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Multi objective optimization of diesel engine performance and emission characteristics using taguchi-grey relational analysis

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Abstract

A promising solution to the problem of fuel depletion and energy security is the use of biodiesel as an alternative fuel for diesel engines. It is used in blended or pure forms without any engine modification. The aim of this study is to reduce smoke and nitrogen oxide (NOx) emissions while maintaining brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) in a biodiesel-fuelled variable compression ratio (VCR) diesel engine. Experiments were conducted using a Taguchi design based L9 orthogonal array. The effects of three control parameters were investigated: engine load, blend ratio, and compression ratio (CR). The signal-to-noise (S/N) ratio of Taguchi was calculated based on their performance characteristics. Using a response table and a response graph, the optimal level of control factors was determined based on this grade. An analysis of variance (ANOVA) is used to estimate the individual effects of components. The results of the trials show that 75% engine load, 20% blend ratio, and a CR of 18 are the best combinations for reducing smoke and NOx. When compared to diesel this combination results in a 32.3% reduction in smoke, a 19.7% reduction in NOx emissions, a marginal decrease of 2.17% in BTE, and a 5.9% decrease in BSFC. It is evident that Taguchi design combined with grey relational analysis (GRA) can efficiently predict response values using an optimal combination of control factors.

Keywords

Diesel engine, Biodiesel, Emission, Taguchi design, GRA, ANOVA.

1.Introduction

The end of the pandemic has caused a surge in primary energy consumption in China and India, with diesel being the most common [1]. Diesel is known for its superior thermal efficiency, lean burning ability, and long durability, but crude oil reserves are expected to be limited and non-renewable. There have been serious concerns over oil price fluctuations and the environmental impact of emissions generated by its use [2]. In the specific context of India, imports of crude oil, coal, and natural gas have an adverse impact on forex reserves. Various efforts are being made to reduce the use of crude oil in engines, such as using vegetable oils, biofuels, and biodiesel. The National Bioenergy Mission was introduced to provide a regulatory environment for high capital investment in biomass-based power plants [3].

In 2017, bioenergy was the third largest contributor, accounting for 21% of the primary energy supply in India [4]. The National Biofuels Mission was implemented in 2018 with the aim of 20% fuel blending for biodiesel and bioethanol, respectively [5]. The "Biofuels for Atmanirbhar Bharat" policy was implemented to promote non-food feedstocks and biodiesel blending in transportation, stationary uses, and portable uses [6]. However, biodiesel production in India is still in its early stages, with up to 5% blends marketed in 3400 locations [7].

Biodiesel fuel needs to overcome a few challenges to gain wider acceptance among end users. An existing diesel engine can be used to blend up to 20% biodiesel with conventional diesel without any significant engine modifications, which lowers associated technical costs [8]. Research has investigated the performance and emission behaviour of diesel engines fuelled with biodiesel blends,

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finding that with an increase in blend ratio, diesel engines have lower brake thermal efficiency (BTE) and higher brake specific fuel consumption (BSFC). However, such engines exhibit high nitrogen oxide (NOx) reduction potential at lower engine loads [9–12]. The goals of reducing NOx and smoke emissions and increasing BTE and BSFC engine performance are at odds. To balance them, multi-criteria decision-making approaches were used to determine the ideal operating parameter combination. Taguchi is a method used in design of experiments (DOE) for parameter optimization with the advantages of fewer experimental runs and higher standards of quality control.

Research has shown that the Taguchi approach works efficiently in optimizing engine parameters to meet predetermined goals and was developed and successfully applied in engine research [13]. It is concluded that the earlier investigations had a single objective of either increasing BTE or reducing emissions from biodiesel fueled diesel engines. The current work aims to minimize emissions while maintaining reductions in BTE and BSFC at a minimum level. Taguchi Design with grey relational analysis (GRA) is applied for the multi-objective optimization.

The research is divided into five sections. An overview of previous research investigating the impacts of biodiesel blends on engine performance, the impact of additives, and multi-objective performance and emission optimization is provided in the literature review section. The descriptions of the materials, the experimental setup that was used, the experiment's design, the Taguchi design orthogonal array (OA), and the experiment's values that were determined through trials are all included in the third section. The steps taken in the research are then described in detail and supported by equations. The fourth section lists the specific results of the Taguchi GRA method, regression analysis, analysis of variance (ANOVA), and confirmation trial. The fifth section includes a thorough explanation of the findings and their justification, as well as the study's limitations. In the final section, a conclusion is presented along with potential areas for additional research.

2.Literature review

Several researchers have investigated the effect of blending biodiesel in combustion ignition (CI) engines on performance and emissions. Previous studies [14–18] have investigated engine performance by using various biodiesels mixed with diesel up to full load. It is observed that engines produce less power and have a lower BTE when compared to diesel-fuelled engines. The lower value of BTE indicates a higher BSFC since more fuel is required to produce the same amount of power. This fact can be justified by the lower calorific value of biodiesel. With the rise in the blend proportion, overall hydrocarbon (HC), carbon monoxide (CO), and CO_2 emissions were reduced except for NOx emissions, which might be due to the high cetane number, high viscosity, and reduced ignition delay.

Certain measures, such as the use of fuel additives, aftertreatments like exhaust gas treatment (EGR) and engine modifications, are explored to maintain engine performance and emissions at acceptable levels. Additives are compounds that are added in fractional quantities for the improvement of fuel properties like cetane number, oxidation stability, and antioxidant tendency. The employment of fuel additives ultimately results in reduced ignition delay, higher flame temperature and heat release rates, better combustion, lower emissions, better efficiency, and lower fuel consumption [19]. Researchers [20–24] have investigated the effects of different additives on a biodiesel-fuelled engine under different loads and blend proportions. It is concluded that the use of additives improves BTE, reduces BSFC, and reduces CO, HC, and NOx emissions. The additives reduce the mean exhaust gas temperature (EGT), which lowers the formation of NOx. Several studies [25–27] have investigated the effect of EGR on biodiesel-fuelled diesel engine performance. The use of moderate rates of EGR helps reduce NOx emissions with slightly reduced power and BTE. This can be justified by the fact that EGR results in dilution of the charge and a lower peak cylinder temperature.

