

Article

Optimization of CI Engine Performance and Emissions Using Alcohol–Biodiesel Blends: A Regression Analysis Approach

Suman Dey ¹, Akhilendra Pratap Singh ¹, Sameer Sheshrao Gajghate ², Sagnik Pal ³, Bidyut Baran Saha ^{4,5,*}, Madhujit Deb ³ and Pankaj Kumar Das ³

¹ Department of Mechanical Engineering, Indian Institute of Technology (BHU), Varanasi 221005, Uttar Pradesh, India; suman2013mech@gmail.com (S.D.); akhilendra.mec@iitbhu.ac.in (A.P.S.)

² Department of Mechanical Engineering, G H Raisoni College of Engineering and Management, Pune 412207, Maharashtra, India; sameer.gajghate@raisoni.net

³ Department of Mechanical Engineering, National Institute of Technology, Agartala 799046, Tripura, India; sagnikpal1987@gmail.com (S.P.); madhujitme79@gmail.com (M.D.); pankaj_642004@yahoo.co.in (P.K.D.)

⁴ International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, Fukuoka 819-0385, Japan

⁵ Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0385, Japan

* Correspondence: saha.baran.bidyut.213@m.kyushu-u.ac.jp

Abstract: This research paper investigates the optimum engine operating parameters, namely engine load, palm biodiesel, and ethanol percentage, by using a regression analysis approach. The study was conducted on a single-cylinder, four-stroke diesel engine at varying engine loads and constant speed. A general full factorial design was established using Minitab software (Version 17) for three different input factors with their varying levels. The test results based on the regression model are used to optimize the engine load and percentages of palm biodiesel and ethanol in diesel–biodiesel–ethanol ternary blends. The analysis of variance (ANOVA) revealed a significant effect on performance and emission parameters for all three factors at a 95% confidence level. From the regression study, optimum brake thermal efficiency (BTE), nitrogen oxide (NO_x), carbon monoxide (CO), and unburnt hydrocarbon (UHC) emissions were found to be 12.57%, 436.2 ppm, 0.03 vol.%, and 79.2 ppm, respectively, at 43.43% engine load, 11.06% palm biodiesel, and 5% ethanol share. The findings of this study can be used to optimize engine performance and emission characteristics. The regression analysis approach presented in this study can be used as a tool for future research on optimizing engine performance and emission parameters.

Keywords: optimization; CI engine; performance; emissions; alcohol–biodiesel blends; regression analysis; analysis of variance (ANOVA)



Citation: Dey, S.; Singh, A.P.; Gajghate, S.S.; Pal, S.; Saha, B.B.; Deb, M.; Das, P.K. Optimization of CI Engine Performance and Emissions Using Alcohol–Biodiesel Blends: A Regression Analysis Approach. *Sustainability* **2023**, *15*, 14667. <https://doi.org/10.3390/su152014667>

Academic Editors: Huaqiang Chu and Dongdong Wang

Received: 4 September 2023

Revised: 25 September 2023

Accepted: 7 October 2023

Published: 10 October 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The rapid decline in fossil fuel stocks, hikes in crude oil import bills, and strict policies on emission regulations are the major cruces that have threatened the future development of the modern world. Transportation and power generation are the two major areas where the application of diesel engines is predominant. Diesel engines are widely used worldwide for many transport applications like buses, trucks, diesel locomotives, marine engines, etc., which make global transportation much easier and more convenient. The diesel engine is supreme, and it provides high fuel economy but at the cost of very high NO_x and particulate matter (PM) emissions [1]. In recent years, automotive industries have been facing a twin crisis of fossil fuel depletion and engine emissions, which threatened engine manufacturers to a great extent. Hence, renewable fuels' importance is growing as a promising sustainable energy resource [2]. Global warming and other carbon footprint issues due to diesel combustion have encouraged the use of bio-based alternative fuels

in diesel engines without any engine modification. Based on the high turnover per year, rapeseed [3], soybean [4,5], palm [6], jatropha [7] oil, etc. have become some of the major biodiesel feedstocks. However, higher kinematic viscosity, density, pour, and flashpoint of biodiesel deteriorate the engine combustion. To overcome these difficulties, many researchers have introduced methanol, ethanol, octanol, pentanol, and diethyl ether (DEE) as an additive [8–10]. Yasin et al. [11] experimentally investigated the performance of a palm biodiesel blend in a diesel engine and observed a 4.7% increase in NO_x and a 3.5% decrease in CO emissions compared to diesel. However, they also mentioned that the use of exhaust gas recirculation (EGR) can reduce NO_x emission by 22% during engine operation with a palm biodiesel blend. Appavu et al. [12] observed better engine performance and lower engine emissions while operating palm biodiesel (PB100) in an unmodified direct-injection diesel engine. They found 23, 24, 39, and 5% lower CO, HC, smoke, and NO_x emissions, respectively, compared to diesel but at the cost of higher fuel consumption. Ma et al. [13] performed a study where they experimentally compared diesel and biodiesel operations with ethanol and pentanol blended ternary fuels at varying engine speeds. They observed higher indicated thermal efficiency for diesel–biodiesel–ethanol ternary blends compared to baseline diesel and biodiesel operation, irrespective of engine speed. Using non-edible biodiesel and ethanol, Sathish et al. [14] experimentally found that biodiesel–ethanol, diesel–ethanol, and diesel–biodiesel–ethanol blends resulted in higher BTE and lower engine emissions compared to diesel. Devarajan et al. [15] experimentally investigated the combustion performance of octanol, palm biodiesel, and diesel ternary blends and observed earlier and smooth combustion compared to palm biodiesel blend operation. They observed higher BTE and low fuel consumption during operation with ternary blends. The better performance could be accounted for by the reduction in viscosity due to octanol addition, which helps in better atomization of fuel that leads to faster combustion. Alcohol, like n-butanol, is effective in increasing the BTE and can decrease NO_x emissions by 20–60% when used in a ternary blend [16]. Uslu and Aydin [17] investigated DEE addition in palm biodiesel–diesel blends and observed that lower DEE and palm biodiesel fractions help in improving BTE and fuel economy. They also reported that engine input variables like advance injection, engine load, and DEE percentage in the blends need to be optimized to obtain better performance and emissions.

Conventional methods of engine experiments are considered cost-ineffective and take much time. These drawbacks can be overcome by using new computational techniques by optimizing the working parameters. To obtain a trade-off between engine performance and emission characteristics, optimization of engine parameters is one of the prime choices [18]. In addition to conventional engine experiments, the prediction and optimization of experimental design by using soft computational tools may encourage the making of optimal decisions on engine operating parameters. Many techniques, like response surface methodology (RSM) [19,20], artificial neural network (ANN) [21], genetic algorithm [22], etc., are used for the prediction of input variables like load, injection pressure, start of injection, biodiesel proportion, etc. From the viewpoint of multi-objective problems [23], engine manufacturers are concerned about predicting responses that are required for selecting the optimum design parameters. RSM results in a better combination in terms of improving performance and reducing emissions with the lowest prediction errors. Using the RSM technique, Singh et al. [24] optimized BTE, UHC, and NO_x emissions with error values of 2.4, 4.95, and 0.93%, respectively.

