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To cite this article: Ashish Dubey, Ravi Shankar Prasad, Jitendra Kumar Singh & Ashish Nayyar (2022): Response surface methodology (RSM) based experimental and model analysis of diethyl ether-biodiesel-diesel blends with exhaust gas recirculation (EGR) on stationary diesel engine, Petroleum Science and Technology, DOI: [10.1080/10916466.2022.2092136](https://doi.org/10.1080/10916466.2022.2092136)

To link to this article: <https://doi.org/10.1080/10916466.2022.2092136>



Published online: 01 Jul 2022.



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Response surface methodology (RSM) based experimental and model analysis of diethyl ether-biodiesel-diesel blends with exhaust gas recirculation (EGR) on stationary diesel engine

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ABSTRACT

In compliance with proposed targets of green energy and reduced emissions during the Glasgow summit, the study of blended fuels in internal combustion engines is of great significance. To address this issue, a detailed study of the engine performance and exhaust emissions has been conducted with ternary fuel blends of diethyl ether (DEE), waste soybean cooking oil (WSCO) biodiesel, and ultra-low sulfur diesel (ULSD). Ternary blends were prepared by adding 0–15% v/v DEE with the B35 blend (35% v/v WSCO biodiesel + 65% v/v ULSD), and tests were carried out with 15% EGR. The RSM based modeling and experimental approaches have been used for analysis. With a desirability of 0.961, the ternary blend DEE10B35EGR15 (10% v/v DEE + 90% v/v B35 at 15% EGR) was found to be an optimal blend. The measured responses are 0.272 kg/kWh, 31.47%, 18.94 HSU%, 91 ppm, 0.030%, and 24 ppm for brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), smoke, nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbon (HC) emissions, respectively. An innovative approach to analysis and quantifying the responses to ternary blends with EGR has been presented in the form of mathematical equations for future use and scope.

Abbreviations: ULSDEGR0: Ultra low sulfur diesel without EGR; B35EGR15: 35% (v/v) WSCO biodiesel + 65% (v/v) ULSD at 15% EGR; DEE5B35EGR15: 5% (v/v) DEE + 95% (v/v) B35 at 15% EGR; DEE10B35EGR15: 10% (v/v) DEE + 90% (v/v) B35 at 15% EGR; DEE15B35EGR15: 15% (v/v) DEE + 85% (v/v) B35 at 15% EGR; ANOVA: analysis of variance

KEYWORDS

diethyl ether; EGR; exhaust emissions; response surface methodology; WSCO biodiesel

1. Introduction

With the rapid growth in transport, industry and urban sectors, energy requirements increase at the same pace globally (Yadav et al. 2017; Ulusoy et al. 2018; Simsek 2020; Atmanli and Yilmaz 2021). Fossil fuels are the important sources for fulfilling the energy demands of the exhausted earth's crest (Nautiyal, Subramanian, and Dastidar 2017; Asokan et al. 2019). Furthermore, particulate matter, including polycyclic aromatic hydrocarbon emissions (PAH), is the main combustion product responsible for environmental pollution and human health problems (Yilmaz and Donaldson 2007). As a result, a wide range of renewable energy sources have been investigated all over the world (Atmanli, Ileri, et al. 2015). Alternative fuels for diesel engines, particularly biodiesel, have been a principal concern in studies (Devarajan et al. 2020; Saravanan et al. 2020; Atmanli and Yilmaz 2021; Taha et al. 2021;). Past investigations (Chauhan, Kumar, and Cho 2012; Yilmaz, Ileri, and Atmanli 2016; Nair, Kaviti, and Daram 2017; Zhang et al. 2018; Narayanan, Ramesh, and Sakthivel 2019; Seraç et al. 2020; Subramaniam et al. 2020) showed that reductions in HC, CO, and particulate matter emissions were observed using diesel-biodiesel blends. But the NO_x emissions are reported to have increased generally. The use of higher alcohols can reduce the engine emissions by lowering the combustion temperature (Atmanli and Yilmaz 2020; Yilmaz, Ileri, and Atmanli 2016). Yilmaz, Atmanli, and Vigil (2018) evaluated the performance and emissions using quaternary blends of diesel fuel (40% v/v), biodiesel (40% v/v), soybean oil (10% v/v), and alcohols such as propanol and pentanol (10% v/v respectively) with a diesel-biodiesel blend (with an equal volume of 50% v/v). The test results indicated that the blend containing propanol reduced NO_x emissions by 11.9% as compared to the diesel-biodiesel blend. While CO and HC emissions showed an increment with the addition of propanol and pentanol. However, the use of alcohol lowers the cetane number (CN) of blends, so it is required to mix cetane improvers for better exhaust emissions (Atmanli 2016). Another method to reduce NO_x levels, EGR, has some advantages, such as simplicity, lower cost, and an effective method for NO_x reduction (Bhowmick et al. 2019; Nanthagopal et al. 2019; Rajasekar et al. 2020).

