Energy Nexus 7 (2022) 100136

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

Combined effects of biodiesel – ULSD blends and EGR on performance and emissions of diesel engine using Response surface methodology (RSM)

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ARTICLE INFO

Keywords:
WSCO biodiesel
EGR
RSM
NO_x
Smoke emission

ABSTRACT

Diesel engines are commonly employed in transportation and power generation. Due to the fast usage of fossil fuels such as diesel, alternative fuels for transportation and power generation are required. In present study, waste soybean cooking oil (WSCO) biodiesel is used as an alternative fuel in an agriculture-based diesel engine. The investigation has been done with blends of WSCO biodiesel-ultra-low sulfur diesel (ULSD) at different EGR rates using Response surface methodology (RSM). Binary blends were prepared by adding 20–35% v/v of WSCO biodiesel with ULSD. The results show that blend 35% v/v WSCO biodiesel-ULSD at 15% EGR (B35EGR15) has found maximum desirability. There is a significant reduction in NO_x and smoke emissions by 59.04% and 17.46% respectively for B35EGR15 as compared to ULSDEGR0 with tolerable limit of BTE. The cost analysis shows that B35EGR15 is more economical than ULSDEGR0. It is concluded that all WSCO biodiesel-ULSD blends are shown to be effective in decreasing emissions in diesel engines.

1. Introduction

Increased industrialization and automation have led to a drastic increase in demand for fossil fuels [1,2]. As a result finite reserves and environmental deteriorate [3–5]. Alternative fuels are gaining widespread recognition as a partial answer to environmental degradation, energy security, import limitations, rural employment, and agricultural economic challenges [6–8]. One of the finest alternatives to petroleum fuels is biofuels [9–11]. Biodiesel is described as mono-alkyl esters of vegetable oils or animal fats produced by the transesterification of an oil or fat with an alcohol [12,13]. Presently, edible vegetable oils such as rapeseed, soybean palm, and sunflower oil account for more than 95% of global biodiesel production. Because these edible vegetable oils are also used as food, their widespread usage in biofuel production might result in food scarcity [14]. In recent years, research has switched to producing biodiesel from non-edible resources such as waste cooking oil, Jatropha, Neem, Kusum, Yellow Oleander, and Karanja oil in order to avoid this contradiction between energy and food need [15–17]. Only a small proportion of the world's energy needs are now being filled by renewable energy sources like biofuels, while the majority of low-temperature recoverable waste heat is simply discharged into the environment without being converted into usable energy. In this context, prior studies looked at a combined cooling, heating, and power system utilizing biofuels [18–20].

Nelson et al. [21] evaluated the engine generator performance using biodiesel obtained from soybeans, sunflower, chicken fat, and beef tallow. The results showed that sunflower and soybean oil-based biodiesel gave better engine generators with a marginally higher overall efficiency. Many studies showed the engine performance and emission parameters for CI engine, running with biodiesel blends obtained from Sal, soybean oil, Cotton seed oil and animal fat, safflower oil, canola oil [22–26]. With jatropha oil biodiesel as a fuel, authors [27] employed hot EGR to reduce NO_x emissions. They found that when the engine was operated at hot EGR levels between 5 and 25%, NO_x emissions were decreased, and they optimized the EGR level at 15% for the lowest possible smoke, CO, and HC emissions, as well as appropriate BTE. Nanthagopal et al. [28] showed a considerable drop by 58.9% in NO_x while utilizing WCO methyl ester fuel at 30% EGR. The previous studies supports that EGR is an effective technique to reduce NO_x emission [29–33].

Research is currently paying more attention to mathematical tools than to traditional analytical techniques. In addition to being able to be used to optimize input variables for the best replies, mathematical mod-

Abbreviations: ULSD, ultra low sulfur diesel; WSCO biodiesel, waste soybean cooking oil biodiesel; EGR, exhaust gas recirculation; RSM, response surface methodology; ULSDEGR0, ultra low sulfur diesel without EGR; B35EGR15, 35% (v/v) WSCO biodiesel + 65% (v/v) ULSD at 15% EGR; BTE, brake thermal efficiency; NOx, nitrogen oxides; ppm, parts per million; HSU, hartridge smoke unit; ANOVA, analysis of variance.

