

Numerical optimization of the emission characteristics and performance of a diesel engine energized with Jatropha biodiesel along with exhaustgas recirculation

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Abstract: Using of energy resources could bring an encouraging influence on both atmosphere, and economy. The present paper investigates the modeling and optimization performance/emission characteristics of a single cylinder diesel engine supported with Jatropha biodiesel. The main studied parameters were Exhaust gas recirculation (EGR) ratio, engine load, and Injection Timing (IT). The engine-out parameters were Brake thermal efficiency (BTE), Exhaust Gas Temperature (EGT), Carbonmonoxide (CO), Oxides of Nitrogen (NOX), and Unburned hydrocarbons (UHC). Response surface model based on historical design was used to predict/simulate the engine data. It is accomplished that the optimal value for the engine load, EGR ratio and IT were found to be ~94%, 0%, and 25 degree, respectively. At obtained optimal point, the value of BTE, UHC, NO_x, EGT, and CO were predicted as around 34%, 24 ppm, 970 ppm, 380, and 0.03%, respectively. Based on the results, the Response surface methodology (RSM) techniques is an efficient way to model a singlecylinder diesel engine.

Keywords: diesel, biodiesel, exhaust gas recirculation, response surface methodology.

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1 Introduction

A nation's accomplishments can be projected from the energy consumed by each citizen of the country(Mahla et al.,2023; Safieddin Ardebili, 2020).

Extreme portion of the current energy is in use as fossil fuels, and in accordance with accessible reasonableness these fuels are non-renewable and unsurprising to endure for a few more decades, moreover, it also emits venomous gases for instance

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oxides of nitrogen, smoke, carbon monoxides which lead to dreadful environmental conditions and global heating (Safieddin Ardebili et al., 2019; Goga et al., 2020). Due to enhanced efficiency, more consistency, lesser fuel consumption and comparatively lesser cost of fuel diesel engines are leading requisites in several sectors these days (Goga et al., 2019). Nevertheless, it too emits lethal gases that are incredibly detrimental for the human beings (Mahla et al., 2021; Rabeti et al., 2023). Extreme utilization of petroleum products has led to the adversity caused to environment which can be checked by the adoption of biomass derived alternative fuels (Goga et al., 2021). This inspires every nation to grow renewable sources such as solar energy, wind energy and biofuels. Since the automobile is dependent on diesel engine, biodiesel can be a potential alternate for diesel. The pollution from automobiles is a significant problem in present time. This pollution can be reduced by using biodiesel (Goga et al., 2018).

Bio-based fuel like biodiesel as a substitute for diesel, which has attracted many researchers' attention as a novel/alternative fuel in the past decade. Biodiesel can easily be produced from vegetable oils such as jatropha, karanja, mahua, peanut etc., Animal fats such as fish oil, tallow etc. Generally utilization of edible oil may result in the food crisis, therefore it is crucial to adopt non-edible oil for producing of bio-based diesel fuel. It has been observed that mahua, karanja and jatropha are very suitable for biodiesel production (Mirbagheri et al., 2020; Safieddin Ardebili and Khademalrasoul, 2022). Biodiesel has low sulphur and aromatic contents. It can be blended with petroleum diesel without any major engine modifications. In view of higher price and limited source of fossil fuels, biodiesel can be a viable substitute to petroleum diesel fuel. Because of its high lubricating property, it is the only alternative fuel which increases engine life. Easy blending of biodiesel with petroleum diesel is a very remarkable property which makes it suitable to store and dispense similar as diesel fuel. Higher value of flash point of biodiesel makes it more suitable as compared to conventional fuel (Goga et al., 2025).

Additionally, lower volatility of biodiesel makes it safe when stored in large quantity because low volatile nature of biodiesel reduces the possibility to catch fire. Comparing with diesel fuel, having high value of certain number of bio-based fuel such as biodiesel furnishes its ignition quality. Owing to the high value of certain number of bio-diesel it is possible to ignite it during winter or at low temperature additionally it makes low idle noise. Carbon dioxide released from fossil fuels plays a major role in the greenhouse effect, but biofuels limit this effect because CO₂ emission is limited. The disadvantages of biodiesel are that biodiesel has a tendency to choke injectors. Cold climate can cloud and even gel biodiesel fuel. Generally it has been observed that dust like impurities mixed with diesel can choke the fuel filter and nozzle and biodiesel collects the impurities from the engine and may clog the filter. Certain value or quality of the biodiesel varies with variation in the blend. Oxides of nitrogen contents are the major emission from biodiesel, which contributes smog formation. Distribution of biodiesel is not convenient as compared to petroleum products like diesel and petrol. Biodiesel contains less sulphur and other chemical pollutants and hence aids in reducing the harmful exhaust emissions like CO, HC, smoke etc., but owing to the excessive amount of oxygen it results in exceeded NO_x emissions.

Exhaust gas recirculation (EGR) is a process of allowing the engine emission to recirculate within combustion chamber, whereas percentage of emission induces within the combustion chamber is known as EGR %. Gases emitted from engine have oxides of carbon, oxides of nitrogen, oxides of sulphur and water molecules with high specific heat value. The working principle of EGR is to reduce the combustion chamber temperature or dilution of fresh air mixture by recirculation of controlled amount of gases resulting fewer oxides of nitrogen determined in emission.

Application of EGR ensures the engine intake contains fresh air with recycled exhaust gases. Fresh air is the mixture of gases consists of small amount of carbon dioxide (negligible) whereas engine emission

have subsequent amount of CO₂. The amount of CO₂ usually increases when incorporated through EGR. Especially CO₂ is simply a product of combustion. Therefore, it is instinctive and reasonable, to check the ratio of EGR by finding the concentrations of CO₂ between the intake and exhaust of the engine (Zheng et al., 2004).

Generally, it is noted that effect of EGR or reduction in concentration of oxides of nitrogen increases Ignition delay (ID), enhance heat capacity and more dilution of charge within the combustion chamber. Thus it ensures that high ignition delay plays the same role as offered by reduction in IT. It is a well known fact that adding the exhaust gases into intake enhances specific heat of un-reactive products presents for the duration of burning process. Higher heat capacity means decrease in peak combustion temperature. Dilution theory states that when EGR is used the temperature in the cylinder is reduced and oxides of nitrogen are decreased (Pierpont et al., 1995).

Numerous researchers have energized Compression Engine (CI) engine with biodiesel by utilizing EGR technology to reduce the harmful emissions of the engine. Singh and Sandhu (2020) done experiments on a multicylinder Common rail direct injection (CRDI) engine energized with blends of argemone biodiesel. The blend AB20 showed highest BTE and lowest Brake thermal fuel consumption (BSFC) among the fuels used. A10 and A20 showed low HC in contrasted with diesel. The rich blend A30 and A50 showed higher HC emission in contrasted with diesel. The blending up to 30% found to have low smoke as compared to diesel.

