Eco-Performance Optimization of a CI Engine Fueled with Waste Chicken Fat Biodiesel and 2-EHN Additive Using RSM and Correlation Heatmap Analysis

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Abstract. The current study investigates the effect of Engine Load (EL), compression ratio (CR) and cetane attractive EHN additive on the performance and emission properties of a single-cylinder diesel engine operating on a blend of BD20 biodiesel and diesel. An interactive analysis between these parameters on brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), exhaust gas temperature (EGT) and significant emissions such as CO, HC, NOx and smoke opacity was conducted using a Central Compositional Design (CCD) Response Surface Methodology (RSM). Experimental data bring that higher load and compression ratios are knowingly optimistic in combustion efficiency with BTE expanding to 30 per cent in optimal conditions, and BSFC decreasing to 0.25 kg/kWh full load. EGT values rose with load and compression which indicated the enhancing of combustion and the reduction of CO and HC emissions was significantly lower because of the increased oxidation. Under full-load conditions, higher combustion temperatures is the cause for an increase in Nox and smoke emissions. As part of the typical efficiency-emission trade-off; the addition of EHN helped regulate and maintain smoke and Nox levels within acceptable limits. Statistical testing provided the performance of an excellent model with an R2 of over 0.99 and emissions at over 0.97, although experimental and imitating data proved error margins less than 2 percent. The research shows that suitable modification of engine load (EL), compression ratio (CR)and the addition of EHN additive can improve engine efficiency, combustion characteristicsand reduce exhaust emissions, thereby providing valuable insights into the sustainable utilization ofbiodiesel-diesel blends in CI engines.

1 Introduction

Industrialization, urbanization and increased transport systems have increased the energy requirements of the world, leading to a situation where the world will rely on fossil-based fuels which cannot be sustainable [1]. Diesel, petroleum in especially, continues to (CI) engine technology due to its great energy density and recognized infrastructure. The issues of the reduction of fossil fuel reserves, the variability of crude oil prices and the growing environmental issues connected with greenhouse gases (GHG) emissions and the levels of the environmental pollution require the alternative renewable sources of fuel [2]. In this regard, biodiesel has attracted a lot of attention as a potential alternative due to its ability to be biodegraded, carbon neutral and its ability to be used with the current diesel engines [3]. Triglycerides are usually transesterified with short-chain alcohols, typically methanol, in the absence of a catalyst to generate biodiesel [4]. Biodiesel is an environmentally attractive substitute for petro-diesel due to its physicochemical characteristics, which include a higher flash point, improved lubrication, and a lower sulphur content [5]. Though, issues with feedstock supply and cost competitiveness have impeded the broad adoption of biodiesel [6]. Edible oils, though initially used for biodiesel production, are no longer considered sustainable due to food-versus-fuel conflicts, high production costs and ethical concerns [7]. Consequently, non-edible oils, waste cooking oil as well as lipids of animal fat are now being explored as potential cheap feedstocks [8]. The use of chicken fat as one of the waste-derived materials to generate biodiesel has gained a lot of appeal. There is a lot of fat involved in chicken production that become a by-product of the poultry industry and also contributes to the pollution and waste management problems [9]. Besides providing a low-cost renewable fuel, the application of this waste as a source of biodiesel synthesis is viewed as a solution to the issue of waste disposal and the popularisation of the principles of the circular economy [10]. Moreover, chicken fat is suitable in the transesterification process because it has a relatively high lipid value [11]. It has a high (FFA) content which is a challenge, like soap formation in conventional base-catalysed reactions, thus requiring pretreatment or acid or heterogeneous catalysts [12]. To report these challenges, various catalytic pathways were systematically investigated. CaO, which is a waste eggshell material, has been reported to be a promising solid, catalyst in improving the conversion efficiency and reducing secondary reactions in Fe- and Ni-doped and Ce-doped oxides [13-15]. Ultrasonic-assisted and

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microwave-assisted transesterification processes have greatly cut down on reaction times and enhanced yield compared to the traditional batch processes [16,17]. The methods of optimization (RSM), (CCD) and the artificial intelligence algorithms have been extensively used to determine the most significant operating parameters and produce the highest yield of biodiesel [18-20]. The density and the calorific value of chicken fat biodiesel, the kinematic viscosity, as well as density, are compared to that of petro-diesel with slight variations [21]. It has a better cetane number, which enhances the quality of ignition as well as the oxygenated structure of fatty acid methyl esters increases the complete combustion [22]. However, the comparatively increased viscosity and reduced volatility than diesel can influence the atomization and combustion, particularly at lower temperatures [23]. Therefore, it is a common practise to use blending strategies (e.g., B20, B50) to trade off the combustion efficiency and emission properties [24].

Though a few studies have looked at the production of biodiesel and the use of the fuel in CI engines, little has been done to carefully optimise engine operating variables like the engine load, compression ratio and ignition improvers under experimentation. The previous literature addresses the efficiency of feedstock conversion, or engine performance under the changes of one variable, which creates a gap in the knowledge about the overall impact of several parameters on the performance and emissions. Diesel and biodiesel blend (EL: 0, 50, and 100 percent), different compression ratios (16, 17 and 18), cetane modifier EHN additive concentration (2, 4 and 6 percent) are the input parameters of the present work. It will be possible to assess their interactive effects in a complete manner, and such a review will aim at determining the best operating conditions in order to achieve higher engine efficiency and lower emissions.

2 Materials and Methodology

2.1 Preparation of test fuels

In the preparation of test fuels, chicken fat was used as the feedstock in the production of biodiesel shown in figure 1. Properties shown in table 1. The raw chicken fat was taken off and washed with much water to remove dirt and other undesirable particles. To eliminate moisture steam heat was applied to the cleaned fat followed by the filtration to isolate suspended impurities. In the case of oil recovery, hexane was employed as a solvent to remove oil in the feedstock. As the fat of animals typically has a large percentage of the free fatty acids (FFA) an esterification step was used with methanol and an acid catalyst to lower the FFA level to an acceptable level. This oil was then transesterified with methanol in the presence of potassium hydroxide (KOH) catalyst to form (FAME). Phase separation was left to be done on the transesterified product, in which the biodiesel layer, which was light, would be collected at the top of the product, and the heavier glycerol would be collected at the bottom. The biodiesel was washed several times with warm distilled water to make sure that it is very pure and then dried to get rid of the moisture. The resulting biodiesel was then mixed with regular diesel in set amounts and subjected to stability before being experimented with the engine.