The performance of a diesel engine is made up of variables that work against one another. An effort to increase BTE results in higher NOx and smoke emissions, and vice versa. This challenge prompts researchers to use optimization techniques. The technique for order preference by similarity to ideal solution (TOPSIS) method transforms the output responses of each criterion into a single objective function or a preference index in order to calculate the value of the solution that comes the closest to the ideal. Dambhare et al. [24] use the TOPSIS method to determine the ideal blend ratio for a stationary variable compression ratio (VCR) diesel engine running on jatropha oil biodiesel at various loads. It was found that a 10% blend with a CR of 15 was the optimum combination. Jayabal et al. [25] used TOPSIS optimization to find the optimal input conditions for engine load, CR, and EGR using a 50% blend of sapota methyl ester in a common rail direct injection (CRDI) engine. Results confirmed that the optimum operating conditions are full load, 20% EGR, and a CR 16. Sivaraja and Sakthivel [26] employed TOPSIS, multi-criteria optimization and compromise solution (VIKOR), and elimination and choice translating reality (ELECTRE) to obtain the ranking of the combination of injection timing and blend ratio for a fish oil biodiesel engine. It is concluded that mixing 20% biodiesel with diesel is suggested as a good replacement for diesel. Singh et al. [27] employed response surface methodology (RSM) for optimization of BTE, BSFC, NOx, and smoke and for proposing a prediction model. The model predicts that the engine produces 31.357% BTE and BSFC of 274.97 g/kWh with lower values of CO2 (869.075 g/kWh), particulate matter (PM) (0.2807 g/kWh), and NOx (1804.97 ppm) while running at a load of 64.634, CR of 16.50, and 20% blend, respectively. Alternative fuels are ranked based on their fuel qualities using multi-objective optimization based on ratio analysis (MULTIMOORA) and stepwise weighted assessment ratio analysis (SWARA). Balki et al. [28] employed step-wise weighted assessment ratio analysis-additive ratio assessment-to investigate optimal parameters using a pure methanol-fueled SI engine. The results showed that 10% excess air, a CR of 9, and injection timing of 20° CA were found to be the optimum working parameters.

Sivaiaha and Chakradhar [29] investigated the machinability of a 17-4 PH stainless steel tool by measurement of surface roughness and tool flank wear. The experimental design was based on Taguchi L9, OA, consisting of control factors such as feed rate, depth of cut, cutting speed, and coolant used. While optimum process parameters were determined using Taguchi analysis, ANOVA confirmed that cutting speed had the largest influence on the machining performance. Uslu and Aydin [30] investigated the effect of injection timing, diethyl ether (DEE) blend ratio, and engine load on BTE, BSFC, EGT, and emissions (smoke, NOx, CO, and HC) using a diesel engine running on palm oil biodiesel. Experimental trials were conducted based on Taguchi L27 OA. Lesser injection advance and a lower DEE ratio at average engine loads produced higher BTE, BSFC, and EGT. 20% blends with a higher DEE ratio and an injection advance of 35OCA yielded BTE of 30.73%, BSFC of 824.59 g/kWh, NOx of 292.20 ppm, and smoke of 68.91%, respectively.

Sanjeevannavar et al. [31] employed Taguchi analysis to reduce the number of trials when evaluating the performance and emissions of a CI engine using Jatropha oil biodiesel and H_2O_2 as an additive. It was reported that the use of 30% biodiesel and 10% H_2O_2 resulted in 20% rise in BTE, 25% drop in BSFC, 3.53% fall in CO_2, 17.54% fall in HC, 24.6% drop in smoke, and a slight increase in NOx emissions when compared to the use of 40% biodiesel without H_2O_2.

Saravanan et al. [32] investigated the effects of several control parameters on the BSFC, NOx, and smoke emissions of a diesel engine fired with Jatropha methyl ester and 20% n-butanol using Taguchi design for optimization. Results showed that the engine was projected to produce 1.127 kg/kWh of BSFC, 359.13 ppm of NOx emissions, and 74.83% of smoke opacity. Daniel et al. [33] investigated the combined influence of input parameters (cutting speed, depth of cut, feed rate, reinforcement percentage, and particle size of SiC) on the milling of aluminium hybrid metal matrix composites using Taguchi-GRA. Further, it was found that the predicted values proposed by the artificial neural network (ANN) model were much more significant than the values suggested by the regression model.

3.Materials and methods

The flowchart of the present work is depicted in *Figure 1*. The entire project is broken down into three sequences: experiment, analysis, and validation. If the experiment's results are found to be insufficiently valid in the final stage, all these stages must be repeated.

3.1Preparation of fuel

Cotton seed oil, which is easily available, is utilized to make biodiesel in the form of cotton seed oil methyl ester. For the engine test, biodiesel fuel is made with diesel in various ratios of 10% (B10), 20% (B20), and 30% (B30). In *Table 1*, the characteristics of mineral diesel and cotton seed oil biodiesel are compiled together. From the fuel property values listed in *Table 1*, it was concluded that cottonseed biodiesel is competitively comparable to the biofuel families and closer to base diesel in terms of energy content and density [34].

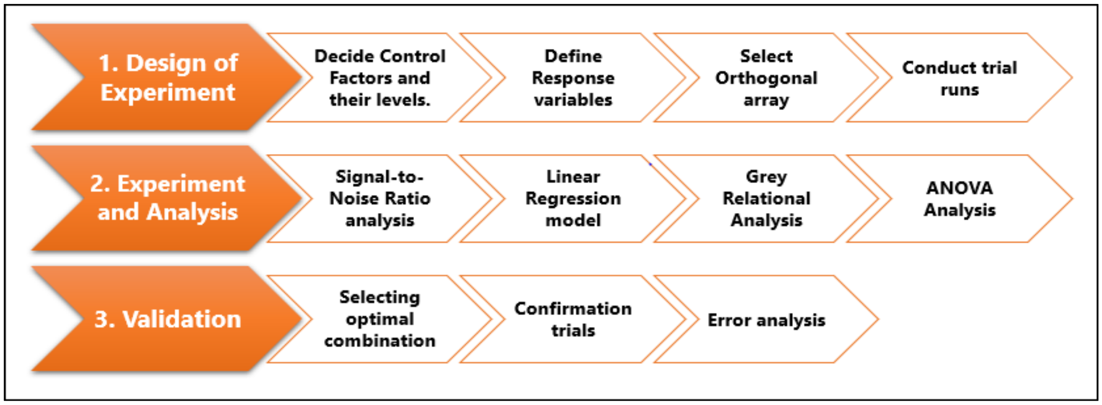

Figure 1 Flowchart of the research work

Table 1 Comparison of fuel properties

Property	Diesel	B10	B20	B30	Method
Density at 15°C, g/CC	0.831	0.843	0.852	0.862	ASTM D4052
Kinematic viscosity at 40°C, cSt	3.12	3.45	4.87	5.05	ASTM D445
Flash point, °C	51	104	106	110	ASTM D93
Fire point, °C	57	114	118	121	ASTM D5853
Cloud point, °C	-10	-3	-3	-2	ASTM D2500
Calorific value, kJ/g	44800	42434	42012	41534	ASTM D240

3.2Experimental setup

The setup consists of a single-cylinder, four-stroke VCR Research engine connected to an eddy current dynamometer. It is provided with the necessary instruments for combustion pressure, crank-angle, airflow, fuel flow, temperatures, and load measurements. These signals are interfaced to the computer through a high-speed data acquisition device. The setup has a stand-alone panel box consisting of an air box, twin fuel tanks, a manometer, a fuel measuring unit, transmitters for air and fuel flow measurements, a process indicator, and a piezoelectric power unit. Rotameters are provided for cooling water and calorimeter water flow measurements. The schematic for the full engine test setup is shown in *Figure 2*. *Table 2* describes the specifications of the engine setup used. A computer is used to alter engine load using an eddy current dynamometer as the loading unit. The di-gas 444N multi gas analyzer and 437C smoke meter were used, respectively, to measure emission values and smoke intensity.

