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Research Article

Optimization of Performance and Emission Characteristics of Diesel Engine with Biodiesel Using Grey-Taguchi Method

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Engine performances and emission characteristics of Karanja oil methyl ester blended with diesel were carried out on a variable compression diesel engine. In order to search for the optimal process response through a limited number of experiment runs, application of Taguchi method in combination with grey relational analysis had been applied for solving a multiple response optimization problem. Using grey relational grade and signal-to-noise ratio as a performance index, a particular combination of input parameters was predicted so as to achieve optimum response characteristics. It was observed that a blend of fifty percent was most suitable for use in a diesel engine without significantly affecting the engine performance and emissions characteristics.

1. Introduction

Rudolf Diesel, the father of Diesel engine, demonstrated the first use of vegetable oil in compression ignition engine. He used peanut oil as fuel in his engine. Because of the increase in the crude oil prices and limited reserve of fossils fuels, there has been a renewed focus on usage of vegetable oils as suitable alternative to diesel fuel. They are known as biodiesel, essentially an ester of vegetable oil. A brief discussion of some important research findings related to this field is presented below.

Carraretto et al. [1] conducted experiment on a CI engine firstly on a test bench and later on an urban bus. They observed that with biodiesel, there was an increase in specific fuel consumption and emission of oxides of nitrogen (NO_x). However, carbon monoxide (CO), carbon dioxide (CO_2) emissions were reduced. Raheman and Phadatare [2] observed that Karanja oil methyl ester blended with diesel could be a suitable alternative fuel. Their emission study indicated that CO and NO_x were reduced by a good percentage compared to diesel. Agarwal [3] produced biodiesel from Ratanjyot (Jatropha), Karanja, Nagchampa, and Rubber by using both methyl and ethyl alcohol. He also claimed that biodiesel could be a better alternative to petroleum diesel since there was no need for engine modification.

Raheman and Ghadge [4, 5] carried out experiment using Mahua biodiesel and its blends in a Ricardo E6 engine. They varied the compression ratio from 18 to 20. It had been observed that with an increase in percentage of biodiesel, brake-specific fuel consumption increased while brake thermal efficiency decreased. Rao et al. [6] concluded from his investigation that the vegetable oils were promising alternative fuels for agricultural diesel engines. However, these vegetable oils exhibited slightly inferior performance in respect to higher smoke emission. Kalbande and Vikhe [7] studied the performance of Jatropha and Karanja biodiesel and their blends with diesel. The efficiency of Karanja biodiesel was found to be higher for B20 (20% biodiesel and 80% diesel) and B40 (40% biodiesel and 60% diesel) blend among different combination of Karanja bio-diesel blend. In case of Jatropha, B60 and B80 delivered the maximum efficiency. Fontaras et al. [8] investigated the combustion and emission characteristics of biodiesel using soybean biodiesel in a diesel passenger car complying EURO 2 emission standard. They observed that there had been a problem of cold starting while using soybean biodiesel.

Godiganur et al. [9] observed that after trans-esterification mahua oil showed a similar kind of property as that of diesel. Among the different blends, 20% (B 20) blend was found to be the most suitable. Baiju et al. [10] produced Karanja oil ethyl ester and Karanja oil methyl ester from Karanja oil. Both of them showed good emission characteristics except presence of NO_x being on the higher side. They also claimed that the methyl ester exhibited a better performance than ethyl ester. In a study made by Sahoo et al. [11], Jatropha, Karanja, and Polanga methyl esters were blended with diesel. The maximum power output was obtained from B 50 blend. The smoke emission was found to be reduced in case of biodiesel at full throttle. However, CO and NO_x emission increased a bit compared to diesel.