The initial (FFA) content of the extracted chicken fat oil was first reduced through acid esterification using methanol as catalyst and controlled conditions of 60°C reaction temperature, 60 min reaction time, 6:1 methanol-to-oil molar ratio and 1% catalyst concentration by volume. After reducing the FFA level to below 2% transesterification was carried out using methanol and 1 wt of %(KOH) catalyst at 60°C for 90 min with a 6:1 methanol-to-oil molar ratio. The biodiesel production yield obtained from chicken fat oil was approximately 89% after purification and drying.

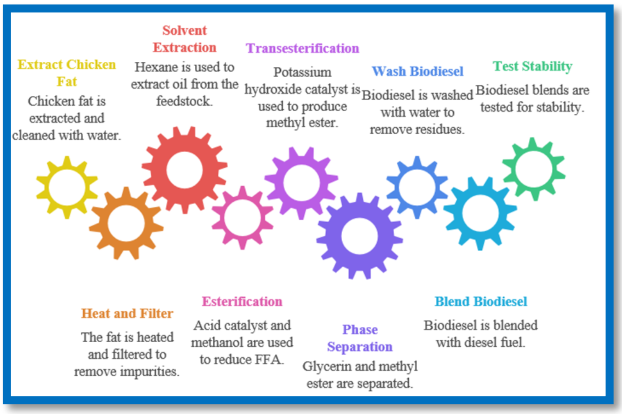


Fig. 1. Preparation of Chicken Fat Biodiesel.

Table 1. Properties of diesel and biodiesel

Property	**Unit**	**Diesel**	**Chicken Fat Biodiesel (B100)**	**Test Method**
Density at 15 °C	g/mL	0.825	0.875	ASTM D1298
Kinematic viscosity at 40 °C	mm^2/s	2.28	2.90	ASTM D445
Flash point	°C	70	130	ASTM D92
Calorific value	MJ/kg	42.5	40.5	ASTM D270

Cetane number	–	48	54	ASTM D976

3 Experimental Setup

A single-cylinder, four-stroke, water-cooled diesel engine with a variable compression ratio system was used for the trials shown in figure 2. Brake power output was measured and load was placed using an eddy current dynamometer. A piezoelectric pressure sensor was used to record the in-cylinder pressure, and an encoder linked to a data collecting system provided the crank angle signals for performance monitoring. A smoke meter and a calibrated exhaust gas analyser were used to monitor emissions, such as CO, HC, NOx and smoke opacity. Its conventional fuel system supplied test fuels, ranging from diesel, biodiesel, and biodiesel blends with Ethyl Hexyl Nitrate (EHN). All data were got once steady operating conditions were reached.

3.1 Experimental test rig

The concentration of the additive ethyl hexyl nitrate (EHN), the engine load (EL) and the compression ratio (CR) were considered as three important input parameters in the experimental trials. The blends consisted of three levels of biodiesel energy, namely 0, 50 and 100 percent. The engine compression ratio was also changed to 16, 17 and 18 to establish the effect of increased cyclone pressure on combustion. Ethanol hexyl nitrate (EHN) was used as a cetane improver additive by volume, 2-percent, 4-percent, and 6-percent. In order to evaluate the joint effect on BTE, BSFC, EGT, and exhaust emissions, these selected input parameters were systematically varied based on the created experimental matrix.

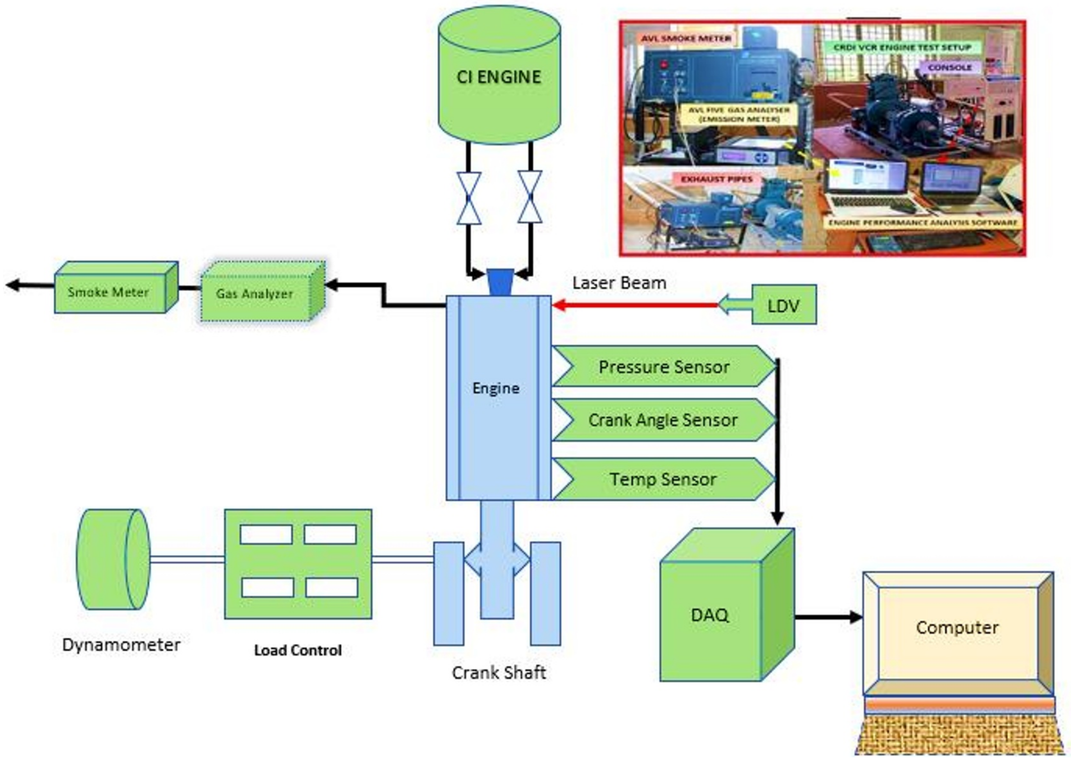


Fig. 2. Experimental Setup.