The oxygenated additives improve the engine performance along with lower engine emissions (Swaminathan and Sarangan 2012; Krishna Kolli et al. 2019). DEE has a low ignition temperature, a high volatility, a high CN, and a high oxygen content, all of which favor its use in diesel engines (Zhang et al. 2011; Krishnamoorthi, Malayalamurthi, and Sakthivel 2019;). Swaminathan and Sarangan (2012) performed experiments using fish oil-based biodiesel (BFO) and DEE at a constant 15% EGR rate. The significant reduction was found in NO_x, CO, and unburnt hydrocarbons as 92%,

91%, and 90% respectively for the blend of BFO with 2% v/v DEE at 15% EGR. The variation in BSFC was negligible while the BTE increased with BFO blends. Dabi, Sahoo, and Saha (2021) investigated the engine performance and exhaust emissions using VO30 (30% v/v Mesua ferrea Linn oil + 70% v/v diesel) and different proportions of diethyl ether. This investigation revealed that the addition of 10% v/v DEE improved the BTE, CO, and NO_x by 2.3%, 13%, and 11.9%, respectively, while HC emissions increased by 48% as compared to the VO30 blend. Seela, Alagumalai, and Pugazhendhi (2020) analyzed the engine performance and emission parameters using B20 and B30 blends of jatropha methyl ester with DEE and isobutanol (IB) in the 5–10% v/v blending ratio. B20 + 10% DEE blend increased BSFC, BTE, and NO_x emissions while B30 + 10% IB blend decreased CO emissions. Swaminathan, Sarangan, and Michael (2019) reported the improvement in NO_x, HC, and CO emissions using sunflower biodiesel with different DEE ratios (% v/v) at a 15% EGR rate.

In comparison to conventional methods of analysis, mathematical tools are now getting more attention in research. Mathematical models can provide a wealth of information regarding the analysis and prediction of responses, and they can also be applied to optimize input variables for best responses (Özgür 2021). The response surface method is an effective statistical method for optimizing input variables (Baranitharan, Ramesh, and Sakthivel 2019). The main advantages of RSM are that it reduces the number of experiments, provides a high level of information and statistically reliable outcomes, and determines the best response value (Betiku et al. 2014; Atmanli, Ileri, and Yilmaz 2016; Samuel and Okwu 2019). Atmanli, Ileri, et al. (2015) optimized the concentration of diesel, n-butanol, and cotton oil to 65.5% v/v, 23.1% v/v, and 11.4% v/v, respectively (DnBC) using the RSM technique. The test results showed that for the DnBC blend, the brake torque, brake power, BTE, and brake mean effective pressure were reduced as compared to diesel, while BSFC increased. NO_x, CO, and HC emissions were reduced by 11.33%, 45.17%, and 81.45%, respectively.

From the review of literature, it is observed that studies have been done to investigate the engine performance and exhaust emissions for biodiesel-diesel and oxygenated (DEE)-diesel blends. Some of them also used DEE-biodiesel-diesel blends as fuel. In general, the ratio of biodiesel is limited by 20% in ternary blends. In the present study, DEE was mixed up to 15% with a 35% blend of WSCO biodiesel at 15% EGR. Mathematical modeling has been used to set up the empirical relationship between input and output parameters with reduced experiments. The B35 blend and 15% EGR rate were chosen in accordance with prior investigation (Dubey et al. 2022). An agriculture-based engine was chosen for research to address the needs of a general audience.

Table 1. Specifications of experimental setup.

Item	Specification
Engine	Kirloskar-TV1
Type	Single cylinder, 4 stroke, VCR engine
Bore × stroke (mm)	87.5 × 110
Rated power (kW)	3.75
Rated speed (rpm)	1500
Intake system	Naturally aspirates
Cooling type	Water cooling
Software used	LABVIEW
Dynamometer	Power MAG
Type	Eddy current type
Exhaust gas analyzer	AVL India, Model: 444 N
Smoke meter	AVL India, Model: 437 C

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 Figure 1.

2.2. Exhaust gas recirculation (EGR)

EGR is a technique for reducing NO_x levels in which a part of the engine exhaust is 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. (1) (Balasubramanian et al. 2021).

$$\text{EGR (\%)} = \frac{(\text{CO}_2)_{\text{int}} - (\text{CO}_2)_{\text{atm}}}{(\text{CO}_2)_{\text{out}} - (\text{CO}_2)_{\text{atm}}} \quad (1)$$

where $(\text{CO}_2)_{\text{int}}$ and $(\text{CO}_2)_{\text{out}}$ are the concentration of CO_2 at the inlet and the outlet, respectively.

2.3. Fuel preparation

The biodiesel was obtained using WSCO by the transesterification process. The following process parameters were chosen to achieve a 92% biodiesel yield: molar ratio (methanol to oil) of 5:1, reaction temperature of 60 °C, reaction time of 80 min, and an amount of KOH catalyst of 0.75 wt% (Dubey, Prasad, and Singh 2020). The Redwood Viscometer, Density meter, Pansky-Martens apparatus, and Bomb calorimeter were used to measure the viscosity, density, flash point, and lower heating value of ULSD, WSCO

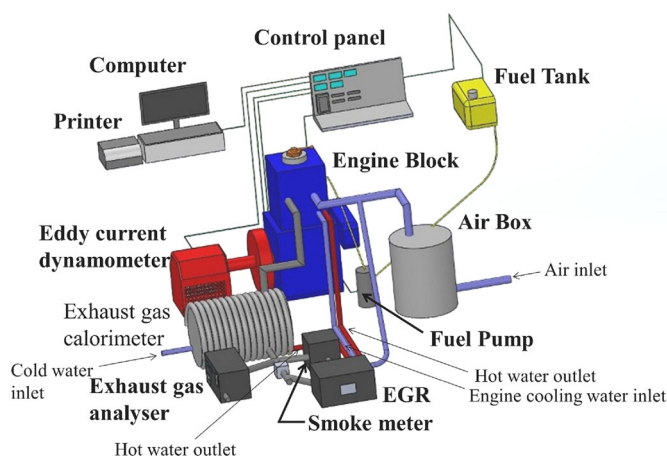


Figure 1. Schematic diagram of experimental setup.

