Performance and emission characteristics of CI engine operated on Madhuca Indica (Mahua) biodiesel using multi-objective optimization by applying Taguchi grey relational analysis

[#1]Shubhangi S. Nigade, [#2]Sachin V. Mutalikdesai

[1]Mechanical Engineering Department, SVPMs Institute of Technology and Engineering Malegaon (bk), Baramati, Pune, MH, INDIA
[2]Mechanical Engineering Department, KJ's, Trinity College of Engineering and Research, Pune, MH, INDIA

Abstract: This paper presents approach combines the orthogonal array design of experiments with grey relational analysis. Grey relational theory is adopted to determine the best input parameters that give lower emission and higher performance of CI engine. Five design parameters namely; compression ratio, injection pressure, injection nozzle geometry, additive and fuel fraction were selected, and four levels for each factor. To reduce an experimental effort the experiments have been performed by employing Taguchi's L16 orthogonal array for various engine performance and emission related responses. Injection nozzle geometry was found to most influencing factors. The optimal combination so obtained was further confirmed through experimentation was suitable for optimizing the performance and emission parameters of diesel engine. The optimal combination of the input parameters in CI engine operated on Madhuca indica biodiesel blend is: Compression ratio (CR) 18, fuel injection pressure (FIP) 310 bar, injection nozzle geometry (NG) 3H, fuel fraction (FF) 15% and without additive (ADD).

Keywords: Madhuca Indica biodiesel, optimization, Taguchi method, Grey relational analysis.

I. INTRODUCTION

Biodiesel production is a very modern and technological area for researchers as an alternative fuel for diesel engines because of the increase in the petroleum prices, its renewability and the environmental advantages (Marchetti, *et al*, 2007). Biodiesel can be produced from renewable sources such as vegetable oil, animal fat and used cooking oil (Balat and Balat, 2010). The use of non-edible plant oils when compared with edible oils is very significant because of the tremendous demand for edible oils as food, and they are far too expensive to be used as fuel at present (Ashraful, *et al.* 2014).

Nearly 1.60 million diesel engines are operating in India and finding wide applications in agricultural, transport and commercial sectors (Balat and Balat, 2010). ("UN States statistical", 2013) after the United States, China, and Japan in 2013, and it was also the fourth-largest net importer of crude oil and petroleum products. The gap between India's oil demand and supply is widening, as demand reached nearly 3.9 million barrels per day (bbl/d) in 2013. U. S. Energy Information Administration projects India's demand will more than double to 8.2 million bbl/d by 2040(BP Statistical, 2014, "UN States statistical", 2013). The consumption of liquid petroleum products, especially diesel fuel, has grown up significantly due to growth of major economic sectors viz., transport, agriculture and industry. But, the excessive dependency on export grade fuel and limitations associated with fossil fuel become a concern for desired (Mythili, *et al.* 2014). To reduce the uncertainties associated with the petro-diesel, Government of India, like other nations of the world, have made plan to promote alternative sustainable fuels ("BP Statistical Review of World Energy, 2014).

Energy strategy of a country aims at efficiency and security and to provide access which being environment friendly and achievement of an optimum mix of primary resources for energy generation (National biofuel policy, 2004). According to Greenpeace report release on March 24, 2009 in New Delhi, renewable energy can successfully meet over 35% of power demand in India by 2030, and half of forecasted energy needs can be met just by efficient and judicious production, distribution and use of energy ("BP Statistical Review of World Energy June 2012). Green energy evolution will not only help in saving money and, but also facilitate to deal with the catastrophe of climate change (Iglesias, *et al.* 2012). Biofuels are eco-friendly fuels and their utilisation would address global concerns about contamination of carbon emissions (Boro, *et al*, 2012). India has a ray of hope in providing energy security through development of biofuel. Indian approach towards the biofuels, in particular is somewhat different to the current international approaches which could lead to conflict with food security (Kumar and Msangi, 2002). It depends solely on non-food feedstock to be raised on degraded/ marginal or waste land that is not suited to agriculture, thus avoiding a possible conflict of security (Silitonga, *et al*, 2013).

The country's energy demand is expected to grow at an annual rate of 6.8 per cent over the next couple of decades. Most of the energy requirements are currently satisfied by fossil fuels – coal, petroleum based products and natural gas (planning and

Commission, Government of India, 2008). Domestic production of crude oil can only fulfill 25-30 per cent of national consumption rest we are importing from other countries (Refi and Trade, 2013). In these circumstances biofuels are going to play an important role in meeting India's growing energy needs. Biofuels offer an attractive alternative to fossil fuels, but a consistent scientific framework is needed to ensure policies that maximize positive & minimize the negative aspects of biofuels (Santori, *et al,* 2012).

