This data article presents the experimental data set on the optimization of four important parameters which are type of blending fuel, blending ratio, compression ratio and injection timing for four objective functions namely higher brake thermal efficiency, lower brake specific fuel consumption, lower oxides of nitrogen emission and lower unburnt hydrocarbon emission using grey relational analysis and orthogonal array based experimental design. Each parameter was fixed with three levels and L9 orthogonal array has been chosen for experimental analysis. The data obtained from the experimental work reported that butanol as blending fuel, 40% of maximum blending ratio, compression ratio of 16:1 and injection timing of 26 °CA before top dead centre were identified as optimized set of parameters.

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1. Data

This data article is presenting the data set on parametric optimization of four key parameters such as compression ratio, type of blending fuel, blending ratio and injection timing for four different objectives namely higher brake thermal efficiency, lower brake specific fuel consumption, lower oxides of nitrogen emission, and lower unburnt hydrocarbon emission.
nitrogen emission and lower unburnt hydrocarbon emission using grey relational analysis and orthogonal array based experimental design and statistical analysis. Experimental design was carried out using L9 orthogonal array and experimental results were given in Table 6 [1]. Further grey relational analysis was performed and related data were present in Tables 7 and 8. The mean analysis and range analysis were conducted and results were plotted in Figs. 4 and 5 respectively. Finally percentage contribution of each parameter was calculated and presented in Table 10. Confirmation test was conducted results were given in Table 11 [2].

2. Experimental design, materials, and methods

The step by step methodology followed in this research work is shown in Fig. 1. In the first step the four objectives of the research work were fixed as higher brake thermal efficiency, lower brake specific fuel consumption, lower oxides of nitrogen emission and lower unburnt hydrocarbon emission. In the second step four process parameters (two engine parameters and two blending fuel parameters) were chosen. Next three levels of each parameters were fixed. The selected parameters and their levels were given in Table 1. Suitable orthogonal array was selected based on number of parameters and number of levels in the step 4 and given in Table 2. Designed experiments were carefully conducted and data were recorded [1]. To convert the multi-objective optimization problem in to single objective optimization problem grey relational analysis (GRA) was performed in step 6. GRA is a simple and accurate mathematical technique to find an appropriate solution for real time multivariate problems by computing grey relational grade. Once the grey relational grade was computed statistical analyses such as analysis of means, analysis of range and analysis of variance were performed in step 7. In the next step optimized set of parameters were selected [3]. In the final step a confirmation experiment was conducted and results were validated.
2.1. Chemicals and materials used

Raw pongamia pinnata oil was purchased from the local market, 85% pure laboratory grade potassium hydroxide in pellet form, concentrated sulphuric acid and methanol with 99% purity were used for preparation of biodiesel. 99% pure methanol, ethanol and butanol were purchased and used for engine experiments.

2.2. Preparation of biodiesel

The free fatty acid value of Pongamia pinnata oil was found to be 8.78%. To reduce the FFA value, first acid catalytic esterification was done with 6:1 M ration of methanol to oil and 1% (w/w) sulphuric acid. The FFA value was reasonably reduced to 1.35% and then transesterification was processed with 6:1 M ration of methanol to oil, 1% (w/w) KOH, 90 minutes reaction time, 60 °C process temperature, and stirring speed of 500 rpm. Then the products were settled in settling flask for 24 hours and pure biodiesel Pongamia Pinnata Methyl Ester (PPME) was separated from crude glycerol [4]. Physi-chemical properties of prepared biodiesel, diesel, methanol, ethanol and butanol were tested using respective ASTM standard procedure for each property and listed in Table 3.