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https://doi.org/10.1016/j.nexus.2022.100136
Received 9 March 2022; Received in revised form 29 July 2022; Accepted 1 September 2022
Available online 5 September 2022
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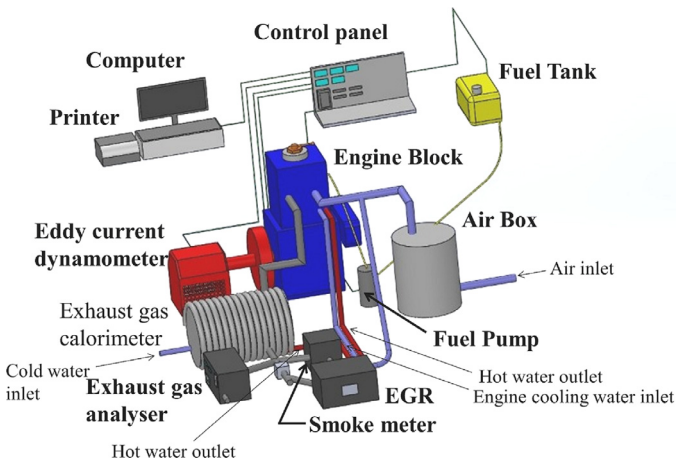

Fig. 1. Schematic of engine setup.

els may offer a plethora of information on the analysis and prediction of responses [34]. The response surface method is an effective statistical method for optimizing input variables [35]. Can et al. [36] used the RSM method to analyze the engine efficiency and emissions of WCO biodiesel-diesel blends. The optimal WCO biodiesel blend (9.17% v/v) produced the maximum results. Khanjani and Sobati [37] investigated the influence of waste fish oil (WFO) biodiesel (3, 5, and 7% v/v), water (3, 5, and 7% v/v), and surfactant (1, 1.5, and 2% v/v) on engine performance and emissions using RSM. The optimum values were identified as 3% v/v WFO-biodiesel, 6.13% v/v water, and 1% v/v surfactant. It was observed that CO, HC, and NO_x were reduced by 42.86%, 34.02%, and 25.53%. Murugapoopathi and Vasudevan [38] applied RSM for analysis of engine performance and emissions using rubber seed oil (RSO) biodiesel (0–20% v/v) with varying operating parameters. At optimum RSO biodiesel (20% v/v), BTE improved while CO, HC, and NO_x were reduced compared to diesel. Simsek and Uslu [39] investigated biodiesel-diesel blends (0–100% v/v) to maximize BTE and minimize exhaust gas temperature (EGT), NO_x, smoke, and CO_2. The RSM model revealed that the optimum responses of BTE (20.54%), EGT (199.88 0C), smoke (0.26%), NO_x (558.4 ppm), and CO_2 (4.52%) were found using 25.79% v/v RSO-biodiesel-diesel blends. Dubey et al. [40] applied the RSM approach to engine performance and tailpipe emissions with different proportions of waste cooking oil biodiesel (20–35% v/v) and EGR (0–15%). They found the 35% v/v biodiesel blend and 15% EGR as the optimum conditions for a significant reduction in smoke and NO_x emissions.

After literature review, it is observed that there is a scope of research on the analysis of the combined effect of blending ratio and EGR rate on engine performance and emissions. Also, the quantification of input parameters (percentage of WSCO and EGR rate) for the targeted outputs in terms of mathematical relations was not addressed for the selected combinations. Thus, the main aim of this research paper is to analyze the combined effect of different blending ratios of WSCO and EGR rates on engine performance and emissions with the help of modeling and develop the empirical relationship between output and input parameters.

