 12 compares the performance and emissions of optimal blend B35EGR15 and ULSDEGR0 under full load conditions. The experiments showed using the B35EGR15 blend that BSFC, CO, and HC were increased by 6.61%, 17.54%, and 11.76%, and BTE, smoke, and NO_x were decreased by 5.30%, 19.09%, and 59.04% as compared to ULSDEGR0.

4.2. Economical assessment

The operating cost analysis is based on the optimal WSCO biodiesel blend (B35EGR15) and ULSDEGR0. From Table 12, it is clear that the B35EGR15 is more economical than the ULSDEGR0 on the basis of per kW output (kg/kW.h).

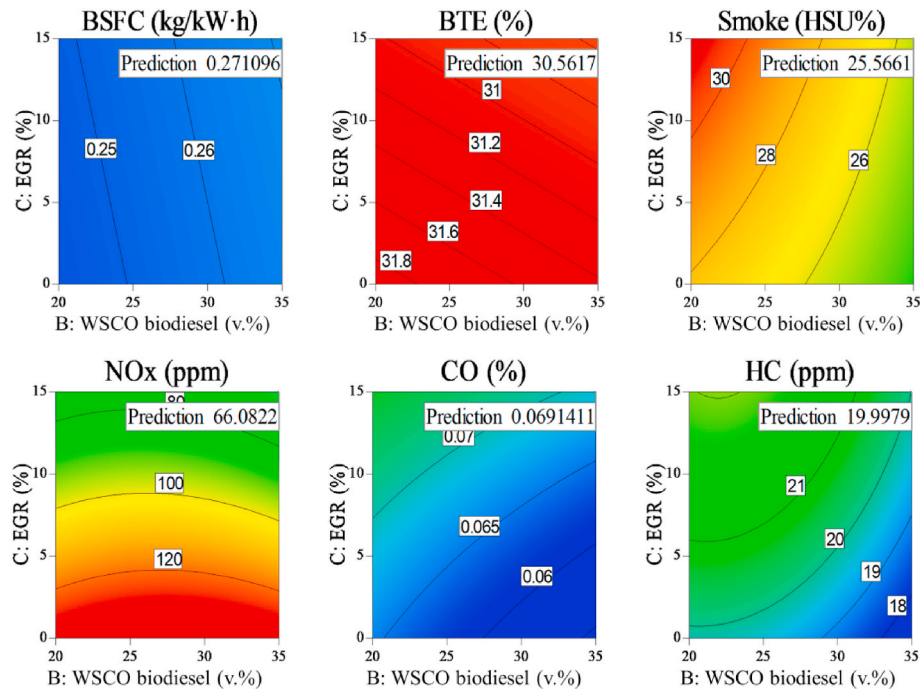
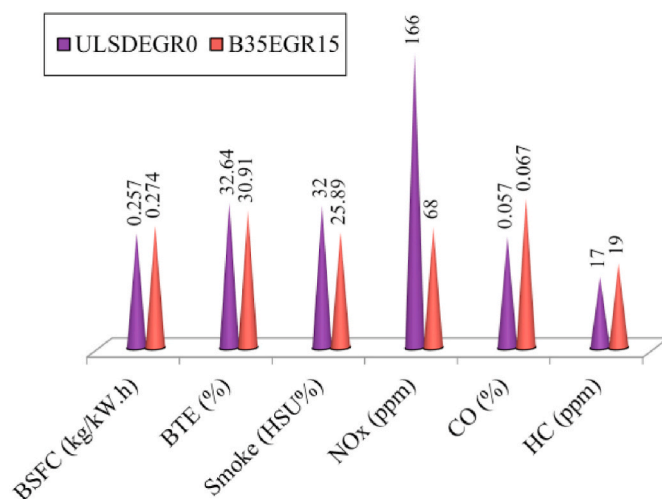
5. Conclusion

In this investigation, 92% of the WSCO biodiesel yield was produced by the transesterification process. Engine loads (25–100%), WSCO biodiesel blends (20–35 v.%), and EGR rates (0–15%) were selected for input variables. In the present study, the optimum values of load, biodiesel blend ratio, and EGR were obtained to achieve the minimum emissions with little penalty on engine performance. An ANOVA analysis is done to evaluate the significance of the experiments and model designed. Based on experimental results, the following conclusions may be drawn:

Table 11

Confirmation test results for WSCO biodiesel blends.