From the above studies, it was noted that compared to biodiesel blends, better engine performance and emissions have been observed using ternary blends. In the previous literature, studies on the trade-off between engine performance and emission parameters in the optimal engine operating range using optimization techniques are rare. None of the studies mentioned in the literature refer to the application of the regression approach on palm biodiesel. Also, no previous study has investigated the optimization using the regression technique for diesel–palm biodiesel–ethanol ternary blends. This motivates us to explore a general full-factorial-design-based regression model to quantify the optimum

engine input parameters for a better performance–emission balance. This present work aims to optimize engine operating parameters for optimum performance and emission characteristics using a regression model. For this, three factors, namely engine load, palm biodiesel, and ethanol percentage at different levels, are considered as the input factors for the investigation. A non-linear regression model was developed for BTE, NO_x , CO, and UHC emissions. Significant effects of linear, square, and interaction terms of all three factors are investigated by ANOVA analysis. Finally, using a regression model, the optimization of performance–emission characteristics was evaluated.

2. Materials and Methods

2.1. Engine Setup

The engine that was used in the experimental investigation is a single-cylinder, four-stroke, water-cooled, DI (direct injection) computerized diesel engine. The schematic diagram and full specifications of the engine are shown in Figure 1 and Table 1. An eddy current dynamometer at a constant speed of 1500 rpm connected to a speed sensor was coupled to the engine crankshaft to measure the outputs from the engine. The engine speed for every 1° crank angle was measured using a crank angle sensor (make: Kubler) fixed with the crankshaft. The engine was connected to a data acquisition (DAQ) system comprising a computer with a crank angle encoder and graphical user interface (GUI)-based Engine Soft post-processing software (Version 9.0) [25]. The DAQ system that was installed was designed to measure cylinder pressure and temperature at every 1° crank angle interval. A piezoelectric transducer was installed at the top of the engine cylinder head to measure in-cylinder gas pressure. All the measurements of exhaust gas temperature (EGT), cooling water outlet and inlet temperature, and performance data are reported over a period of time. The whole computerized system was then connected with the engine setup using the NI lab view centralized data acquisition system (NI USB-6210 Bus Powered M Series) interfaced with “Engine soft” software. Exhaust gases were measured using a 5-gas analyzer (Make: AVL India; model: 444) fitted with a Digas sampler to measure the NO_x , UHC, CO, CO_2 , and O_2 .

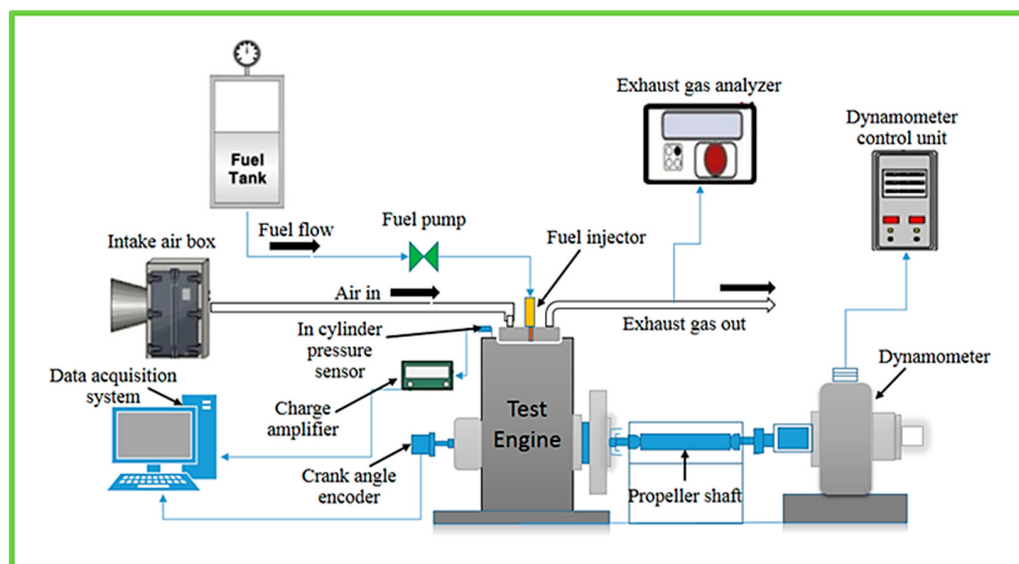


Figure 1. Schematic diagram of the experimental engine setup.

Table 1. Engine specifications.

Parameters	Specifications
Engine	1-C, 4-S, VCR (variable compression ratio) diesel engine
Product code	234
Dynamometer	Eddy-current-type
Cooling type	Water-cooled
Data acquisition system	NI USB-6210, 16-bit, 250 kS/s
Crank angle sensor	1° resolution, speed 5500 rpm with TDC pulse
Temperature sensor	RTD, PT100, and K-type thermocouple
Load sensor	Strain-gauge-type (range 0–50 Kg)
Rotameter	Engine cooling (40–400 LPH); calorimeter (25–250 LPH)
Stroke	110 mm
Bore	87.5 mm
Displacement	661 cc
Compression Ratio	17.5:1
Output power	3.5 kW
Speed	constant 1500 rpm
Fuel Injection pressure	220 bar

2.2. Experimental Methodology and Fuel Preparation

The present experimental investigation was performed at varying engine loads from 20 to 100%. For the present study, diesel and ethanol were purchased from a local vendor, while palm biodiesel was prepared in the lab, as shown in Figure 2. Different proportions of diesel, palm biodiesel, and ethanol were mixed for the preparation of ternary blends. For the preparation of different ternary blends, the mix proportions of diesel, palm biodiesel, and ethanol were varied between 70 and 90%, 5 and 20%, and 5 and 10%, respectively. For the total volume of 100%, the proportions of diesel, palm biodiesel, and ethanol were accurately measured using a measuring cylinder. Finally, the entire mixture was stirred to make a homogeneous mix of the blends before running the engine. The blends are denoted by D90B5E5 where D, B, and E stand for diesel, palm biodiesel, and ethanol, respectively, and the subsequent number shows their respective volumes in percentages. The physicochemical properties of different blends are listed in Table 2. The fuel consumption was measured using a fuel burette (12.4 mm diameter) for an interval of 60 s. Ambient temperature and relative humidity during the tests were recorded as 27 °C and 60%, respectively. Before taking the reading, the engine was allowed to run for 10–15 min to come to a steady condition. For each ternary blend, engine operation was performed at 20, 40, 60, 80, and 100% load. For each individual blend, the load was varied from 20 to 100% using the engine control panel. After being set to a particular load, the engine was allowed to run a minimum of five minutes to take the reading of engine performance for 60 s of fuel consumption, and the same procedure was repeated for the other blends. For each blend at different load conditions, NO_x, CO, and HC emissions were recorded five times and their average was taken.