Murugesan et al. [12] observed that methyl ester of Karanja oil could be directly used in CI engines without any modification. In case of biodiesel, brake-specific fuel consumption was found to be higher than that of diesel and the emission characteristics were reduced. They noted that the B 20 Blend was the most suitable alternative for diesel. Duraisamy et al. [13] carried out experiment by mixing the methyl esters of Jatropha, Pongamia, Mahua, and Neem seed oil. In engine performance study, the B 40 biodiesel showed a thermal efficiency almost equal to that of diesel. Emission study indicated a reduction of hydrocarbon (HC) and carbon monoxide (CO) at any percentage mix but increased in NO_x and smoke density.

The review of the literature clearly indicated that researchers have put sincere attempt to find out the suitable alternative to diesel fuel without going through major engine modification. In most cases, they varied different input parameters, such as load, blend of fuels, and compression ratio, one at a time and observed the performance and emission characteristics of the engine. However, it may be pointed out that the number of input parameters was more than one and response of the system was not unidirectional. In other words, for a few responses lower values were better while for others higher values were better. As a result, the study became a multiresponse optimization problem that required a systematic approach to ascertain the number of experiments to be made in order to cover the entire domain of input parameters.

Based on the above-mentioned observations, an attempt was made to determine an optimum combination of input parameters that maximizes response characteristics. Design of experiment was carried out in such a fashion that the number of experiments to be carried out should be minimum while output data to be maximum. In the present investigation, Karanja biodiesel was taken as a fuel for experimentation. The performance test of biodiesel was conducted on a Kirloskar-made single-cylinder variable-compression-ratio engine.

The objective of the study was to determine the optimum blend of Karanja biodiesel and diesel oil that would result in a better engine performance along with minimum emission characteristics. Following Grey-Taguchi approach, a multiresponse problem was converted into a single one using weighting factors of grey relational analysis. Lastly, validation of the result was carried out by actual experimentation.

Table 1: Design factors and their levels.

Design factor	Levels				
	1	2	3	4	5
Load in kg (A)	4	8	12	16	20
Blend (B)	B 0	B 25	B 50	B 75	B 100
Compression Ratio (C)	14 : 1	15 : 1	16 : 1	17 : 1	18 : 1

Table 2: Fuel property table of diesel and Karanja oil methyl ester.

Property	Diesel	Karanja bio-diesel	ASTM standards
Specific gravity	0.824	0.880	D 3142-05
Density (gm/cc)	0.717	0.766	D 1298
API gravity	40.24	29.3	D 4052
Ash content (%)	0.060	0.094	D 874
Water content (%)	0.070	1.66	D 2709
Carbon residue (%)	0.080	0.530	D 189
Flash point (°C)	66	190	D 6450
Pour point (°C)	15	4	D 5949
Fire point (°C)	72	395	D 3828
Calorific value (kcal/kg)	10056.23	8095.24	D 5453-93
Viscosity (cSt)	4.2	32.3	D 2171
Cetane number	48	56.61	D 613

2. Methodoloy

In order to determine the optimum blend of Karanja biodiesel and diesel on engine performance and emission characteristics of a variable compression ignition engine, three major input parameters, namely, load (A), blend of fuels (B), and compression ratio (C) were considered to be main design factors. Each factor was further subdivided into five levels as shown in Table 1. The levels and their ranges were selected based on the previous findings as described on the open literature. All together, eight response (output) parameters were analysed; three of them belonged to performance characteristics of the engine, namely, brake power (BP), brake-specific fuel consumption (BSFC), and brake thermal efficiency (BTE). The rest five responses were emission characteristics of the engine, namely, CO, CO_2, O_2, NO_x, and HC. The relevant fuel properties of diesel and Karanja biodiesel were tested as per ASTM standard (Table 2).

Since there were many input and output variables, a large number of experiments had to be conducted to cover entire domain. A well-designed experiment could produce significantly more information with fewer runs compared to an unplanned experimentation. Accordingly, Taguchi's parameter design method was adopted to understand the effect of different input parameters on response. However, conventional Taguchi method could effectively establish optimal parameter settings for single performance characteristics. Since multiple performance characteristics with conflicting goals were present, Grey-Taguchi method was adopted to generate a single response from different performance characteristics.