Table 2. Physicochemical properties of ULSD, WSCO biodiesel, and diethyl ether (Swaminathan and Sarangan 2012; Krishnamoorthi, Malayalamurthi, and Sakthivel 2019;; Nayyar et al. 2019; Dubey, Prasad, and Singh 2020).

Property	ULSD	WSCO biodiesel	Diethyl ether
Molecular formula	$C_{10}H_{20} - C_{15}H_{28}$	$C_{19}H_{36}O_2$	$(C_2H_5)_2O$
Density (kg/m^3) at 20 °C	829	881	739
Flash point (°C)	68	190	−45
Boiling point (°C)	180–360		35
Lower heating value (MJ/kg)	43	37.45	34.57
Latent heat of vaporization (kJ/kg)	250	40.5	351.16
Auto-ignition temperature (°C)	315	–	180
Cetane number	55.5	52	>121
Viscosity (cST) at 40 °C	3.2	5.35	0.23
Specific gravity	0.829	–	0.7
Oxygen content (wt %)	0	10.97	21.6
Carbon content (wt %)	87.0	77.10	64.9
Hydrogen content (wt %)	12.6	11.81	13.5

biodiesel, and diethyl ether according to the ASTM D-445, ASTM D-4052, ASTM D-93, and ASTM D-240 standards and illustrated are in Table 2. Further, the B35 blend is prepared by mixing 35% v/v WSCO biodiesel with ULSD, and then DEE is added in various proportions. The properties of DEE are shown in Table 2.

2.4. Uncertainty in measurement

The possibility of error or uncertainty during experiments owing to operational parameters, equipment's calibration, measuring instrument precision, human mistakes, and experiment design (Moffat 1988). Table 3 shows the results of calculating the uncertainty of various parameters.

Overall uncertainty of measurements (δU)_{overall} can be written as (Huang et al. 2015):

Table 3. Range, resolution, and % uncertainties of instruments.

Measured parameter	Experimental range	Resolution	Uncertainty (%)
BSFC (kg/kW.h)	0.22–0.762	–	±0.114
BTE (%)	11.52–31.82	–	±0.114
Smoke (%HSU)	3–31.7	0.1 %	±0.05
NO _x (ppm)	15–132	1 ppm vol.	±3
CO (%)	0.029–0.091	0.001 %	±3
HC (ppm)	16–33	1 ppm vol.	±5

Table 4. Factors and levels for DEE-B35EGR15 blends.

Parameter	Coded values	Levels			
		1	2	3	4
Load (%)	A	25	50	75	100
DEE (% v/v)	B	0	5	10	15

$$\begin{aligned}
 (\delta U)_{\text{overall}} &= \sqrt{\{(\delta U_{\text{BSFC}})^2 + (\delta U_{\text{BTE}})^2 + (\delta U_{\text{smoke}})^2 + (\delta U_{\text{NO}_x})^2 \\
 &\quad + (\delta U_{\text{CO}})^2 + (\delta U_{\text{HC}})^2\}} \\
 (\delta U)_{\text{overall}} &= \sqrt{\{(0.114)^2 + (0.114)^2 + (0.05)^2 + (3)^2 + (3)^2 \\
 &\quad + (5)^2\}} = 6.56\% \quad (2)
 \end{aligned}$$

2.5. Test methodology

The investigations were executed at 1500 rpm speed and different engine loading conditions (i.e. 25%, 50%, 75%, and 100%). All experiments were conducted under the following operating conditions: compression ratio (CR) of 19, injection timing (IT) of 23°CA bTDC and injection pressure (IP) of 210 bar.

2.5.1. Experimental design

Design of experiments (DOE) software (Design-Expert®, version 13, Stat-Ease, Inc., USA) was used for experimental design, optimization, and validation. The input variables with their levels are shown in Table 4. All input variables are taken as numeric factors. The load (25–100%) and (0–15% v/v) of DEE in DEE-B35EGR15 blends (at 15% EGR) are selected for the objective of maximizing BTE and minimizing BSFC, smoke, NO_x, CO, and HC emissions.

2.5.2. Response surface methodology

RSM is a statistical method which helps to develop quadratic or cubic prediction models for the input variables and their response variables. RSM assists in finding the influence of input variables on response variables, reducing the number of experiments, providing time and cost savings, and

optimizing the response variables (Ganapathy, Gakkhar, and Murugesan 2011; Yilmaz, Ileri, and Atmanli 2016).

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

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.

The generated model was examined using ANOVA, followed by a regression analysis to produce coefficients and mathematical relationships that may be used to predict the output responses from the experiments (Sakthivel et al. 2019). Finally, the input variables were optimized using the desirability technique, which selects the solution set with the highest desirability as the optimum set.

3. Results and discussion

3.1. Model and ANOVA analysis for DEE-B35EGR15 blends

Figures 2–4 show fair accuracy and a strong correlation between predicted and actual results of models generated for performance and emission parameters. Table 5 illustrates the experimental design matrix, including observed data.