3.2 DOE – RSM/CCD

A (CCD) based on (RSM) was used to analyse the combined effect of three factors shown in table 2, Energy Level (EL), Compression Ratio (CR) and Ethyl Hexyl Nitrate (EHN) additive concentration on engine performance and emission characteristics shown in table 3. Each factor was used at three levels and the actual values were converted into coded variables using the standard transformation:

$$x_i = (X_i - X_i) / \Delta_i \tag{1}$$

where x_i is the oblique value of the X_i the actual value, X_i the central level and Δ_i half the range of variation. The experimental data were used to a second-order polynomial model of the form:

$$y = \beta_0 + \Sigma\, \beta_i x_i + \Sigma\, \beta_{ii} x_i^2 + \Sigma\, \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

where y is the forecast response (BTE, BSFC, NOx), β_0 is the intercept, β_i, β_{ii} and β_{ij} are regression coefficients for linear, quadratic and interaction terms respectively and ε represents the residual error. The estimation of coefficients was carried out using the least-squares method:

$$\beta = (X^T X)^{-1} X^T y \qquad (3)$$

where X is the design matrix and y the vector of experimental observations. This method allowed assessment of both individual and interactive effects of the parameters on the measured responses while minimizing the number of experiments.

Table 2. Input Parameters

Input Parameters	Units	Level 1	Level 2	Level 3
EL	%	0	50	100
CR	NA	16	17	18
EHN Additive	%	2	4	6

Table 3. Output Parameters - Performance

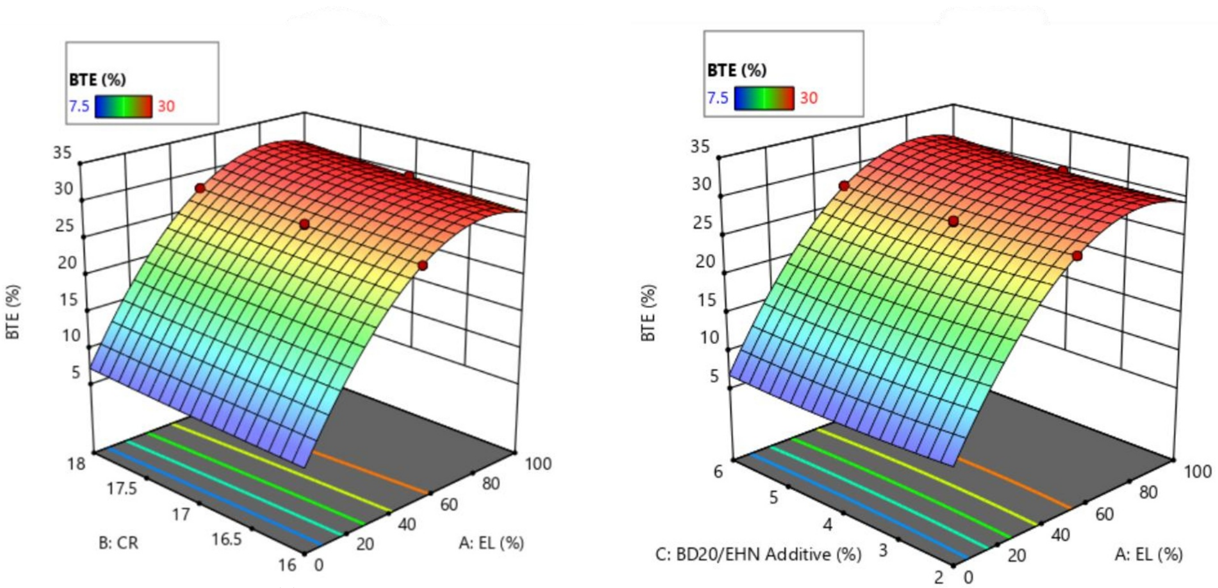
Sl.No	EL (%)	CR	BD20/EHN (%)	BTE (%)	BSFC (kg/kW·h)	EGT (°C)	CO (%)	HC (ppm)	NOx (ppm)	Smoke (%)
1	50	17	4	26.5	0.34	480	0.16	55	620	36
2	100	16	6	29	0.27	690	0.14	50	910	42
3	50	17	4	26.8	0.33	500	0.15	53	640	36
4	100	17	4	29.5	0.26	710	0.13	48	940	43
5	50	17	4	27	0.32	520	0.15	52	660	37
6	50	17	2	27.2	0.31	540	0.14	51	680	37
7	100	18	2	30	0.25	730	0.12	46	980	44
8	50	16	4	26.2	0.35	470	0.17	56	610	35
9	50	17	4	26.9	0.32	510	0.15	54	650	37
10	0	18	6	8	0.55	250	0.21	72	180	18
11	50	17	4	27.1	0.31	530	0.14	53	670	38
12	0	16	2	7.5	0.57	230	0.22	70	160	17
13	50	17	6	27.5	0.3	560	0.13	50	700	39
14	50	18	4	27.8	0.29	580	0.13	49	720	39
15	50	17	4	27	0.31	520	0.14	52	660	37

4 Results and Discussion

4.1 Performance

The experimental results and the 3D surface map show that variations in the Engine Load (EL) and Compression Ratio (CR) shown in figure 3, in addition to the amounts of BD20/EHN additive, have a major effect on the BTE of diesel engines. With optimal efficiency achieved close to 30% at the maximum EL and CR settings, the visualisation confirms that BTE increases steadily as both EL and CR grow. This has been made possible by improved air-fuel mixing and higher in-cylinder pressure at higher load and compression ratios due to the increased combustion and more efficient conversion to energy. This expressive positive correlation is graphically highlighted through the colour gradient of the graph where the blue (low BTE) shift to red (high BTE) indicates regions of the highest efficiency at high load and compression. The findings indicate that engine load and compression strategic tuning as well as accurate additive dosing can significantly improve engine performance and provides useful insights to the optimization of fuel blends and the design of advanced engines.