Indian crude oil import has jumped 9.5% to 347432 Crore in 1st five months of current fiscal (Aug 2013) on account of sharp (Haas, *et al.* 2006). Estimated demand for 2013-14 of petrol, diesel and LPG is 16335MT, 73500MT and 16712MT respectively. Almost 79% (78.75%) of Indian crude oil requirements have to be imported. The issue of oil import has come under focus in the context (Sharma and Singh, 2009) of country spiraling current account deficit. As per the working group report this ministry for 12th five year plans the estimated demand of petroleum products during 2016-17 would be 186.2 MMT (Ahmad, *et al.* 2011). India spends 92,000 Crore on diesel subsidy every year which is great loss to exchange with the country being a signatory of green fuel treaty by next few years around a 20% diesel usage will be replaced by biodiesel (Shay, 1993). The government of India has formulated an ambitious National.

Biodiesel Mission to meet 20 per cent of the country's diesel requirements by 2016-2017(planning and Commission, 2012-17).

Transesterification is the process by which the glycerides present in fats or oils react with an alcohol in the presence of a catalyst to form esters and glycerol (Helwani, *et al,* 2009). The oils and fats are filtered and pre-processed to remove water and contaminants. If, free fatty acids are present, they can be removed or transformed into biodiesel using special pretreatment technologies. The pre-treated oils and fats are then mixed with an alcohol (usually methanol) and a catalyst (usually sodium methoxide)(Leung, *et al,* 2010). The oil molecules (triglycerides) are broken apart and reformed into esters and glycerol, which are then separated from each other and purified (Barnwal and Sharma, 2005). The edible oils like soybean, sunflower, mustard, palm, cotton seeds, whose acid values are less than 3.0 are transesterified with methanol in the presence of sodium methoxide as catalyst (Rodrı, 2005). Non-edible oil like, Mahua, karanja and jatropha oils having acid values more than 3.0 are undergoes esterification followed by transesterification (Olutoye and Hameed, 2011). The methyl esters produced by these methods are analyzed to ascertain their suitability as diesel fuels. The byproduct of this process is glycerol and it can be separated from biodiesel by separation under gravity and purified to get pure glycerin which can be used in cosmetic, pharmaceutical, soap industries resulting in final cost reduction of biodiesel production (Karaosmanog, 2004).

The most common optimization technique used for engine analysis is response surface method, grey relational analysis, non-linear regression, genetic algorithm and Taguchi method. Taguchi technique has been popular for parameter optimization in design of experiments (Karnwal *et al,* 2011). Application of Taguchi method for experimental planning has greatly reduced the experimental time and costs (Ganapathy, Murugesan and Gakkhar, 2009). Grey relational analysis and entropy measurement are used to overcome the in multiple quality analysis (Talebian, *et al,* 2013). In view of the above, the aim of the present investigation was to reduce the emission without compromising the performance of CI engine. In order to get complete picture, several design & operating variables like fuel fraction, compression ratio, fuel injection pressure, nozzle geometry and fuel additive have been investigated for their combined effect on output variables like BSFC, CO & NOx. Five major influencing input parameters with their four levels were selected for controlling them on the basis of three output variables. For optimizing multi-objective characteristics, Taguchi grey relational analysis (TGRA) technique has been used on their relative importance.

This work hoped a positive way towards energy security in future which will meet the qualities of petrol based diesel produced from non-edible oils. Such alternative fuels will meet the same performance as that of petrol based diesel fuel with lowering the exhaust gas emission.

1. Assortment of Mahua as feedstock

- Mahua is tree born non edible oil seed which can be grown on waste marginal land and cultivated in warm regions.
- Mahua seed contains near about 40% oil. Potential capacity of mahua seed is 510000 tones in India.
- Ripen fruit can be used for human consumption and seed is used for oil extraction which can be used as fuel. It is also used for care of skin, manufacturing of soaps, detergents and vegetable butter.
- Seed cakes obtained after oil extraction used as very good fertilizers, biogas production and mushroom cultivation.
- Flowers used to produce alcoholic drink, bark is used for medicinal purpose
- Leaves are high nutritious can be fodder for cattle, goat and sheep's.

II. EXPERIMENTAL

2.1 Physical-chemical Characterization of Madhuca Indica Methyl Ester

The oil was extracted from Madhuca indica crush using soxhelet extractor with N-hexane as the solvent. The duration for each batch of extraction was fixed at 5h; while the volume of solvent per kilogram of seed was varied from 5 liter to 7 liter for maximization of oil yield. The extracted oil was then measured to calculate the content of oil in the kernel of madhuca indica. The physio-chemical properties and fatty acid composition of Madhuca indica oil (MIO) are shown in Table 1 and 2.