2. Experimental setup and materials

2.1. Engine setup

The engine test setup is schematically represented in Fig. 1. The tests were conducted on single cylinder, four-stroke, 3.75 kW diesel engine generally used in agriculture and stationary applications. The compression ratio and injection timing were set as 19:1 and 23 °CA BTDC respectively at 1500 rpm speed.

Table 1
Error analysis.

Measured parameter	Experimental range	Resolution	Error (%)
BTE (%)	12.58–31.82	–	±0.114
NO_x (ppm)	15–132	1 ppm vol.	±3
Smoke (%HSU)	11.36–31.7	0.1%	±0.05

Table 2
Optimum operation conditions for transesterification of WSCO.

Operating condition	Optimum value
Molar ratio (methanol to WSCO oil)	5:1
KOH catalyst amount (wt%)	0.75
Reaction Temperature (°C)	60
Reaction Time (min)	80

Table 3
Physicochemical properties of WSCO biodiesel.

Property	WSCO biodiesel	Standard
Viscosity at 40 °C (cST)	5.35	ASTM D-445
Lower heating value (MJ/kg)	37.45	ASTM D-240
Density at 20 °C (kg/m$^{3)}$	881	ASTM D-4052
Cetane number	52	ASTM D-613
Flash point	190	ASTM D-93

2.2. Error analysis

The possibility of error or uncertainty during experiments owing to operational parameters, equipment's calibration, measuring instrument precision, human mistakes, and experiment design [41]. Table 1 shows the results of calculating the uncertainty of various parameters.

Overall error of measurements $(\delta_E)_{overall}$ can be written as [42]:

$$(\delta E)_{overall} = \sqrt{\left\{ (\delta E_{BTE})^2 + (\delta E_{NOx})^2 + (\delta E_{smoke})^2 \right\}}$$
$$(\delta U)_{overall} = \sqrt{\left\{ (0.114)^2 + (3)^2 + (0.05)^2 \right\}} = 3.09\% \quad (1)$$

2.3. Production of WSCO biodiesel

The WSCO has been collected from the local street food shops. The biodiesel was obtained by transesterification process at the optimum operation conditions as shown in Table 2. At the end of transesterification, the biodiesel and glycerol were obtained at the upper side and lower side of the separating flask. In the next step, the biodiesel was separated and washed; then heated for removing the moisture. After the completion of transesterification process 92% yield was achieved. Table 3 illustrates the physicochemical properties of WSCO biodiesel [43]. Further, different proportions of WSCO biodiesel-ULSD blends were prepared according to the design matrix.

2.4. Response surface methodology

RSM is a statistical approach for the input variables and their response variables that aids in the development of quadratic or cubic prediction models. RSM helps by minimizing the number of experiments, reducing cost, and determining the effect of input factors on response variables [44].

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

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

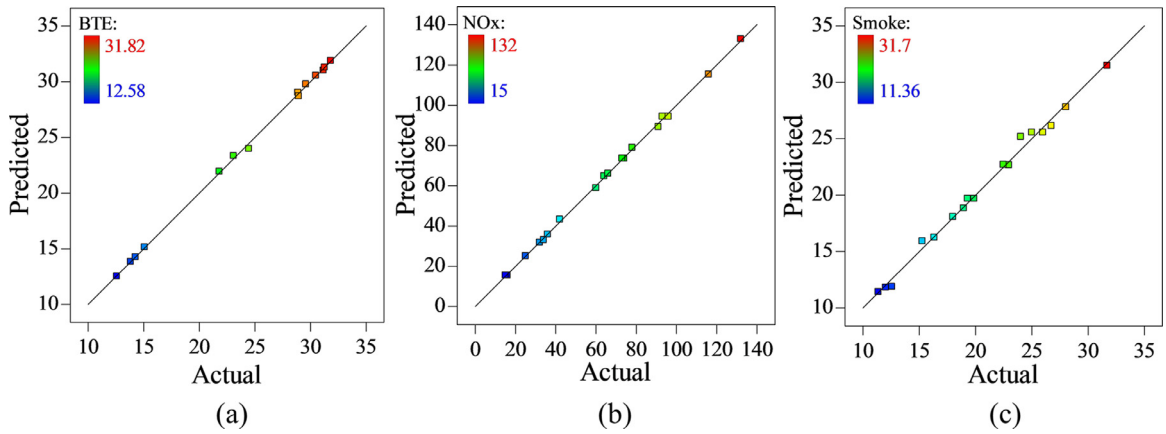

Fig. 2. Predicted vs. actual value for WSCO biodiesel and EGR for (a) BTE (b) NO_x and (c) smoke.