Table 6 presents response surface quadratic/cubic models of BSFC, BTE, smoke, NO_x , CO, and HC. The ANOVA analysis was carried out with a significance level of 0.05, corresponding to a 95% confidence level. For BSFC, the R^2 values are close to 1, which presents the accuracy and adequacy of the model (Rajamohan et al. 2021). There is reasonable agreement between the Adjusted R^2 (Adj. R^2) value and the Predicted R^2 (Pred. R^2) value as the difference between them is less than 0.2 (Baranitharan, Ramesh, and Sakthivel 2019). The value of Adequate Precision is higher than 4, which indicates an adequate signal. Table 7 shows the “Prob. > F” value for the BSFC 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^2 , Adj. R^2 , Pred. R^2 , and Adequate Precision of BTE, smoke, NO_x , CO, and HC 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, smoke, NO_x , CO, and HC models is obtained at less than 0.05, indicating that models are significant. The polynomial regression equations for BSFC, BTE, smoke, NO_x , CO, and HC are presented by Eqs. (3)–(8), respectively in Table 8. Similar trends for R^2 values (close to 1) were reported by Atmanli, Ileri, and Yilmaz (2016), and the prediction errors (%) for

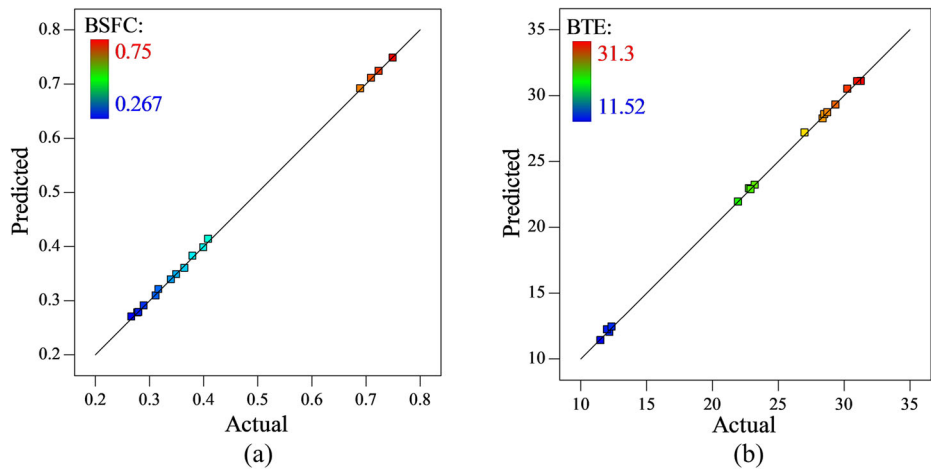


Figure 2. Actual and predicted values for (a) BSFC and (b) BTE.

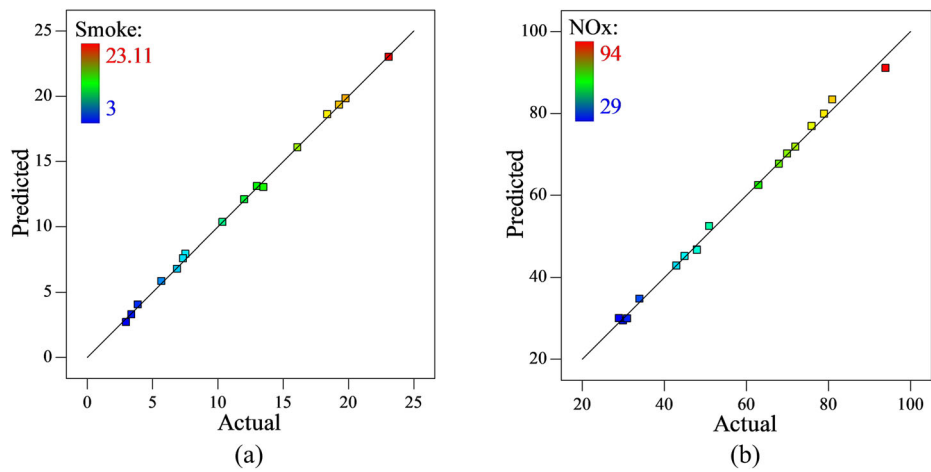


Figure 3. Actual and predicted values for (a) smoke and (b) NO_x.

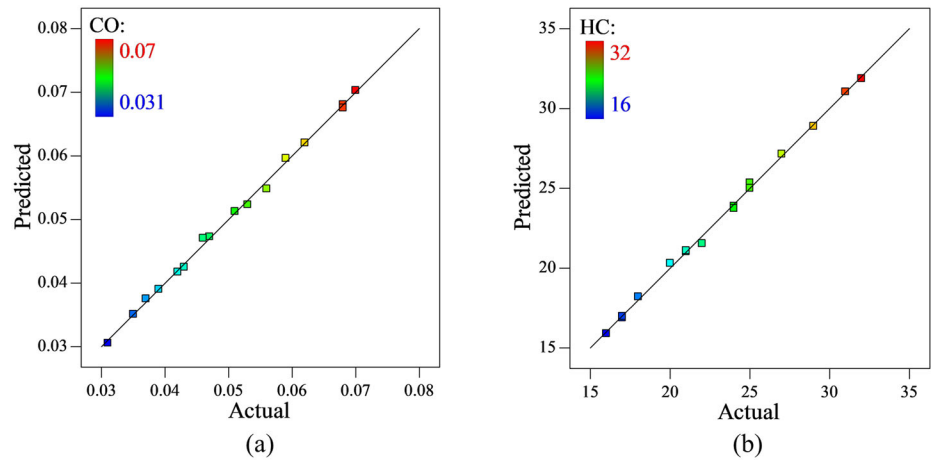


Figure 4. Actual and predicted values for (a) CO and (b) HC.

Table 5. Experimental design matrix with results for DEE-B35EGR15 blends.