Table 1 Physiochemical properties of Madhuca indica oil

Sr. No	Physical character	Value
1	Refractive Index at 40°C	1.45-1.462
2	Iodine Value	64
3	Saponification value	189
4	Unsaponificable matter	1.1%
5	Specific gravity	0.979

6	Colour	Dark Yellow

The saponification value (SV) is measured in KOH mg/g (As per AOCS standard). The fatty acid composition of Madhuca indica oil is shown in table 2. Oleic acid are the main constituents in the MIO

Table 2 Fatty acid composition of the Madhuca indica oil

Fatty acid	Chemical Structure	Structure	Content mass (%)
Palmitic	$C_{16}H_{32}O_2$	16:0	17.6
Stearic	$C_{18}H_{36}O_2$	18:0	14.3
Oleic	$C_{18}H_{34}O_2$	18:1	46.2
Linoleic	$C_{18}H_{32}O_2$	18:2	17.5
Arachidic	$C_{20}H_{40}O_2$	20:0	1.7
Total Saturated Fatty Acid			33.3
Total unsaturated Fatty Acid			64.2

The fuel properties of the biodiesel (Madhuca indica biodiesel) and mineral Diesel were determined using standard test procedures (are given in Table 3).

Table 3 Comparison of Physico-chemical key properties of synthesized Madhuca indica biodiesel with different non-edible Methyl Esters (ASTM D 6751)

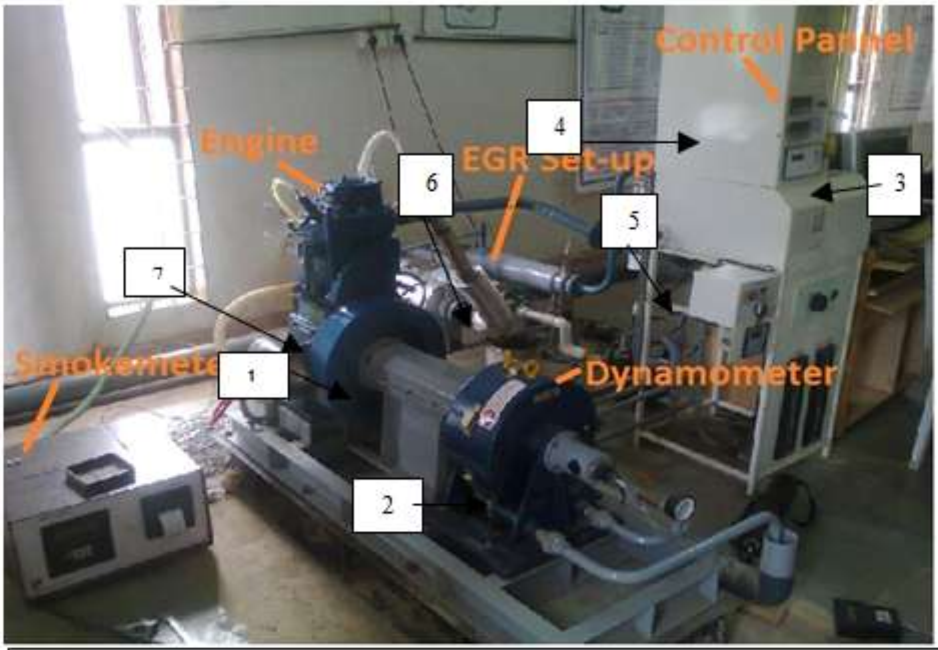
Property	Test Method	Diesel	*Jatropha Methyl Ester	MIOME
Density at 15^0C (Kg/m^3)	ASTMD 1298	832	0.880	882
Kinematic viscosity @ 40°C (cSt)	ASTM D445	4.7	4.84	5.6
Calorific Value (MJ/kg)	ASTM D240	42.49	37.2	36,900
Flash Point(°C)	ASTM D93	53	103	129
Fire point(°C)	ASTM D93	58	132	174
Cloud Point (°C)]	ASTM D2500	-2	11	8
Pour Point(°C)	ASTM D2500	-5	6	4

**(Anjana Srivastava and Ram Prasad, 2000)*

The calorific value is a measure of energy content of the fuel and is a very important property of biodiesel, which determines its suitability as an alternative to mineral Diesel. The calorific value of Madhuca indica oil biodiesel (MIOB) and Madhuca indica oil is 37.2 and 35.8 MJ/kg, which is almost 83.1% and 79.9% of the diesel calorific value (44.8 MJ/kg), respectively. The lower calorific value of MIOB is because of the presence of oxygen in the molecular structure, which is confirmed by elemental analysis also. The flash point and fire point were tested with a closed cup Pensky Marten’s apparatus. The flash point is the measure of the tendency of a substance to form flammable mixtures when exposed to air. This parameter is considered in the handling, storage and safety of fuels. The high value of flash point and fire point in the case of MIOB represents it is a safer fuel to handle.