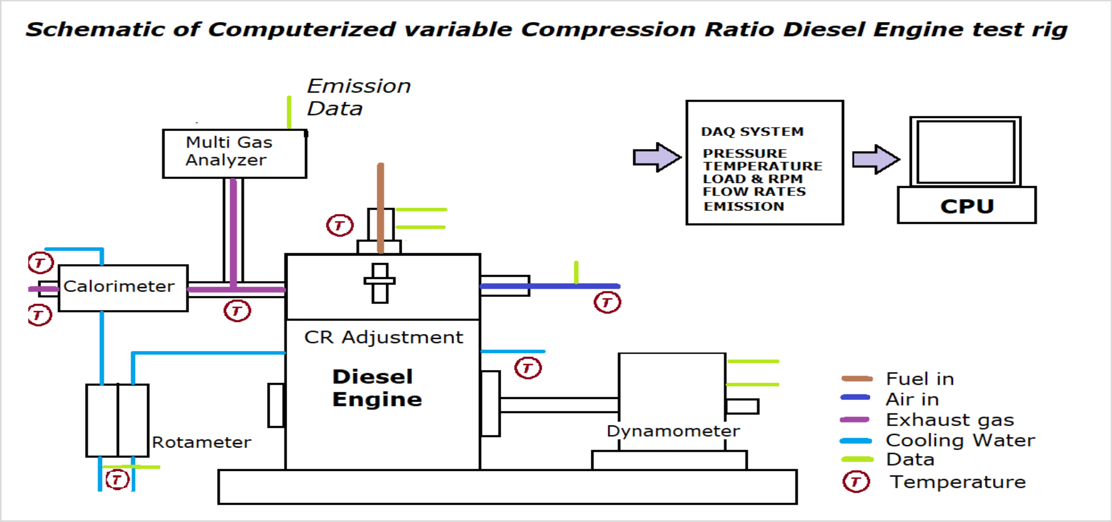

Figure 2 Schematic of engine and accessories

Table 2 Specifications of engine test setup

Equipment	**Details**
Engine	Make Kirloskar, Single cylinder, four stroke, water cooled, stroke 110 mm, bore 87.5 mm, 3.5 KW@ 1500 rpm, tilting block arrangement for changing CR.
Dynamometer	eddy current, water cooled with loading unit
Load sensor	Load cell, type strain gauge, range 0-50 Kg
Piezo sensor	Cylinder & fuel line: low noise, Range 350 bar
Calorimeter	Pipe in pipe, water cooled
Temperature Sensor	Type resistance temperature detector(RTD) and Thermocouple, Type K, Range 0–1200 ^{o}C
Crank angle sensor	Resolution 1 Degree, Speed 5500 revolutions per minute(RPM) with top dead centre (TDC)pulse

The test engine was used to run on diesel for a certain period of time. A series of performance tests were carried out with various load settings once the engine warmed up, and various results were recorded using engine analysis software. Different biodiesel blends were used in subsequent engine tests. For different loading conditions, each blend's measurements were recorded. The engine's speed was checked before each operation and kept essentially constant. The test results were then saved and examined for forthcoming research. The engine assembly is as shown in *Figure 3*.

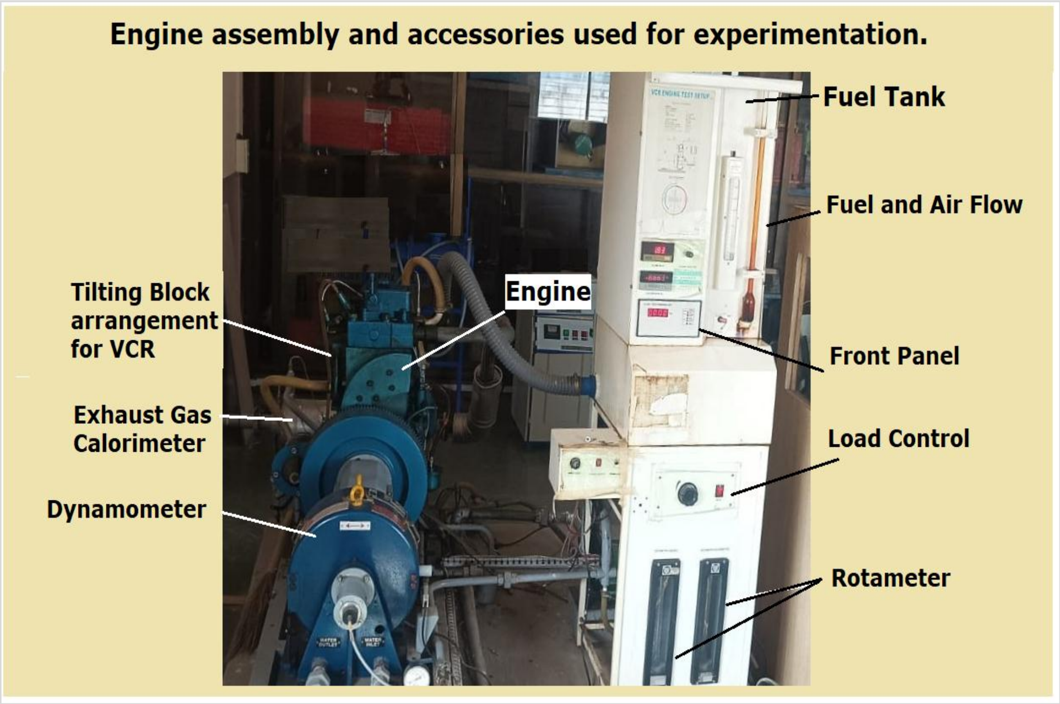

Figure 3 Engine set up for experimentation

3.3Uncertainty analysis

The accuracy of the experiments depends on the operating conditions and ambient circumstances, which include the equipment selection, calibration of equipment, planning the experiment, taking observations, and taking readings among others. An analysis of uncertainty aids in proving the validity of the experiment. Both random and fixed errors are to contribute to the uncertainties [35]. *Table 3* lists the computed uncertainty for the various investigated parameters in the current work.