Run	Load (%)	DEE (% v/v)	BSFC (kg/kW-h)	BTE (%)	Smoke (HSU%)	NO _x (ppm)	CO (%)	HC (ppm)
1	75	10	0.29	28.75	12.04	76	0.039	25
2	50	10	0.365	23.24	6.9	51	0.047	24
3	50	15	0.409	22.8	7.54	45	0.051	29
4	100	0	0.28	29.37	23.11	72	0.042	18
5	25	5	0.71	12.01	3.4	31	0.068	21
6	50	0	0.4	21.97	10.38	43	0.059	16
7	75	15	0.35	28.52	13.51	68	0.043	31
8	100	5	0.278	30.27	19.8	81	0.037	22
9	100	10	0.267	31.3	18.4	94	0.031	25
10	50	5	0.38	22.92	7.36	48	0.056	20
11	25	10	0.69	12.36	3	34	0.062	24
12	100	15	0.34	31.02	19.3	79	0.035	32
13	25	0	0.724	11.52	5.7	29	0.07	17
14	25	15	0.75	12.2	3.9	30	0.068	27
15	75	0	0.317	27.02	16.11	63	0.053	17
16	75	5	0.312	28.4	13.02	70	0.046	21

Table 6. Model evaluation.

	BSFC	BTE	Smoke	NO _x	CO	HC
Model	Cubic	Cubic	Quadratic	Cubic	Cubic	Cubic
SD	0.004	0.173	0.26	1.819	0.008	0.325
Mean	0.430	23.35	11.47	57.13	0.05	23.06
C.V. %	0.900	0.742	2.25	3.184	1.6	1.411
PRESS	0.001	0.911	1.7	138.5	0.002	7.451
R ²	0.999	0.999	0.998	0.996	0.998	0.998
Adj R ²	0.999	0.999	0.9984	0.992	0.996	0.996
Pred R ²	0.998	0.998	0.9973	0.979	0.992	0.980
AP	165.99	171.6	128.42	45.18	65.69	62.15

Abbreviations: AP, adeq precision; SD, standard deviation.

Table 7. Summary of ANOVA.

Response variable	Degree of freedom	SS	F Value	p-value Prob > F
BSFC	8	0.476	4034.08	< 0.0001
BTE	6	816.8	4529.09	< 0.0001
Smoke	5	623.84	1870.19	< 0.0001
NO _x	8	6492.59	245.29	< 0.0001
CO	8	0.00233	447.44	< 0.0001
HC	9	370.3	388.77	< 0.0001

Table 8. Equation of polynomial models in terms of coded factors for DEE-B35EGR15 blends.

Parameter	Eq.
BSFC = $0.312 - 0.094 \times A - 0.037 \times B + 0.009 \times AB + 0.171 \times A^2 + 0.039 \times B^2 + 0.012 \times A^2B - 0.120 \times A^3 + 0.0467 \times B^3$	(3)
BTE = $26.354 + 8.026 \times A + 0.601 \times B + 0.288 \times AB - 4.721 \times A^2 - 0.679 \times B^2 + 1.208 \times A^3$	(4)
Smoke = $9.484 + 8.112 \times A - 1.364 \times B - 0.47 \times AB + 1.371 \times A^2 + 2.198 \times B^2$	(5)
NO_x = $62.593 + 37.531 \times A + 10.312 \times B + 2.16 \times AB - 1.969 \times A^2 - 7.875 \times B^2 - 4.894 \times AB^2 - 9.563 \times A^3 - 8.438 \times B^3$	(6)
CO = $0.046 - 0.012 \times A - 0.013 \times B - 0.001 \times AB + 0.003 \times A^2 + 0.005 \times B^2 + 0.003 \times A^2B - 0.004 \times A^3 + 0.008 \times B^3$	(7)
HC = $22.438 + 1.375 \times A + 5.625 \times B + 0.878 \times AB + 0.423 \times A^2 + 0.703 \times B^2 - 0.928 \times A^2B + 1.097 \times AB^2 - 0.984 \times A^3 + 1.267 \times B^3$	(8)

responses were less than 0.4, indicating that responses were well predicted. Atmanli, Yüksel, et al. (2015) applied the RSM technique to optimize the concentration of diesel, n-butanol, and cotton oil. The results showed that

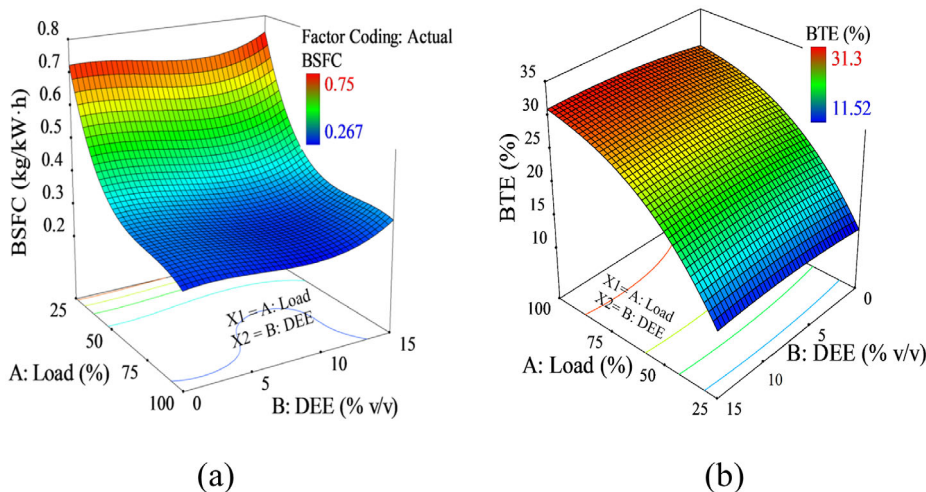


Figure 5. Interactive effect of load and DEE-B35EGR15 blends on (a) BSFC and (b) BTE.

the prediction errors for experimental and fitted responses were less than 1.2%, and the R^2 values indicate that the model is accurate. In the study (Yilmaz and Donaldson 2007), the experimental and computational approaches were done for the minimum generation of PAH emissions. The observations showed that the PAH emissions were found to be minimal at an equivalence ratio of 1. PAH emissions were fairly in accord in the cases of naphthalene and phenanthrene as well.