2.2 Engine Testing Method

The engine was provided with a hemispherical combustion chamber with overhead valves operated through push rods. Eddy current dynamometer has been used for measurement of output. The injector opening pressure and the static injection timing as specified by the manufacturer was 205 bar and 23°BTDC respectively.



1. VCR Diesel Engine 2.Eddy current dynamometer 3.Control Panel 4. Fuel tank with fuel meter 5. Air Box unit with Intake line 6. EGR unit 7.VCR Adjustment

Fig.1 Experimental setup

The Cooling of the engine was accomplished by circulating water through the jackets on the engine block and cylinder head. A piezoelectric pressure transducer was mounted with the cylinder head surface to measure the cylinder pressure. Engine performance tests were performed on a single-cylinder, constant-speed (1500 rpm), four-stroke variable compression ratio (VCR) diesel engine fitted with an eddy current dynamometer as shown in Figure 1.
The specifications of the engine are given in table 4

Table 4 Experimental engine specifications

Engine Type	Single-cylinder, 4-stroke, constant speed (1500 rpm), variable compression ratio (VCR) CI engine
Make and Model	Kirloskar, TV1
Ignition System	Compression Ignition
Bore	87.5 mm
Stroke	110 mm
Displacement Volume	660 cc
Range of Compression Ratio	12:1 to 18:1
Arrangement of Valves	Overhead
Cooling Medium	Water Cooled
Rated Power	3.75 kW at 1500 rpm
Fuel Injection Timing	24o bTDC
Type of Combustion Chamber	Hemispherical Open

The experiments were performed at different loads with various combinations of input parameters like Methyl Ester blend, compression ratio, nozzle opening pressure, injection nozzle geometry and fuel additive. Engine performance parameters such as the brake specific fuel consumption (BSFC) were measured at a step of 25% load from no-load to full load after ensuring stable engine condition. In addition, the emission parameters like concentrations of CO, CO_2, ʎ, NO_x, and HC were measured by an AVL exhaust gas analyzer (See Table 5 for specifications). Each test run was replicated three times for 16 runs.

Table 5 Gas analyzer specifications

Measured Parameter	Measuring Range	Accuracy
CO	0-10% vol	±0.03% vol ±5% of value

CO_2	0-20% vol	±0.5% vol ±5% of value
UBHC	0-20,000 ppm vol	±10 ppm ±5% of value
NO_x	0-5,000 ppm vol	±50 ppm ± 10% of value
O_2	0-22% vol	±0.1% vol ±5% of value
Lambda	0.9.999	---------

2.3 Design of experiments

Taguchi method was used to optimize the engine operating parameters. Orthogonal L_{16} array was used to design the experiment. The factors for which the engine is optimized are: compression ratio, injection pressure, nozzle, biodiesel fuel fraction and fuel additive (ml/ltr). Four levels of each factor are considered hence L_{16} array was the suggested and most suitable array. Levels of each factor are shown in table 6.

In the present study, the optimization of multiple performance characteristics of the diesel engine is done on the basis of a single grey relational grade rather than complicated performance characteristics. Equal weightage was assigned to each output variable (performance & emission). The BSFC was selected as performance variable & CO, NO_x were selected as emission variables.

Table 6 Input Parameters with their levels

Parameters	Level 1	Level2	Level3	Level4
A. Compression Ratio	16	17	17.5	18
B. Injection Pressure (Bar)	330	310	290	270
C. Nozzle(Number of Holes)	1	2	3	4
D. Fuel fraction(% volume)	15	30	50	100
E. Additive(ml/ltr)	0	3	6	9

Fuels used for the test include Mahua oil methyl ester and its blends. The combination of B15, B30, B50, and B100 were selected for the optimization. As the additive is used to improve the combustion properties of fuel, high percentage of biodiesel were selected for the experiment.
An experimental plan was prepared by applying taguchi method with L16 orthogonal array for limiting number of experiments. Five engine input parameters considered in the present study are: compression ratio, injection pressure, injection nozzle geometry, fuel fraction and fuel additive. Sixteen sets of experiments with five input parameters with their four levels and corresponding output variables are shown in Table 7. The response variables chosen for the present investigation are: BSFC, CO and NOx. Hence, smaller-the-better quality characteristic has been used for calculating the signal to noise (S/N) ratio for these responses using following equation 1.

$$\eta = -10 \log\left[\frac{1}{n}\sum_{1}^{n} y_i^2\right] \dots\dots\dots (1)$$

Where η represent the quality characteristic i.e. signal to noise ratio in decibels, yi is the response value for ith experiment, i is the experiment number and number of tests in each group.