Table 3 Uncertainty of measured parameters

Measured parameter	**Uncertainty**	**Total uncertainty**
Engine Speed	±0.5%	Total Uncertainty = square root of sum of squares of individual uncertainties $= \sqrt{(0.5^2 + 0.5^2 + 0.5^2 + 0.6^2 + 1^2 + 0.1^2 + 0.3^2 + 0.1^2 + 0.8^2)}$ =±1.69%
Engine Load	±0.5%	
Brake Power	±0.5%	
BTE	±0.6%	
BSFC	±1.0%	
Carbon monoxide, (CO)	±0.1%	
Unburnt HC	±0.3%	
Nitrogen oxides (NOx)	±0.1%	
Smoke	±0.8%	

3.4Design of experiment

Using the Taguchi approach, the DOE is used to identify the engine trials. The Taguchi approach is built on OA experiments, which have the advantage of reducing variance with the fewest possible experiments. Signal-to-noise (S/N) ratios are logarithmic functions of the intended output that are also used as the objective functions for optimizing. S/N ratios are useful for forecasting the best results in addition to helping with data analysis [36]. The data analysis, ANOVA, and linear modeling were done using Minitab statistical software. The control factors for the current study were determined to be engine load, blend ratio, and CR. Based on the research literature, three levels of each control factor were chosen for DOE, as shown in *Table 4.*

To minimize the number of experiments, an OA design L9 (3^3) was used. The following response variables were chosen for the current study: smoke, NOx emissions, BTE, and BSFC. *Table 5* displays specific control factor values together with the related measured response variables.

Table 4 Levels of control factors

Control factors	**Nomenclature**	**Values**		
		1	**2**	**3**
Engine load, %	A	25	50	75
Blend ratio, %	B	10	20	30
Compression ratio	C	16	17	18

Table 5 L9 orthogonal array design

	Taguchi design			**Input parameters**			**Larger the better**	**Smaller the better**		
SN	**A**	**B**	**C**	**Engine load %**	**Blend ratio %**	**Compression ratio, CR**	**BTE**	**BSFC**	**NOx**	**Smoke**
1	1	1	1	25	10	16	14.82	0.54	339	2.4
2	1	2	2	25	20	17	15.6	0.54	98	8.4
3	1	3	3	25	30	18	13.94	0.61	523	1.4
4	2	1	2	50	10	17	20.54	0.41	764	4.9
5	2	2	3	50	20	18	20.88	0.41	366	2.3
6	2	3	1	50	30	16	20.16	0.39	768	7.3
7	3	1	3	75	10	18	23.75	0.36	1008	7.6
8	3	2	1	75	20	16	23.65	0.38	843	7.1
9	3	3	2	75	30	17	24.04	0.35	1017	9.9

3.5Design optimization

Following the experimental work, NOx and smoke emission response variables are optimized while BTE and BSFC are maintained at their highest levels. Due to the multi-criteria nature of the decision-making process, Taguchi Design is additionally examined using GRA.

3.5.1Taguchi S/N ratio analysis

For the current optimization effort, there are two S/N ratios that must be considered. The smaller, the better S/N ratios are calculated as shown in below Equation

1, and the larger, the better S/N ratios are calculated as shown in Equation 1 an 2.

$$S/N\ ratio = -10\log_{10}(\frac{1}{n}\sum_{i=1}^{n} y_i^2) \qquad (1)$$

It gives the S/N ratio values for the smaller the better characteristic, which should ideally have zero values because it is undesirable.

$$S/N\ ratio = -10\log_{10}(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}) \qquad (2)$$

Equation 2 provides the S/N ratio, the larger the better. Such qualities should have maximum values that fall within the range allowed since they are desirable. Here 'i' is an entire number of experiments, 'y_i'is the experimental outcome of i^{th}experiments, and n is the total number of runs performed in the OA of Taguchi design.

3.5.2Normalizing the S/N ratio by GRA

When combining several response variables with less data, GRA is a preferable approach. The measured output values from the Taguchi design OA are accepted as input and normalized as the initial step of data pre-processing. The normalized values now fall inside the interval of 0 to 1 [37]. The normalization equation for the smaller the better characteristic is written as shown in Equation 3.

$$Y_{i,j} = \frac{max(z_{i,j}) - z_{i,j}}{(max(z_{i,j}) - min(z_{i,j}))} \qquad (3)$$

The normalization equation for greater the better characteristic is written as shown in Equation 4.

$$Y_{i,j} = \frac{z_{i,j} - min(z_{i,j})}{(max(z_{i,j}) - min(z_{i,j}))} \qquad (4)$$

Here $z_{i,j}$ represents the measured values from experimental runs of Taguchi design, while $min(z_{i,j})$ and $max(z_{i,j})$ are the minimum and maximum values for the set of measured values of a response variable.

3.5.3Grey relational coefficients(GRC)

The normalized data is calculated using the below Equation 5.

$$GRC_{i,j} = \frac{\delta_{min} - \gamma\delta_{max}}{\delta_{i,j} - \gamma\delta_{max}} \qquad (5)$$

Here, $\delta_{i,j}$ stands for the variance between the compatibility sequence and the reference sequence, whereas γ is the identifying or distinguishing coefficient, with a range of values from zero to one. The distinguishing coefficient is typically thought to be 0.5. The optimal or ideal value and the actual value discovered through trial are related by the grey relational coefficient (GRC). A higher GRC value denotes the optimal confluence of eminence characteristics.

3.5.4Grey relational grade

Similarly, the following equation can be used to determine the grey relational grade (GRG) from the GRC values. The simple average of all GRC is used to calculate GRG as shown in Equation 6.

$$GRG_i = \frac{1}{n}\sum GRC_{i,j} \qquad (6)$$

The collected GRG values are then ranked from highest to lowest value. The level of the process parameters that has the highest GRG is regarded as optimal [38].

4.Results

4.1S/N ratio analysis

Response tables for the S/N ratio for the current work are calculated using the Taguchi design. The same are shown in *Table 6* below. It shows that the engine load, followed by the blend ratio and CR, is the control variable that has the greatest influence on all the response variables.

Table 6 Response tables

Larger the better				Smaller the better			
Level	**Engine load**	**Blend ratio**	**Compression ratio**	**Level**	**Engine load**	**Blend ratio**	**Compression ratio**
1	23.39	25.73	25.66	1	-43.51	-51.34	-50.84
2	26.25	25.91	25.91	2	-50.78	-45.11	-47.78
3	27.54	25.53	25.6	3	-54.81	-52.64	-50.47
Delta	4.15	0.38	0.31	Delta	11.3	7.53	3.05
Rank	1	2	3	Rank	1	2	3

The optimal configuration of input parameters for greater BTE is A3B2C2, as shown in *Figure 4,* according to the graphs for mean S/N ratios. It shows that the engine produces the highest BTE with 75% engine load, 20% blend ratio, and a CR of 17. The control factor that has the greatest impact on the BTE is the engine load, and as the engine load increases, the BTE also increases.