3.2. Brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE)

Figure 5a and b show the variation of BSFC and BTE with load and DEE-B35EGR15 blends. It is observed that BSFC decreases and BTE increases with an increase in load. The BSFC and BTE are improved by using the DEE10B35EGR15 blend as compared to B35EGR15. This is mainly due to the high CN and oxygen content (21.6%) of DEE that allows better combustion of fuel and results in a high rate of heat release. Also, DEE reduces the interfacial tension between molecules of blended fuels and promotes better fuel atomization. Devaraj, Robinson, and Ganapathi (2015) presented similar arguments and reported a lower BSFC and higher BTE for DEE-waste plastic pyrolysis oil blends. The increased proportion of DEE in blended fuel by 15% (i.e. DEE15B35EGR15) increases BSFC and decreases BTE. That is because a higher proportion of DEE lowers the calorific value and increases the latent heat of vaporization of blended fuel (Ibrahim 2018). Sivalakshmi and Balusamy (2013) reported that the high concentration of DEE reduces BTE due to the loss of power caused by the lower calorific value of the blend, and BSFC increases. It is observed that the BSFC

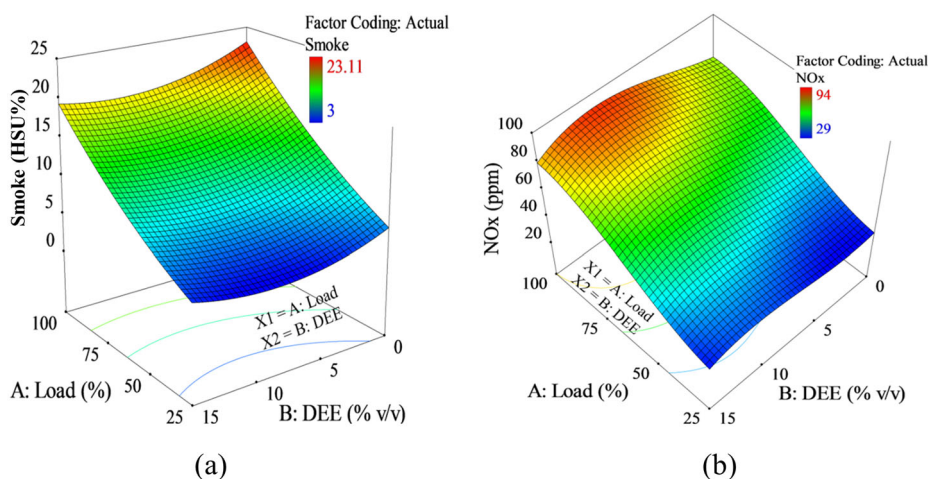


Figure 6. Interactive effect of load and DEE-B35EGR15 blends on (a) smoke and (b) NO_x .

is reduced by 4.6% and the BTE is increased by 6.2% for DEE10B35EGR15 as compared to B35EGR15 at full load condition.

3.3. Smoke emission

The interactive effects of load and DEE-B35EGR15 blends on smoke emission are depicted in Figure 6a. It reveals that smoke emissions increase with an increment in load. The maximum reduction in smoke emissions was observed for DEE10B35EGR15 compared to the other DEE-B35EGR15 blends. DEE improves the spray atomization and fuel-air mixing, which reduces the rich mixture zones that result in reduced smoke. These results are in agreement with the results obtained by Patil and Thipse (2015). Iranmanesh, Subrahmanyam, and Babu (2008) reported the minimum reduction in smoke emissions with 10%v/v DEE-diesel blends. DEE improves the oxygen availability in the blends, leading to better diffusion combustion, which results in smoke reduction. The smoke emission of DEE15B35EGR15 was found to be higher than that of other DEE-B35EGR15 blends but lower than that of B35EGR15. This may be due to the high proportion of DEE causing the phase separation and the mixture becoming heterogeneous, which results in incomplete combustion. Sivalakshmi and Balusamy (2013) observed a similar trend in smoke emissions with DEE-biodiesel blends. At full load, DEE10B35EGR15 showed a significant reduction in smoke (20.3%) when compared to B35EGR15.

3.4. NO_x emission

Figure 6b shows the interactive effects of load and DEE-B35EGR15 blends on NO_x emissions. In general, when the load increases, the level of NO_x

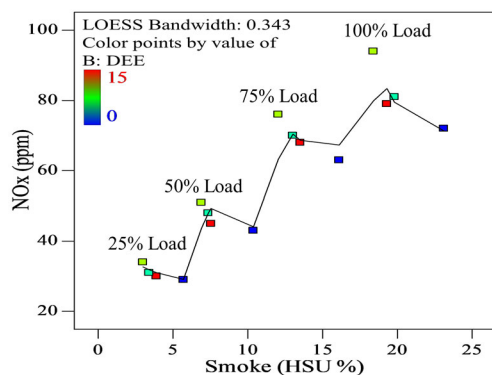


Figure 7. Smoke-NO_x trend for DEE-B35EGR15 blends.