2.1. Taguchi Analysis. The Taguchi method, developed by Dr. Taguchi, involved reduction of variation in a process through robust design of experiments. A standard orthogonal array could be selected for designing the experimental plan based on the total number of degree of freedom, number of factor, and level of each factor. In the present study an orthogonal array (L25) was considered having 25 rows corresponding to the total number of tests (24 degrees of freedom) with 3 columns of input parameters each having 5 levels.

2.1.1. Grey Relational Analysis. Signal-to-noise ratio (S/N) is a measure used in science and engineering for comparing the level of a desired signal to the level of background noise. Since the present study aimed at optimizing eight response parameters, it might so happen that the higher S/N ratio for one performance characteristic may exhibit a lower S/N ratio for another characteristic. Therefore, the overall evaluation of the S/N ratio was required for the optimization of multiple performance characteristics. Grey relational analysis [14, 15] was found to be an efficient tool for analyzing this kind of problem. It was used to determine the key factors of the system and their correlations. The key factors were identified by the input and output sequences.

In the present paper, the experimental results were first normalized in the range between zero and one. Afterwards, the grey relational coefficients were obtained from the normalized experimental data to express the relationship between the desired and actual experimental data. Lastly, the overall grey relational grade was obtained by averaging the grey relational coefficients corresponding to each selected process response. The evaluation of the multiple process response was based on the grey relational grade. This method was employed to convert a multiple response process optimization problem into a single response problem with the objective function of overall grey relational grade. The corresponding level of parametric combination with the highest grey relational grade was considered as the optimum process parameter.

Therefore, when the target value of the original sequence was "the higher-the-better" the original sequence was normalized as follows:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}. \quad (1)$$

When the purpose was "the lower-the-better" the original sequence was normalized as follows

$$x_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)}, \quad (2)$$

$y_i(k)$ is the original reference sequence, $x_i(k)$ is the sequence for comparison, $i = 1, 2, \ldots, m$, $k = 1, 2, 3, \ldots, n$, with m, n being total no of experiments and responses. min $y_i(k)$ is the smallest value of $y_i(k)$ and max $y_i(k)$ is the highest value of $y_i(k)$.

Here, $x_i(k)$ was the value after the grey relational generation. An ideal sequence was $x_0(k)$. The grey relational grade revealed the relational degree between the experimental run sequences [$x_0(k)$ and $x_i(k)$, $i = 1, 2, \ldots m$].

The grey relational coefficient $\xi_i(k)$ could be calculated as

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{oi}(k) + \psi\Delta_{\max}}, \quad (3)$$

where

$$\Delta_{0i} = \left\| x_0(k) - x_i(k) \right\| \quad (4)$$

was the difference of the absolute value between $x_0(k)$ and $x_i(k)$. $\Delta_{\min}$, $\Delta_{\max}$ were the minimum and maximum values of the absolute differences (Δ_{0i}) of all comparing sequences. The purpose of distinguishing coefficient ψ ($0 \le \psi \le 1$) was to weaken the effect of $\Delta_{\max}$ when it became too large. In the present analysis, the value of ψ was taken as 0.5.

After averaging the grey relational coefficients, the grey relational grade γ_o was be calculated. The higher value of grey relational grade was considered to be the stronger relational degree between the ideal sequence $x_0(k)$ and the given sequence $x_i(k)$. The ideal sequence $x_0(k)$ was supposed to be the best process response in the experimental layout. Thus the higher relational grade implied that the corresponding parameter combination was closer to the optimal.

2.2. Grey Relational Grade Generation. With respect to increase in blend of fuel, engine performances exhibited demising nature while emission characteristics showed increasing trend. Since reduction of engine emission could be achieved by means of different types of external equipments, such as exhaust gas recirculation (EGR), the analysis was carried out in such a way that the performance of the engine did not suffer even when diesel was replaced by blend of Karanja biodiesel and diesel oil.