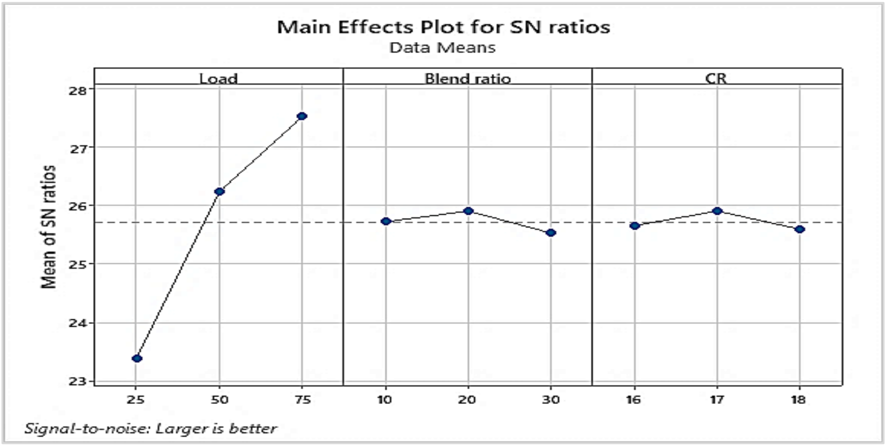

Figure 4 Effect of control factors on BTE

The best input parameter setting for the lowest combined BSFC, NOx, and smoke emission is A3B3C1, as shown in *Figure 5*. The engine produces the least amount of BSFC, NOx, and smoke with a 75% engine load, 30% blend ratio, and CR of 16. The control element that has the greatest impact on BSFC, NOx, and smoke emission is engine load, and as engine load rises, the response variables decline.

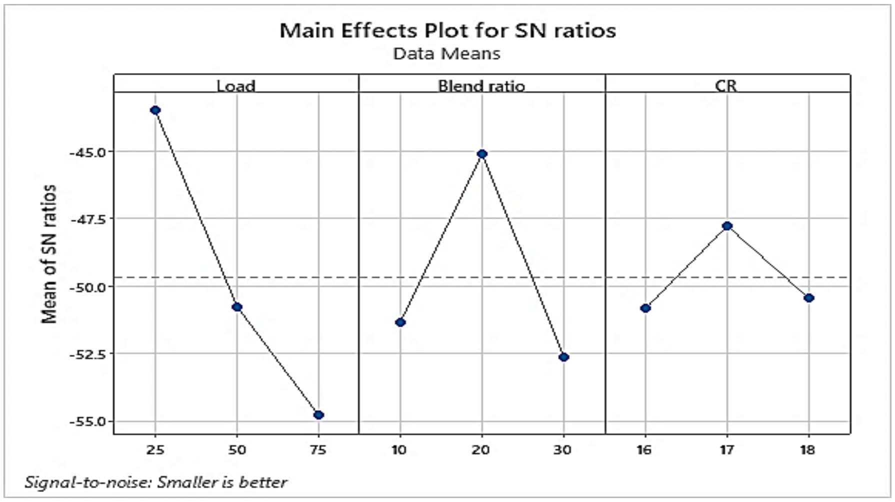

Figure 5 Effect of control factors on BSFC, NOx and Smoke

4.2Regression model analysis

Regression model techniques are frequently employed to find relationships between response variables and control variables [39, 40]. The regression equations created through regression analysis are expressed as Equations 7 to 10.

$$BTE = 11.18 + 0.1805 \times A - 0.0162 \times B - 0.01 \times C \quad (7)$$

$$BSFC = 0.432 - 0.004 \times A + 0.00067 \times B + 0.0117 \times C \quad (8)$$

$$NOx = 85 + 12.72 \times A + 3.28 \times B - 8.8 \times C \quad (9)$$

$$Smoke = 15.9 + 0.0827 \times A + 0.062 \times B - 0.92 \times C \quad (10)$$

Engine load (A), blend ratio (B), and CR (C) are all inputs here. The projected experimental outcomes produced using the regression model can also be compared with the GRA model. The experimental tests were carried out to validate the predicted values of the regression model. The testing outcomes came from the L9 orthogonal experimental design at random. The results are compiled in *Table 7*. It was discovered from the comparison that the predicted results from the models and the experimental data were in good agreement.

Table 7 Comparison of confirmation test and the prediction model

Run	Experimental value				Predicted value				Error, %			
	BTE	BSFC	NOx	Smoke	BTE	BSFC	NOx	Smoke	BTE	BSFC	NOx	Smoke
1	14.82	0.54	339	2.4	15.367	0.525	304.22	3.3333	-3.56	2.86	11.43	-28.00
4	20.54	0.41	764	4.9	19.87	0.4367	630.97	5.0833	3.37	-6.11	21.08	-3.61
6	20.16	0.39	768	7.3	19.55	0.4383	677.89	7.2333	3.12	-11.02	13.29	0.92
9	24.04	0.35	1017	9.9	24.0606	0.35	987.06	8.3833	-0.09	0.00	3.03	18.09
-	-	-	-	-	-	-	-	-	-	Avg.	error	1.55

4.3Grey relational analysis(GRA)

Taguchi design is a statistical technique that sticks to single objective optimization, whereas GRA is utilized for multiple response optimization problems [41]. The experimental values of the response variables BTE, BSFC, NOx, and smoke are converted into normalized values as shown in *Table 8*. The deviation sequences are calculated, as are the GRC and the GRG that were derived using the formulation discussed before. The greatest value of the GRG demonstrates the optimal solution of control elements. From the table, it is observed that the 5th design (2-2-3) is the optimal solution for the function under consideration.

Table 8 Grey relational grade for response variables

SN	Taguchi Design			Normalized Values				Deviation Sequences				Grey relational coefficient				Grey relational grade	Rank
	A	B	C	BTE	BSFC	NOx	Smoke	BTE	BSFC	NOx	Smoke	BTE	BSFC	NOx	Smoke		
1	1	1	1	0.0871	0.2692	0.7378	0.8824	0.9129	0.7308	0.2622	0.1176	0.3539	0.4063	0.6560	0.8095	0.5564	6
2	1	2	2	0.1644	0.2692	1.0000	0.1765	0.8356	0.7308	0.0000	0.8235	0.3744	0.4063	1.0000	0.3778	0.5396	8
3	1	3	3	0.0000	0.0000	0.5375	1.0000	1.0000	1.0000	0.4625	0.0000	0.3333	0.3333	0.5195	1.0000	0.5465	7
4	2	1	2	0.6535	0.7692	0.2753	0.5882	0.3465	0.2308	0.7247	0.4118	0.5906	0.6842	0.4083	0.5484	0.5579	5
5	2	2	3	0.6871	0.7692	0.7084	0.8941	0.3129	0.2308	0.2916	0.1059	0.6151	0.6842	0.6316	0.8252	0.6890	1
6	2	3	1	0.6158	0.8462	0.2709	0.3059	0.3842	0.1538	0.7291	0.6941	0.5655	0.7647	0.4068	0.4187	0.5389	9
7	3	1	3	0.9713	0.9615	0.0098	0.2706	0.0287	0.0385	0.9902	0.7294	0.9457	0.9286	0.3355	0.4067	0.6541	3
8	3	2	1	0.9614	0.8846	0.1893	0.3294	0.0386	0.1154	0.8107	0.6706	0.9283	0.8125	0.3815	0.4271	0.6374	4
9	3	3	2	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000	1.0000	0.3333	0.3333	0.6667	2

Figure 6 displays the Taguchi response for the mean of all GRG values of BTE (the higher the better). *Figure 7* displays the Taguchi response for the S/N ratios of the BSFC, NOx, and smoke grey relationship grades (lower the better). From both statistics, it can be inferred that A3B2C3, 75% engine load, 20% blend ratio, and an 18 CR are the ideal parameter combinations for greatest BTE and lowest BSFC, NOx, and smoke.