$$BTE = 26.8833 + 11.4583 * A + 0.8 * B + 0.15 * C + 0.275 * AB + 0.425 * AC + 0.583333 * BC + -8.84167 * A\text{^}2 + 0.116667 * B\text{^}2 + 0.466667 * C\text{^}2 \qquad (4)$$

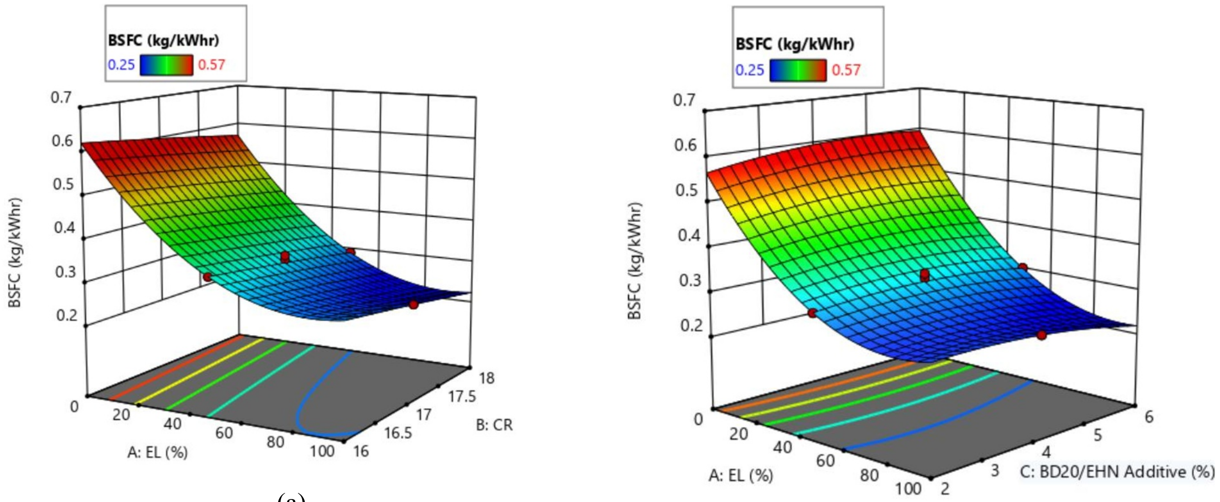


(a) (b)

Fig. 3.(a) BTE – CR vs EL (b) B20/EHN vs EL

The BSFC variation throughout the engine operating conditions depicts the evident trends that are determined by the load, compression rate and BD20/EHN additives level as represented in figure 4. At a higher load (100%), the BSFC values are especially lower with a minimum of 0.25 kg/kW*h and at part-load (50) it is within the range of 0.29-0.35 kg/kW*h and at no-load it reaches a steep above 0.55 kg/kW*h. This decrease under high load is largely because increasing load increases the efficiency of the injected fuel in combining with the fuel being used, in that high load increases efficiency of combustion, and decreases the percentage of fuel used to overcome losses due to friction and pumping. More so, a rise in compression ratio between 16 and 18 decreases BSFC, further increase in compression enhances the thermodynamic efficiency of the cycle, and efficient combustion. This further reduction in BSFC is also achieved by the addition of cetane improver (EHN) in the BD20 blend to reduce ignition delay and ensure faster release of heat to convert more fuel chemical energy to useful work. The results indicate that operating the engine at higher load and compression ratios, combined with suitable additive dosing, meaningfully improves fuel economy by lowering BSFC.

$$BSFC = -0.18 + -0.00513333 * A + 0.0683333 * B + 0.196667 * C + -0.0001 * AB + -0.0002 * AC + -0.00916667 * BC + 4.26667e-05 * A^2 + -0.00166667 * B^2 + -0.00416667 * C^2 \quad (5)$$



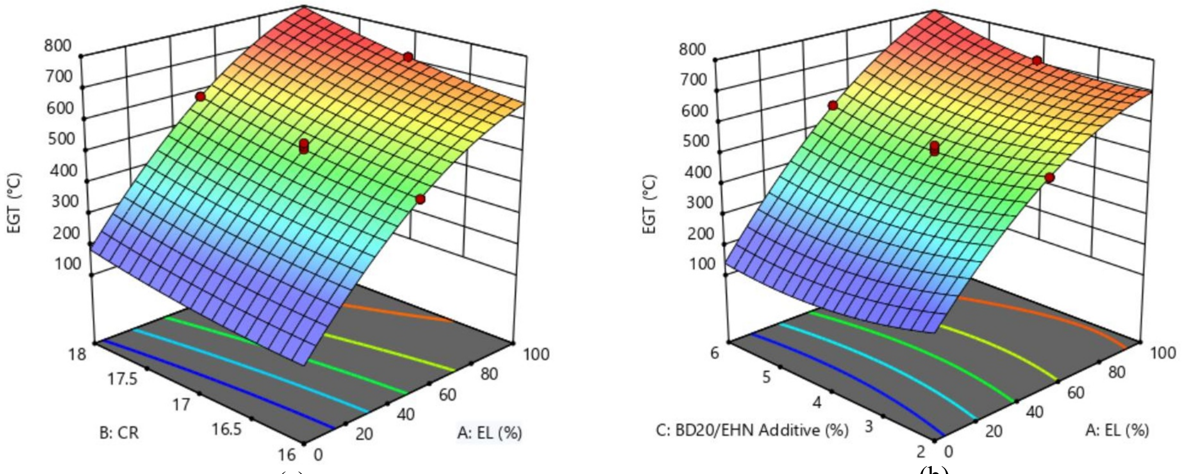
(a) (b)

Fig. 4.(a) BSFC – CR vs EL (b) B20/EHN vs EL

Exhaust gas temperature (EGT) increased steadily with higher engine load and compression ratioshown in figure 5, though a sharp reduction was observed at no-load conditions. At full load, EGT values reached as high as 730 °C due to greater fuel injection, higher in-cylinder pressure and complete combustion releasing more heat energy. At part load, the temperature ranged between 470 °C and 580 °C, as the lower fuel quantity reduced heat release compared to full load.