Table 4
Factors with their levels.

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

2.5. Development of prediction models

The prediction models were developed by using Response surface methodology (RSM) in Design of experiments (DOE) software (Design-Expert 13®). The factors with their levels are shown in Table 4. The importance of RSM to determine mutual relationship between input and response variables, decrease the count of tests and find the optimum value for input variables. The values of BTE, NO_x and smoke emissions were measured according to the design matrix.

3. Results and discussion

3.1. Comparison of estimated and measured responses

Fig. 2 shows the relationship between predicted and actual values for BTE, NO_x and smoke emissions. These graphs reveal that the actual and predicted values are very similar to one another. This indicates that the model is significant. The plots also show that the majority of the points are grouped near the 45° line. This indicates that the replies a good least square fit for the BTE, NO_x and smoke. Table 5 illustrates the experimental design matrix, including observed data

3.2. ANOVA analysis

ANOVA results from Table 6 for BTE, the R-Sq value is close to 1, which presents the accuracy and adequacy of the model [45]. There is reasonable agreement between the Adjusted R-Sq (Adj. R-Sq) value and the Predicted R-Sq (Pred. R-Sq) value as the difference between them is less than 0.2 [35]. The value of Adequate Precision is higher than 4, which indicates an adequate signal. Table 7 shows the 'Prob. > F' value for the BTE model is obtained at less than 0.05, indicating that the model is significant.

In the same manner, Table 6 shows the values of R-Sq, Adj. R-Sq, Pred. R-Sq and Adequate Precision of NO_x and smoke are well suited within the mandated limits for accuracy and adequacy of the models for desired responses. In Table 7, the value of 'Prob. > F' for BTE, NO_x and smoke models is obtained at less than 0.05, indicating that models are significant. The polynomial regression equations for BTE, NO_x and smoke are presented in Table 7. Similar trends for R-Sq values (close to 1) were reported by Atmanl et al. [46], and the prediction errors (%) for responses were less than 0.4, indicating that responses were well predicted.

3.3. Performance and emissions of engine using WSCO biodiesel blends and EGR

3.3.1. Brake thermal efficiency (BTE)

Fig. 3 shows the contour plots representing the interactions between load vs. WSCO biodiesel and load vs. EGR for BTE. Low, medium, and high levels of BTE are depicted by the bluish, greenish, and reddish zones respectively. Fig. 4 shows that the BTE is gradually increased with increase in load and decreases with increasing the WSCO blends at all loads. This is due to same reason responsible for increased BSFC. The BTE decreases with increasing the EGR rate. The lower oxygen concentration inside the cylinder and high heat capacity of exhaust gasses causing reduced peak combustion temperature result the reduction on BTE [32,36]. Bhaskar et al. [32] presented similar arguments and reported a reduced BTE with EGR addition. It is observed that the BTE of B35EGR15 is reduced by 1.5% as compared to B20EGR0 at full load condition.

3.3.2. NO_x emission

Fig. 4 shows the contour plots representing the interactions between load vs. WSCO biodiesel and load vs. EGR for NO_x. Low, medium, and high levels of NO_x are depicted by the bluish, greenish, and reddish zones respectively. NO_x is gradually increases with increasing the engine loading. The observed data showed the increment of NO_x emission with percentage of WSCO biodiesel. Because WSCO biodiesel contains enough oxygen, appropriate oxidation occurs in the rich fuel area, raising the cylinder temperature. As a result of the higher cylinder temperature, more NO_x is produced [47]. The inclusion of EGR, on the other hand, reduces NO_x emissions. The reduction in NO_x might be due to a lower combustion temperature. Thus, the combine influence of EGR and WSCO biodiesel blends decreases the NO_x emission. The experimental result was obtained by Raju et al. [48] about NO_x emission is likewise in line with present investigation. A similar trend was reported in the literature [28]. As a result, the 50% NO_x reduction was seen in B35EGR15 as compare to B20EGR0 at full load condition.