4.4ANOVA

ANOVA is used to determine the importance and degree of influence of the control factors on the response variables. An ANOVA of S/N ratios can be used to calculate the percentage contribution [42]. According to the ANOVA results shown in *Table 9*, the engine load was the largest predominant factor in the improvement of BTE. According to *Table 10*, the engine load was the controlling factor that had the greatest impact on the production of NOx and smoke. The production of NOx and smoke also rises as engine load increases.

4.5Confirmation experiment

The experimental values obtained when optimized response variables (75% load, 20% blend, and a CR 18) are used are noted in *Table 11*. When these values are compared to those obtained when the engine is run normally without blending. At optimal combination, the biodiesel engine produced 2.17% lower BTE, 5.9% lower BSFC, 19.7% lower NOx, and 32.3% less smoke. The comparison confirms that there is quantitative improvement in the response variables.

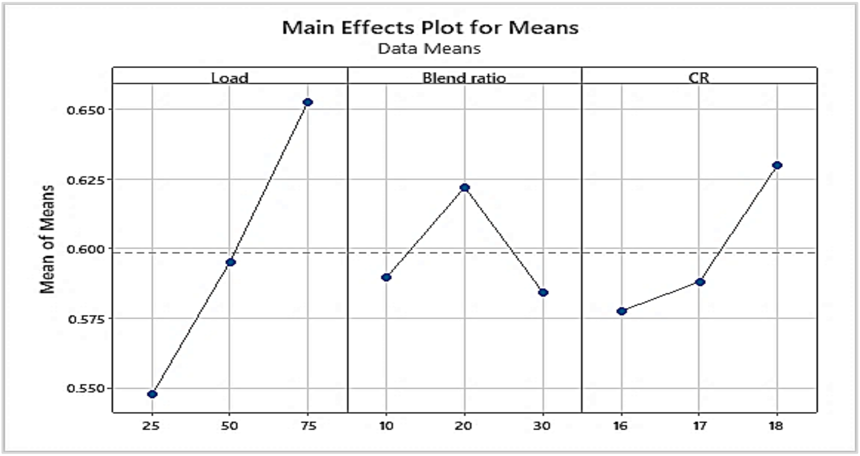

Figure 6 Effect on BTE using GRA

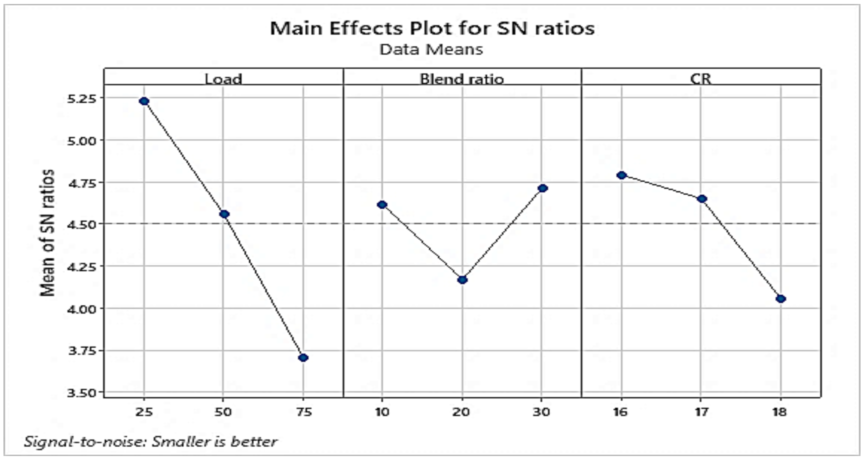

Figure 7 Effect on BSFC, NOx and Smoke using GRA

Table 9 ANOVA of BTE

Source	Degree of freedom	Sum of squares	Adj. Sum of squares	Mean of squares	F	P	Influence rank
Engine Load	2	27.0353	27.0353	13.5177	174.66	0.006	1
Blend ratio	2	0.2167	0.2167	0.1083	1.4	0.417	2
CR	2	0.1647	0.1647	0.0823	1.06	0.485	3
Residual Error	2	0.1548	0.1548	0.0774	-	-	-
Total	8	27.5715	-	-	-	-	-

Table 10 ANOVA for BSFC, NOx and smoke

Source	Degree of freedom	Sum of squares	Adj. Sum of squares	Mean of squares	F	P	Influence Rank
Engine load	2	196.81	196.81	98.403	6.84	0.127	1
Blend ratio	2	97.16	97.16	48.581	3.38	0.228	2
CR	2	16.66	16.66	8.329	0.58	0.633	3
Residual error	2	28.75	28.75	14.377	-	-	-
Total	8	339.38	-	-	-	-	-

Table 11 Optimized results

Run	**Biodiesel engine (Optimized Solution)**				**Diesel engine (Normal Solution)**				**Change, %**			
	BTE	BSFC	NOx	Smoke	BTE	BSFC	NOx	Smoke	BTE	BSFC	NOx	Smoke
5	24.04	0.35	1017	9.9	24.574	0.372	1267	14.62	-2.17	-5.91	-19.73	-32.28

5.Discussion

The impact of diesel engine operating parameters, such as engine load, blend ratio, and CR, on the objective function can be assessed through Taguchi design and GRA.

Response tables for the S/N ratio calculated using Taguchi design are presented in *Table 6*. The Delta value is the difference between the largest and the smallest S/N ratio for each parameter. The larger the delta value, the greater is the influence of that control variable. Results show that engine load has rank 1 with the highest delta value, while blend ratio has rank 2, and CR has rank 3. The mean S/N ratio graphs are as shown in *Figure 4* for BTE and *Figure 5* for the combination of BSFC, smoke and NOx, respectively. The interpretation of the graph indicates that the larger the sensitivity of a control characteristic to noise factors, higher the variation in S/N ratios. S/N ratio graphs also confirm that engine load has the greatest impact on the objective function, as compared to the blending ratio and the CR.

The ANOVA results for S/N ratios show that among all three control variables, engine load has the highest contribution (lowest p value) as compared to the contributions of blend ratio and CR. Similar results are obtained from Taguchi design and S/N ratio analysis. Hence, ANOVA has confirmed the Taguchi design approach employed in the study.