Patel and Sankhavera (2020) done experimentation on a CI engine using 100%, 50%, 30%, 20% and 10%, blends of karanja biodiesel. The brake thermal efficiency of K100, K50, K30 and K20 was found 8.5%, 5.8%, 3.5% and 3.9% reduced respectively in contrasted with diesel. However, the BTE for BD10 was 4.4% higher than pure diesel owing to the extra quantity of oxygen in the biodiesel. At 100% load, the emission of NO_x for K100, K50, K30, K20 and K10 were noted as 10.2%, 7.2%, 5.4%, 3% and 1.6% more

than pure diesel. At 100% load, emissions of CO for K100, K50, K30, K20 and K10 were 42.81%, 25.92%, 14.07%, 17.78% and 11.12% correspondingly lower than mineral diesel. The CO emission increased with increasing load. At higher load rich mixture produced cause incomplete combustion and the CO emission was increased. Up to 50% load there is not much difference between CO emission for diesel and Karanja biodiesel. However at higher load CO emission for entire range of fuel blends were found less as compared to diesel. This was owing to availability of more oxygen concentration in biodiesel, which provides better burning of fuels and CO emission was reduced.

Kolakoti and Rao (2020) used preheated Jatropha biodiesel in a diesel engine to find optimum values of various parameters using Taguchi and Gray technique. Jatropha biodiesel heated at different temperatures (50°C - 100°C) was used at different load and fuel consumption. The optimal characteristics were found for Jatropha biodiesel at 60°C with half load. The Jatropha biodiesel at 60°C showed about 15% more BSFC than diesel. HC emissions were found lowered by 66% and 50% at 100% and 75% loads in relation with diesel fuel for Jatropha biodiesel at 60°C. It was observed that CO emissions reduced by 85% and 80% at 100% and 75% loads corresponding to diesel fuel. NO emissions decreased by 15% and 14% Jatropha biodiesel at 60°C at 100% and 75% load than diesel fuel.

Kumar et al. (2019) tested Mahua biodiesel in diesel engine in volume ratio of 20%, 40%, 60% and 80% with diesel. It was noted that performance characteristics for 20% biodiesel and 40% biodiesel were slightly improved at low load and were close to diesel as the load was increased. But for rich blending i.e for B60 & B80, the BSFC and BTE were lower than diesel. HC, CO and smoke were observed to be less for entire range of fuels utilized during the experimentation, however when temperature was high, more oxides of nitrogen were produced. The NO_x production was affected by high O₂ concentration, temperature, ID and pressure. The NO_x was found to

enhance with increasing the Brake Power (BP). More NO_x emissions were produced by biodiesel as compared to the diesel. The highest NO_x was noted for 40% biodiesel at elevated loads. The high O₂ content of biodiesel helped in complete combustion and finally produced high temperature. The biodiesel blends produced a smaller amount of smoke as in relation with pure diesel. Low carbon and high oxygen content of biodiesel was reason for this. The smoke opacity was also found increased with increasing the brake power.

John et al.(2020)experimentally analyzed the combustion process for a CI engine using 20% blend of sesame biodiesel (S20) as a fuel. The experiments were performed at various Compression ratio (CR). The in-cylinder pressure for S20 was noticed slightly lesser than diesel. However, the pressure difference was reduced at higher CR. The ID for S20 was higher than diesel and the ID got decreased with increasing BP. The combustion stages for S20 and diesel were similar. It was noted that the combustion started earlier for S20.

Yesilyurt (2019)noted the impact of (Ignition Pressure) IP on exhaust emission and engine performance using waste cooking oil biodiesel. The experiments were performed on full load condition with six different injection pressures and almost eleven different engine speeds to find out the best IP. It was investigated that engine torque, BP and efficiency increase with the increase in IP. The engine emission had a mixed trend with the increase in IP. The unburnt hydrocarbon and carbon emission reduced and NO_x and CO₂increase with IP.

Yousefi et al.(2019)checked the outcome of advancing the Injection Timing (IT) for natural gas and dual diesel-fueled engine. The NO_x emission was the main emission from the engines based on biodiesel due to high peak elevation temperature in the engine cylinder. They found that advancing the IT could be an alternative to this problem and can also upgrade the engine performance and emissions. By advancing the IT in low load and speed engine, the amount of smoke and other greenhouse gases increased with the increasing gengine efficiency and BTE. But when the

engine load was medium to high, the amount of unburnt methane decreased by improving the combustion process and thus ultimately improved the engine performance.

Mirhashemi and Sadrnia (2020) reviewed the NO_x generation and possible solution to minimize the NO_x emission with biodiesel. Blending of gasoline, alcohol and gas in the biodiesel was found useful to minimize the NO_x emission. NO_x emission can also be minimized by delaying IT.

Shareef and Mohanty (2020) executed tests on a diesel engine at various IT using dairy scum biodiesel. The biodiesel was used in 10%, 20%, 30% and 100% proportion with diesel. At standard IT of 23° before top dead centre (BTDC), the CO emission for the biodiesel blends were less than pure diesel. The CO emissions for 10%, 20%, 30% and 100% proportion were 11.5%, 23%, 29.4% and 34.6% less in comparison with pure diesel at 100% load. HC emission for B10 and B20 were 4.6% and 11.6% less than pure diesel. Both the HC and CO emissions were found lowest at the advance IT of 26°BTDC. The CO and HC emission for B20 at 26°BTDC reduced by 11.7% and 5.5% respectively as compared to the standard IT of 23°BTDC. The highest NO_x emission was noted at 26°BTDC. The NO_x at 26°BTDC increased by 9.8% in relation with the actual IT of 23°BTDC. The lowest NO_x emission for B20 was noted at IT of 20°BTDC which was 1.2% lower than the standard IT of 23°BTDC.

An effort was made to assess the performance of engine by varying the injection pressure of VatariaIndica biodiesel by Rao et al. (2019)Biodiesel in different blending ratio (V10-10%, V15-15%, V20-20% and V25-25%) was investigated at different IP. The BTE was observed to increase as IP was increased. The peak BTE was obtained for all blends and diesel at peak pressure of 220 bar. NO_x emissions were observed to increase with the IP, but the peak NO_x was at 200 bars, not 220 bar pressure. The disassociation effect separates NO_x to its atomic states when the IP was raised from 200 bar to 220 bar and thus decreased NO_x emissions were observed as the IP enhanced from

200 bar to 220 bar. There was no much change in CO emission as IP was changed from 180 bar to 220 bars. HC emission was reduced by 11.1%, 11.7%, 17.6%, 12.5%, as IP rose from 180 bar to 220 bar for V10, V15, V20 and V25 respectively (Rao et al. 2019).