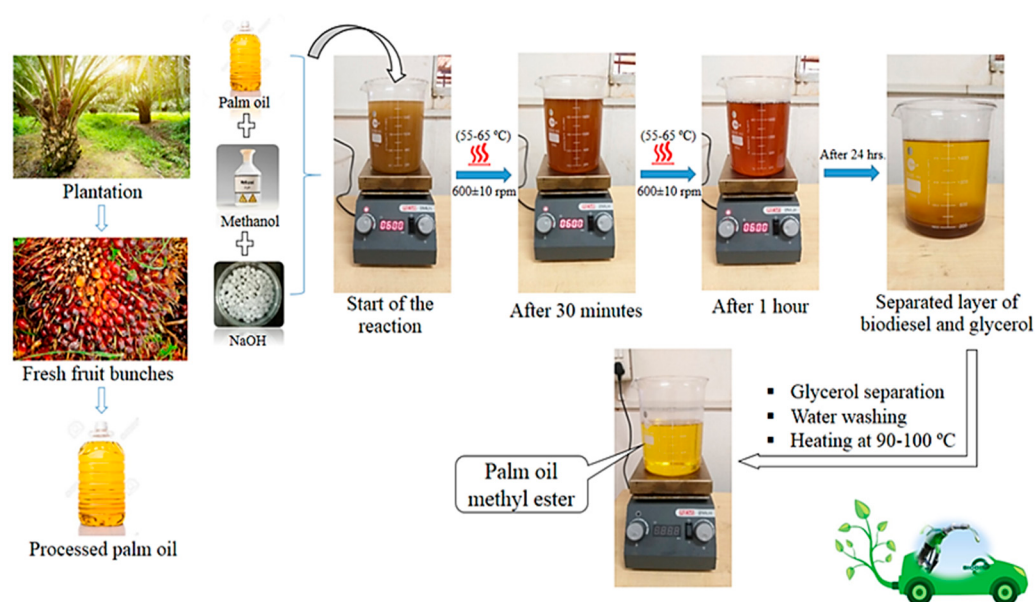


Figure 2. Trans-esterification process of palm biodiesel preparation.

Table 2. Properties of the different diesel, palm biodiesel, and ethanol blends.

Samples	Density at 20 °C (kg/m ³)	Cetane Number	Kinematic Viscosity at 40 °C (cSt)	Calorific Value (kJ/kg)	Flashpoint (°C)
	ASTM D-1298	ASTM D-613	ASTM D-445	ASTM D-240	ASTM D-93
Diesel	836	49	2.45	42,800	100
Palm Biodiesel	925	62	4.56	39,849	167
Ethanol	789	8	1.09	29,700	16.60
D90B5E5	838.1	47.6	2.49	41,998	99.2
D85B10E5	842.6	48.3	2.59	41,850	102.8
D80B15E5	847	48.9	2.7	41,702	105.9
D75B20E5	851.5	49.6	2.8	41,555	109.2
D85B5E10	835.8	45.6	2.42	41,343	95
D80B10E10	840.2	46.2	2.53	41,195	98.4
D75B15E10	844.7	46.9	2.63	41,047	101.7
D70B20E10	849.1	47.5	2.7	40,900	105.1
% measurement uncertainty	±0.3	±0.15	±0.22	±0.75	±0.2

2.3. Uncertainty of Measurement

The purpose of the uncertainty measurement is to evaluate the quality of the experimental readings obtained from any measurements. Providing an exact count of the errors in the measurements, uncertainty analysis is very important in meeting the standard quality of explanation. Uncertainty analysis gives a proper explanation of the repeatability of the investigations. By using the root mean square (RMS) method, the total uncertainty of the engine performance parameters is calculated. The total percentage uncertainty of the computed performance parameters is listed in Table 3. Total percentage uncertainty was calculated using Equation (1), where ΔU is total uncertainty, and $\Delta x_1, \Delta x_2, \Delta x_3, \dots, \Delta x_n$ are the errors of $x_1, x_2, x_3, \dots, x_n$. The accuracy of the emission measuring instrument is shown in Table 4.

$$\Delta U = \sqrt{\left(\frac{\partial U}{\partial x_1} \Delta x_1\right)^2 + \left(\frac{\partial U}{\partial x_2} \Delta x_2\right)^2 + \left(\frac{\partial U}{\partial x_3} \Delta x_3\right)^2 + \dots + \left(\frac{\partial U}{\partial x_n} \Delta x_n\right)^2} \quad (1)$$

Table 3. Total uncertainty analysis of performance parameters [21].

Performance Parameter	Measured Variables	Instrument Involved in the Measurement	% Uncertainty of the Instrument	Calculation	Total % Uncertainty of Parameters
BP	Load, RPM	Load sensor, load indicator, speed measuring unit	0.2, 0.1, 0.9	$\sqrt{0.2^2 + 0.1^2 + 0.9^2}$	0.9
BSFC	SFC (Liquid Fuel), BP	Fuel measuring unit, fuel flow transmitter, as For BP measurement	0.05, 1.5, 0.92	$\sqrt{0.05^2 + 1.5^2 + 0.92^2}$	1.8
BSEC	SFC (Liquid Fuel), BP	As for SFC measurement, as for BP measurement	1.84, 0.92	$\sqrt{1.84^2 + 0.92^2}$	2

Table 4. Accuracy of the emission measuring instrument (AVL DIGAS 444-5 gas analyzer) [26].

Measured Parameter	Measurement Principle	Measuring Range	Resolution	Accuracy	% Uncertainty in Sampling
CO	NDIR	0–10% vol.	0.01% vol.	<0.6% vol.: $\pm 0.03\%$ vol.; $\geq 0.6\%$ vol.: $\pm 5\%$ of value	± 0.2 ± 0.3
CO ₂	NDIR	0–20% vol.	0.1% vol.	<10% vol.: $\pm 0.5\%$ vol.; $\geq 10\%$ vol.: $\pm 5\%$ of value	± 0.15 ± 0.2
HC	NDIR	0–20,000 ppm vol. (n-hexane equivalent)	≤ 2000 : 1 ppm vol. > 2000 : 10 ppm vol.	<200 ppm vol.: ± 10 ppm; ≥ 200 ppm vol.: $\pm 5\%$ of value	± 0.1 ± 0.2
O ₂	Electro chemical sensor	0–22% vol.	0.01% vol.	<2% vol.: $\pm 0.1\%$ vol.; $\geq 2\%$ vol.: $\pm 5\%$ of value.	± 0.2 ± 0.3
NO	Electro chemical sensor	0–5000 ppm vol.	1 ppm vol.	<500 ppm vol.: ± 50 ppm vol ≥ 500 ppm vol.: $\pm 10\%$ of value	± 0.2 ± 0.9

3. Results and Discussion

3.1. Effect of Control Factors on Performance and Emission Characteristics

BTE is the measure of the conversion of heat energy by an engine from fuel to mechanical power. The variations in BTE with load, biodiesel percentage, and load ethanol percentage are shown in Figure 3a,b. The contour plots in Figure 3a,b express the effect of individual variations in palm biodiesel and ethanol on BTE. It was observed that BTE increases with an increase in load and is found to be highest at 100% load. A BTE maximum of 18.96% was found for 5% biodiesel and 5% ethanol addition at 100% load. It was observed that a minimal substitution of biodiesel and ethanol results in higher BTE. The addition of more ethanol, from 5 to 10%, leads to a decrease in the overall calorific value of the diesel–biodiesel–ethanol blend that retards the combustion performance of the engine. Engine emissions like NO_x, CO, and UHC are shown in Figures 4–6. NO_x and UHC emissions were found to have an increasing trend with load because of biodiesel and ethanol in the ternary blend. The rapid rise in temperature generation during combustion at full load is the main reason for high NO_x emission. Similar trends were reported by Sathish et al. [14], who observed 4.4 to 6.3% higher NO_x emissions from different ternary blends compared to baseline diesel. Most of the CO emissions were found in the range from 0.038 to 0.054 vol.%. A high amount of oxygen content in both biodiesel and ethanol accelerates the combustion, which results in lower CO emissions. The more complete combustion can indicate a drop in CO emission due to the ethanol addition. The oxygenated property of

ethanol and palm biodiesel enhances the rate of combustion and the blend burns faster, which leads to low CO emissions [27,28].