Number	Load	Blend	EGR	BSFC	BTE	Smoke	NO _x	CO	HC
1 Selected	100	35	15	0.271	30.56	25.67	66.08	0.069	19.98
2	74.302	24.77	11.92	0.270	28.426	23.95	57.28	0.084	22.39
3	71.18	27.74	5	0.262	28.18	21.35	75.19	0.079	21.04
Confirmation Test	100	35	15	0.274	30.91	25.89	68	0.067	19
% Error	–	–	–	1.09	1.14	0.85	2.83	–2.98	–5.16

**Fig. 11.** Graphs of predicted responses.**Fig. 12.** Comparison of B35EGR15 with ULSDEGR0.**Table 12**

Cost analysis of ULSDEGR0 and B35EGR15 at full load.

Parameter	ULSDEGR0	B35EGR15
Price (INR/l)	90.90	70.62
Price (INR/kg)	109.65	83.36
Operating cost (INR/kW.h)	28.18	22.85

1. The coefficient determination of R^2 for BSFC, BTE, smoke, NO_x, CO, and HC was 0.998, 0.999, 0.995, 0.999, 0.995, and 0.996.
2. The most desirable solution was validated via experimental outcomes within a 6% error in prediction.
3. The BSFC of B35EGR15 was increased by 4.74% and 6.61%, and the BTE of B35EGR15 was reduced by 2.85% and 5.30% as compared to B20EGR0 and ULSDEGR0 at full load.
4. Smoke and NO_x emissions of B35EGR15 were decreased as compared to B20EGR0 (by 13.81% and 50.36%) and ULSDEGR0 (by 19.09% and 59.04%). The CO emissions of B35EGR15 were increased by 1.5% and 17.54% as compared to B20EGR0 and ULSDEGR0. The HC emissions of B35EGR15 were reduced by 11.76% as compared to ULSDEGR0 at full load.
5. At full load, the operation cost of the B35EGR15 is reduced by 23.34% when compared to the ULSDEGR0.

It is concluded that 35 v.% WSCO biodiesel with diesel at 15% EGR (B35EGR15) is suitable for existing diesel engines and could be the potential candidate for the CI engine's fuel. Further tests may be conducted using blend B35EGR15 with Cetane improvers at various injection timings and injection pressures. This will likely lead to substantial improvements in the combustion and performance characteristics of the engine.

CRediT authorship contribution statement

Ashish Dubey: Conceptualization, Investigation, Writing - original draft. Ravi Shankar Prasad: Methodology, Supervision. Jitendra Kumar

Singh: Supervision. Ashish Nayyar: Methodology, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors are grateful to Swami Keshvanand Institute of Technology, Management and Gramothan (SKIT), Jaipur, for facilitating this research.