2.3. Experimental setup and procedure

The experimental setup consists of a Kirloskar single cylinder four stroke direct injection variable compression ratio engine coupled with an eddy current dynamometer. AVL 444 model 5 gas analyzer for measurement of various pollutants from engine exhaust was also equipped with experimental setup. The detailed specification of the test engine is given in Table 4. The schematic and photographic views of test setup are shown in Figs. 2 and 3 respectively. The list of instruments used, range of measurement, accuracy, measurement technique and percentage uncertainties are given in Table 5. A set of experiments given in L9 orthogonal array were conducted at rated full load, at the rated constant speed of 1500 rpm. Three repetitions of each experiment was conducted and the mean value of the trials has been taken into consideration. Once the engine has attained the rated speed during each experiment, time to consume 20 cm³ of fuel and emissions such as UBHC and NOx were recorded [5,6].

2.4. Grey relational analysis

Grey relational analysis is one of the reliable statistical method to convert multi-objective optimization problem in to single objective optimization problem. In GRA the data collected from experiments are known as original sequence. The original sequence collected from experiments for different objective performance characteristics are in different dimensions. They should be normalized between 0 and 1. The normalized value of the original sequence is called as comparability sequence. Subsequently, the deviation sequence is calculated from the comparability sequence. For calculating deviation sequence, reference sequence should first set as highest normalized value. Then the grey relational coefficient is calculated. In grey relational coefficient the value of distinguishing coefficient should be set any value between 0 and 1. The distinguishing coefficient can be adjusted by the decision

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Table 1
Selected parameters and levels.

| Parameters                  | Levels |
|-----------------------------|--------|
| A Type of Blending Fuel     | Methanol Ethanol Butanol |
| B Blending Ratio (%)        | 20     30     40     |
| C Compression Ratio         | 14     16     18     |
| D Injection Timing (°CA)    | 20     23     26     |

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Table 2
Selected L9 orthogonal array for four parameters at three levels (3<sup>4</sup>).

| Experiment no. | Parameters and their levels | A | B | C | D |
|----------------|-----------------------------|---|---|---|---|
| 1              |                            | 1 | 1 | 1 | 1 |
| 2              |                            | 1 | 2 | 2 | 2 |
| 3              |                            | 1 | 3 | 3 | 3 |
| 4              |                            | 2 | 1 | 2 | 3 |
| 5              |                            | 2 | 2 | 3 | 1 |
| 6              |                            | 2 | 3 | 1 | 2 |
| 7              |                            | 3 | 1 | 3 | 2 |
| 8              |                            | 3 | 2 | 1 | 3 |
| 9              |                            | 3 | 3 | 2 | 1 |

Table 3
Physicochemical properties of test fuels.

| Properties                      | Diesel | PPME | Methanol | Ethanol | Butanol |
|---------------------------------|--------|------|----------|---------|---------|
| Chemical formula                | C<sub>10</sub>H<sub>18</sub> | Fatty acid group of C6-C24 | CH<sub>3</sub>OH | C<sub>2</sub>H<sub>5</sub>OH | C<sub>4</sub>H<sub>9</sub>OH |
| Density (gm/cc)                 | 0.83   | 0.873| 0.792    | 0.789   | 0.81    |
| Kinematic viscosity (mm<sup>2</sup>/s) | 3.11   | 7.82 | 0.59     | 1.52    | 3.6     |
| Calorific value (MJ/kgK)        | 41860  | 38600| 22700    | 26800   | 33100   |
| Cetane number                   | 48     | 45   | 5        | 8       | 25      |
| Flash point                     | 63     | 135  | 11       | 14      | 35      |

Table 4
Specifications of test engine.

| Details                          | Specification |
|----------------------------------|---------------|
| Engine                           | Single cylinder, 4 stroke, water cooled |
| Make                             | Kirloskar     |
| Stroke                           | 110 mm        |
| Bore                             | 87.5 mm       |
| Capacity                         | 661 cc        |
| Power                            | 3.5 kW        |
| Rated speed                      | 1500 rpm      |
| Compression Ratio range          | 12:1 to 18:1  |
| Injection variation              | 0 - 30° CA BTDC (23° CA BTDC standard) |
| Dynamometer                      | Eddy current, water cooled |
| Piezo sensor                     | Range 350 Bar, (Combustion & Diesel injection line) |
| Crank angle sensor               | Resolution 1 Deg, Speed 5500 rpm with TDC pulse. |
| Data acquisition device          | NI USB-6210, 16-bit, 250kS/s. |
| Temperature sensor               | Type K Thermocouple |
| Load sensor                      | Strain gauge type Load cell, range 0–50 Kg |