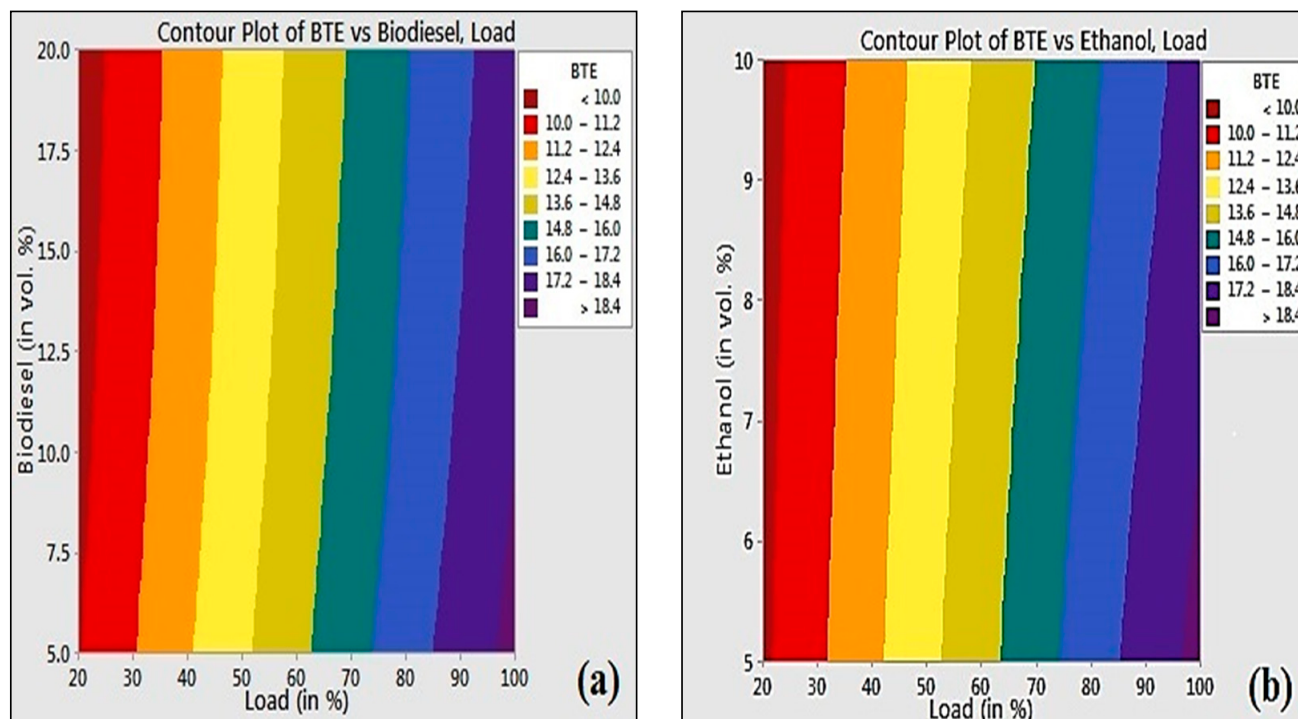


Figure 3. (a) Contour plot of BTE vs. biodiesel, load; (b) Contour plot of BTE vs. ethanol, load.

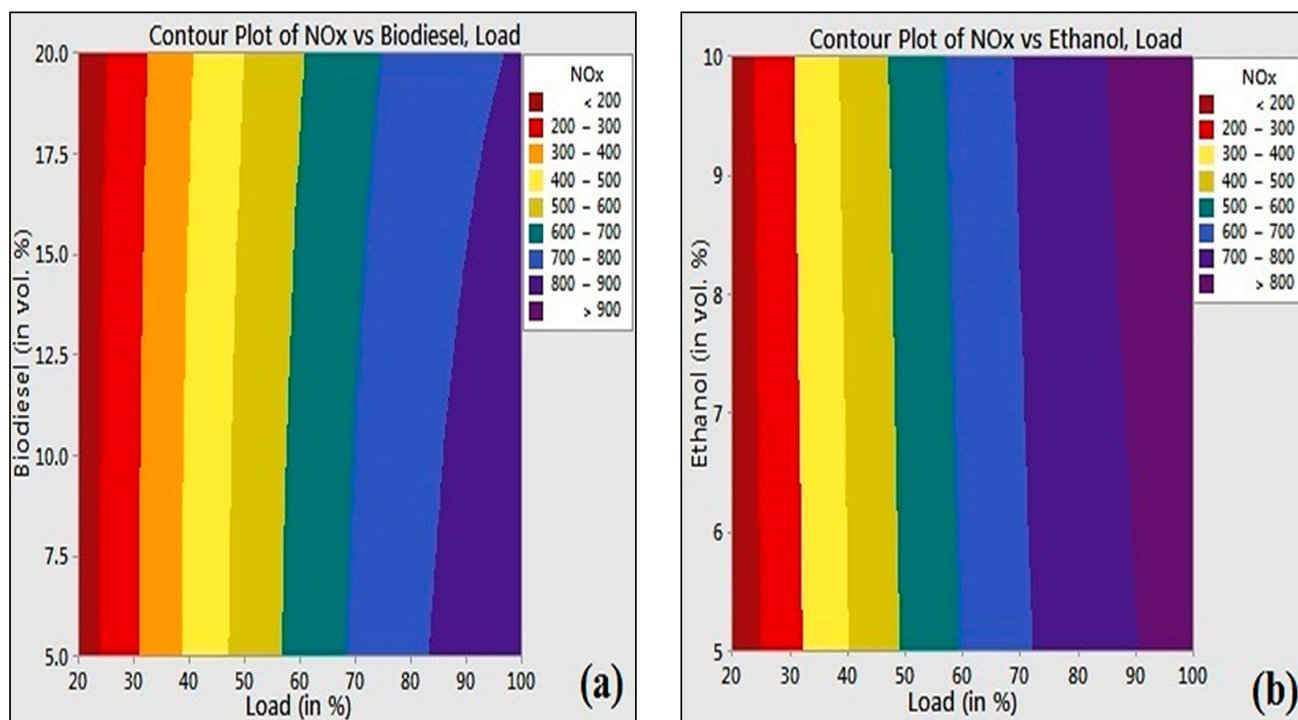


Figure 4. (a) Contour plot of NO_x vs. biodiesel, load; (b) contour plot of NO_x vs. ethanol, load.