Kulkarni et al.(2019) made an effort to utilize the heat carried by exhaust gases within the engine to lower down the environmental temperature gain due to hot emissions. This is done by covering the engine cylinder walls and head ceramic materials. The ceramic materials are found to be very effective to make the walls almost insulated to restrict the heat loss to the surroundings. The engine was tested for diesel and diesel-MOME (Mahua oil methyl esters) blend and evaluated that the BTE, carbon and hydrocarbons emission decreased and nitrogen based emissions increased.

Kulkarni et al. (2019) used EGR to minimize the harmful NO_x emission in corn seed oil biodiesel engine. They used the different ratio of the exhaust gases and observed that the NO_x emission decreased with enhancement in recirculation ratio. Although, engine performance and higher soot generation were noticed at higher recirculation ratio.

Kumar et al.(2019) conducted experiments on a CI engine using biodiesel extracted from fish oil and jatropha oil. Only 20% blends and 20% EGR were used in this work. It was found that the HC emissions were increased on applying the EGR for both the biodiesel at all load conditions. Due to the EGR, the O₂ in the combustion chamber get decreased and poor combustion is produced which further increases HC emission. The NO_x emissions were decreased on applying EGR. This happened because the EGR produced two major effects in the combustion chamber. The O₂ concentration was reduced, which produced poor combustion and high specific heat of exhaust gases reduces the temperature in the chamber. Due to reduced temperature, the NO_x emission gets reduced. At 100% loading, The NO_x emissions for Jatropha and fish oil reduced by 35.5% and 15.7% on applying 20% EGR as compared to the emission at zero EGR.

Ayhan et al. (2020)used corn oil biodiesel in a diesel engine at various blending concentration and different EGR in order to find the optimum conditions using Taguchi method. For CO emission the optimum condition was 40% load, 1600 rpm, 50% blending and 0% EGR. The same optimum conditions were observed for HC emission. The HC and CO emission were found to be increased with increasing EGR. The optimum conditions for NO_x emission were 40% load, 2400rpm, 0% blending and 20% EGR. The NO_x was found to be increased with enhancing load owing to the rise in temperature on increasing load. RSM method has also been implemented by a lot of diesel engine experts for modeling and optimizing various issues pertaining to engine parameters as depicted in Table 1.

The literature review revealed that biodiesel can be an efficient substitute for fossil fuels. Numerous works has been reported on the performance and emission parameters of biodiesel. The research review also revealed that the HC, CO and smoke for diesel are less in relation with diesel. But NO_x for biodiesel is higher in most of previous work studied. So there is a need for the reduction of NO_x while using biodiesel as fuel in CI engines. Also, the current diesel engines are designed to be used to run on diesel. So there is a need for research which develops any changes in engine parameters like IT so that for the biodiesel can be used in an engine more efficiently. To reduce research gaps, experimentation was done by blending 20 percent biodiesel with diesel in conjunction with EGR system and varying the IT of the engine to check its performance and emission parameters.

2 Materials and Methods

2.1 Properties of fuels and blending

The raw jatropha oil and other chemicals like sodium hydroxide (purity (97%) was obtained from SVM agro processor, Nagpur, Maharashtra, India. Sodium hydroxide was utilized as catalyst for preparation of biodiesel. The biodiesel was procured from jatropha oil by two-step transesterification process. Properties of diesel and biodiesel produced from Jatropha seeds are depicted in Table 2. Blends of

diesel and jatropha biodiesel were used in this study to energize the engine. 20% Jatropha biodiesel was blended with pure diesel and named as B20.

Table 1 Numerous articles pertaining to performance and emissions of engine using RSM

RefNo.	Fuel	Engine	Operating parameters	Response parameters	RSM method/design of experiments
Mahla et al., 2021	Diesel/n-butanol/Biogas	Dual fuel engine	Nbutanol/Engine load/ Biogas flow rate /concentration	BTE, CO, UHC, NOx, soot	Three levels of studied parameters
Mahla et al., 2024	Diesel and biogas	Dual fuel engine	Compression ratio, load, type of fuel	BTE, CO, UHC, NOx, soot	Three levels of studied parameters
Awad et al., 2017	gasoline blended fuel	Four-cylinder, four-stroke petrol engine	petrol blended ratio of fuel, wide throttle opening position and speed of engine	BSFC, BTE, BP, NOx, HC, and CO	–
Dasari et al., 2017	Castor oil biodiesel and diesel	1-cylinder, 4-stroke DI diesel engine	Temperature, concentration of catalyst, molar ratio and reaction time	Conversion from castor oil to biodiesel	Central composite design
Dhingra et al., 2013	Diesel and mahua oil biodiesel	Kirloskar 1-cylinder, four stroke, Variable compression ratio	Compression ratio, speed, engine load, Blending ratio and Injection timing	Peak Pressure, BSFC, BTE, All emission parameters	5 level, 5 factor design (L32 array)
Bose et al., 2017	Diesel-ethanol-hexane-diethyl ether	1- cylinder, 4-stroke diesel engine	Engine load and concentrations of blended fuel	CO, HC, NOx, and BSFC	D-Optimal
Sharma et al., 2019	Biogas, Ethanol and Soya biodiesel	single-cylinder, 4-stroke, DI diesel engine	Load on engine, flow rate, Fuel blends, engine speed and air flow rate	CO, NOx and HC BTE	Five levels of studied variables
Yusri et al., 2017	Secondary butyl alcohol–gasoline blends	4-cylinder, 4-stroke petrol engine	Engine speeds and fuel blends	NOx, CO, CO2 HC, BP, BMEP, BSFCand BTE	Central composite design

2.2 Experimental Set up

The experimentation was performed on a CI engine. The actual engine setup is shown in Figure 1. Experiments were performed at a 20% blend of jatropha, biodiesel. Engine details are shown in Table 3. The speed of the engine was fixed at 1500 rpm, and load was changed from 0 to 100% and the outcomes were noted down. AVL gas analyzer was utilized to check emissions of the engine. The AVL 437 smoke meter was utilized to calculate the smoke opacity. The uncertainty of the measuring system is shown in Table 4.