Table 5
List of instruments, range of measurement, accuracy, measurement technique and percentage uncertainties.

| Name of the instrument           | Range of measurement | Accuracy | Measurement technique | Percentage uncertainties |
|----------------------------------|----------------------|----------|-----------------------|--------------------------|
| AVL 444 – 5 gas analyzer        | CO – 0–10% vol       | 0.01% vol| NDIR principle        | ±0.2                     |
|                                  | CO<sub>2</sub> - 0 - 20% vol | 0.1% vol| NDIR principle        | ±0.15                    |
|                                  | HC – 0 - 20000 ppm   | 10 ppm vol| Electrochemical      | ±0.05                    |
|                                  | NO<sub>x</sub> – 0 – 5000 ppm | 1 ppm vol| Electrochemical      | ±0.02                    |
| EGT indicator                    | 0–1000 °C            | ±1 °C    | K type thermocouple   | ±0.15                    |
| Engine speed measuring unit     | 0–10000 rpm          | ±10 rpm  | Magnetic pickup       | ±0.1                     |
| Load measuring unit             | 0–50 kg              | ±0.1 kg  | Strain gauge type load cell | ±0.2                    |
| Fuel Measuring burette          | 0–100 cm<sup>3</sup> | ±0.1 cm<sup>3</sup> |                       | ±0.1                     |
| Stop watch                      | 0.6 sec              | ±0.6 sec |                       | ±0.2                     |
| Air flow meter                  | 0.2–20 m/s           | ±0.1 m/s | Hot wire anemometer   | ±0.1                     |
maker exercising judgment and in this study it is set as 0.5. Finally the grey relational grade is computed by averaging the grey relational coefficients of all individual responses. Important relations used in grey relational analysis are given below [7].

The normalization can be done by the following relations,

For higher-the-better

$$x_i^*(z) = \frac{x_i^o(z) - \min x_i^o(z)}{\max x_i^o(z) - \min x_i^o(z)}$$

(1)

For lower-the-better

$$x_i^*(z) = \frac{\max x_i^o(z) - x_i^o(z)}{\max x_i^o(z) - \min x_i^o(z)}$$

(2)

The deviation sequence is computed using the following relation,

$$\Delta_{ai}(z) = ||x_i^o(z) - x_i^*(z)||$$

(3)

The grey relational coefficient is calculated using the following relation

$$\xi_i(z) = \frac{\Delta min + \zeta \Delta max}{\Delta_{ai}(z) + \zeta \Delta max}$$

(4)

$$\Delta min = \min_{\forall i \in i} \min_{\forall k} ||x_k^o(z) - x_i^*(z)||$$

(5)

$$\Delta max = \max_{\forall i \in i} \max_{\forall k} ||x_k^o(z) - x_i^*(z)||$$

(6)

The grey relational grade is calculated using the following relation

$$Y_i = \frac{1}{N} \sum_{z=1}^{N} \xi_i(z)$$

(7)

where.

**Table 6**

Experimental conditions and response sequence.

| Experiment Number | Parameters | Response Sequence |
|-------------------|------------|------------------|
|                   | A | B | C | D | BTE (%) | BSFC (kg/kW-hr) | NOx (ppm) | UBHC (ppm) |
| 1                 | M | 20 | 14 | 20 | 25.76 | 0.54 | 897 | 80 |
| 2                 | M | 30 | 16 | 23 | 24.93 | 0.77 | 703 | 93 |
| 3                 | M | 40 | 18 | 26 | 26.05 | 0.52 | 690 | 67 |
| 4                 | E | 20 | 16 | 26 | 25.85 | 0.48 | 711 | 59 |
| 5                 | E | 30 | 18 | 20 | 24.07 | 0.59 | 686 | 90 |
| 6                 | E | 40 | 14 | 23 | 20.37 | 0.75 | 761 | 67 |
| 7                 | B | 20 | 18 | 23 | 28.28 | 0.47 | 803 | 85 |
| 8                 | B | 30 | 14 | 26 | 27.96 | 0.49 | 813 | 89 |
| 9                 | B | 40 | 16 | 20 | 29.81 | 0.44 | 786 | 51 |
Table 7
Normalized sequence and deviation sequence.