Table 7 Input Parameters with their levels

R	CR	IP (Bar)	ING	AD (%)	FF (%)
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3

7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

The experimental results of CI engine performance and emissions using Madhuca Indica Biodiesel are Brake specific fuel consumption, Carbon Monoxide and Oxides of Nitrogen respectively shown in Table 8.

Table 8 Experimental Results

R	CR	IP (Bar)	ING	AD (%)	FF (%)	BSFC Kg/kWh	CO %v	NOx ppm
1	16	330	1H	15	0	0.73	0.25	50
2	16	310	2H	30	3	0.58	1.38	60
3	16	290	3H	50	6	0.38	0.62	141
4	16	270	4H	100	9	0.49	0.93	107
5	17	330	2H	50	9	0.51	0.38	64
6	17	310	1H	100	6	0.47	0.62	52
7	17	290	4H	15	3	0.54	1	100
8	17	270	3H	30	0	0.39	0.61	134
9	17.5	330	3H	100	3	0.38	0.77	157
10	17.5	310	4H	50	0	0.51	0.93	93
11	17.5	290	1H	30	9	0.58	0.89	57
12	17.5	270	2H	15	6	0.52	0.82	71
13	18	330	4H	30	6	0.29	1.93	86
14	18	310	3H	15	0	0.33	0.17	176
15	18	290	2H	100	9	0.51	0.44	75
16	18	270	1H	50	3	1.6	0.49	95

2.4 Grey Taguchi Approach

Statistical analysis was carried out on the experimental data obtained through Taguchi experimental design using statistical software MINITAB 14. Analysis of variance (ANOVA) was performed to determine the influence of input parameters on the output response variables. Since the major focus of the study is on grey relational analysis, the results of Taguchi experiments have not been elaborated here.

2.5 Grey relational analysis

In the present case, the problem has three output variables which need to be minimized by choosing appropriate conditions. Hence, it is necessary to convert multi-objective problem into a single objective problem using grey relational analysis. The grey relational grade in grey relational analysis determines the rank of the experimental sets.

2.6 Investigation approach

The engine input parameters correspond to 16 sets of different experiments (comparability sequence) forming 16 subsystems for GRA. The influence of these subsystems on the output variables will be subsequently analyzed using GRA technique. The parametric conditions corresponding to the highest weighted grey relational grade gives minimum values of the engine output variables finalizing the set of input parameters.

2.7 Formulation of the problem

The multi-objective optimization problem in the present investigation can be stated as: Minimize output variables such as: BSFC, CO, NO_x with best combination of compression ratio (CR), injection pressure (IP, bar), injection nozzle geometry (ING, No. of holes), fuel fraction (FF, %) and additive (ADD, ml/lit), Input parameters. The above multi-objective problem was converted into a single-objective problem using grey relational grade as: “Maximize GRG ($0\leq$ GRG≤1)”.

2.8 Methodology

Step 1: Normalization of S/N ratio.

The first step in the grey relational analysis is normalization of the S/N ratio (see Table 9). This is done by converting values of output variables to a comparable sequence.

Table 9 Signal-to-noise ratio for the output variables

Run	BSFC	CO	NOx
1	2.7335	12.0412	-33.9794
2	4.7314	-2.7976	-35.5630
3	8.4043	4.1522	-42.9844
4	6.1961	0.6303	-40.5877
5	5.8486	8.4043	-36.1236
6	6.5580	4.1522	-34.3201
7	5.3521	0.0000	-40.0000
8	8.1787	4.2934	-42.5421
9	8.4043	2.2702	-43.9180
10	5.8486	0.6303	-39.3697
11	4.7314	1.0122	-35.1175
12	5.6799	1.7237	-37.0252
13	10.752	-5.7111	-38.6900
14	9.6297	15.3910	-44.9103
15	5.8486	7.1309	-37.5012
16	-4.0824	6.1961	-39.5545

Linear normalization is usually done due to different range and unit of output variables.

Step 2: Grey Relational Generation

A linear normalization of the S/N ratio in the range between zero and unity is also called as the grey relational generation [Lin and Ho 2003]. The "smaller-the-better" (see Eq. 1) is a characteristic of the original sequence, and it is used to compare levels in the grey relational generation GRGn. The original sequence was normalized using equation 2.

$$y_i(K) = \frac{\max y_i(K) - y_i(K)}{\max y_i(K) - \min y_i(K)} \quad \ldots..(2)$$

Where y_i (K) is the value after the grey relational generation, $\max y_i(K)$ is the largest value of y_i (K), $\min y_i(K)$ is the smallest value of $y_i(K)$ for the K^{th} response. The normalized data after grey relational generation is presented in Table 10.