3.3.3. Smoke emission

Fig. 5 shows the contour plots representing the interactions between load vs. WSCO biodiesel and load vs. EGR for smoke. Low, medium, and high levels of smoke are depicted by the bluish, greenish, and reddish zones respectively. It is seen that with increased engine load, the smoke emission of blends also increased linearly. The smoke mitigation

Table 5
Experimental design matrix with results.

Run	Load (%)	WSCO biodiesel (% v/v)	EGR (%)	BTE (%)	NO_x (ppm)	Smoke (HSU%)
1	25	20	15	14.26	21	13.33
2	100	20	15	31.16	78	28.7
3	50	30	0	23.08	64	17.27
4	25	30	5	13.82	34	12.57
5	75	35	0	28.94	96	21.87
6	50	20	5	24.45	47	18.94
7	100	35	15	30.48	66	22.98
8	25	25	0	15.08	36	13.02
9	75	20	10	28.89	65	24.02
10	75	20	0	29.58	96	24.47
11	25	35	10	12.58	25	11.36
12	100	20	0	31.82	137	30.04
13	75	25	5	28.86	78	22.96
14	100	35	15	30.48	66	22
15	75	35	0	28.94	93	21.3
16	50	30	15	21.8	32	14.99
17	100	30	5	31.27	116	26.74
18	25	35	10	12.58	25	11.36
19	25	20	15	14.26	20	13.33
20	100	20	15	31.16	79	28.7

Table 6
ANOVA tables for BTE, NO_x and smoke (at significance level of 0.05).

BTE Source	SS	F Value	p-value	NO_x Source	SS	F Value	p-value	Smoke Source	SS	F Value	p-value
Model	1066.5	4096.7	< 0.0001	Model	21,141	1568.9	< 0.0001	Model	790.24	474.7	< 0.0001
R-Sq	0.9995	SD	0.21	R-Sq	0.9993	SD	1.22	R-Sq	0.9955	SD	0.53
Adj R-Sq	0.9992	Mean	24.17	Adj R-Sq	0.9987	Mean	61.70	Adj R-Sq	0.9934	Mean	20.50
Pred R-Sq	0.9990	C.V.%	0.86	Pred R-Sq	0.9970	C.V.%	1.98	Pred R-Sq	0.9912	C.V.%	2.57
AP	157.04	PRESS	1.10	AP	135.67	PRESS	63.28	AP	64.353	PRESS	6.99

SS–Sum of squares; SD–Standard deviation; AP–Adeq Precision.

Table 7
Final equations for BTE, NO_x and smoke.

Parameter	Equation
BTE = + 26.20 + 8.64 × Load - 0.69 × WSCO biodiesel - 0.63 × EGR + 0.45 × Load × WSCO biodiesel + 0.20 × Load × EGR - 3.61 × $Load^2$	3
NO_x = + 58.12 + 38.09 × Load + 1.41 × WSCO biodiesel - 19.78 × EGR - 3.0 × Load × WSCO biodiesel - 12.05 × Load × EGR - 2.17 × WSCO biodiesel × EGR + 9.25 × $Load^2$ - 5.45 × WSCO $biodiesel^2$ + 1.67 × EGR^2	4
Smoke = + 20.04 + 7.25 × Load - 1.97 × WSCO biodiesel + 1.27 × EGR - 0.39 × Load × WSCO biodiesel - 0.03 × Load × EGR - 0.59 × WSCO biodiesel × EGR	5