Under no-load operation, EGT released radically to around 230-250 °C because most of the fuel energy was consumed in overcoming frictional and pumping losses, with limited useful work produced. An increase in compression ratio also elevated EGT, since higher compression raises peak temperature and pressure, increasing combustion. The use of EHN additive in BD20 blends contributed to slightly higher EGT by improving ignition quality, reducing ignition delay and accelerating heat release. These drifts clearly establish that EGT rises with improved combustion and fuel burning at high load and compression, while it decreases under low load conditions due to incomplete fuel utilization.

$$EGT = 510 + 290 * A + 55 * B + 10 * C + 15 * AB + 40 * AC + 55 * BC + -90 * A\hat{}2 + 15 * B\hat{}2 + 40 * C\hat{}2 \quad (6)$$



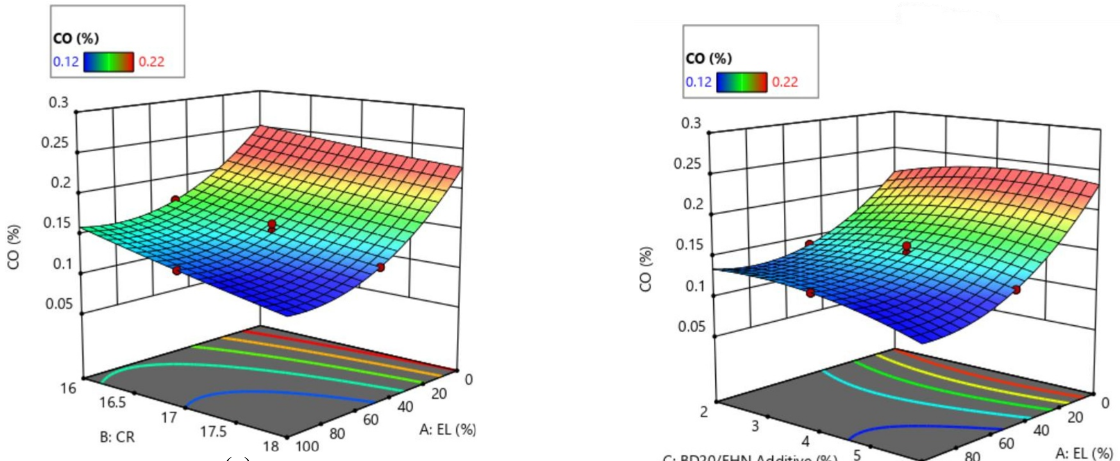
(a) (b)

Fig. 5.(a) EGT – CR vs EL (b) B20/EHN vs EL

4.2 Emission

The emissions of carbon monoxide (CO) were evidently dependent on load, compression ratio and additive level shown in figure 6. The lowest CO values were found at full load (0.12-0.14%), since increased fuel injection and high cylinder pressure allowed more complete combustion and complete oxidation of carbon. During part load the CO levels were still slightly higher (0.14-0.17%), because the temperatures of combustion were lower and there was a lack of effective mixing, which slowed the oxidation process. At no-load, CO rose to hard 0.21- 0.22 due to incomplete combustion subject due to poor fuel usage and an increased share of quenching adjacent to the cylinder walls. Carbon monoxide (CO) emissions decreased with an increase in compression ratio, thereby resulting rise in in-cylinder pressure and temperature gives more complete combustion of the fuel.Introduction of EHN in BD20 blends helped to reduce CO by reducing the ignition delay and allowing faster and promote more homogenous combustion. The findings indicate that the CO emission decreases with an increase in the load and compression because of the increased combustion efficiency and increases with low load where uncomplete combustion occurred.

$$CO = 0.148333 + -0.0541667 * A + -0.02 * B + -0.005 * C + -0.0075 * AB + -0.0125 * AC + -0.0116667 * BC + 0.0358333 * A^2 + 0.00166667 * B^2 + -0.0133333 * C^2 \quad (7)$$

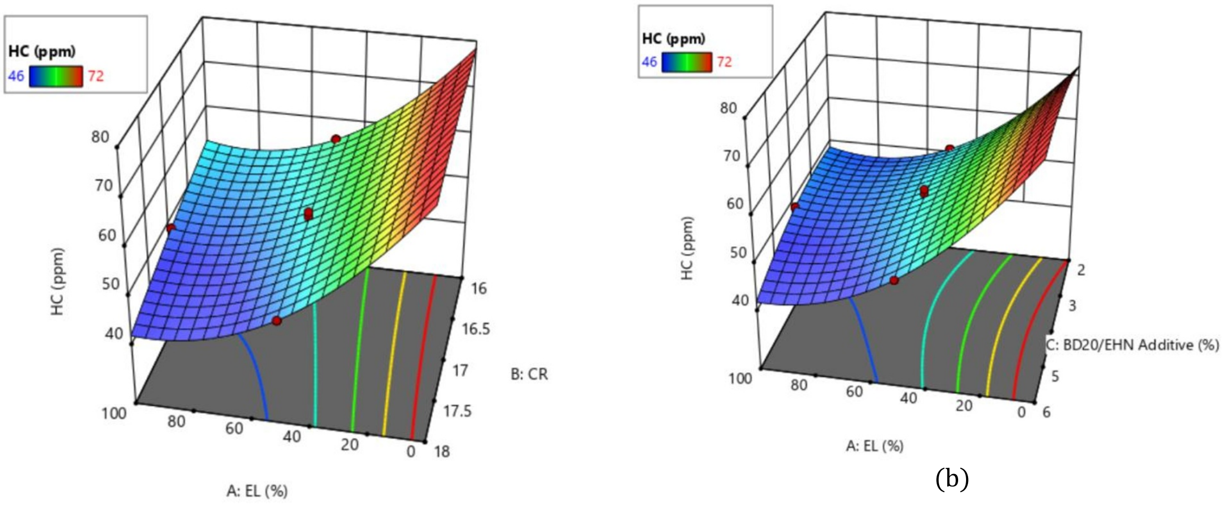


(a) (b)