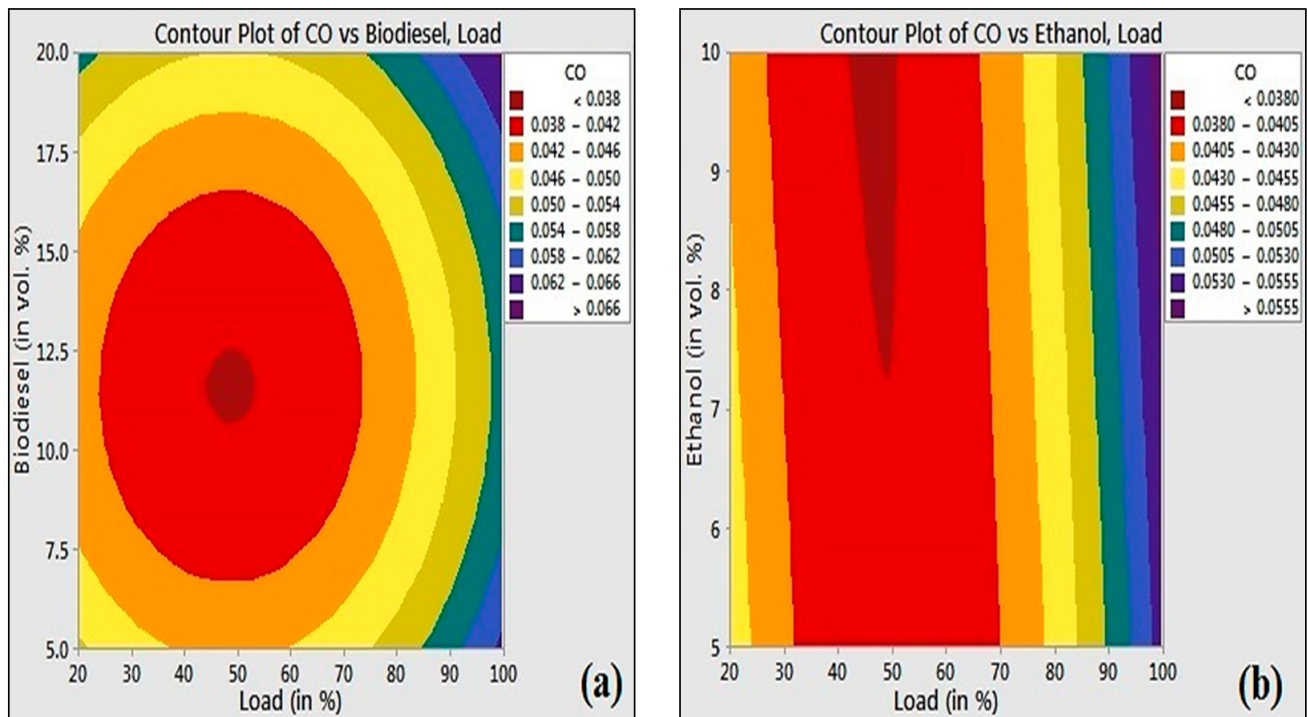


Figure 5. (a) Contour plot of CO vs. biodiesel, load; (b) contour plot of CO vs. ethanol, load.

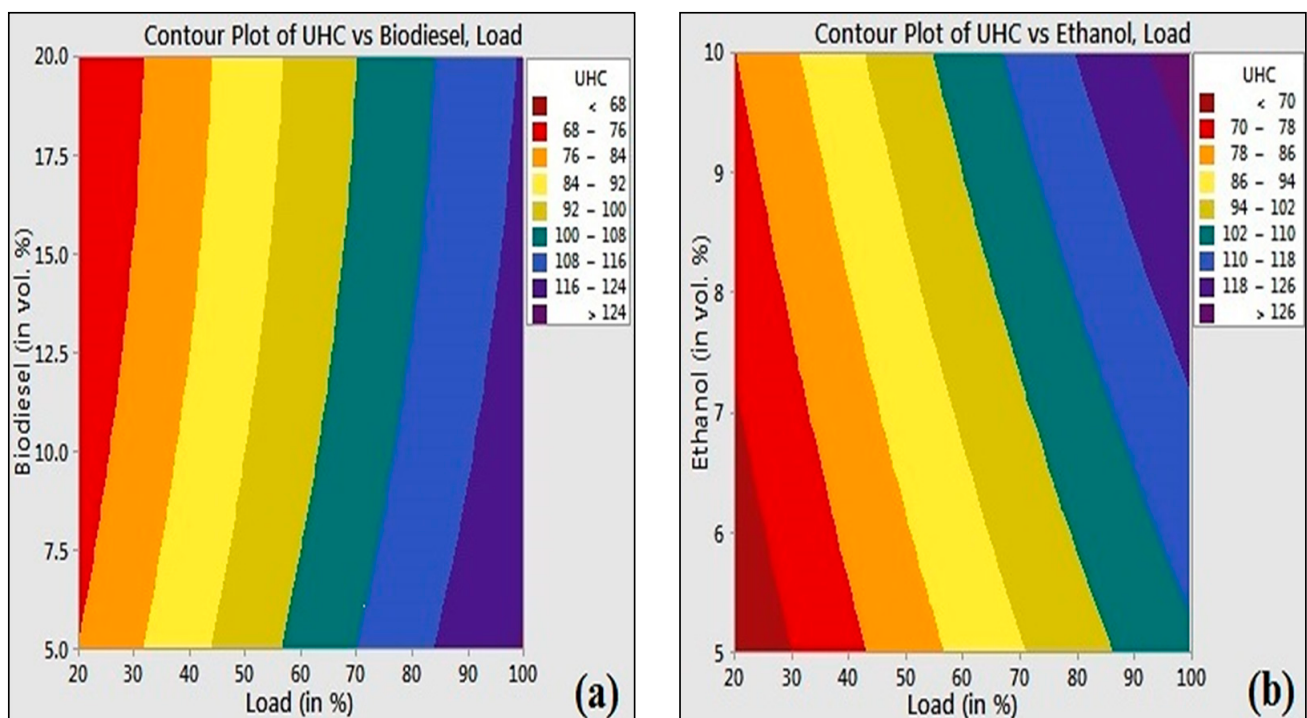


Figure 6. (a) Contour plot of UHC vs. biodiesel, load; (b) contour plot of UHC vs. ethanol, load.

3.2. Non-Linear Regression Analysis

Due to the different complexities and difficulties of running experiments in a conventional way, the design of experiments (DOE) is one efficient statistical technique to reduce the number of experiments [29]. The developed regression model is a tool for the prediction of engine performance–emission characteristics for the optimization of multivariable problems. The BTE is the main performance index, whereas NO_x ,

CO, and UHC are the important pollutants that are used for model optimization. In this paper, before performing the regression analysis, a general full factorial design matrix was developed for conducting the experiments. In this design, three factors were selected, namely load, biodiesel, and ethanol percentage at five, four, and two levels each, respectively (in Table 5). An ordinary second-order non-linear regression model [30] was developed for the prediction of performance emissions of the diesel engine. The experiments were carried out at different loads (20, 40, 60, 80, and 100%), and varying palm biodiesel (5, 10, 15, and 20% by vol.) and ethanol (5 and 10% by vol.) fractions. The model was analyzed after generating a full factorial design of the experiment among three design variables for 20 different experimental runs. A relationship was developed between the outputs and the input design variables to evaluate statistical terms like F-value, *p*-value, and R^2 values [31]. The regression equations for BTE, NO_x , CO, and UHC were calculated by using load (A), palm biodiesel (B), and ethanol (C), as shown below.

$$\text{BTE} = 7.065 + 0.13600 A + 0.0114 B + 0.1142 C - 0.000096 A \times A + 0.00152 B \times B - 0.000253 A \times B - 0.001841 A \times C - 0.01048 B \times C \quad (2)$$

$$\text{CO} = 0.0678 - 0.000741 A - 0.00284 B + 0.00115 C + 0.000007 A \times A + 0.000170 B \times B + 0.000012 A \times C - 0.000144 B \times C \quad (3)$$

$$\text{NO}_x = -344.3 + 18.658 A + 10.89 B + 17.65 C - 0.07905 A \times A - 0.093 B \times B - 0.0396 A \times B + 0.0211 A \times C - 1.152 B \times C \quad (4)$$

$$\text{UHC} = 54.6 + 0.599 A - 1.65 B + 1.68 C - 0.00106 A \times A + 0.0245 B \times B + 0.00023 A \times B + 0.0179 A \times C + 0.0636 B \times C \quad (5)$$

Table 5. Experimental factors and their levels.