Accordingly, while converting multiple grey relation grades, the value of weighting factor in engine performance was taken higher than that of emission characteristics. When appropriate, weighting factors β was used with the sequence values; the general form of grey relational grades became

$$\gamma_o = \sum_{k=1}^{n} \xi_i(k)\,\beta\gamma_i \ldots, \quad \sum \beta = 1. \quad (5)$$

In the present case, the following values of weighting factors had been taken for different responses: brake power = 0.3, brake-Specific fuel consumption = 0.3, brake thermal efficiency = 0.3, CO emission = 0.01, HC emission = 0.01, CO_2 emission = 0.03, O_2 emission = 0.01, and NO_x emission = 0.04.

The different sequence value of weighting factor (β) could be specified from experience, or appropriate weights could be computed by processes such as singular value decomposition using preliminary grey relational grade values. One should note that the use of weighting factors would not be equivalent to changes in the sequence value units used or the choice made for sequence normalization [15, 16].

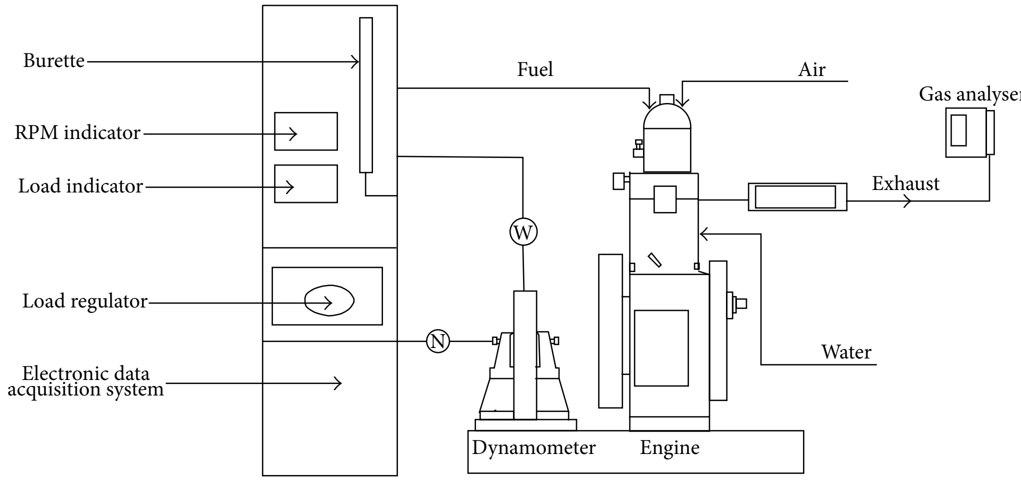

Figure 1: Schematic diagram of experimental setup.

3. Experimental Setup

The engine was directly coupled to an eddy current dynamometer using flexible coupling (Figure 1). The output of the eddy current dynamometer was fixed to a strain gauge load cell for measuring load applied to the engine. A gas analyzer was used for the measurement of carbon monoxide (CO), oxides of nitrogen (NO_x), unburned hydrocarbon (HC), oxygen (O_2), and carbon dioxide also. CO was measured as percentage volume and NO_x, HC was measured as n-hexane equivalent, parts per million (ppm). A glass burette was provided at the fuel tank for the measurement of fuel consumption by volume per minute. For this purpose a stopwatch was used to measure the diesel and biodiesel fuel separately. The engine was subjected to different loads (4 kg, 8 kg, 12 kg, 16 kg, and 20 kg), corresponding to load ranging from 20% at the lowest level and 100% at the highest level. Knowing the dynamometer shaft length (0.185 m), torque applied on the engine was determined. All the experiments were carried out at a rated speed of 1500 rpm maintaining 23° BTDC (before top dead centre) for both diesel and biodiesel. The experiments were conducted using B 0 (0% Karanja, 100% diesel), B 25 (25% Karanja, 75% diesel), B 50 (50% Karanja, 50% diesel), B 75 (75% Karanja, 25% diesel), and B 100 (100% Karanja) under different load conditions on the engine and the results are presented in Table 4. The compression ratios (CR) were varied (14 : 1, 15 : 1, 16 : 1, 17 : 1, and 18 : 1). During the experiment, whenever fuel was changed, the fuel lines were cleaned and the engine was left to operate for 30 min to stabilize at its new condition. Figure 2 shows the whole engine assembly used for the experiment. The specifications of the engine and eddy current dynamometer are given in Table 3. The engine exhaust (CO, HC, CO_2, O_2, and NO_x) was analyzed and calculated by AVL DIG AS 444 gas analyzer fitted with DIGAS SAMPLER at the exhaust. Specification of the gas analyzer is furnished in Table 3.