Fig. 6.(a) CO – CR vs EL (b) B20/EHN vs EL

Unburned hydrocarbon (HC) emissions were also dependent on engine load, compression ratio and proportion of the additive shown in figure 7. The HC values were lowest at full load (46-50 ppm), due to the increased cylinder pressure and temperature which favored full combustion and efficient oxidation of fuel. The HC levels were in the middle range (51-56 ppm) at part load because of relatively lower temperatures of combustion and less turbulence that restricted the oxidation of unburned fuel. The emission of HC increased to 70-72 ppm under no-load conditions, as combustion efficiency was low and the dominance of incomplete combustion occurred as a result of counteracting frictional losses and leaving higher percentage of unburned hydrocarbons. Compression ratio increased slowed HC formation, as with increased pressure and temperature the flame propagation was improved and the oxidation of the fuel-air mixture was made simpler. Further addition of EHN in the BD20 blends assisted in reducing the emission of HC by enhancing the quality of ignition, shortening the ignition delay and providing a greater opportunity to burn all the fuel. These measurements verify that under the influence of high load and compression, HC emissions decline, whereas they are enhanced when the load is low or not at all because of incomplete combustion.

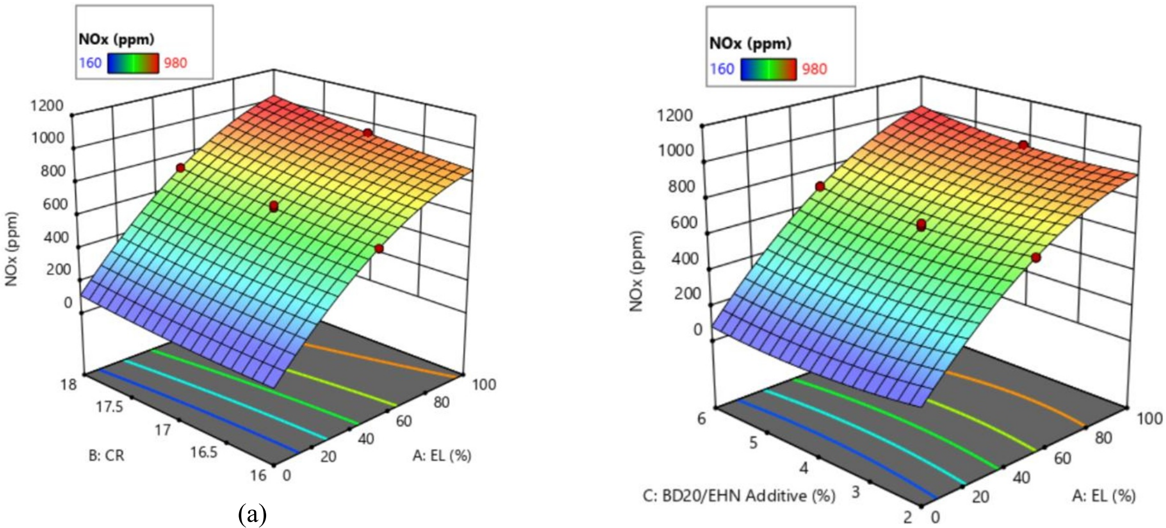
$$HC = 53.1667 + -14.8333 * A + -3.5 * B + -0.5 * C + -2 * AB + -3 * AC + -3.33333 * BC + 9.66667 * A^2 + -0.666667 * B^2 + -2.66667 * C^2 \quad (8)$$



(a)

(b)

Fig. 7.(a) HC – CR vs EL (b) B20/EHN vs EL



(a)

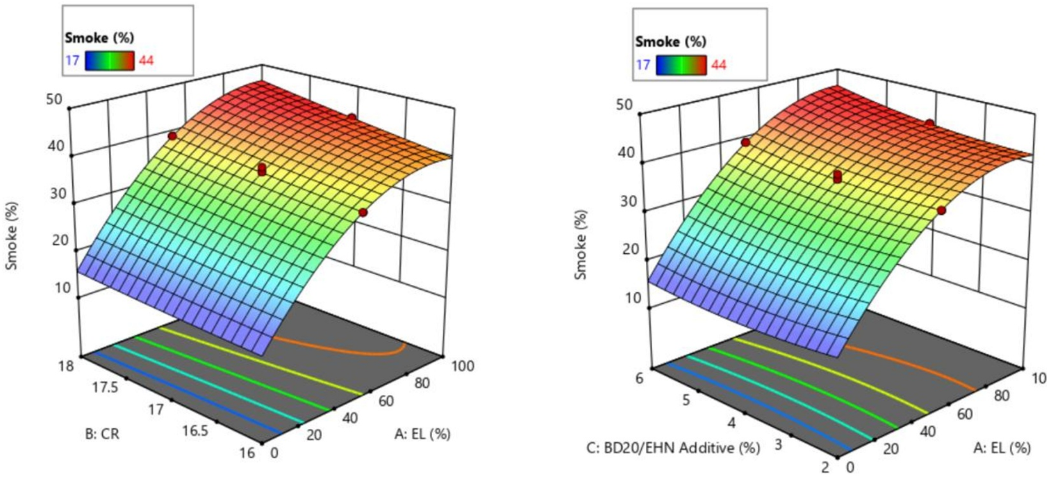
(b)

Fig. 8.(a) NOx – CR vs EL (b) B20/EHN vs EL

Emissions of oxides of nitrogen (NOx) were significantly affected by the engine load, compression ratio and fuel blend conditions shown in figure 8. The highest NOx levels were observed at full load of 910-980 ppm because elevated in-cylinder pressures and temperatures favored the formation of thermal NOx by the Zeldovich reaction.