Factors	Symbolic Representation	Levels				
Load (%)	A	20	40	60	80	100
Palm Biodiesel (vol.%)	B	5	10	15	20	-
Ethanol (vol.%)	C	5	10	-	-	-

3.2.1. Analysis of Variance (ANOVA)

The main purpose of the analysis of variance (ANOVA) was to observe the significant influence of input variables on the engine output responses since ANOVA reveals the percentage significance of input design factors on a response. ANOVA analyses for the BTE, NO_x , CO, and UHC are shown in Table 6 to observe the influence of linear, square, and interaction terms of the input factors in the model [32]. To meet the 95% level of significance, *p*-values less than 0.05 for the load were found for all targets [33]. *P*-values less than 0.05 in the interaction terms of different targets were found for different interactions of factors. A significant effect of biodiesel was observed at a 95% confidence level for both its linear and interaction effect in the NO_x emission. However, no such significant effect of ethanol on NO_x , CO, and UHC emissions was observed. Except for CO emission, an R^2 value of more than 90% was observed for BTE, NO_x , and UHC, resulting in a high accuracy of the model with the experimental values.

3.2.2. Response Optimization

The optimization of different engine operating parameters using a regression model is shown in Figure 7. For the test conditions, a maximum value of BTE and minimum values of NO_x , CO, and UHC emissions were set as the optimum model target. In Figure 7,

the optimization of BTE-NO_x-CO-UHC is shown where D and d signify composite and individual desirability of the response, respectively. Composite and individual desirability (d) evaluate the optimization of a set of responses and a single response, respectively. Desirability ranges between 0 and 1, and the higher value represents a favorable result overall. Desirability analysis was performed on the response values. With the condition that the larger the value, the better the desirability function, a desirability value of 0.6053 was obtained as the optimal condition for BTE, NO_x, CO, and UHC. A similar kind of desirability analysis has been performed by Awad et al. [34], who obtained a 0.7 desirability value, which is very similar to the result obtained in this study. Optimization using a regression model reveals 43.43% engine load, 11.06% palm biodiesel, and 5% ethanol as the optimal input variables, which can optimize BTE, NO_x, CO, and UHC emissions at 12.57%, 436.21 ppm, 0.037 vol.%, and 79.24 ppm, respectively. The optimization of the BTE-NO_x-CO-UHC parameters describes the contributions of palm biodiesel and ethanol that were effectively optimized by the regression model for the performance–emissions synergy. Corresponding to the optimized engine load, palm biodiesel, and ethanol percentage from the regression analysis, the experimental results at 40% engine load, 10% palm biodiesel, and 5% ethanol share were compared for validation. The detailed comparison study is shown in Table 7. From Table 7, it is clear that the optimized performance–emission parameter values are almost similar to the experimental values. Hence, the regression model can be used as an optimization tool to predict and optimize the engine output variables within the range of the tested targets, which can reduce experimental runs by saving time and money.

Table 6. Analysis of variance for BTE, NO_x, CO, and UHC.

Source	BTE		NO _x		CO		UHC	
	F-Value	p-Value	F-Value	p-Value	F-Value	p-Value	F-Value	p-Value
Regression	746.21	0.000	957.45	0.000	4.86	0.001	39.30	0.000
A	229.39	0.000	795.38	0.000	6.57	0.015	5.72	0.023
B	0.06	0.814	9.42	0.004	3.36	0.077	1.50	0.229
C	4.90	0.034	21.57	0.000	0.48	0.494	1.36	0.252
A × A	2.60	0.117	325.54	0.000	12.24	0.001	0.41	0.527
B × B	0.91	0.348	0.63	0.434	11.00	0.002	0.30	0.585
A × B	1.01	0.322	4.55	0.041	0.00	0.951	0.00	0.974
A × C	10.70	0.003	0.26	0.614	0.48	0.495	1.30	0.263
B × C	13.55	0.001	30.14	0.000	2.47	0.126	0.64	0.429
R-sq.	99.48		99.49		55.66		91.02	
R-sq. (adj.)	99.35		99.23		44.21		88.71	

Table 7. Comparison of performance–emission parameters between experimental and optimized input variables.

Engine Output Parameters	Experimental (Input Variables: 40% Engine Load, 10% Palm Biodiesel, 5% Ethanol)	Optimized (Input Variables: 43% Engine Load, 11% Palm Biodiesel, 5% Ethanol)
BTE (%)	12.52	12.57
NO _x (ppm)	401	436.2
UHC (ppm)	87	79.24
CO (vol.%)	0.05	0.037

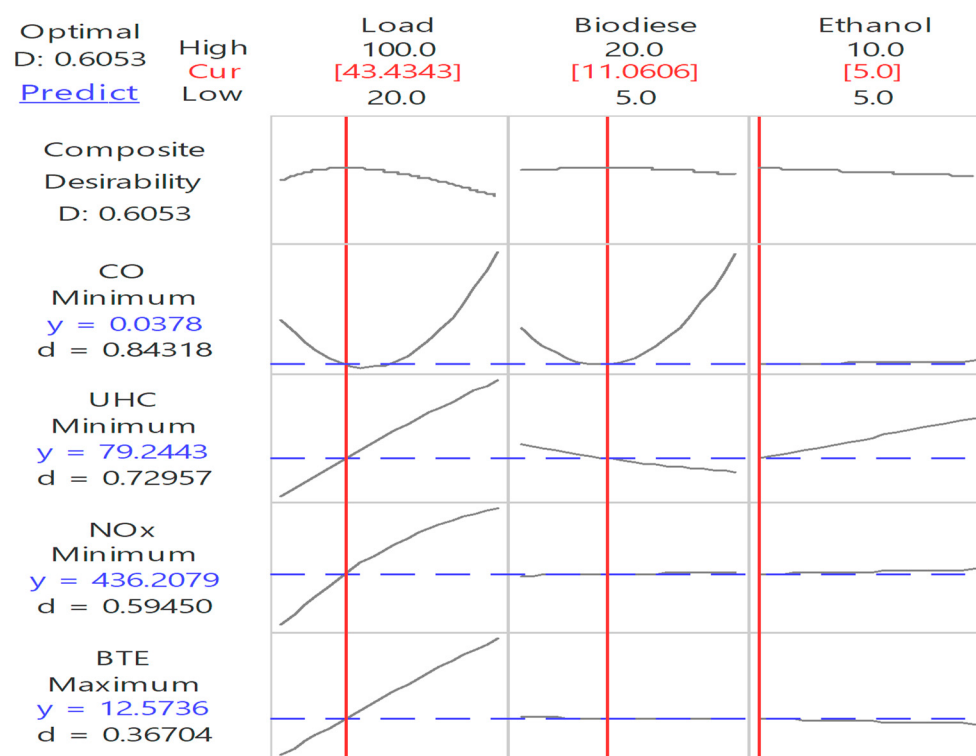


Figure 7. Optimization of BTE-NO_x-CO-UHC using the statistical regression model.