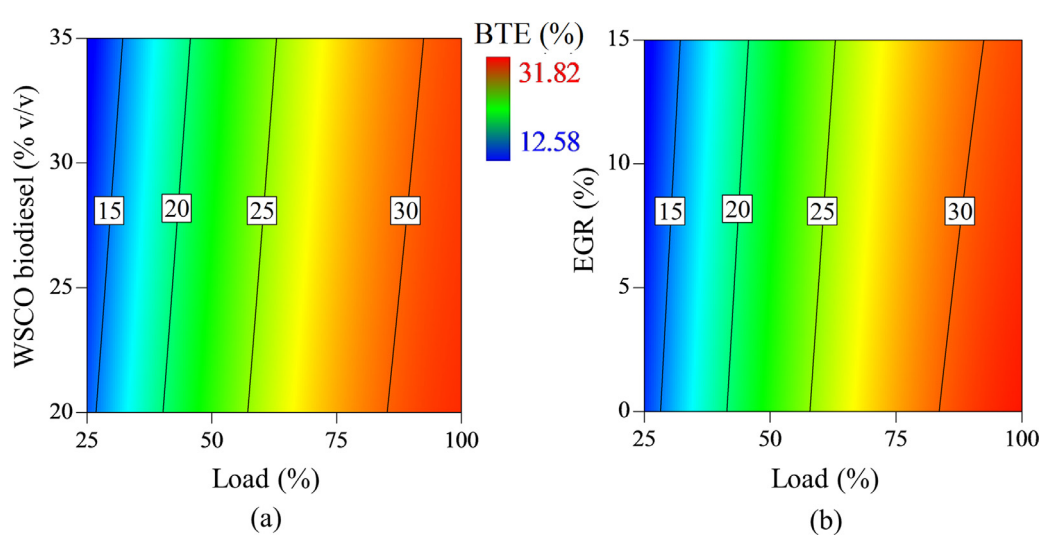

Fig. 3. Interactive effects of (a) Load and WSCO biodiesel (b) Load and EGR on BTE.

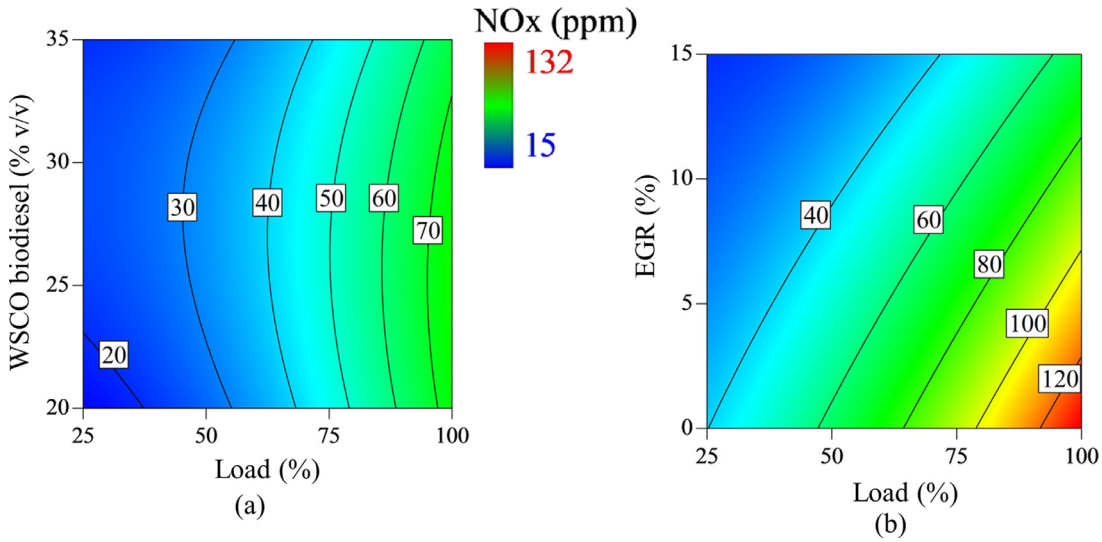

Fig. 4. Interactive effects of (a) Load and WSCO biodiesel (b) Load and EGR on NO_x.