EGR system was also incorporated in the engine that aids in recirculation of a part of the exhaust gases reverse into the engine cylinder. The gases sent back into the cylinder were controlled by a control valve. One tenth and One fifth gases were recirculated in the

engine cylinder and the performance and the emissions were checked diesel and J20. The quantity of EGR was checked during the assessment of CO₂ in intake and exhaust manifold. The EGR was calculated using the following equation:

$$\% EGR = \frac{CO_2 \text{ percentage in intake manifold}}{CO_2 \text{ percentage in exhaust manifold}} \times 100 \quad (1)$$

The available engine was fixed on IT of 23° BTDC and injection pressure of 200 bar. The IT was retarded or advanced by adjusting the shim beneath the fuel injection pump. The spill method was used to check the IT. A circular protractor attached to the flywheel was used to check the crank angle. The IT gets changed by 1° crank angle by adding or eliminating a shim of 0.2 mm thickness. The engine speed was fixed at 1500 rpm.



Figure 1 Experimental setup

Table 2 Properties of fuels used

Properties	Jatropha biodiesel	Diesel	ASTM standard
Cloud point in degree celsius	5	2	-2 to 12
Energy content (KJkg ⁻¹)	36200	45200	>33000
Pour point in degree celsius	6	-2	-15 to 10
Kinematic viscosity @ 40°C (mm ² s ⁻¹)	5.3	3.65	1.9-6
Flash point in degree celsius	189	69	>130
Density	895	842	900

Table 3 Test rig details

Engine set up	Kirloskar TV 1
Engine	Four stroke diesel engine with single cylinder
CR	17.5
Connecting rod	234 mm
Length of stroke	110 mm
Swept volume, cc	661.45
Diameter of bore	87.5 mm
Engine speed	1500 RPM
Engine power	5.2 kW

Table 4 Uncertainty analysis of parameters measured

S. No	Instrument/ Parameter	Uncertainty (%)
1	Type K-Thermocouple / Temperature	0.25
2	Differential Pressure Transducer/ Fuel flowmeter	0.065
3	Load cell/engine load	0.025
4	Thermocouple RTD PT100/temperature	0.25
5	Pressure transmitter/air-flow rate	0.25
6	Sensor-Piezo / pressureinside cylinder	0.008
7	Encoder installed for measuring crank angle /RPM	0.018
8	BSFC	0.08
9	BTE	0.08
10	Emissions of NOx	0.02
11	Smoke opacity	0.1
12	Emissions ofCO	0.1
13	Emission ofHC	0.005

Table 5 Statistical findings for the studied engine-out parameters

Variable	BTE		UHC		CO		NO _x		EGT	
	F value	Pvalue	Fvalue	Pvalue	Fvalue	Pvalue	Fvalue	Pvalue	Fvalue	Pvalue
Model	327.09	< 0.0001	476.28	< 0.0001	95.09	< 0.0001	35.55	0.0001	633.55	< 0.0001
EGR ratio	9.36	0.02	1133.39	< 0.0001	29.53	0.0016	28.33	0.0018	180.17	< 0.0001
Engine load	2899.17	< 0.0001	3199.31	< 0.0001	821.89	< 0.0001	300.04	< 0.0001	5746.07	< 0.0001
IT	32.55	0.0006	66.91	< 0.0001	6.98	0.0271	1.57	0.2827	34.61	0.0005
Cor. total	967.46		335.18		6.073E-3		1.567E+6		1.717E+5	

Recently, the response surface methodology (RSM) as a great technique is used for evaluating and modeling of different engineering issues like predicting engine performance and emissions characteristics. The RSM can effectively model the interactive influence of engine parameters on the engine-out parameters (Kocakulak et al., 2023). Therefore, in present investigation, based on the three factors of the engine i.e., engine load, EGR ratio and different IT, the RSM based on the historical design was employed to both model and optimize the engine performance and emission characteristics to achieve lower emission and higher performance.

3 Results and discussion

3.1 Evaluation of the Models

The effects of adding Jatropa biodiesel fuel into diesel fuel, EGR ratio and engine load at different IT on the engine performance including BTE and emissions characteristics (i.e., UHC, CO, NO_x, and EGT) were investigated. ANOVA (Analysis of variance) as a popular statistical tool was employed to create mathematical models between response variables and engine parameters. The statistical findings for the studied engine-out parameters are shown in Table 5. As can be seen in the Table 5, the *p*-value of the models were less than 0.05, indicating the derived models are statistically significant. Second-order equations of each response variable derived by employing RSM technique to estimate the engine-out factors, which are illustrated in Equations 2-6.

$$BTE(\%) = 26.5 - 0.5A + 8.84B - 1.37C - 0.21AB + 0.29AC - 0.83BC - 0.23A^2 - 4.13B^2 \quad (2)$$

$$UHC(ppm) = 19.21 + 2.85A - 4.53B + 1.02C - 0.02AB - 26AC + 0.25BC - 0.09A^2 + 1.75B^2 \quad (3)$$

$$CO(\%) = 0.029 + 0.03A + 0.02B + 0.002C - 0.002AB + 0.001AC - 0.003BC - 0.003A^2 + 0.007B^2 \quad (4)$$

$$EGT = 242.3 - 21.81A + 116.85B + 11.97C - 6.78AB + 0.089AC + 2.45BC + 10.18A^2 + 22.75B^2 \quad (5)$$

$$NO_x(ppm) = 278.35 - 102.4A + 348.85B + 0.17C - 83.32AB - 52.65AC - 29.32BC + 60.91A^2 + 159.06B^2 \quad (6)$$

3.1.1 BTE

The changes in BTE at different engine loads and EGR ratios is depicted in Figure 2 as a three-dimensional (3D) and two-dimensional (2D) surface plots. Figure 2 shows that increasing engine load increases BTE. According to the results obtained, with increasing engine load from 20% to 100%, the BTE increased from 12.7 to ~29. In general, with increasing engine load the BTE increases mainly due to high flame speed which results in complete combustion of the fuel (Tan et al., 2023). Based on the results depicted in Table 1, as the *f*-value of the engine load is higher than other parameters, therefore, the effect of engine load is greater than other studied parameters. At 100% engine load, the maximum BTE was recorded to be approximately 29%.

A slight decreasing trend was also observed when the EGR ratio increased to 20%. As depicted in Figure 2(b), with increasing the EGR ratio from 0% to 20%, the BTE decreased from 25.6% to 25.1%. The BTE was found to be the minimum value when the EGR ratio reaches 20%. According to results obtained in Table 1, it can be concluded that the engine load and EGR ratio have a more significant influence on the BTE in comparison with different IT parameter. The lowest BTE value was reported as 24.5% at IT value

of 21 degree (Figure 3). Blending jatropha biodiesel into diesel fuel produced higher BTE than neat diesel

fuel that can be attributed to its comparatively lower heating value (Imtenan et al., 2014).