4. Conclusions

This paper discusses the effect of biodiesel and ethanol at different proportions in ternary blends at different engine loads. Using a non-linear regression model, a four-stroke diesel engine's prediction of optimum performance and emission characteristics was investigated. A significant effect of various input factors was found for the optimization of engine parameters. Optimum performance–emission parameters were observed as 12.57%, 436.2 ppm, 0.03 vol.%, and 79.2 ppm for BTE, NO_x, CO, and UHC, respectively, at optimum input parameters of 43.43% engine load, 11.1% palm biodiesel, and 5% ethanol share. Based on the aforementioned results, BTE-NO_x-CO-UHC optimization reveals an active contribution of palm biodiesel and ethanol that can be used for diesel engine combustion. Hence, this paper contributes to accurate decision-making by optimizing engine performance and emission parameters using a statistical regression model. This approach provides practical ideas to the decision-maker for the development of IC engine research. Further, for future work, other operating parameters like varying the compression ratio (CR), main injection pressure, timing, and duration of main injection could be taken into consideration for obtaining an optimized share of palm biodiesel and ethanol fractions in ternary blend operation.

Author Contributions: Conceptualization, S.D., M.D., B.B.S. and P.K.D.; methodology, S.D., M.D. and P.K.D.; software, S.D. and M.D.; validation, S.D., S.S.G., S.P. and M.D.; formal analysis, S.D.; investigation, S.D. and M.D.; resources, A.P.S., S.S.G., S.P. and M.D.; data curation, S.D.; writing—original draft preparation, S.D., A.P.S., M.D. and P.K.D.; writing—review and editing, S.D., S.S.G., B.B.S., S.P., M.D. and P.K.D.; supervision, A.P.S., S.S.G., B.B.S., S.P., M.D. and P.K.D.; project administration, S.S.G., B.B.S., S.P. and M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank the Mechanical Engineering Department, National Institute of Technology Agartala, Tripura (West), India, for the support and permission to conduct this experiment in the Internal Combustion Engine laboratory.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

1-C	Single-cylinder
4-S	Four-stroke
A	Load (%)
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
B	Palm biodiesel (vol.%)
BTE	Brake thermal efficiency
BP	Brake power
BSFC	Brake-specific fuel consumption
BSEC	Brake-specific energy consumption
C	Ethanol (vol.%)
CO	Carbon monoxide, ppm or %
CO ₂	Carbon dioxide, %
CI	Compression ignition
CR	Compression ratio
D	Diesel
DAQ	Data acquisition
DOE	Design of experiments
DI	Direct injection
D90B5E5	90% Diesel + 5% palm biodiesel + 5% ethanol
D85B10E5	85% Diesel + 10% palm biodiesel + 5% ethanol
D80B15E5	80% Diesel + 15% palm biodiesel + 5% ethanol
D75B20E5	75% Diesel + 20% palm biodiesel + 5% ethanol
D85B5E10	85% Diesel + 5% palm biodiesel + 10% ethanol
D80B10E10	80% Diesel + 10% palm biodiesel + 10% ethanol
D75B15E10	75% Diesel + 15% palm biodiesel + 10% ethanol
D70B20E10	70% Diesel + 20% palm biodiesel + 10% ethanol
E	Ethanol
EGT	Exhaust gas temperature, °C
GUI	Graphical user interface
LPH	Liters per hour
NDIR	Non-dispersive infrared
NI	National instruments
NO _x	Nitrogen oxides, ppm
O ₂	Oxygen, %
rpm	Revolutions per minute
RMS	Root mean square
RSM	Response surface methodology
R ²	Coefficient of determination
TDC	Top dead center
UHC	Unburnt hydrocarbon, ppm
VCR	Variable compression ratio

References

- Hasan, A.O.; Osman, A.I.; Al-Muhtaseb, A.H.; Al-Rawashdeh, H.; Abu-Jrai, A.; Ahmad, R.; Gomaa, M.R.; Deka, T.J.; Rooney, D.W. An experimental study of engine characteristics and tailpipe emissions from modern DI diesel engine fuelled with methanol/diesel blends. *Fuel Process. Technol.* **2021**, *220*, 106901. [[CrossRef](#)]
- Yusuf, A.A.; Ampah, J.D.; Veza, I.; Atabani, A.; Hoang, A.T.; Nippae, A.; Powoe, M.T.; Afrane, S.; Yusuf, D.A.; Yahuza, I. Investigating the influence of plastic waste oils and acetone blends on diesel engine combustion, pollutants, morphological and size particles: Dehalogenation and catalytic pyrolysis of plastic waste. *Energy Convers. Manag.* **2023**, *291*, 117312. [[CrossRef](#)]