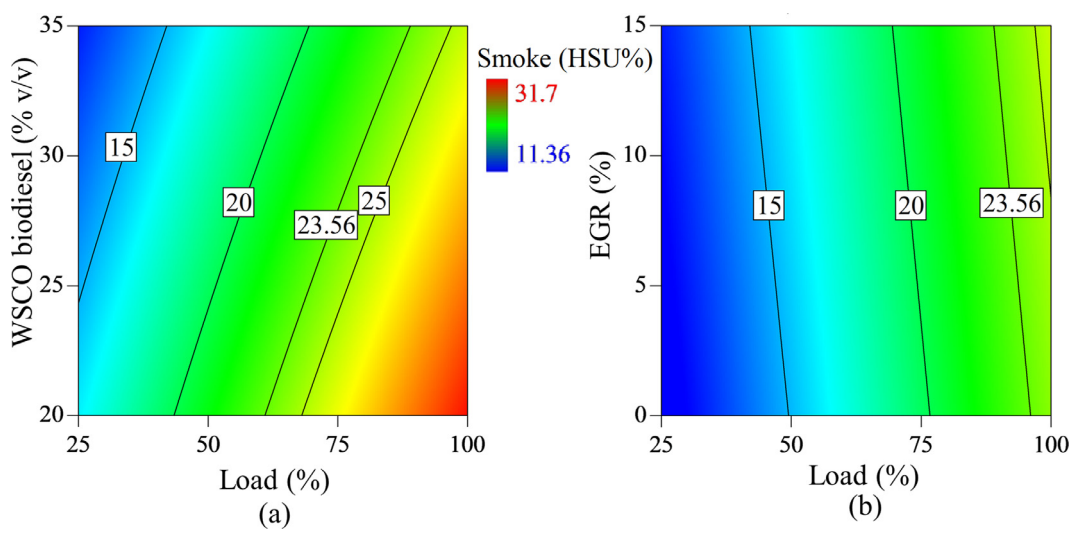

Fig. 5. Interactive effects of (a) Load and WSCO biodiesel (b) Load and EGR on smoke.

follows same fashion for all WSCO biodiesel blends and smoke reduced with increased percentage of WSCO biodiesel in blend. The more quantity of oxygen present in WSCO biodiesel is the main reason for smoke reduction [49]. Chauhan et al. [17] reported a reduction in smoke emissions with an increased percentage of biodiesel blends. The inclusion of EGR, on the other hand, increases the quantity of smoke produced. Owing to a lack of oxygen molecules in the cylinder due to exhaust gas recirculation, partial fuel combustion occurs, resulting in an increase in smoke [50]. A comparable pattern has been reported by Dhana Raju and Kishore [51]. The addition of WSCO biodiesel and EGR reduced the smoke significantly by 18.4% for B35EGR15 as compared to B20EGR0 at full load condition.

3.3.4. Optimization and validation

The numerical optimization for input variables and the response variables are shown in Table 8. These prediction values stand for the optimal solution for maximize BTE and minimize smoke & NO_x emissions. The conformation test was conducted at full load condition for B35EGR15 blend (at 15% EGR) and ULSDEGR0 (at 0% EGR). Fig. 6 shows the most favorable desirability (0.916) of all constraints for the most desirable solution.

Table 8,
Confirmation test results for WSCO biodiesel blends.

	Optimum parameter	Confirmation Test	% Error (× 100)
Load	100	100	–
WSCO biodiesel	35	35	–
EGR	15	15	–
BTE	30.56	29.57	−3.35
NO_x	66.08	68.0	2.82
Smoke	25.56	26.41	3.22

4. Comparison between ULSDEGR0 and B35EGR15

4.1. Cost analysis

The operating cost analysis is based on the full load condition of WSCO biodiesel blend and ULSDEGR0 (at 0% EGR). From the Table 9, it is observed that the B35EGR15 is economical than ULSDEGR0. The cost of B35EGR15 is reduced by 22% as compare to ULSDEGR0.