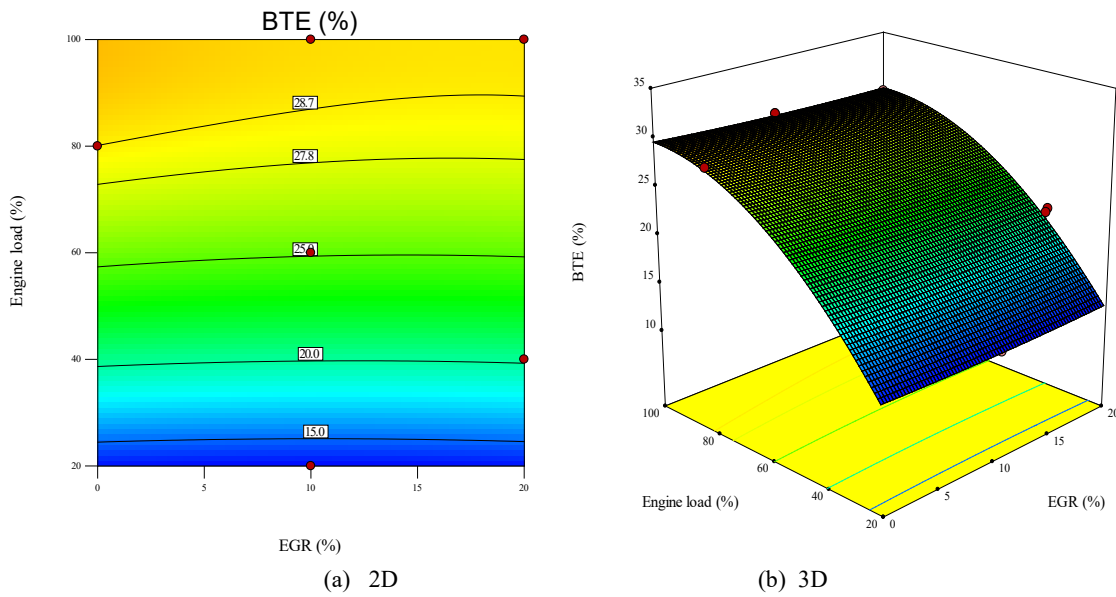


Figure 2 Interactive effects of engine parameters on the BTE

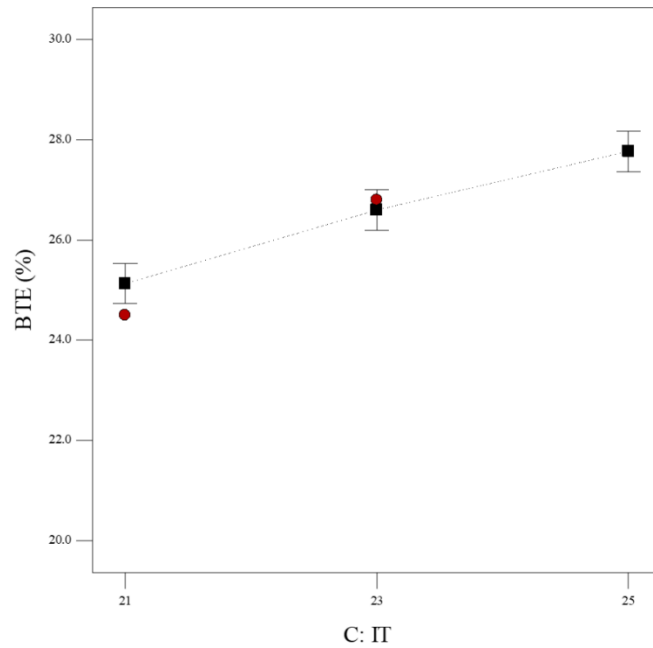


Figure 3 The effect of IT on the BTE

3.1.2 UHC emissions

Figure 4(a) and 4(b) show the effect of the EGR ratio and engine load on the emitted UHC emissions. As can be seen in Figure 4(a), the UHC emissions declined with the increase of the load of engine. With increasing load of the engine in the tests from 20% to maximum load, the emitted UHC reduced significantly from 26.27 ppm to 17.7 ppm. Forming UHC emissions mostly is affected by a number of factors like low-temperature of the combustion chamber, engine loads and speeds (Khalife et al., 2017). Working engine at

higher loads improves combustion due to reducing incomplete combustion loss, resulting in increased temperature of the cylinder chamber and thus, reducing UHC emissions (Yaman et al., 2022). At the full load condition, the UHC emissions were found to be ~17 ppm. Similar trend was also recorded when IT value increased. Considering the results depicted in Figure 4(a), with increasing IT value from 21 to 25-degree results in decreasing UHC formation. However, the UHC emissions increased when EGR ratio enhanced. It was found UHC emissions were increased

by ~29% with increasing EGR ratio from 0% to 20%.

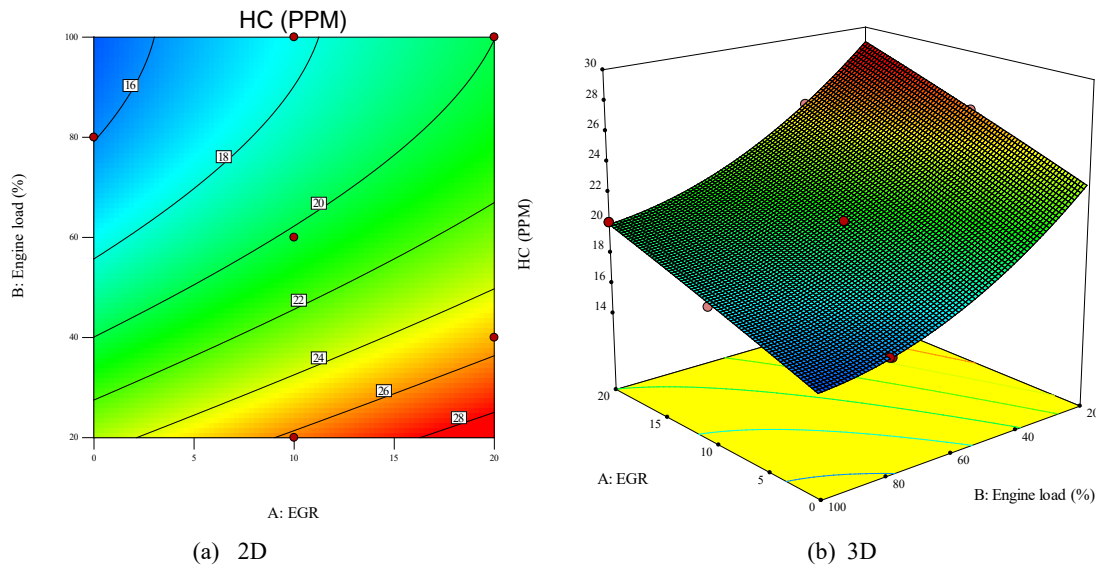


Figure 4 Interactive effects of engine parameters on UHC emissions

The division of emitted UHC according to IT values is presented in Figure 5. As can be seen in Figure