References

- Ahamad Shaik, A., Rami Reddy, S., Dhana Raju, V., Govindarajan, M., 2020. Combined influence of compression ratio and EGR on diverse characteristics of a research diesel engine fueled with waste mango seed biodiesel blend. *Energy Sources, Part A Recovery, Util. Environ. Eff.* 1–24 <https://doi.org/10.1080/15567036.2020.1811809>.
- Asokan, M.A., Prabu, S.S., Kiran, P., Bade, K., Nekkanti, V.M., Sai, S., Gutta, G., 2019. Performance, combustion and emission characteristics of julfiflora biodiesel fuelled DI diesel engine. *Energy* 173, 883–892. <https://doi.org/10.1016/j.energy.2019.02.075>.
- Avinash, A., Murugesan, A., 2017. Economic analysis of biodiesel production from waste cooking oil. *Energy Sources B: Econ. Plan. Policy* 12 (10), 890–894. <https://doi.org/10.1080/15567036.2017.1319438>.
- Awad, O.I., Mamat, R., Ali, O.M., Azmi, W.H., Kadrigama, K., Yusri, I.M., Leman, A.M., Yusaf, T., 2017. Response surface methodology (RSM) based multi-objective optimization of fusel oil-gasoline blends at different water content in SI engine. *July Energy Convers. Manag.* 150, 222–241. <https://doi.org/10.1016/j.enconman.2017.07.047>.
- Aydin, S., 2020. Comprehensive analysis of combustion, performance and emissions of power generator diesel engine fueled with different source of biodiesel blends. *Energy* 205, 118074. <https://doi.org/10.1016/j.energy.2020.118074>.
- Ayhan, V., Cangal, C., Cesur, I., Coban, A., Ergen, G., Cay, Y., Kolip, A., Ozsert, I., 2020. Optimization of the factors affecting performance and emissions in a diesel engine using biodiesel and EGR with Taguchi method. *Fuel* 261. <https://doi.org/10.1016/j.fuel.2019.116371>. May 2019.
- Balasubramanian, D., Hoang, A.T., Papla Venugopal, I., Shanmugam, A., Gao, J., Wongwuttanasatit, T., 2021. Numerical and experimental evaluation on the pooled effect of waste cooking oil biodiesel/diesel blends and exhaust gas recirculation in a twin-cylinder diesel engine. *August Fuel* 287, 119815. <https://doi.org/10.1016/j.fuel.2020.119815>.
- Bhaskar, K., Nagarajan, G., Sampath, S., 2013. Optimization of FOME (fish oil methyl esters) blend and EGR (exhaust gas recirculation) for simultaneous control of NOx and particulate matter emissions in diesel engines. *Energy* 62, 224–234. <https://doi.org/10.1016/j.energy.2013.09.056>.
- Bhowmick, P., Jeevanantham, A.K., Ashok, B., Nanthagopal, K., Perumal, D.A., Karthickeyan, V., Vora, K.C., Jain, A., 2019. Effect of fuel injection strategies and EGR on biodiesel blend in a CRDI engine. *Energy* 181, 1094–1113. <https://doi.org/10.1016/j.energy.2019.06.014>.
- Bokhari, A., Yusup, S., Chuah, L.F., Klemes, J.J., Asif, S., Ali, B., Akbar, M.M., Kamil, R.N. M., 2017. Pilot scale intensification of rubber seed (Hevea brasiliensis) oil via chemical interesterification using hydrodynamic cavitation technology. *Bioresour. Technol.* 242, 272–282. <https://doi.org/10.1016/j.biortech.2017.03.046>.
- Chaichan, M.T., 2018. Performance and emission characteristics of CIE using hydrogen, biodiesel, and massive EGR. *Int. J. Hydrogen Energy* 43 (10), 5415–5435. <https://doi.org/10.1016/j.ijhydene.2017.09.072>.
- Chauhan, B.S., Kumar, N., Cho, H.M., 2012. A study on the performance and emission of a diesel engine fueled with Jatropa biodiesel oil and its blends. *Energy* 37 (1), 616–622. <https://doi.org/10.1016/j.energy.2011.10.043>.
- Chuah, L.F., Aziz, A.R.A., Yusup, S., Bokhari, A., Klemes, J.J., Abdullah, M.Z., 2015. Performance and emission of diesel engine fuelled by waste cooking oil methyl ester derived from palm olein using hydrodynamic cavitation. *Clean Technol. Environ. Policy* 17 (8), 2229–2241. <https://doi.org/10.1007/s10098-015-0957-2>.
- Chuah, L.F., Aziz, A.R.A., Yusup, S., Klemes, J.J., Bokhari, A., 2016. Waste cooking oil biodiesel via hydrodynamic cavitation on a diesel engine performance and greenhouse gas footprint reduction. *July Chem. Eng. Trans.* 50, 301–306. <https://doi.org/10.3303/CET1650051>.
- Chuah, L.F., Klemes, J.J., Yusup, S., Bokhari, A., Akbar, M.M., 2017. Influence of fatty acids in waste cooking oil for cleaner biodiesel. *Clean Technol. Environ. Policy* 19 (3), 859–868. <https://doi.org/10.1007/s10098-016-1274-0>.
- Chuah, L.F., Mohd Salleh, N.H., Osnin, N.A., Alcaide, J.I., Abdul Majid, M.H., Abdullah, A.A., Bokhari, A., A. Jalil, E.E., Klemes, J.J., 2021. Profiling Malaysian ship registration and seafarers for streamlining future Malaysian shipping governance. *Aust. J. Marit. Ocean Aff.* 13 (4), 225–261. <https://doi.org/10.1080/18366503.2021.1878981>.
- Damodharan, D., Sathiyagnanam, A.P., Rana, D., Kumar, B.R., Saravanan, S., 2018. Combined influence of injection timing and EGR on combustion, performance and emissions of DI diesel engine fueled with neat waste plastic oil. *November 2017 Energy Convers. Manag.* 161, 294–305. <https://doi.org/10.1016/j.enconman.2018.01.045>.
- Datta Bharadwaz, Y., Govinda Rao, B., Dharma Rao, V., Anusha, C., 2016. Improvement of biodiesel methanol blends performance in a variable compression ratio engine using response surface methodology. *Alex. Eng. J.* 55 (2), 1201–1209. <https://doi.org/10.1016/j.aej.2016.04.006>.