Emissions at the part load (610-720 ppm) were moderate and Emission of NOx at no-load (160-180 ppm) were minimal because of low combustion temperatures and incomplete oxidation. Compression ratio was also increased to a higher level, which increased NOx emissions as greater compression raised the temperature of the flames and residence time of gases, and also enhanced producers of NOx. The Higher NOx levels were also contributed by the fact that the presence of EHN additive in BD20 blends enhanced ignition quality and combustion phasing which in turn increased the peak temperature. These findings indicate the traditional trade-off between efficiency and NOx emissions where better combustion at higher load and compression results in better performance but formation of NOx.

$$NOx = 650 + 437.5 * A + 55 * B + 10 * C + 22.5 * AB + 32.5 * AC + 50 * BC + -147.5 * A^2 + 15 * B^2 + 40 * C^2 \quad (9)$$



(a) (b)

Fig. 9.(a) Smoke – CR vs EL (b) B20/EHN vs EL

The smoke opacities of the BD20/EHN blends depended on engine load, level of compression ratio and additives, indicating the efficiency of the combustion of the blends shown in figure 9. Smoke values were highest at full load (42-44%), when more injected fuel was present, and rich areas and incomplete oxidation were more likely to occur, resulting in greater particulate formation. During part load, smoke was moderate (35-39%), and during no-load operation the values significantly decreased to 17-18% as the lower fuel supply minimized the number of soot precursors and generally lowered the quantity of particles formed. Compression ratio was slightly increased, with the consequence that smoke emissions were increased at higher loads because the high in-cylinder temperature and pressure were conducive to fuel cracking and localized rich combustion, but this was not as dominant as load. The more EHN added to the quality of combustion and aided in suppressing smoke in some conditions through reducing the ignition delay and encouraging cleaner combustion, but at very high load the higher fuel density in the chamber counterbalanced this advantage. In general, the load-affection of smoke emission was caused by the unfinished oxidation in richer mixtures whereas low load and additive effects favored the reduced formation of particulate.

$$Smoke = 36.8333 + 14.0833 * A + 2 * B + 1 * C + 1.25 * AB + 1.25 * AC + 1.33333 * BC + -7.91667 * A^2 + 0.166667 * B^2 + 1.16667 * C^2 \quad (10)$$

Table 4. Performance Statistical analysis of B20 + EHN Additive

Parameters	BTE (%)	BSFC (kg/kW·h)	EGT (°C)
P – Value	< 0.0001	< 0.0001	< 0.0001
R2	0.9997	0.9945	0.9942
Adjusted R2	0.9991	0.9846	0.9838
Std.dev	0.2137	0.0117	17.89
Mean	24.93	0.3387	521.33
C.V. %	0.8571	3.45	3.43

The statistical analysis of the performance parameters of the B20 blend with EHN additive reveals that the model is very reliable and significant. The p-values (0.0001) of (BTE), (BSFC) and (EGT) are very low, and they indicate that the differences are found to be statistically significant. The coefficient of determination (R2) is found greater than 0.99, and adjusted R2 values greater than 0.98 reveal that experimental data is well-fitted by the model trends and makes it robust. The fact that the standard deviations are low indicates the consistency of the results, the values of the coefficient of variation (C.V.%) are less than 5%, indicating good precision and reproducibility of the experimental results. The average values of BTE (24.93%), BSFC (0.3387 kg/kW*h) and EGT (521.33 degC) are well connected with the predicted tendencies of biodiesel diesel blends, which proves the efficiency of EHN as a performance enhancer. The findings validate that the implementation of EHN has a positive known effect on fuel use and combustion efficiency without losing statistical reliability when it comes to the performance assessment shown in table 4

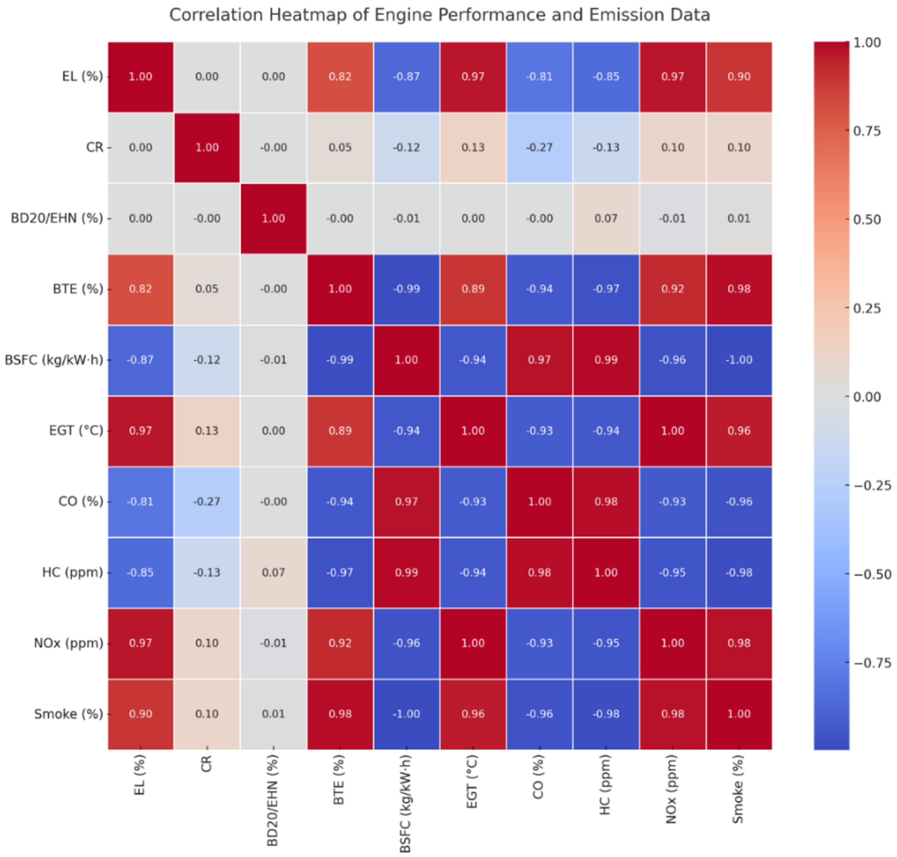
Table 5. Emission Statistical analysis of B20 + EHN Additive