| Experiment Number | Normalized Sequence | Deviation Sequence |
|-------------------|---------------------|--------------------|
|                   | BTE (%) BSFC (kg/kW-hr) NOx (ppm) UBHC (ppm) | BTE (%) BSFC (kg/kW-hr) NOx (ppm) UBHC (ppm) |
| 1                 | 0.5710 0.6970 0.0000 0.3095 | 0.4290 0.3030 1.0000 0.6905 |
| 2                 | 0.4831 0.0000 0.9194 0.0000 | 0.5169 1.0000 0.0806 1.0000 |
| 3                 | 0.6017 0.7576 0.9810 0.6190 | 0.3983 0.2424 0.0190 0.3810 |
| 4                 | 0.5805 0.8788 0.8815 0.8095 | 0.4195 0.1212 0.1185 0.1905 |
| 5                 | 0.3919 0.5455 1.0000 0.0714 | 0.6081 0.4545 0.0000 0.9286 |
| 6                 | 0.0000 0.0606 0.6445 0.6190 | 1.0000 0.9394 0.3555 0.3810 |
| 7                 | 0.8379 0.9091 0.4455 0.1905 | 0.1621 0.0009 0.5545 0.8095 |
| 8                 | 0.8040 0.8485 0.3981 0.0952 | 0.1960 0.1515 0.6019 0.9048 |
| 9                 | 1.0000 1.0000 0.5261 1.0000 | 0.0000 0.0000 0.4739 0.0000 |

Table 8
Grey relational coefficient and grey relational grade.

| Experiment Number | Grey Relational Coefficient | Grey Relational Grade |
|-------------------|----------------------------|-----------------------|
|                   | BTE (%) BSFC (kg/kW-hr) NOx (ppm) UBHC (ppm) |                       |
| 1                 | 0.5382 0.6226 0.3333 0.4200 | 0.4785                |
| 2                 | 0.4917 0.3333 0.8612 0.3333 | 0.5049                |
| 3                 | 0.5566 0.6735 0.9635 0.5676 | 0.6903                |
| 4                 | 0.5438 0.8049 0.8084 0.7241 | 0.7203                |
| 5                 | 0.4512 0.5238 1.0000 0.3500 | 0.5813                |
| 6                 | 0.3333 0.3474 0.5845 0.5676 | 0.4582                |
| 7                 | 0.7552 0.8462 0.4742 0.3818 | 0.6143                |
| 8                 | 0.7184 0.7674 0.4538 0.3559 | 0.5739                |
| 9                 | 1.0000 1.0000 0.5134 1.0000 | 0.8783                |

Mean grey relational grade 0.6111

Fig. 1. Flow chart representation of research methodology of the current work.
\begin{align*}
z &= 1 \text{ to } N \\
i &= 1 \text{ to } n \\
N &= \textit{Number of performance characteristics} \\
n &= \textit{Number of experiments} \\
\chi^i(z) &= \textit{Original sequence} \\
x^*_i(z) &= \textit{Normalized or comparability sequence} \\
x^0_i(z) &= \textit{Reference sequence} \\
\min x^0_i(z) &= \textit{Smallest value of } x^0_i(z) \\
\max x^0_i(z) &= \textit{Largest value of } x^0_i(z) \\
\zeta &= \textit{Distinguishing coefficient } (0 \leq \zeta \leq 1)
\end{align*}
Fig. 4. Mean grey relational grade graph for each parameters.