Table 10 Grey Relational Generation for the output variables

Run	BSFC	CO	NO_x
1	0.54	0.16	0.30
2	0.41	0.86	0.00
3	0.16	0.53	0.65
4	0.31	0.70	0.81
5	0.33	0.33	1.00
6	0.28	0.53	0.86
7	0.36	0.73	0.48
8	0.17	0.53	0.40
9	0.16	0.62	0.94
10	0.33	0.70	0.60
11	0.41	0.68	0.91
12	0.34	0.65	0.92
13	0.00	1.00	0.40
14	0.08	0.00	0.38
15	0.33	0.39	0.28
16	1.00	0.44	0.68

Step 3: Calculation of grey relational coefficients

GRCs for all the sequences expresses the relationship between the ideal (best=1) and actual normalized S/N ratio. If the two sequences agree at all points, then their grey relational coefficient is 1. The Grey relational coefficient was calculated using equation 3.

$$\xi_i(K) = \frac{\delta\min + \psi.\delta\max}{\delta_{0i} + \psi.\delta\max} \ldots\ldots\ldots (3)$$

Where $\delta_{0i} = \|y_0(K) - y_i(K)\|$, ψ is distinguishing coefficient $0 \leq \psi \leq 1$. It will be generally 0.5 [Lin and Ho 2003]. The higher Grey relational coefficient implies that the corresponding experimental result is closer to the optimal (best) normalized value for the single response. The grey relational coefficients are presented in Table 11.

Table 11 Grey relational coefficient for the output variables

Run	BSFC	CO	NO_x
1	0.48	0.76	0.62
2	0.55	0.37	1.00
3	0.76	0.48	0.44
4	0.62	0.42	0.38
5	0.60	0.60	0.33
6	0.64	0.48	0.37
7	0.58	0.41	0.51
8	0.74	0.49	0.56
9	0.76	0.45	0.35
10	0.60	0.42	0.45
11	0.55	0.42	0.35
12	0.59	0.44	0.35
13	1.00	0.33	0.56
14	0.87	1.00	0.57
15	0.60	0.56	0.64
16	0.33	0.53	0.42

Step 4: Calculation of weighted grey relational grade (GRG)

After calculating the Grey relational coefficients, the overall grey relational grade was calculated using equation (5). Higher value of GRG represent desirability level.

$$\Delta_i = \sum_{K=1}^{n} w_K\, \xi_i(K) \ldots\ldots (5)$$

Where w_K is the weighting value for each Grey relational coefficient ranging from 0 to 1, and the sum of w_K is equal to 1. In the present study, equal weightages were selected for all output variables. Hence, 0.33 (w1), 0.33 (w2) and 0.33 (w3) were the values assigned to weighting factors for the response variables BSFC, CO, NO_x respectively.

The Grey relational grade (GRG) for each experiment using the L_{16} orthogonal array is represented in Table 12. The highest Grey relational grade corresponds to the best S/N ratio as it is closer to the ideal S/N ratio. In the present problem, it was observed that the experimental run #14 scores the highest Grey relational grade and hence it is considered as the best experimental set among 16 sets.

Table 12 GRG and Rank of Output Variables

Run	**Grey relation grade (GRG)**	**Rank**
1	0.6211	4
2	0.6397	2
3	0.5597	7
4	0.4725	13
5	0.5123	9
6	0.4969	11
7	0.4986	10
8	0.5956	6
9	0.5177	8
10	0.4908	12
11	0.4432	15
12	0.4602	14
13	0.6301	3
14	0.8123	1
15	0.6013	5
16	0.4303	16

III. RESULTS AND DISCUSSION

3.1 Analysis of signal to noise ratio

Signal-to-noise ratio methodology was adopted to analyse the Grey relational grades obtained (See Table 11) in order to determine the optimal combination of factor levels. The signal-to-noise ratio for respective GRG was calculated by using equation (6). The “higher-the-better” criterion was used for determining the optimal combination of factor levels which correspond to the highest computed S/N ratio.

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

Where i is experiment number, u is trial number and N_i is number of trials for i^{th} experiment.