Parameters	**CO (%)**	**HC (ppm)**	**NOx (ppm)**	**Smoke (%)**
P – Value	< 0.0017	< 0.0001	< 0.0001	< 0.0001
R2	0.9752	0.991	0.9978	0.9967
Adjusted R2	0.9307	0.9749	0.9939	0.9908
Std.dev	0.0075	1.17	17.89	0.7528
Mean	0.152	54.07	652	35.67
C.V. %	4.95	2.16	2.74	2.11

The statistical analysis of the parameters of the B20 blend with the EHN additive on the emission shows that reliability is high and model accuracy is great. The p-value of CO, HC, NOx and smoke are less than 0.05, indicates that variations experienced by experiential are statistically important. The good R2 values (0.9752-0.9978) and the adjusted R2 values greater than 0.93 show that there is great agreement between the experimental and the predicted values. The standard deviations and coefficients of variation (less than 5) of the experimental measurements are low and reveal the accuracy and repeatability of the experiment. The CO (0.152 percent) and HC (54.07 ppm) and NOx (652 ppm) and smoke (35.67 percent) mean values are within the range of expected values of CO, HC, and NOx in biodiesel-diesel mixtures with EHN leading to lower values of CO, HC and smoke at the cost of slightly higher NOx concentration, due to increased burning temperatures. The resultsshows the validity of the experimental data and indicate that the statistical model can be used to obtain a valid estimate of emission characteristics shown in table 5.

Comparison of the experimental and simulated results of the B20 + EHN blend indicates that the results are excellent with all the parameters displaying very small error margins. The deviation in BTE was just 0.37 percentage, and BSFC variance was 0.65 percentage, which proves that the predictive model is reliable to capture the trends of fuel economy. The emission parameters as well attended to hydrocarbon (HC) and carbon monoxide (CO) with less than 1.5% error NOx and smoke with a marginally higher but still minor error of 1.82% and 1.62 respectively. These minute variations show that the simulation technique is useful in replicating actual engine behavior, which is a fact that one can trust to use it to predict performance and emission of biodiesel diesel blends with additives. The experimental results are justified by the close and the strength of the model in engines performance analysis.

Correlation analysis between engine performance and emission parameters indicates the different interrelations between the measured variables shown in figure 10. BTE was strongly negatively correlated with BSFC, which confirms the fact that the higher the efficiency is the better the fuel is used. The positive relationship between BTE and EGT enhanced the combustion at higher thermal loads, helped in raising the NOx emissions as a result of raising the in-cylinder temperatures. There was a positive correlation of CO, HC and smoke opacity with fuel consumption, The incomplete combustion at an increased level of BSFC resulted in increased formation of HC, CO and particulates. The compression ratio demonstrates a positive correlation with efficiency as well as encouraged NOx proves the typical trade-off between performance and emissions. The effect of cetane improver (EHN) introduction in BD20 blends resulted in reduced CO, HC and smoke emissions, along with a slight increase in NOx emissions, shorter ignition delay and faster combustion rates. The correlation table confirmed the anticipated interactions of the combustion emissions and the role of additives in optimization of biodiesel diesel blends towards enhanced performance with regulated emission effect.



	EL (%)	CR	BD20/EHN (%)	BTE (%)	BSFC (kg/kW·h)	EGT (°C)	CO (%)	HC (ppm)	NOx (ppm)	Smoke (%)
EL (%)	1.00	0.00	0.00	0.82	-0.87	0.97	-0.81	-0.85	0.97	0.90
CR	0.00	1.00	-0.00	0.05	-0.12	0.13	-0.27	-0.13	0.10	0.10
BD20/EHN (%)	0.00	-0.00	1.00	-0.00	-0.01	0.00	-0.00	0.07	-0.01	0.01
BTE (%)	0.82	0.05	-0.00	1.00	-0.99	0.89	-0.94	-0.97	0.92	0.98
BSFC (kg/kW·h)	-0.87	-0.12	-0.01	-0.99	1.00	-0.94	0.97	0.99	-0.96	-1.00
EGT (°C)	0.97	0.13	0.00	0.89	-0.94	1.00	-0.93	-0.94	1.00	0.96
CO (%)	-0.81	-0.27	-0.00	-0.94	0.97	-0.93	1.00	0.98	-0.93	-0.96
HC (ppm)	-0.85	-0.13	0.07	-0.97	0.99	-0.94	0.98	1.00	-0.95	-0.98
NOx (ppm)	0.97	0.10	-0.01	0.92	-0.96	1.00	-0.93	-0.95	1.00	0.98
Smoke (%)	0.90	0.10	0.01	0.98	-1.00	0.96	-0.96	-0.98	0.98	1.00

Fig. 10. Corelation Heat map

5 Conclusion

The experimental investigation shows the combined influence of engine load, compression ratio and cetane improver (EHN) on diesel engine performance and emission characteristics. The analysis of results is:

- The maximum brake thermal efficiency of 30% was obtained at 100% EL, CR = 18 and 2% EHN additive, compared with the baseline value of 7.5% under diesel mode (CR = 16, 0% EL, 2% EHN), mainly due to higher oxygen content improving combustion efficiency.
- Brake specific fuel consumption decreased from 0.57 kg/kWh at CR = 16 with diesel to a minimum of 0.25 kg/kWh at CR = 18 and 100% EL, which can be attributed to improved atomization and improved ignition quality with EHN addition.
- Exhaust gas temperature rose from 230 °C at baseline conditions to 730 °C at 100% EL and CR = 18, confirming more complete combustion and higher heat release under oxygenated blends and higher compression ratios.
- Carbon monoxide emissions reduced from 0.22% to 0.12% with EL and EHN addition, owing to improved oxidation of CO facilitated by the oxygen-enriched fuels.
- Hydrocarbon emissions decreased from 70 ppm at diesel baseline to 46 ppm at 100% EL and CR = 18 with 2% EHN, mainly due to improved combustion efficiency and reduced quenching effect.
- Nitrogen oxides increased from 160 ppm under diesel mode to a peak of 980 ppm at higher CR and EL levels, as a result of higher in-cylinder temperatures and longer residence time of combustion gases.
- Smoke levels were reduced at medium load from 42% to 35% with EL and EHN addition, but increased again to 44% under high CR and EL conditions due to rich combustion zones

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