5. The lowest UHC emissions was determined as 20 ppm at IT value of 21 degree.

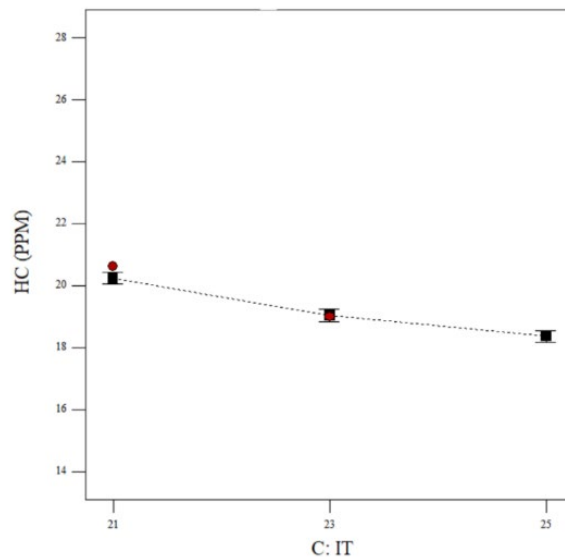


Figure 5 The variation of UHC emissions versus IT values

3.1.3 CO emissions

The CO emission derived model was quadratic. Table 5 indicates that the factors considered for developing this model were statistically significant at level of 1%. According to the F-value recorded, the EGR had least effect on the formation of CO emissions. Using EGR at high engine load conditions could not improve the formation of CO emissions mainly because of the deterioration of normal combustion process. It may be due to the chemical effect of EGR, oxygen-deprived and also the presence of heat gases conditions (Kumar et al., 2016). Checking the results are shown in Figure 6 (a), with rising the EGR ratio

from 0% to 20%, the CO emissions increased from 0.02% to 0.03%. Conversely, the variation of IT could effectively mitigate the CO emissions. As depicted in Figure 7, the finding of the modeling using RSM techniques indicated that with increasing the IT from 21 to 25, the exhaust CO emissions mitigate from 0.031% to 0.025%. As depicted in Figure 6(b), different loading conditions in the studied diesel engine could significantly affect the CO emissions. According to the results, high engine load condition could enhance the CO emissions drastically. With increasing the load of the diesel engine from 20% to high level of load, the formation of emitted CO

increased from 0.015% to ~ 0.061%. The F-value for the EGR ratio, IT, and engine load was recorded as 29.53, 821.29, and 6.98, respectively. Higher values of F reported in Table 5 for engine load highlights greater significance of the influence of engine load on the amount of exhaust CO emissions mainly due to the fact

that the CO formation is the result of low temperature and consequently in-complete combustion. However, the higher oxygen content specially at high engine loads in the J20 fuel could leads to significant increases in CO emission(Khalife et al., 2017; Gad et al., 2021).

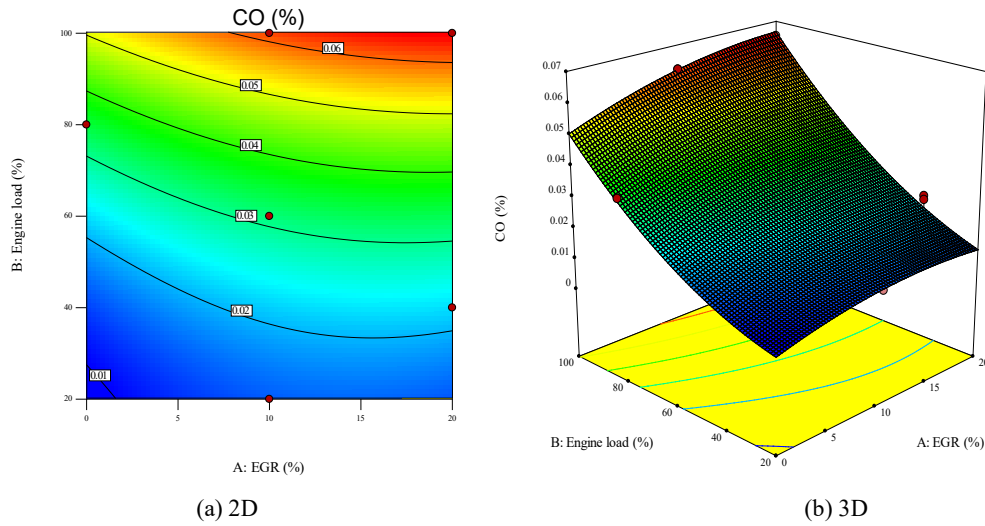


Figure 6 Interactive effects of engine parameters on CO emissions

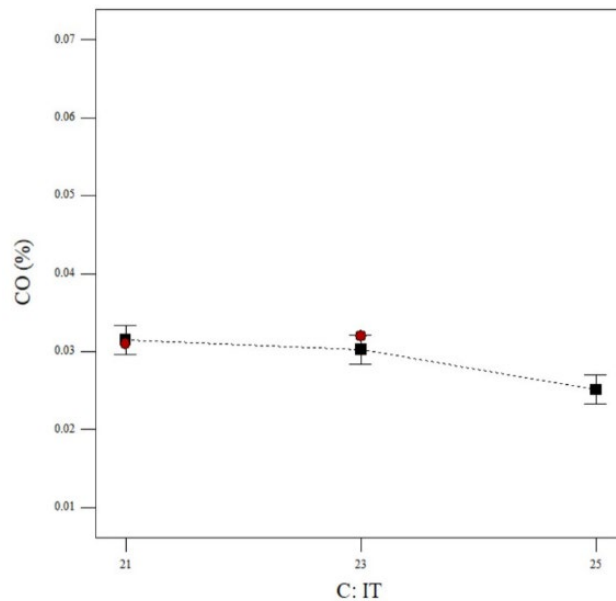


Figure 7 The positive effect of increasing IT value on the formation of CO emissions