- De Pours, M.V., Sathiyagnanam, A.P., Rana, D., Rajesh Kumar, B., Saravanan, S., 2017. 1-Hexanol as a sustainable biofuel in DI diesel engines and its effect on combustion and emissions under the influence of injection timing and exhaust gas recirculation (EGR). *Appl. Therm. Eng.* 113, 1505–1513. <https://doi.org/10.1016/j.applthermaleng.2016.11.164>.
- Dhna Raju, V., Kishore, P.S., 2019. Effect of exhaust gas recirculation on performance and emission characteristics of a diesel engine fuelled with tamarind biodiesel. *Int. J. Ambient Energy* 40 (6), 624–633. <https://doi.org/10.1080/01430750.2017.1421579>.
- Dubey, A., Prasad, R.S., Singh, J.K., 2020. An analytical and economical assessment of the waste cooking oil based biodiesel using optimized conditions on the process variables. *Energy sources, Part A recovery. Util. Environ. Eff.* 1–16 <https://doi.org/10.1080/15567036.2020.1839600>.
- Ganapathy, T., Gakkhar, R.P., Murugesan, K., 2011. Optimization of performance parameters of diesel engine with Jatropa biodiesel using response surface methodology. *Int. J. Sustain. Energy* 30, 37–41. <https://doi.org/10.1080/14786451.2011.594889>.
- Huang, H., Liu, Q., Yang, R., Zhu, T., Zhao, R., Wang, Y., 2015. Investigation on the effects of pilot injection on low temperature combustion in high-speed diesel engine fueled with n-butanol-diesel blends. *Energy Convers. Manag.* 106, 748–758. <https://doi.org/10.1016/j.enconman.2015.10.031>.
- Joy, N., Devarajan, Y., Nagappan, B., Anderson, A., 2018. Exhaust emission study on neat biodiesel and alcohol blends fueled diesel engine. *Energy Sources, Part A Recovery. Util. Environ. Eff.* 40 (1), 115–119. <https://doi.org/10.1080/15567036.2017.1405119>.
- Khanjani, A., Sobati, M.A., 2021. Performance and emission of a diesel engine using different water/waste fish oil (WFO) biodiesel/diesel emulsion fuels: optimization of fuel formulation via response surface methodology (RSM). *November 2020 Fuel* 288, 119662. <https://doi.org/10.1016/j.fuel.2020.119662>.
- Krishnamoorthy, V., Dhanasekaran, R., Rana, D., Saravanan, S., Rajesh Kumar, B., 2018. A comparative assessment of ternary blends of three bio-alcohols with waste cooking oil and diesel for optimum emissions and performance in a CI engine using response surface methodology. *September 2017 Energy Convers. Manag.* 156, 337–357. <https://doi.org/10.1016/j.enconman.2017.10.087>.
- Mahalingam, A., Munuswamy, D.B., Devarajan, Y., Radhakrishnan, S., 2018. Emission and performance analysis on the effect of exhaust gas recirculation in alcohol-biodiesel aspirated research diesel engine. *Environ. Sci. Pollut. Res.* 25 (13), 12641–12647. <https://doi.org/10.1007/s11356-018-1522-4>.
- Moffat, R.J., 1988. Describing the uncertainties in experimental results. *Exp. Therm. Fluid Sci.* 1 (1), 3–17. [https://doi.org/10.1016/0894-1777\(88\)90043-X](https://doi.org/10.1016/0894-1777(88)90043-X).
- Mofijur, M., Masjuki, H.H., Kalam, M.A., Atabani, A.E., 2013. Evaluation of biodiesel blending, engine performance and emissions characteristics of Jatropa curcas methyl ester: Malaysian perspective. *Energy* 55, 879–887. <https://doi.org/10.1016/j.energy.2013.02.059>.
- Murugapopathi, S., Vasudevan, D., 2021. Experimental and numerical findings on VCR engine performance analysis on high FFA RSO biodiesel as fuel using RSM approach. *Heat Mass Tran.* 57 (3), 495–513. <https://doi.org/10.1007/s00231-020-02961-3>.
- Nanthagopal, K., Raj, R.T.K., Ashok, B., Elango, T., Saravanan, S.V., 2019. Influence of exhaust gas recirculation on combustion and emission characteristics of diesel engine fuelled with 100% waste cooking oil methyl ester. *Waste Biomass Valorization* 10 (7), 2001–2014. <https://doi.org/10.1007/s12649-018-0194-0>.
- Nayyar, A., Sharma, D., Soni, S.L., Bhardwaj, B., Augustine, M., 2019. Modeling and experimental investigation for performance and emissions on a diesel engine using bio-oxygenated ternary fuel blends. *Energy* 168, 136–150. <https://doi.org/10.1016/j.energy.2018.11.098>.
- Ozgun, C., 2021. Optimization of biodiesel yield and diesel engine performance from waste cooking oil by response surface method (RSM). *Petrol. Sci. Technol.* 39 (17–18), 683–703. <https://doi.org/10.1080/10916466.2021.1954019>.
- Palash, S.M., Masjuki, H.H., Kalam, M.A., Masum, B.M., Sanjid, A., Abedin, M.J., 2013. State of the art of NOx mitigation technologies and their effect on the performance and emission characteristics of biodiesel-fueled Compression Ignition engines. *Energy Convers. Manag.* 76, 400–420. <https://doi.org/10.1016/j.enconman.2013.07.059>.
- Rajasekar, V., Geo, V.E., Martin, L.J., Nagalingam, B., 2020. The combined effect of low viscous biofuel and EGR on NO-smoke tradeoff in a biodiesel engine-an experimental study. *Environ. Sci. Pollut. Res.* 27 (15), 17468–17480. <https://doi.org/10.1007/s11356-019-05449-8>.
- Sahar Sadaf, S., Iqbal, J., Ullah, I., Bhatti, H.N., Nouren, S., Rehman, Habib-ur, Nisar, J., Iqbal, M., 2018. Biodiesel production from waste cooking oil: an efficient technique to convert waste into biodiesel. *Sustain. Cities Soc.* 41, 220–226. <https://doi.org/10.1016/j.scs.2018.05.037>.
- Serac, M.R., Aydin, S., Yilmaz, A., Sevik, S., 2020. Evaluation of comparative combustion, performance, and emission of soybean-based alternative biodiesel fuel blends in a CI engine. *Renew. Energy* 148, 1065–1073. <https://doi.org/10.1016/j.renene.2019.10.090>.