emissions also increases. It was seen that the level of NO_x emissions for DEE15B35EGR15 was followed by DEE5B35EGR15 and DEE10B35EGR15. The high oxygen content of DEE (21.6%) assists more complete combustion, which results in increased NO_x emission at low and medium blends of DEE-B35EGR15. The further addition of DEE causes the low combustion temperature and results in low NO_x emission. Rakopoulos et al. (2014) observed that DEE-diesel blends produced less NO_x emissions than their corresponding ethanol-diesel and n-butanol-diesel blends. This might be due to the lower temperature experienced during the combustion process. Krishnamoorthi, Malayalamurthi, and Sakthivel (2019) reported that the high concentration of DEE lowers the combustion temperature, which reduces NO_x emissions. At full load, the DEE15B35EGR15 shows a minimum increase of 8.8% when compared to the B35EGR15.

3.5. Smoke-NO_x relationship

Figure 7 reveals the smoke-NO_x tradeoff with an increasing DEE percentage in DEE-B35EGR15 blends. It has been observed that an increase in NO_x emissions is associated with a reduction in smoke emissions, and vice versa. When compared to the rate of reduction/increment in smoke/NO_x with increasing DEE, the rate of increase in NO_x emission is lower at low loads and higher at high loads as compared to the reduction rates of smoke emission in these load ranges, respectively. Previous studies support this trend in the smoke-NO_x association (Sivalakshmi and Balusamy 2013; Devaraj, Robinson, and Ganapathi 2015; Krishnamoorthi, Malayalamurthi, and Sakthivel 2019;). DEE10B35EGR15 shows the optimum tradeoff between smoke-NO_x at all the loads.

3.6. CO emission

The interactive effects of load and DEE-B35EGR15 blends on CO emission are depicted in Figure 8a. It reveals that CO reduces with an increment in

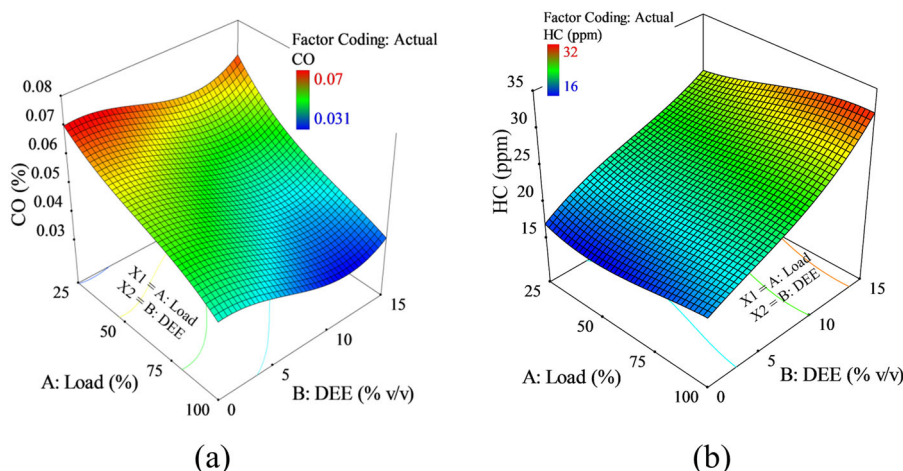


Figure 8. Interactive effect of load and DEE-B35EGR15 blends on (a) CO and (b) HC.

load. A similar trend was reported by Yilmaz and Morton (2011), who found that increasing load reduces CO emissions by increasing the fuel/air equivalence ratio, which raises the oxygen level inside the combustion chamber. As a result, improved combustion takes place. Among the DEE-B35EGR15 blends, DEE10B35EGR15 showed the greatest reduction in CO emission. This may be due to better fuel–air mixing and high combustion temperatures encouraging the oxidation of CO in combustible products (Dabi, Sahoo, and Saha 2021). The CO emissions are reduced by 26.2% with DEE10B35EGR15 as compared to B35EGR15 at full load.

3.7. HC emission

Figure 8b depicts the interaction effect of load and blending ratios on HC emission. It is observed that HC emissions increase with an increase in load and DEE ratios. The HC emission may increase due to: (i) higher latent heat of evaporation of DEE cause lowering the temperature near the cylinder walls that ceases the complete combustion near the walls, (ii) the fuel remaining in the nozzle sac volume escaping late into the cylinder (iii) the development of the lean outer flame zone, where flame cannot exist (Sivalakshmi and Balusamy 2013). Patil and Thipse (2015) observed a similar incremental trend in HC emissions with DEE blends. The increment in HC emissions with the addition of DEE has been discussed in the literature (Dabi, Sahoo, and Saha 2021). At full load, DEE5B35EGR15 has a minimum increase in HC emissions of 18% when compared to B35EGR15.

4. Optimization and validation

Table 9 shows optimization criteria to be implemented to attain the maximum value of BTE with a minimum value of BSFC and exhaust emissions (Sakthivel

Table 9. Optimization criteria.