The regression model is developed to relate control variables with response variables. This model can be used to determine predicted values of the BTE, BSFC, NOx, and smoke functions. The experimental values and predicted values shall match with good accuracy. The difference between each pair of a predicted value and an experimental value is the residual error. *Table 7* shows that the average error is 1.55% for the entire optimization function. The average error for predicted values of BTE, BSFC, and smoke is below 3.5%. It can be concluded that the regression models are satisfactory in predicting the values of response variables without the need to run actual engine trials.

Figure 6 shows the Taguchi response for the mean S/N ratio of BTE (the larger the better) GRG. For each control variable, the highest value of the means is the optimum value. As the graph illustrates, BTE is maximum if engine load is 75%, blend ratio is 20, and CR is 18. *Figure 7* shows the Taguchi response for the mean S/N ratio of GRG for a combination of BSFC, smoke, and NOx (smaller is better). It is evident that the minimum objective function is achieved if engine load is 75%, blend ratio is 20, and CR is 18. Thus, it is concluded that 75% engine load, 20% blend ratio, and a CR of 18 can attain both objective functions simultaneously.

Confirmation tests are conducted using the optimized control variables on a biodiesel-fueled engine. When compared with baseline diesel engine results, these optimized trials show that optimization has achieved 2.17% less BTE, 5.9% less BSFC, a reduction of 19.7% in NOx, and a reduction of 32.3% in smoke.

5.1Limitations

For three factors with three response levels, Taguchi design and L27 OA can also be employed for optimization. However, this may result in a higher number of investigative efforts and costs. The diesel engine operates beyond the 75% load; however, in the present study, engine load is limited to 75% to fulfil the requirements of the Taguchi design. A complete list of abbreviations is shown in *Appendix I*.

6.Conclusion and future work

In the current study, Taguchi design and the GRA multi-objective optimization method are used to investigate the impact of operating parameters on the performance of a biodiesel-fueled diesel engine. Engine load, blend ratio, and CR are selected operating parameters, while BTE, BSFC, smoke, and NOx are performance parameters.

According to Taguchi design and GRA, the engine load, followed by the blending ratio and the compression ratio, has the biggest effect on the objective function. The ANOVA results further confirm that the engine load, blend ratio, and CR have a weighted percentage influence on the objective function in descending order. The optimum combination is chosen using the GRA based on Taguchi Design. According to its findings, the optimum diesel engine configuration is one with a load of 75%, a biodiesel content of 20%, and 18 CR. To verify the results, the confirmation test is run. This combination reduces smoke emissions by 32.3%, NOx emissions by 19.7%, BTE by only slightly more than 2.17 percent, and BSFC by 5.9% when compared to diesel. The performance of a diesel engine is predicted using a regression model built on the Taguchi design-GRA. The use of GRA in conjunction with Taguchi design would greatly reduce the number of engine trials, their expense, and time, and provide extremely accurate response value estimation.

Future research based on the current work may address topics like the impact of using higher CR and engine loads greater than 100%, as well as the influence of engine variables like injection pressure, start of ignition, and EGR ratio. The use of additives to alter the characteristics of biodiesel fuel can be studied using an extension of the similar Taguchi-GRA method.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contributions statement

Kiran Chaudhari: Conceptualization, investigation, data collection and presentation, writing – original draft, writing – review and editing. **Nilesh P. Salunke:** Data collection, conceptualization, analysis and interpretation of results. **Vijay R. Diware:** Study planning, supervision and draft manuscript preparation, writing – review and editing.

References

[1] Hoang AT, Nižetić S, Olcer AI, Ong HC, Chen WH, Chong CT et al. Impacts of COVID-19 pandemic on the global energy system and the shift progress to renewable energy: Opportunities, challenges, and policy implications. Energy Policy. 2021; 154:1-11.

[2] Bae C, Kim J. Alternative fuels for internal combustion engines. Proceedings of the Combustion Institute. 2017; 36(3):3389-413.

[3] Bisht AS, Thakur NS. Small scale biomass gasification plants for electricity generation in India: resources, installation, technical aspects, sustainability criteria & policy. Renewable Energy Focus. 2019; 28:112-26.

[4] US Energy Information Administration. International energy outlook 2011: with projections to 2035. Energy Information Administration; 2011.

[5] Kalghatgi G, Levinsky H, Colket M. Future transportation fuels. Progress in Energy and Combustion Science. 2018; 69:103-5.

[6] Gautam R, Ansari NA, Thakur P, Sharma A, Singh Y. Status of biofuel in India with production and performance characteristics: a review. International Journal of Ambient Energy. 2022; 43(1):61-77.

[7] Kedia S, Pandey R, Sinha R. Shaping the post-COVID-19 development paradigm in India: some imperatives for greening the economic recovery. Millennial Asia. 2020; 11(3):268-98.

[8] Kalghatgi GT. Developments in internal combustion engines and implications for combustion science and future transport fuels. Proceedings of the Combustion Institute. 2015; 35(1):101-15.

[9] Palani Y, Devarajan C, Manickam D, Thanikodi S. Performance and emission characteristics of biodiesel-blend in diesel engine: a review. Environmental Engineering Research. 2021:1-40.

[10] Reşitoğlu İA, Altinişik K, Keskin A. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. Clean Technologies and Environmental Policy. 2015; 17:15-27.

[11] Ramalingam S, Rajendran S, Ganesan P. Performance improvement and exhaust emissions reduction in biodiesel operated diesel engine through the use of operating parameters and catalytic converter: a review. Renewable Sustainable Energy Reviews. 2018; 81:3215-22.

[12] Chaudhari K, Salunke NP, Diware VR. A comprehensive review on performance improvement of diesel and biodiesel fueled CI engines using additives. International Journal of Performability Engineering. 2021; 17(9):815-24.

[13] Singh B, Srivastava AK, Prakash O. Performance, emission and heat transfer optimisation of variable compression ratio engine fuelled with Ricinus communis biodiesel by Taguchi-gray rational approach. Process Integration and Optimization for Sustainability. 2023:1-17.

[14] Ajith BS, Math MC, Manjunath PGC, Parappagoudar MB. Engine performance and exhaust emissions of Garcinia gummi-gutta based biodiesel–diesel and ethanol blends. SN Applied Sciences. 2021; 3:1-11.

[15] Bahar D, Kirti G, Mounika R, Rajesham S. Study of performance and emission characteristics of a compression ignition engine using tamarind biodiesel. International Journal of Advanced Technology and Engineering Exploration. 2018; 5(43):134-9.

[16] Alawa B, Chakma S. Experimental investigation in compression ratio on performance, combustion and emission of VCR engine using pyrolysis-oil produced from waste plastic materials. Materials Today: Proceedings. 2023; 72:2593-609.

[17] Arun SB, Suresh R, Yatish KV. Study of performance, combustion and emission characteristics of heterogeneous catalyzed yellow oleander biodiesel on compression ignition (CI) engine. Biofuels. 2018:793-800.