3. Khan, E.; Ozaltin, K.; Spagnuolo, D.; Bernal-Ballen, A.; Piskunov, M.V.; Di Martino, A. Biodiesel from Rapeseed and Sunflower Oil: Effect of the Transesterification Conditions and Oxidation Stability. *Energies* **2023**, *16*, 657. [\[CrossRef\]](#)
4. Lin, C.-Y.; Lin, K.-H. Comparison of the Engine Performance of Soybean Oil Biodiesel Emulsions Prepared by Phase Inversion Temperature and Mechanical Homogenization Methods. *Processes* **2023**, *11*, 907. [\[CrossRef\]](#)
5. Gavhane, R.S.; Kate, A.M.; Soudagar, M.E.M.; Wakchaure, V.D.; Balgude, S.; Fattah, I.M.R.; Nik-Ghazali, N.-N.; Fayaz, H.; Khan, T.M.Y.; Mujtaba, M.A.; et al. Influence of Silica Nano-Additives on Performance and Emission Characteristics of Soybean Biodiesel Fuelled Diesel Engine. *Energies* **2021**, *14*, 1489. [\[CrossRef\]](#)
6. Phromphithak, S.; Meepowpan, P.; Shimpalee, S.; Tippayawong, N. Transesterification of palm oil into biodiesel using ChOH ionic liquid in a microwave heated continuous flow reactor. *Renew. Energy* **2020**, *154*, 925–936. [\[CrossRef\]](#)
7. Gad, M.S.; El-Shafay, A.S.; Abu Hashish, H.M. Assessment of diesel engine performance, emissions and combustion characteristics burning biodiesel blends from jatropha seeds. *Process. Saf. Environ. Prot.* **2021**, *147*, 518–526. [\[CrossRef\]](#)
8. EL-Seesy, A.I.; Waly, M.S.; He, Z.; El-Batsh, H.M.; Nasser, A.; El-Zoheiry, R.M. Enhancement of the combustion and stability aspects of diesel-methanol-hydrous methanol blends utilizing n-octanol, diethyl ether, and nanoparticle additives. *J. Clean. Prod.* **2022**, *371*, 133673. [\[CrossRef\]](#)
9. Saleh, H.E.; Selim, M.Y.E. Improving the performance and emission characteristics of a diesel engine fueled by jojoba methyl ester-diesel-ethanol ternary blends. *Fuel* **2017**, *207*, 690–701. [\[CrossRef\]](#)
10. Gnanamoorthi, V.; Murugan, M. Effect of DEE and MEA as additives on a CRDI diesel engine fueled with waste plastic oil blend. *Energy Sources Part A Recover. Util. Environ. Eff.* **2022**, *44*, 5016–5031. [\[CrossRef\]](#)
11. Yasin, M.H.M.; Mamat, R.; Yusop, A.F.; Idris, D.M.N.D.; Yusaf, T.; Rasul, M.; Najafi, G. Study of a Diesel Engine Performance with Exhaust Gas Recirculation (EGR) System Fuelled with Palm Biodiesel. *Energy Procedia* **2017**, *110*, 26–31. [\[CrossRef\]](#)
12. Appavu, P.; Madhavan, V.R.; Jayaraman, J.; Venu, H. Palm oil-based biodiesel as a novel alternative feedstock for existing unmodified DI diesel engine. *Int. J. Ambient. Energy* **2019**, *43*, 222–228. [\[CrossRef\]](#)
13. Ma, Q.; Zhang, Q.; Liang, J.; Yang, C. The performance and emissions characteristics of diesel/biodiesel/alcohol blends in a diesel engine. *Energy Rep.* **2021**, *7*, 1016–1024. [\[CrossRef\]](#)
14. Sathish, T.; Mohanavel, V.; Arunkumar, M.; Rajan, K.; Soudagar, M.E.M.; Mujtaba, M.; Salmen, S.H.; Al Obaid, S.; Fayaz, H.; Sivakumar, S. Utilization of Azadirachta indica biodiesel, ethanol and diesel blends for diesel engine applications with engine emission profile. *Fuel* **2022**, *319*, 123798. [\[CrossRef\]](#)
15. Devarajan, Y.; Munuswamy, D.B.; Mahalingam, A.; Nagappan, B. Performance, Combustion, and Emission Analysis of Neat Palm Oil Biodiesel and Higher Alcohol Blends in a Diesel Engine. *Energy Fuels* **2017**, *31*, 13796–13801. [\[CrossRef\]](#)
16. Thakkar, K.; Kachhwaha, S.S.; Kodgire, P.; Srinivasan, S. Combustion investigation of ternary blend mixture of biodiesel/n-butanol/diesel: CI engine performance and emission control. *Renew. Sustain. Energy Rev.* **2021**, *137*, 110468. [\[CrossRef\]](#)
17. Uslu, S.; Aydın, M. Effect of operating parameters on performance and emissions of a diesel engine fueled with ternary blends of palm oil biodiesel/diethyl ether/diesel by Taguchi method. *Fuel* **2020**, *275*, 117978. [\[CrossRef\]](#)
18. Sakthivel, G.; Sivakumar, R.; Saravanan, N.; Ikua, B.W. A decision support system to evaluate the optimum fuel blend in an IC engine to enhance the energy efficiency and energy management. *Energy* **2017**, *140*, 566–583. [\[CrossRef\]](#)
19. Dhole, A.E.; Yarasu, R.B.; Lata, D.B.; Baraskar, S.S. Mathematical modeling for the performance and emission parameters of dual fuel diesel engine using hydrogen as secondary fuel. *Int. J. Hydrogen Energy* **2014**, *39*, 12991–13001. [\[CrossRef\]](#)
20. Singh, Y.; Sharma, A.; Tiwari, S.; Singla, A. Optimization of diesel engine performance and emission parameters employing cassia tora methyl esters-response surface methodology approach. *Energy* **2019**, *168*, 909–918. [\[CrossRef\]](#)
21. Dey, S.; Reang, N.M.; Majumder, A.; Deb, M.; Das, P.K. A hybrid ANN-Fuzzy approach for optimization of engine operating parameters of a CI engine fueled with diesel-palm biodiesel-ethanol blend. *Energy* **2020**, *202*, 117813. [\[CrossRef\]](#)
22. Sakthivel, G.; Sivaraja, C.M.; Ikua, B.W. Prediction OF CI engine performance, emission and combustion parameters using fish oil as a biodiesel by fuzzy-GA. *Energy* **2019**, *166*, 287–306. [\[CrossRef\]](#)
23. Bendu, H.; Deepak, B.B.V.L.; Murugan, S. Multi-objective optimization of ethanol fuelled HCCI engine performance using hybrid GRNN-PSO. *Appl. Energy* **2017**, *187*, 601–611. [\[CrossRef\]](#)
24. Singh, Y.; Sharma, A.; Singh, G.K.; Singla, A.; Singh, N.K. Optimization of performance and emission parameters of direct injection diesel engine fuelled with pongamia methyl esters-response surface methodology approach. *Ind. Crops Prod.* **2018**, *126*, 218–226. [\[CrossRef\]](#)
25. ICEngineSoft_9.0_SetupBuild.zip—Google Drive n.d. Available online: <https://drive.google.com/file/d/0BxpHpyYTEWVdMm5oQ0VGamMzVGs/view?resourcekey=0-Nbcv1ozQKZ-Ro1S5U5luUQ> (accessed on 19 September 2023).
26. Dey, S.; Reang, N.M.; Deb, M.; Das, P.K. Study on performance-emission trade-off and multi-objective optimization of diesel-ethanol-palm biodiesel in a single cylinder CI engine: A Taguchi-fuzzy approach. *Energy Sources Part A Recover. Util. Environ. Eff.* **2020**, *42*, 1–21. [\[CrossRef\]](#)
27. Rakopoulos, C.D.; Rakopoulos, D.C.; Kosmadakis, G.M.; Papagiannakis, R.G. Experimental comparative assessment of butanol or ethanol diesel-fuel extenders impact on combustion features, cyclic irregularity, and regulated emissions balance in heavy-duty diesel engine. *Energy* **2019**, *174*, 1145–1157. [\[CrossRef\]](#)
28. Pan, M.; Huang, R.; Liao, J.; Jia, C.; Zhou, X.; Huang, H.; Huang, X. Experimental study of the spray, combustion, and emission performance of a diesel engine with high n-pentanol blending ratios. *Energy Convers. Manag.* **2019**, *194*, 1–10. [\[CrossRef\]](#)

29. Atmanlı, A.; Yüksel, B.; İleri, E.; Karaoglan, A.D. Response surface methodology based optimization of diesel–n-butanol –cotton oil ternary blend ratios to improve engine performance and exhaust emission characteristics. *Energy Convers. Manag.* **2015**, *90*, 383–394. [[CrossRef](#)]
30. Atmanlı, A.; İleri, E.; Yilmaz, N. Optimization of diesel–butanol–vegetable oil blend ratios based on engine operating parameters. *Energy* **2016**, *96*, 569–580. [[CrossRef](#)]
31. Sakthivel, R.; Ramesh, K.; Marshal, S.J.J.; Sadasivuni, K.K. Prediction of performance and emission characteristics of diesel engine fuelled with waste biomass pyrolysis oil using response surface methodology. *Renew. Energy* **2019**, *136*, 91–103. [[CrossRef](#)]
32. Kumar, S.; Dinesha, P. Optimization of engine parameters in a bio diesel engine run with honge methyl ester using response surface methodology. *Measurement* **2018**, *125*, 224–231. [[CrossRef](#)]
33. Najafi, G.; Ghobadian, B.; Yusaf, T.; Ardebili, S.M.S.; Mamat, R. Optimization of performance and exhaust emission parameters of a SI (spark ignition) engine with gasoline–ethanol blended fuels using response surface methodology. *Energy* **2015**, *90*, 1815–1829. [[CrossRef](#)]
34. Awad, O.I.; Mamat, R.; Ali, O.M.; Azmi, W.H.; Kadirgama, K.; Yusri, I.M.; Leman, A.M.; Yusaf, T. Response surface methodology (RSM) based multi-objective optimization of fusel oil-gasoline blends at different water content in SI engine. *Energy Convers. Manag.* **2017**, *150*, 222–241. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.