- Simsek, S., 2020. Effects of biodiesel obtained from Canola, sefflower oils and waste oils on the engine performance and exhaust emissions. *January Fuel* 265, 117026. <https://doi.org/10.1016/j.fuel.2020.117026>.
- Simsek, S., Uslu, S., 2020a. Comparative evaluation of the influence of waste vegetable oil and waste animal oil-based biodiesel on diesel engine performance and emissions. *June Fuel* 280, 1–7. <https://doi.org/10.1016/j.fuel.2020.118613>.
- Simsek, S., Uslu, S., 2020b. Determination of a diesel engine operating parameters powered with canola, safflower and waste vegetable oil based biodiesel combination using response surface methodology (RSM). *January Fuel* 270, 117496. <https://doi.org/10.1016/j.fuel.2020.117496>.
- Singh, M., Sandhu, S.S., 2020. Performance, emission and combustion characteristics of multi-cylinder CRDI engine fueled with argemone biodiesel/diesel blends. *August 2019 Fuel* 265, 117024. <https://doi.org/10.1016/j.fuel.2020.117024>.
- Subramaniam, M., Solomon, J.M., Nadanakumar, V., Anaimuthu, S., Sathyamurthy, R., 2020. Experimental investigation on performance, combustion and emission characteristics of DI diesel engine using algae as a biodiesel. *Energy Rep.* 6, 1382–1392. <https://doi.org/10.1016/j.egy.2020.05.022>.
- Swaminathan, C., Sarangan, J., Michael, B.S., 2019. Investigation of performance and emission characteristics of IC engine using sunflower oil methyl ester as fuel with oxygenated additive and EGR. *Biofuels* 10 (5), 583–589. <https://doi.org/10.1080/17597269.2016.1221300>.
- Ulusoy, Y., Arslan, R., Tekin, Y., Surmen, A., Bolat, A., Sahin, R., 2018. Investigation of performance and emission characteristics of waste cooking oil as biodiesel in a diesel engine. *Petrol. Sci.* 15 (2), 396–404. <https://doi.org/10.1007/s12182-018-0225-2>.
- Yadav, A.K., Khan, M.E., Pal, A., Dubey, A.M., 2017. Experimental investigations of performance and emissions characteristics of kusum (*Schleichera Oleosa*) biodiesel in a multi-cylinder transportation diesel engine. *Waste Biomass Valorization* 8 (4), 1331–1341. <https://doi.org/10.1007/s12649-016-9658-2>.