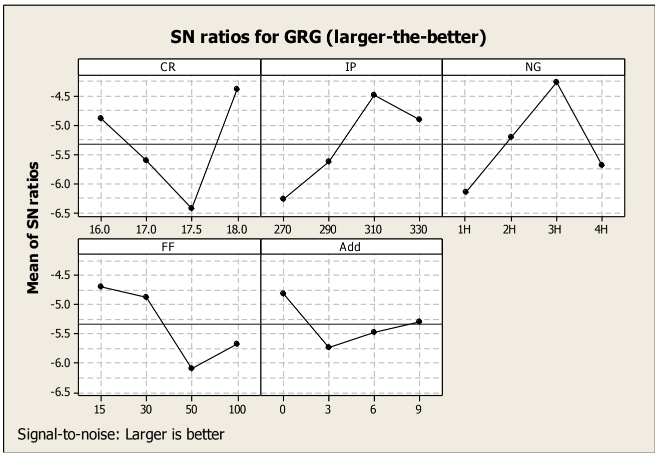


Fig.2 S/N ratio for Grey Relational Grade

Figure 2 shows the graphical representation of S/N ratios obtained for the chosen input parameters CR, FIP, ING, FF and ADD. The optimum process parameter combination was found to be *A4B3C3D1E1*, Compression ratio (CR) 18, fuel injection pressure (FIP) 310 bar, injection nozzle geometry (NG) 3H, fuel fraction (FF) 15% and without additive (ADD). Among the input parameters selected for the present study, injection nozzle geometry is the most significant input parameter whereas fuel Additive is least significant in optimizing engine performance & emission. The smaller fuel fraction (15% blend) in the optimized parameters shows no effect of liquid additives over the CI Engine performance as well only BSFC had taken into consideration.

3.2 Confirmation tests

For the confirmation of the optimum results obtained from the above analysis, confirmation experiment was conducted at the optimized set of parameters. After the optimum process parameter was selected from the S/N ratio plot, predicted S/N ratio Ω was evaluated corresponding to optimum level of process parameters by using the equation 7.

$$\Omega = \Upsilon_m + \sum_{i=1}^{o} (\Upsilon_i - \Upsilon_m) \dots\dots\dots (7)$$

Where, Y_m is overall mean of S/N ratio, Y_iis the mean of S/N ratio for optimum level, and ‘o’ is the number of the main input parameters (decision variables) influencing the output variables (response). The predicted GRG at the optimal setting *(A4B3C3D1E1)* and experimental value of GRG are 0.8324 & 0.8123 respectively. The results are found (please refer Table 13) with three replication for optimized input parameters using TGRA and Madhuca Indica Biodiesel and it’s blend.

Table 13 Results with Replication of Optimized Input Parameters

R	CR	IP (Bar)	ING	AD (%)	FF (%)	BSFC Kg/kWh	CO %v	NOx ppm
14	18	310	3H	15	0	0.21	0.19	39

IV. CONCLUSION

Taguchi's L_{16} orthogonal array was employed to design the experiments. An algorithm involving the combination of Grey relational analysis with Taguchi was also proposed for the optimization of the engine performance and emission. The effect of Compression ratio (CR), fuel injection pressure (FIP), injection nozzle geometry (NG), fuel fraction (FF) and additive (Add) on BSFC, CO and NOx with minimum number of experiments.

The major conclusion of the present investigation is as follows:

- The optimal combination of the input parameters in CI engine operated on Madhuca indica biodiesel blend is: Compression ratio (CR) 18, fuel injection pressure (FIP) 310 bar, injection nozzle geometry (NG) 3H, fuel fraction (FF) 15% and without additive (ADD).
- Injection nozzle geometry (ING) was the most influencing factor for CI Engine Performance.
- Fuel additive has not significant parameters in optimization of engine performance for reducing BSFC, CO and NOx.
- Madhuca Indica Methyl Ester blend can be used in existing diesel engine, with minor modifications.
- The experimental confirmation test reveals that Taguchi grey relational analysis (TGRA) technique is suitable for multi-objective optimization for Madhuca Indica as CI engine fuel and its performance and emission.