Table 3: Specifications of engines and instruments.

Specifications of the engine	
Manufacturer	Kirloskar Oil Engines Ltd.
Model	TV 1
Type	Four stroke, water cooled
No. of cylinder	One
Rated power	5.2 kW @ 1500 RPM
Compression ratio	11 : 1 to 18 : 1
Bore	87.5 mm
Stroke	110 mm
Injection timing	23° before TDC
Method of loading	Eddy current dynamometer
Specifications of the dynamometer	
Manufacturer	Saj Test Plant Pvt. Ltd.
Model	AG10
Type	Eddy current, water cooled
Specifications of the AVL gas analyzer	
Manufacturer	AVL India Pvt. Ltd.
Type	DiGas 444
Model	5 gas analyzer

4. Results and Discussions

Different combinations of three input variables, namely, load, compression ratio (CR), and blends were considered and eight output responses (output) were obtained. In order to search for the optimal process condition through a limited number of experiment, Taguchi's L25 orthogonal array had been selected. Therefore, total number of experiments conducted was 25 ($i = 25$).

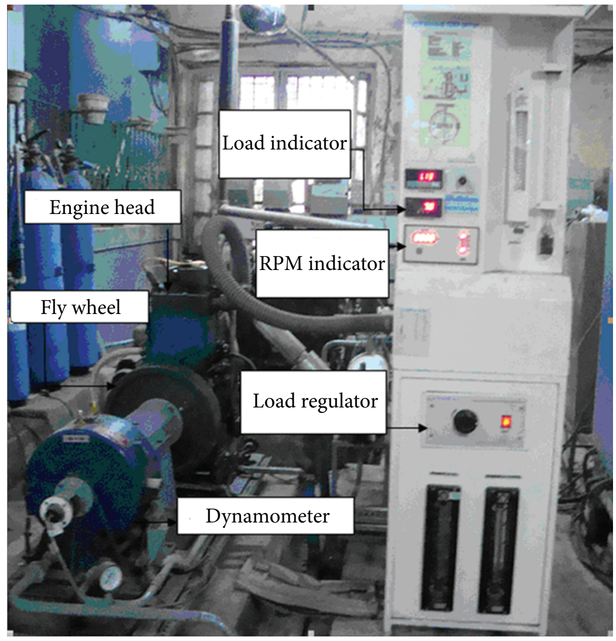

Figure 2: The engine assembly used for the experiment.

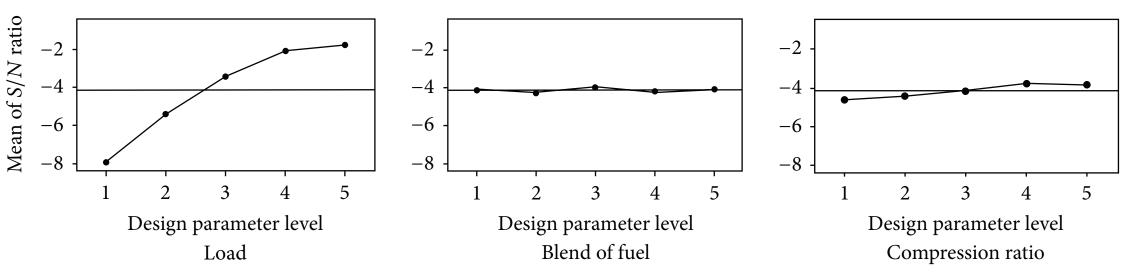

Figure 3: The main effect plots for S/N ratio.