[18] Altaie MA. Performance and emission analysis of enriched biodiesel and its combined blends with petrodiesel. Biofuels. 2020; 11(3):251-60.

[19] Lv J, Wang S, Meng B. The effects of nano-additives added to diesel-biodiesel fuel blends on combustion and emission characteristics of diesel engine: a review. Energies. 2022; 15(3):1-27.

[20] Nagappan B, Devarajan Y, Kariappan E, Philip SB, Gautam S. Influence of antioxidant additives on performance and emission characteristics of beef tallow biodiesel-fuelled CI engine. Environmental Science and Pollution Research. 2021; 28:12041-55.

[21] Rathinam S, Bhargava A. Performance study on nanoparticle/biodiesel blends in CI engine. International Journal of Ambient Energy. 2022; 43(1):1373-7.

[22] Gundoshmian TM, Heidari-maleni A, Jahanbakhshi A. Evaluation of performance and emission characteristics of a CI engine using functional multi-walled carbon nanotubes (MWCNTs-COOH) additives in biodiesel-diesel blends. Fuel. 2021; 287:1-10.

[23] Chandran J, Manikandan K, Ganesh R, Baskar S. Effect of nano-material on the performance patterns of waste cooking biodiesel fuelled diesel engine. International Journal of Ambient Energy. 2022; 43(1):2226-30.

[24] Dambhare SG, Kore SS, Pathan FZ, Vahadane M. Diesel engine performance and emission characteristic enhancement using TOPSIS. International Journal of Advanced Technology and Engineering Exploration. 2019; 6(54):126-32.

[25] Jayabal R, Subramani S, Dillikannan D, Devarajan Y, Thangavelu L, Nedunchezhiyan M, et al. Multi-objective optimization of performance and emission characteristics of a CRDI diesel engine fueled with sapota methyl ester/diesel blends. Energy. 2022.

[26] Sivaraja CM, Sakthivel G. Compression ignition engine performance modelling using hybrid MCDM techniques for the selection of optimum fish oil biodiesel blend at different injection timings. Energy. 2017; 139:118-41.

[27] Singh TS, Rajak U, Samuel OD, Chaurasiya PK, Natarajan K, Verma TN, et al. Optimization of performance and emission parameters of direct injection diesel engine fuelled with microalgae spirulina (L.)–response surface methodology and full factorial method approach. Fuel. 2021; 285:1-13.

[28] Balki MK, Erdoğan S, Aydın S, Sayin C. The optimization of engine operating parameters via SWARA and ARAS hybrid method in a small SI engine using alternative fuels. Journal of Cleaner Production. 2020; 258:1-12.

[29] Sivaiah P, Chakradhar D. Modeling and optimization of sustainable manufacturing process in machining of 17-4 PH stainless steel. Measurement. 2019; 134:142-52.

[30] 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; 275:1-12.

[31] Sanjeevannavar MB, Banapurmath NR, Soudagar ME, Atgur V, Hossain N, Mujtaba MA, et al. Performance indicators for the optimal BTE of biodiesels with additives through engine testing by the Taguchi approach. Chemosphere. 2022.

[32] Saravanan S, Kaliyanasunder R, Kumar BR, Rao GL. Effect of design parameters on performance and emissions of a CI engine operated with diesel-biodiesel-higher alcohol blends. Renewable Energy. 2020; 148:425-36.

[33] Daniel SA, Pugazhenthi R, Kumar R, Vijayananth S. Multi objective prediction and optimization of control parameters in the milling of aluminium hybrid metal matrix composites using ANN and Taguchi-grey relational analysis. Defence Technology. 2019; 15(4):545-56.

[34] Ramkumar S, Kirubakaran V. Biodiesel from vegetable oil as alternate fuel for CI engine and feasibility study of thermal cracking: a critical review. Energy Conversion and Management. 2016; 118:155-69.

[35] Yu W, Zhao F. Formulating of model-based surrogates of jet fuel and diesel fuel by an intelligent methodology with uncertainties analysis. Fuel. 2020; 268:1-16.

[36] Ganapathy T, Murugesan KA, Gakkhar RP. Performance optimization of Jatropha biodiesel engine model using Taguchi approach. Applied Energy. 2009; 86(11):2476-86.

[37] Muqeem M, Sherwani AF, Ahmad M, Khan ZA. Taguchi-based combined grey relational and principal component analyses for multi-response optimization of diesel engines. Grey Systems: Theory and Application. 2017; 7(3):408-25.

[38] Venkatanarayana B, Ratnam CH. Selection of optimal performance parameters of DI diesel engine using Taguchi approach. Biofuels. 2019; 10(4):503-10.

[39] Fumo N, Biswas MR. Regression analysis for prediction of residential energy consumption. Renewable and Sustainable Energy Reviews. 2015; 47:332-43.

[40] Agrawal T, Gautam R, Agrawal S, Singh V, Kumar M, Kumar S. Optimization of engine performance parameters and exhaust emissions in compression ignition engine fueled with biodiesel-alcohol blends using Taguchi method, multiple regression and artificial neural network. Sustainable Futures. 2020; 2:1-12.

[41] Abifarin J, Ofodu J. Modeling and grey relational multi-response optimization of chemical additives and engine parameters on performance efficiency of diesel engine. International Journal of Grey Systems. 2022; 2(1):16-26.

[42] Jasper S, Stalin B, Ravichandran M. Experimental investigation and taguchi optimization of turning process parameters for glass fiber reinforced plastics (GFRP). International Journal of Advanced Technology and Engineering Exploration. 2018; 5(47):394-9.

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Appendix I

S. N.	Abbreviation	Description
1	ANN	Artificial Neural Network
2	ANOVA	Analysis of Variance
3	BSFC	Brake Specific Fuel Consumption
4	BTE	Brake Thermal Efficiency
5	CI	Compression Ignition
6	CO	Carbon Monoxide
7	CR	Compression Ratio
8	CRDI	Common Rail Direct Injection
9	DEE	Diethyl Ether
10	DOE	Design of Experiments
11	EGR	Exhaust Gas Recirculation
12	EGT	Exhaust Gas Temperature
13	ELECTRE	Elimination and Choice Translating Reality
14	GRA	Grey Relational Analysis
15	GRC	Grey Relational Coefficients
16	GRG	Grey Relational Grade
17	HC	Hydrocarbon
18	NOx	Nitrogen Oxides
19	MULTIMOORA	Multi-Objective Optimization Based on Ratio Analysis
20	OA	Orthogonal Array
21	PM	Particulate Matter
22	RSM	Response Surface Methodology
23	RTD	Resistance Temperature Detector
24	RPM	Revolutions Per Minute
25	S/N	Signal-to-Noise
26	SWARA	Stepwise Weight Assessment Ratio Analysis
27	TDC	Top Dead Centre
28	TOPSIS	Technique for Order Performance By Similarity to Ideal Solution
29	VCR	Variable Compression Ratio
30	VIKOR	Multi-Criteria Optimization and Compromise Solution