3.1.4 NO_x emissions

According to the P-value results illustrated in Table 5. All independent terms had a statistically significant influence on the NO_x emission concentration. The most significant factor affecting the NO_x formation were engine load, EGR, and IT values, respectively. Besides, the value of R-square of 0.98 indicated that about 98% for NO_x could be successfully predicted by the models based on the

independent parameters and ~ 2% of the NO_x emission values could not estimate by the suggested model. The relationships between EGR ratio/engine load/IT levels with NO_x emissions are shown in Figure 8. As can be seen in the Figure 8, the increasing engine load levels enhanced the formation of NO_x emissions. It could be attributed to the oxygenated nature of Jatropha biodiesel which results in a complete combustion. With increasing the load from its minimum to

maximum level, the NO_x emissions significantly increased from ~118 ppm to 750 ppm. As can be seen in Figure 9, the quantity of NO_x emissions decreased slightly with increasing IT values. With increasing IT quantity from 21 to 23 degree, the NO_x formation decreased ~17%. However, with increasing the IT value to 25, the NO_x emission is increased approximately 35%. The EGR performance had a

positive effect on the NO_x emissions. With increasing EGR rates the NO_x emissions decreased significantly from 494 ppm to 184 ppm. In similar studies stated that EGR had a positive effect on NO_x emissions (Sayin and Uslu, 2008; Fayad et al., 2023). In Other investigations, higher fuel oxygen content attributed to the reduction of NO_x emissions (Liu et al., 2023).

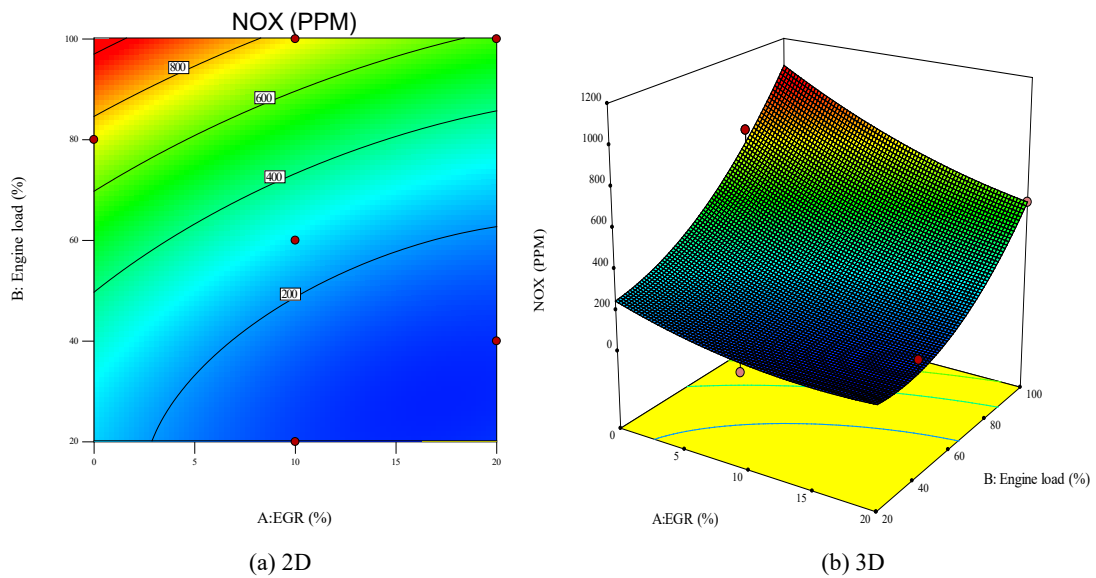


Figure8 Interactive effects of engine parameters on CO emissions

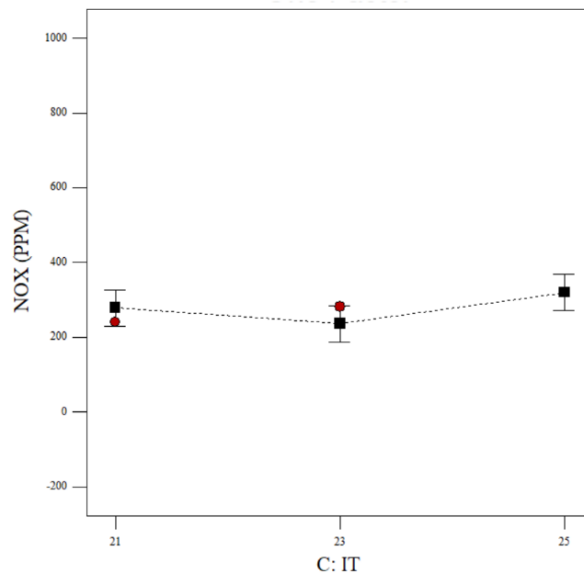


Figure 9 The impact of IT on NO_x emissions

3.1.5 EGT rate

The effects of engine load and EGR ratio on EGT are depicted in Figure 10(a). Higher EGT is attributed to incomplete combustion in the dual-fuel engines (Bora et al., 2022). The EGT was recorded to rise while engine load enhanced (Figure 10(b)). The *p*-values in Table 5 indicate all independent parameters were

statistically significant at level of 1%. Based on the F value results, the engine load had a higher influence on the EGT in comparison with other studied parameters followed by EGR ratio and IT. The F-value for engine load, IT, and EGR ratio was found to be 5746, 180, and 633, respectively. As evidenced from ANOVA in Table 5, the *p*-values obtained for all considered

parameters indicate that those studied parameters contribution were statistically significant to the EGT model. The higher value obtained for R-square, showed that the RSM model could successfully predict the engine parameter. It is evident from Figure 6 that EGT decreased with growing EGR ratio and IT value. With increasing IT value from 21 to 24 degree, the EGT value decreased slightly from ~254°C to ~227°C

(Figure 11). Conversely, EGT has increased excessively as the increasing engine load. According to the results, with increasing the engine load from 20% to 100%, the EGT raised significantly from 158 degree to 396 degree. It is obvious that the in cylinder temperature and subsequently the EGT will increase as the engine load increases for all engine operating conditions.

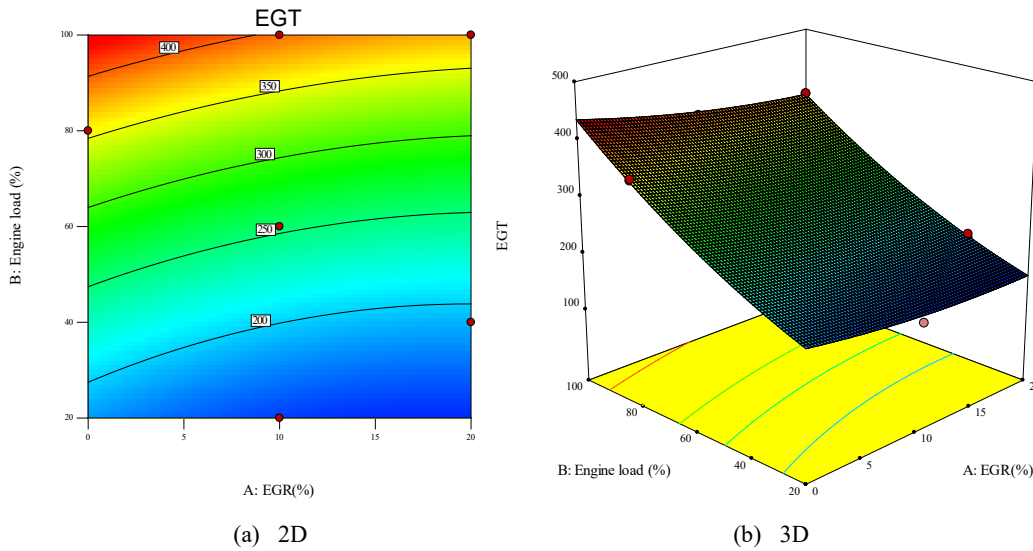


Figure10 Interactive effects of engine parameters on CO emissions.