Following grey relation methods, experimental results were normalized in the range between zero to one. However, it was noted that out of eight responses shown in columns 5 to 12 of Table 4, higher target values of three responses (BP, BTE, and O_2) were better while those for the rest five responses, lower values were desirable. Accordingly, during normalization of data, target values of BP, BTE, and O_2 parameters were calculated using (1) and the rest were obtained from (2). Furthermore, using (3), grey relation coefficients $\xi_i(k)$ were evaluated for each response.

In order to determine the grey relational grades (4) had been used. Considering appropriate weighing factors, the overall grey relation grade, thus, obtained is shown in Table 5.

4.1. Analysis of Signal-to-Noise Ratio. Since the traditional method could not capture the variability of the results signal-to-noise ratio was introduced to analyze the grey relation grade. The signal-to-noise ratio for overall grey relation grade was calculated from (6) presented below. Since the main aim of the experiment was always to determine the highest possible S/N ratio for the result, the higher-the-better (HB) criteria was sort for. A high value of S/N implied that the signal was much higher than the random effects of the noise factors:

$$S/N = -10 \log \left[\frac{1}{N_i} \sum_{u=1}^{N_i} \frac{1}{y_u^2} \right], \qquad (6)$$

where i = experiment number, u = trial number, and N_i = number of trials for experiment i.

The analysis of the output response was done by minitab software. Table 6 shows the average of the selected characteristics for each level of the design factors. The graphical representation of S/N ratio for three factors, load, blend, and compression ratio, is shown in the main effect plot (Figure 3). If the line for a particular parameter is nearly horizontal, the parameter has less significant effect on response. On the other hand, a parameter for which the line has the highest inclination will have the most significant effect. It had been observed from the plot that parameter A (load) had the most significant effect among the three parameters.

Table 4: Experimental results of engine performances and emissions.

No. of exp.	Factors			Engine performance			Emission characteristics				
	Load (%)	Blend	Compression ratio	BP (kw)	BSFC (gm/kw-hr)	BTE	CO (%vol)	HC (ppm/vol)	CO_2 (%vol)	O_2 (%vol)	NO_x (ppm /vol)
1	20.00	0	14	1.223	632.784	13.521	0.35	58	4.8	14.2	117
2	20.00	25	15	1.138	624.431	14.207	0.36	70	4	15.03	105
3	20.00	50	16	1.200	509.584	18.029	0.17	43	3.8	15.53	218
4	20.00	75	17	1.190	474.778	20.317	0.08	17	4	15.45	400
5	20.00	100	18	1.150	599.332	17.734	0.06	11	4.2	15.36	596
6	40.00	0	15	2.330	365.421	23.414	0.06	25	5.6	13.64	702
7	40.00	25	16	2.260	362.915	24.445	0.07	41	5.6	13.33	726
8	40.00	50	17	2.250	345.877	26.562	0.04	37	5.4	13.71	843
9	40.00	75	18	2.342	337.708	28.564	0.05	13	6	13.15	963
10	40.00	100	14	2.443	399.555	26.601	0.21	23	5.8	13.3	247
11	60.00	0	16	3.403	271.750	31.485	0.01	22	7.3	11.42	1154
12	60.00	25	17	3.351	293.691	30.207	0.02	31	7.4	11.28	1316
13	60.00	50	18	3.475	271.973	33.780	0.02	39	7.2	11.5	1130
14	60.00	75	14	3.282	327.154	29.485	0.1	32	7.8	10.86	859
15	60.00	100	15	3.431	317.996	33.424	0.07	18	7.3	11.62	983
16	80.00	0	17	4.469	255.027	33.550	0.02	7	1.1	19.25	123
17	80.00	25	18	4.497	255.320	34.747	0.04	34	9.5	8.59	1240
18	80.00	50	14	4.319	283.192	32.442	0.08	55	9.6	8.6	1298
19	80.00	75	15	4.326	287.354	33.569	0.05	30	9.3	9.05	1337
20	80.00	100	16	4.412	299.319	35.510	0.05	21	9	9.57	1463
21	100.00	0	18	5.272	277.365	30.848	0.32	16	4.5	14.69	482
22	100.00	25	14	5.570	284.662	31.165	0.73	84	11.6	5.29	1209
23	100.00	50	15	5.411	287.639	31.940	0.3	65	11.3	6.06	1350
24	100.00	75	16	5.281	299.598	32.197	0.17	39	11.2	6.57	1360
25	100.00	100	17	5.539	300.610	35.357	0.12	29	11.1	6.81	1410