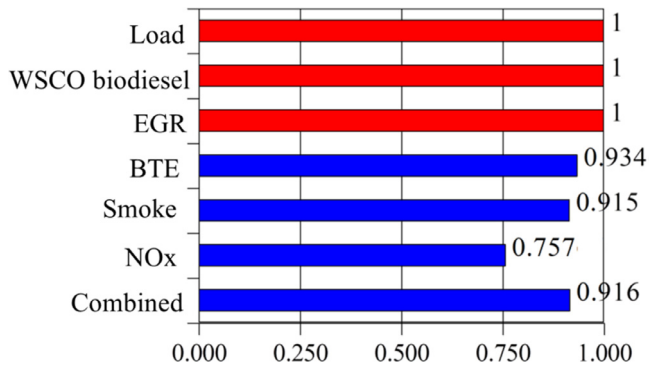

Fig. 6. Desirability graph for the most desirable solution.

Table 9
Cost analysis for ULSDEGR0 and B35EGR15.

Parameter	ULSDEGR0	B35EGR15
Price (INR/litre)*	90.9	70.62

* The Goods and Services Tax rate of 18% is not included for blended fuels.

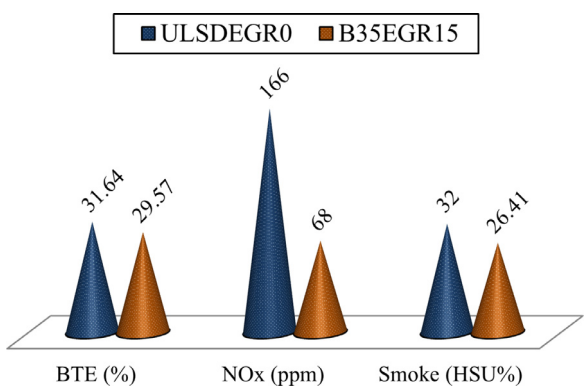

Fig. 7. Performance and emissions comparison of USLDEGR0 and B35EGR15 blends.

4.2. Performance and emission analysis

It is observed from Fig. 7 that there is a significant reduction in NO_x emissions by 74.6% for B35EGR15 as compared to ULSDEGR0. Also, B35EGR15 produces 35% less smoke than ULSDEGR0.

In this study, performance and exhaust emissions of a stationary, agriculture-based, CI engine ran on waste cooking oil-diesel blends were evaluated and analyzed. Mathematical modeling has been done for desired outputs using RSM technique. The empirical relations among input and output parameters are presented in Table 7. The results were validated through confirmation test and for optimum blending ratio and EGR rate the percentage variations in outputs are reported in conclusions.

5. Conclusion

Experiments were conducted at different loads (25–100%), WSCO biodiesel (20–35% v/v) and EGR (0–15%). BTE, NO_x, and smoke were modeled, predicted, and optimized using RSM. The reduced number of trials saves time and money. The following conclusions are drawn on the basis of experimental results:

1 The coefficient determination of R-Sq for BTE, NO_x and smoke was 0.9995, 0.9993 and 0.9955 respectively.
2 The most desirable solution was validated via experimental outcomes within a 5% error in prediction.
3 At full load condition, BTE of B35EGR15 was reduced by 2.85% and 5.30% as compared to B20EGR0 and ULSDEGR0 respectively.
4 At full load condition, NO_x and smoke emissions of B35EGR15 were decreased as compared to B20EGR0 (by 50.36% and 13.81%) and ULSDEGR0 (by 59.04% and 17.46%) respectively.
5 At full load, the operation cost of the B35EGR15 is reduced by 22.3% as compared to the ULSDEGR0.
6 It is concluded that blend B35EGR15 is acceptable for existing diesel engine without any engine modifications. Further research into tribology and its impacts on various engine metallurgical elements will assure the engine's long-term operating viability with this fuel.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests.

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