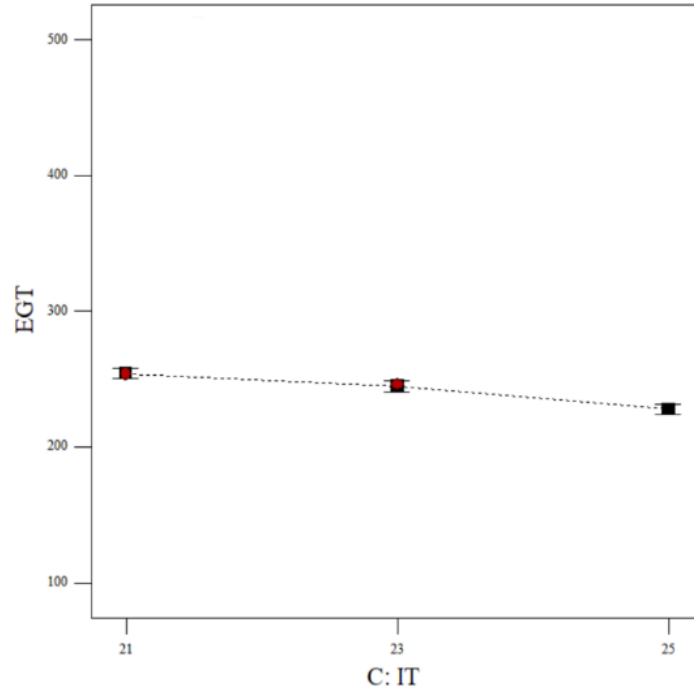


Figure11 The effects of IT variations on the EGT

3.2 Numerical Optimization

In this paper, a multi-objective optimization was used to simultaneously maximize the engine-out parameters including BTE and minimizing the exhaust emissions i.e., CO, NO_x, and UHC emissions. The

input parameters were considered to be IT, EGR percentage and engine load. The final results of RSM optimization for each parameter based on desirability function values in depicted in Figure 12.

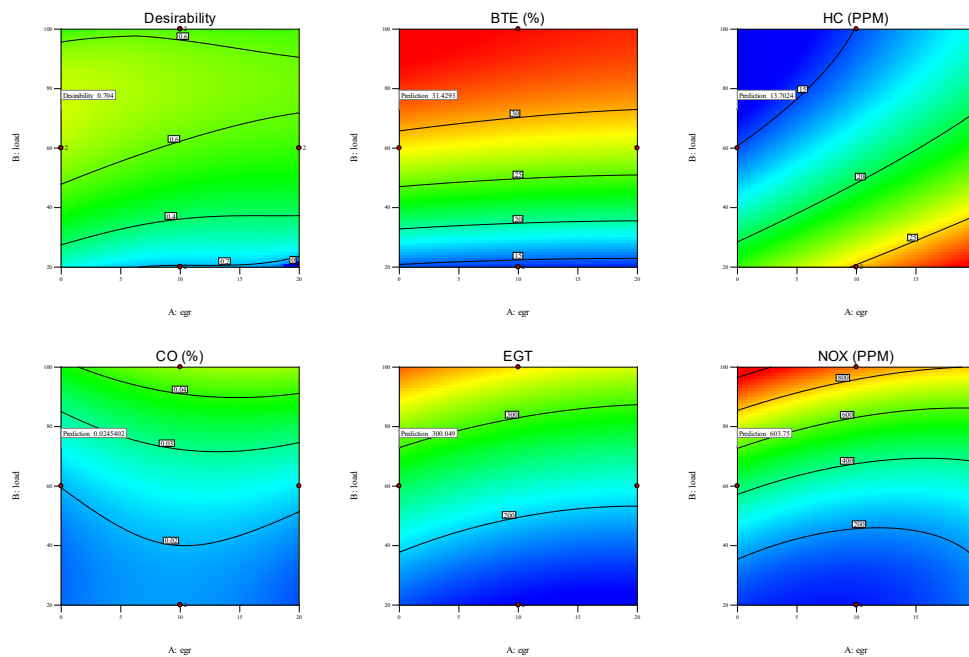


Figure 12 The value of desirability value for independent variables

Using Response surface technique and multi-objective optimization, the optimal value for the engine load, EGR ratio and IT were found to be ~94%, 0%, and 25 degree, respectively. At obtained optimal point, the value of BTE, UHC, NO_x, EGT, and CO were predicted as around 34%, 24 ppm, 970 ppm, 380, and 0.03%, respectively. According to the results depicted Figure 12, using optimal condition, the desirability function value was recorded to be ~ 85%, indicating the predicted mathematical models could successfully follow the engine variation data.

4 Conclusion

In this paper, the experiments were performed at a 20% blend of Jatropha biodiesel. The speed of the engine was fixed at 1500 rpm, and load was changed from 0 to 100% and the outcomes were noted down. All studied parameters were found to be statistically significant on the response parameters. BTE, EGR and emissions parameters including NO_x, CO, and UHC were analyzed using RSM method. The regression models were derived for each parameter. According to the results obtained, with increasing engine load from 20% to 100%, the BTE increased. The BTE was found to be the minimum value when the EGR ratio reaches 20%. With increasing engine load from 20% to 100%, the emitted UHC emissions reduced significantly. Also,

increasing the IT from 21 to 25, the exhaust CO emissions mitigate from 0.031% to 0.025%. Besides, increasing IT quantity from 21 to 23 degree, the NO_x formation decreased ~17%. Using multi-objective optimization, the optimal value for the engine load, EGR ratio and IT were found to be ~94%, 0%, and 25 degree, respectively. At obtained optimal point, the value of BTE, UHC, NO_x, EGT, and CO were predicted as around 34%, 24 ppm, 970 ppm, 380, and 0.03%, respectively.

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