Fig. 5. Range analysis of each parameter.
2.5. Data analysis for optimization

Once the grey relational grade has been computed some statistical analysis such as analysis of means, analysis of range and analysis of variance for identifying best set of parameters for combined optimization were carried out. Analysis of means (ANOM) is one of the important analysis to find out the optimal level of each parameters and optimal set of parameters. Mean values of each parameter at different levels can be represented as $Y_{jk}$. In this research work for $L_9$ orthogonal array of four parameters and three levels each, $j$ represents parameters ($j = A, B, C, D$) and $k$ represents levels ($k = 1, 2, 3$). Mean values of each parameter at different levels can be calculated using the following relations.

\[
\begin{align*}
Y_{A1} &= Y_1 + Y_2 + Y_3; & Y_{A2} &= Y_4 + Y_5 + Y_6; & Y_{A3} &= Y_7 + Y_8 + Y_9 \\
Y_{B1} &= Y_1 + Y_4 + Y_7; & Y_{B2} &= Y_2 + Y_5 + Y_8; & Y_{B3} &= Y_3 + Y_6 + Y_9 \\
Y_{C1} &= Y_1 + Y_6 + Y_8; & Y_{C2} &= Y_2 + Y_4 + Y_9; & Y_{C3} &= Y_3 + Y_5 + Y_7 \\
Y_{D1} &= Y_1 + Y_5 + Y_9; & Y_{D2} &= Y_2 + Y_6 + Y_7; & Y_{D3} &= Y_3 + Y_4 + Y_8
\end{align*}
\]

where $Y_1, Y_2, ..., Y_9$ are response dependent variable (% yield of biodiesel) of experiment numbers 1, 2 ... 9 respectively. The maximum mean value of particular parameter at particular level indicates the best level of that parameter and the combination of highest mean values of each parameter will give the optimal parameter combination. Range analysis is used to identify which parameter will highly influence the dependent variable and assign rank accordingly. The range values of different parameters can be calculated using the following relation

\[
R_j = \max Y_{jk} - \min Y_{jk}
\]

The larger range value is the indication of higher influence of that parameter on dependent variable, hence assigned rank 1 and second larger will be assigned rank 2 and so on. Range analysis will be helpful in ranking the individual parameters based on their influence on response variable, but it will not be helpful in quantifying the percentage contribution of each parameter on the dependent variable. This limitation will be overcome by performing Analysis of Variance (ANOVA) of the experimental data.
SS\text{\textsubscript{j}} = \left( \frac{1}{3} \sum_{k=1}^{3} Y_{jk}^2 \right) - \frac{1}{n} \left( \sum_{i=1}^{n} Y_i \right)^2 \quad (10)

SS\text{\textsubscript{T}} = \left( \sum_{i=1}^{n} Y_i^2 \right) - \frac{1}{n} \left( \sum_{i=1}^{n} Y_i \right)^2 \quad (11)

\% contribution of \text{\textit{j}}^{th} \text{ parameter} = \frac{SS\text{\textsubscript{j}}}{SS\text{\textsubscript{T}}} \times 100 \quad (12)

Where

- SS\text{\textsubscript{T}} – Total sum of squares
- SS\text{\textsubscript{j}} – Sum of squares of \text{\textit{j}}^{th} \text{ parameter}
- \text{\textit{i}} = 1, 2, 3...n
- k = 1, 2, 3
- \text{\textit{j}} = A, B, C, D
- n – Number of Experiments

The experimental conditions and the experimental results or response sequence or original sequence of four objective functions are given in Table 6. The normalized sequence and their corresponding deviation sequence are given in Table 7. The computed grey relational coefficients and grey relational grade are given in Table 8. The mean analysis was carried out for grey relational grade using equation (8). The range values were computed and rank was assigned correspondingly using equation (9). The mean, range and rank values are given in Table 9. The mean grey relational grade graph and range graph are represented in Figs. 4 and 5 respectively. The percentage contributions for each parameter was computed and given in Table 10. The results of confirmation test was compared with results of normal operating condition of engine with 60% PPME and 40% diesel bend (given in Table 11).
and found that 17.93% increase in BTE, 24.07% decrease in BSFC, 14.02% decrease in NOx and 27.12% decrease in UBHC were recorded.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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