REFERENCES

1. L. Ahmad, N.H. Yasin, J.C. Derek, J.K. Lim, (2011), Microalgae as a Sustainable Energy Source for Biodiesel Production: A Review, *Renewable and Sustainable Energy Reviews,* vol. 15 no. 1, pp. 455-460.
2. M. Ashraful, H.H. Masjuki, M. Kalam, I.M. Rizwanul , S. Fattah, S. Imtenan, H.M. Mobarak, (2014), Production and Comparison of Fuel Properties, Engine Performance and Emission Characteristics of Biodiesel from Various Non-Edible Vegetable Oils: A Review, *Energy Conversion and Management,* vol. 80, pp. 202–28.
3. M. Balat, H. Balat, (2010), Progress in Biodiesel Processing. *Applied Energy,* vol. 87 no. 6, pp. 585-594.
4. B. K. Barnwal, M. P. Sharma, (2005), Prospects of Biodiesel Production from Vegetable Oils in India, *Renewable and Sustainable Energy Reviews,* vol. 9 no.4, pp. 363–78.
5. B. Jutika, D. Deka, J. Thakur, (2012), A Review on Solid Oxide Derived from Waste Shells as Catalyst for Biodiesel Production, *Renewable and Sustainable Energy Reviews,* Ivol.16 no. 1, pp. 904–910.
6. "BP Statistical Review of World Energy, (2014-16), pp 1-544. Commission, Planning. "Faster , Sustainable and More Inclusive Growth (2012-17), pp. 1-378.
7. T. Ganapathy, K. Murugesan, R. P. Gakkhar, (2009), Performance Optimization of Jatropha Biodiesel Engine Model Using Taguchi Approach, *Applied Energy,* vol. 86 no. 11, pp. 2476–2486.
8. H. Michael, J. Andrew, J. McAloon, F. Thomas, (2006), A Process Model to Estimate Biodiesel Production Costs, *Bioresource Technology,* vol. 97 no. 4, pp. 671–78.
9. Z. Helwani, M.R. Othman, N. Aziz, W.J. Fernando, J. Kim, (2009), Technologies for Production of Biodiesel Focusing on Green Catalytic Techniques: A Review, *Fuel Processing Technology,* vol. 90 no.12, pp.1502–14.
10. I. Loreto, A. Laca, M. Herrero, M. Diaz, (2012), A Life Cycle Assessment Comparison between Centralized and Decentralized Biodiesel Production from Raw Sun Flower Oil and Waste Cooking Oils, *Applied Energy,* vol. 37, pp. 162–171.
11. K. Filiz, (2004), Optimization of Base-Catalyzed Transesterification, *Applied Energy* , vol. 5 no. 2 pp. 1888–95.
12. A. Karnwal, M. M. Hasan, N. Kumar, A. N. Siddiquee, Z. A. Khan, (2011), multi-response optimization of diesel engine performance parameters using thumba biodiesel-diesel blends by applying the taguchi method and grey relational analysis, *Bioresource Technology,* vol. 12 no. 4, pp. 599–610.
13. P. Kumar, S. Msangi, (2010), Potential , Policy and Emerging, *Bioresource Technology,* vol. 88 no. 8, pp. 674–86.
14. L. Dennis, Y.C. Xuan, M.K. Leung, (2010), A Review on Biodiesel Production Using Catalyzed Transesterification." *Applied Energy*, vol. 87 no.4, pp.1083–95.
15. J. M. Marchetti, V. U. Miguel, A. F. Errazu , (2007), Possible Methods for Biodiesel Production, *Bioresource Technology*, vol. 11, pp. 1300–1311.
16. R. Mythili, P. Venkatachalam, P. Subramanian, D. Uma, (2014), Production Characterization and Effect CI engine of Biodiesel : A Review, *Bioresource Technology,* vol.10, pp. 998-1002
17. M. Olutoye,B. H. Hameed (2011), Synthesis of Fatty Acid Methyl Ester from Crude Jatropha (Jatropha Curcas Linnaeus) Oil Using Aluminium Oxide Modified Mg-Zn Heterogeneous Catalyst. *Bioresource Technology*, vol. 102 no. 11, pp. 6392–98.
18. R. Antonio, (2005), Biodiesel from Used Frying Oil Variables Affecting the Yields and Characteristics of the Biodiesel, *Bioresource Technology,* vol. 34, pp. 5491–99.
19. S. Giulio, G. D. Nicola, M. Moglie, F. Polonara, (2012), A Review Analyzing the Industrial Biodiesel Production Practice Starting from Vegetable Oil Refining. *Applied Energy,* vol. 92, pp.109–32.

20. Y. C. Sharma, B. Singh, (2009), Development of Biodiesel : Current Scenario, *Applied Energy*, vol. 13, pp. 1646–51.
S. E. Griffin, (1993), Diesel Fuel from Vegetable Oils: Status and Opportunities, *Biomass and Bioenergy*, vol. 4 no.4, pp. 227–42.
21. S. Silitonga, H.H. Masjuki, T.M. Mahlia, H.C. Ong, E. Atabani, W.T. Chong, (2013), A Global Comparative Review of Biodiesel Production from Jatropha Curcas Using Different Homogeneous Acid and Alkaline Catalysts: Study of Physical and Chemical Properties, *Renewable and Sustainable Energy Reviews,* vol. 24 pp. 514–533.
22. K. Talebian, N. Amin, S. Amin, H. Mazaheri, (2013), A Review on Novel Processes of Biodiesel Production from Waste Cooking Oil. *Applied Energy,* vol. 104, pp. 683–710.