Parameter	Goal	Limits		Weight	
		Lower	Upper	Lower	Upper
Load	In range	25	100	1	1
DEE	In range	0	15	1	1
BSFC	Minimize	0.267	0.75	1	0.1
BTE	Maximize	11.52	31.30	0.1	1
Smoke	Minimize	3.00	23.11	1	0.1
NO _x	Minimize	29	94	1	0.1
CO	Minimize	0.031	0.070	1	0.1
HC	Minimize	16	32	1	0.1

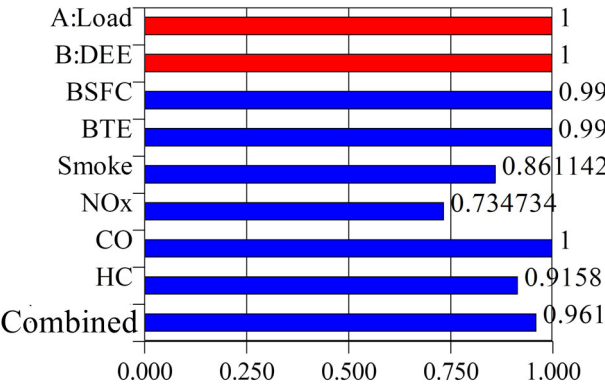


Figure 9. Desirability of all constraints for the optimum solution for DEE-B35EGR15 blends.

et al. 2019). Weights were allocated from 0.1 to 1 to accentuate the target value. Equal importance to all goals was given by selecting the importance value of “5.” DEE10B35EGR15 is considered the optimum blend for best performance and exhaust emissions with the highest desirability (0.961). The desirability of responses for the most desirable solution post optimization through a bar graph is shown in Figure 9. The conformation test was conducted at 100% load and with the DEE10B35EGR15 blend. The % errors of selected solutions are within the tolerance and confirm the accuracy of the prediction model as shown in Table 10. Figure 10 shows the graphs of predicted results.

5. Conclusion

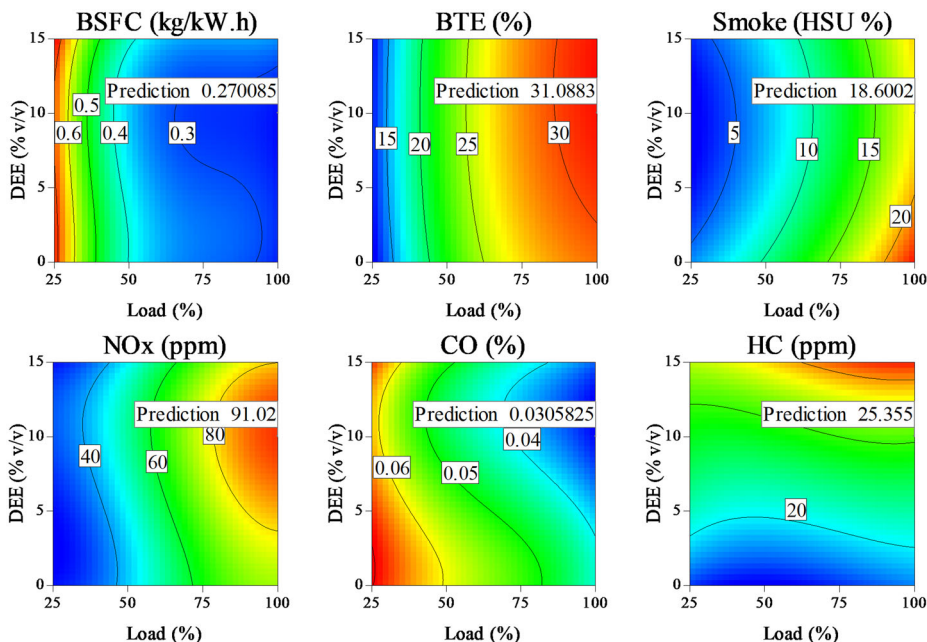
Experiments were conducted at different loads (25-100%) and DEE proportions (0–15% v/v with B35) at 15% EGR. Engine performance and exhaust emissions parameters were modeled, predicted, and optimized using RSM. The reduced number of trials saves time and money. The following conclusions are drawn on the basis of experimental results:

1. The coefficient determination of R^2 for BSFC, BTE, smoke, NO_x, CO, and HC was 0.999, 0.999, 0.998, 0.996, 0.998, and 0.998, respectively. The values confirm the accuracy and adequacy of the model.

Table 10. Confirmation test results for DEE-B35EGR15 blends.

	1 (Selected)	2	3	CT	Error % ($\times 100$)
Load	100	59.66	82.50	100	–
DEE	10	12.30	3.98	10	–
BSFC	0.270	0.324	0.310	0.272	0.74
BTE	31.09	25.813	28.47	31.47	1.21
Smoke	18.60	9.93	15.44	18.94	1.79
NO _x	89.02	69.96	73.78	91	2.18
CO	0.031	0.043	0.046	0.030	–3.34
HC	24.53	26.48	20.56	24	–2.21
D	0.961	0.674	0.635	–	–

Abbreviations: CT, confirmation test; D, desirability.


Figure 10. Graphs of predicted responses.

- Using the desirability approach, the DEE10B35EGR15 blend (10% v/v DEE with B35 at 15% EGR) is predicted to have the best performance and exhaust emissions, with a maximum desirability of 0.961.
- The optimum measured values of BSFC, BTE, smoke, NO_x, CO, and HC are 0.272 kg/kW.h, 31.47%, 18.94 HSU%, 91 ppm, 0.030%, and 24 ppm, respectively.
- The most desirable solution was validated via experimental outcomes within a 5% error in prediction.

It is worth mentioning that the DEE-biodiesel-diesel fuel blends were investigated on an unmodified diesel engine with EGR and encouraging results were observed. The predicted optimum blend, that is, DEE10B35EGR15, would pave the way in the search for clean and green

fuel for the future. Further, responses would be predicted with variable operating parameters (injection timing, compression ratio, and injection pressure). The endurance tests would be conducted to check for long-term viability.

Disclosure statement

No potential conflict of interest was reported by the authors.

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