The optimum process parameter combination corresponding to minimum emission and better engine performance was indicated by the maximum value for signal-to-noise ratio for each input parameter. Thus, from Table 6 and Figure 3, the optimum process parameter combination was found to be *A5B3C4*, that is, load at 100%, blend of fuel at B 50 (50% Karanjal, 50% diesel), and a compression ratio of 17 : 1.

4.2. Confirmation Tests. After the optimum process parameter was selected from the S/N ratio plot, the objective was to predict the result and verify it by actual experimentation. First, corresponding to optimum level of process parameters, the estimated S/N ratio ($\hat{\gamma}$) was evaluated using the following equation

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{o} \left(\overline{\gamma_i} - \gamma_m\right), \quad (7)$$

where γ_m is the total mean of S/N ratio, $\overline{\gamma_i}$ is the mean of S/N ratio for optimum level, and o is the number of the main design factors that affect the output responses. Following (7), the estimated value of $\hat{\gamma}$, corresponding to *A5B3C4,* was obtained as −1.28942.

In order to verify our estimated value, an experiment was actually carried out with *A5B3C4* combination. The corresponding S/N ratio of the grey relational grade was found to be −1.55769 as shown in Table 7. The values of grey relation grade are also mentioned in the table.

In addition, an initial parameter combination of *A3B3C3* (load 60%, blend of fuel B 50, and compression ratio 16) had been chosen as it lay at the mean level. Again, an actual experiment was conducted with this combination and the value of $\hat{\gamma}$ thus obtained was also shown in Table 7. It had been observed that the increase in the S/N ratio from the initial parameter combination to the optimal parameters was 0.38181.

5. Conclusion

In this experimental study, the effect of Karanja oil methyl ester diesel fuel blends (B 0, B 25, B 50, B 75, B 100) on engine

Table 5: Calculated grey relational coefficient of all responses and grey relational grade with weightage.

Weighting factor	0.3	0.3	0.3	0.01	0.01	0.03	0.01	0.04	Total = 1
No. of exp.	Grey relational coefficient								Overall grey relation grade
	BP	BSFC	BTE	CO	HC	CO_2	O_2	NO_x	
1	0.33765	0.333333	0.333333	0.514286	0.430168	0.586592	0.43927	0.982634	0.373445
2	0.333333	0.338321	0.340414	0.507042	0.37931	0.644172	0.417464	1	0.378041
3	0.33642	0.425944	0.386093	0.692308	0.516779	0.660377	0.405343	0.857323	0.417256
4	0.335961	0.462224	0.419843	0.837209	0.793814	0.644172	0.407235	0.697125	0.435404
5	0.333886	0.354246	0.382147	0.878049	0.905882	0.628743	0.409384	0.580342	0.38742
6	0.406158	0.631127	0.476157	0.878049	0.681416	0.538462	0.455316	0.532132	0.512611
7	0.400941	0.636456	0.498413	0.857143	0.531034	0.538462	0.464714	0.522308	0.517082
8	0.400289	0.67522	0.551299	0.923077	0.562044	0.549738	0.453247	0.479181	0.544128
9	0.407054	0.695535	0.612821	0.9	0.865169	0.517241	0.47035	0.44177	0.570799
10	0.414748	0.566512	0.552407	0.642857	0.706422	0.527638	0.465644	0.82704	0.527902
11	0.505474	0.918667	0.732055	1	0.719626	0.458515	0.532418	0.39294	0.698241
12	0.499549	0.830083	0.674644	0.972973	0.616	0.454545	0.538165	0.359259	0.649848
13	0.513915	0.917668	0.864036	0.972973	0.546099	0.462555	0.529189	0.398474	0.738431
14	0.491898	0.723657	0.646022	0.8	0.606299	0.439331	0.556175	0.473831	0.60921
15	0.508724	0.749971	0.840584	0.857143	0.777778	0.458515	0.524418	0.436095	0.68211
16	0.667872	1	0.848695	0.972973	1	1	0.333333	0.974175	0.853667
17	0.673761	0.998456	0.935102	0.923077	0.587786	0.384615	0.678988	0.374311	0.827772
18	0.638985	0.870237	0.781823	0.837209	0.445087	0.381818	0.678328	0.362714	0.730059
19	0.640462	0.853863	0.850008	0.9	0.626016	0.390335	0.649907	0.355311	0.748546
20	0.656787	0.810048	1	0.9	0.733333	0.39924	0.619893	0.333333	0.785884
21	0.881464	0.894241	0.702223	0.537313	0.810526	0.606936	0.426129	0.642992	0.806833
22	1	0.864383	0.716782	0.333333	0.333333	0.333333	1	0.380819	0.809582
23	0.933053	0.852765	0.754927	0.553846	0.398964	0.339806	0.900645	0.352911	0.799523
24	0.884278	0.809076	0.768489	0.692308	0.546099	0.34202	0.845036	0.351086	0.778791
25	0.986204	0.805587	0.986363	0.765957	0.636364	0.344262	0.821176	0.342238	0.875081

performance and exhaust emissions were investigated. The engine performance and emission characteristics had been analysed in the context of applicability of blend of Karanja oil methyl ester with conventional diesel as a suitable alternative fuel resource.

In the study, an attempt was made to optimize the engine responses comprising of eight different parameters when three input parameters were varied simultaneously. Since the investigation clearly indicated possibility of a large number of test combinations, design of experiment was carried out using Taguchi method to limit the number of experiments by the formation of orthogonal array, yet without sacrificing significant information.

Complexity of the optimization problem was evident from the fact that the responses were not unidirectional. Subsequently, multiresponse problem was converted into a single one with the application of weighting factors of grey relational analysis and optimum solution was obtained from the test data.

Table 6: Response for the signal-to-noise ratio.

Level	Load (A)	Blend of fuel (B)	Compression ratio (C)
1	−8.011	−4.144	−4.595
2	−5.448	−4.280	−4.407
3	−3.425	−4.038	−4.141
4	−2.071	−4.217	−3.757
5	−1.795	−4.072	−3.849
Delta	6.216	0.242	0.838
Rank	1	3	2

The total mean S/N ratio $(\overline{\gamma_i}) = -4.15$.

Finally finding of experimental study was validated with the result obtained through actual experimentation. It was concluded that B 50 blend was found to be most suitable blend for diesel engine without significantly affecting the

Table 7: Results of confirmation test.

	Initial parameter combination	Optimal parameter combination	
		Prediction ($\hat{\gamma}$)	Experimentation
Level	$A3B3C3$	$A5B3C4$	
S/N ratio	−1.93950	−1.28942	−1.55769
Grey relation grade	0.79988	0.846867	0.835825

engine performance and emissions characteristics, corresponding compression ratio and engine load being 17 and 80% respectively.

Conflict of Interests

The authors of the paper, do not have a direct financial relation with the commercial identity mentioned in their paper that might lead to a conflict of interests for any of the authors.

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