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Research Article

Optimization of biodiesel powered CI engine process parameters using AHP and Taguchi grey method – A hybrid approach

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ABSTRACT

Blends of algae oil with diesel can act as a substitute for diesel are expected to provide organized efficiency and better emission characteristics by controlling the parameters of the compression ignition engine. The addition of antioxidants like pyrogallol and butylated hydroxy toluene can make biodiesel more effective. An Analytical Hierarchy Process and the Taguchi-Grey method are combined for the first time in the compression ignition engine process to optimize the parameters for better performance and reduce toxic emissions. For analytical hierarchy process analysis, an expert's opinion is collected for the response variables to assign the weightage to the variables. For better performance and reduced emissions, the optimum process parameters are found to be injection timing at 23°, pyrogallol at 0 ppm, and butylated hydroxy toluene at 500 PPM. Furthermore, a confirmation test was conducted to confirm the obtained results from the optimization process, and the results showed that the brake thermal efficiency is enhanced by 3.6 % and NOx is reduced by 6 %. However, the smoke from the CI engine is increased by 10.4 %.

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INTRODUCTION

The depletion and pollution of fossil fuels are the crucial motivation of the search for a new alternative and cleaner fuels. Biomass and biodiesel are identified as the best substitute for diesel in the automobile sector. Biomass is a largely accepted fuel in developed countries for cooking and heating applications to reduce emissions. Biomass is derived from organic matters such as garbage, wood, landfill gas, crops, and alcohol fuels [1]. However, the biodiesel has a greater advantage over biomass. Primary resources utilized in the production of renewable biodiesel include animal fats, used cooking oil, and vegetable oil extraction, among others [2]. Recently, Biofuel derived from algae proves to

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be viable for energy production, with approximately 19,000 to 57,000 liters per acre of biofuel capable of cultivation in optimized environments using photo reactors [3]. The raw biofuel is not suitable for direct use in compression ignition (CI) engines because of its higher viscosity and low volatility, which leads to incomplete combustion and lower atomization thus it is blended with diesel [4]. Biodiesel effectively decreases hydrocarbon (HC) and carbon monoxide (CO) emissions to a significant extent, yet a notable concern arises due to the corresponding increase in nitrogen oxides (NOx) emissions.

The NOx emission not only increases with the usage of biodiesel, but it also depends mainly on engine technology, fuel composition, and operating conditions. Among the variable parameters such as air swirl, size, and shape of nozzle and combustion chamber, injection timing (IT), fuel quantity injected, injection pressure, and additives. IT and antioxidants play a major role in reducing NOx emissions. When the fuel IT is set promptly, the pressure and temperature inside the engine cylinder are lowered and triggering an ignition delay. Likewise, delaying the fuel injection time results in increased inlet pressure and temperature, leading to a reduction in combustion delay. Consequently, the parameter of fuel injection timing (fuel IT) significantly impacts the performance and emissions of biodiesel engines. According to a review conducted by Hoseini et al. [5], 57% of previous research findings indicated an increase in NOx emissions under delayed injection conditions. Additionally, it was determined that both rapid and delayed fuel injection timings lead to a decrease in other pollutants such as CO, HC, and soot. The biodiesel blend forms gums in the system due to polymerization by unsaturated hydrocarbons. The fuel injectors and the filters are affected seriously by these gum clogs. During combustion, oxygen engages with fuels, hindering the initiation of oxidation chain reactions that culminate in the formation of H_2O_2. The highly oxidizing nature of hydrogen peroxide adversely impacts engine metal surfaces, consequently diminishing fuel combustion quality. These difficulties are overcome with the addition of chemical substances called antioxidants in biodiesel [6, 7].

Antioxidants play a crucial role in enhancing the stability of biodiesel by inhibiting the oxidation process, which can lead to the formation of undesirable products such as peroxides and acids. These antioxidants scavenge free radicals and terminate chain reactions initiated by oxygen and heat exposure, thereby preventing the degradation of biodiesel molecules. This preservation of biodiesel stability ensures prolonged shelf life, reduced viscosity increase, and maintenance of its quality during storage and use, crucial for its practical applications in various industries. Antioxidant dismisses the freedom of free radicals formed by unsaturated hydrocarbons at various spots. During the combustion of biodiesel, free radicals act an important role in the formation of NOx. The addition of antioxidants into the biodiesel blend perhaps prevents the formation of free radicals and reduces the formation of NOx in the reaction [8]. Avase et al. [9] studied the influence of pyrogallol (PY) as an antioxidant to stabilize the solidity in the fuel and found that the fuel properties, emission, and performance characteristics of the engine are closer to diesel engines. Hess et al. [10] noted that the inclusion of Butylated hydroxyanisole (BHA) effectively reduces NOx emissions, while also indicating that other additives fail to decrease nitrogen dioxide release. Ryu [11]analyzed the effects of antioxidants in the biodiesel blend and provided the order of effectiveness as Tert Butylhydroquinone > Butylated hydroxyl toluene > Butylated hydroxyanisole> Pyrogallol > α-tocopherol. In this research work, the combined effect of injection timing and anti-oxidants were investigated to determine the optimized combination of injection timing and the anti-oxidants for lower NOx emission of the CI engine fuelled with an algae biodiesel blend.

Genichi Taguchi introduced a robust technique aimed at enhancing efficiency through the optimization of engine parameters, with a focus on investigating the influence of factors on variables. These streamlined procedures are straight forward and require minimal experimentation to uncover system variances, facilitated by the utilization of orthogonal arrays [12, 13]. In the traditional Taguchi approach, only one response can optimize under the effects of various factors. However, this research is addressing the optimization of factors for many variables by merging the Taguchi technique with grey relational analysis. The single grey relational grade (GRG) can be derived from multiple response variables using a globally accepted method called grey relational analysis (GRA) [14]. Generally, all the optimization techniques consider equal weightage for the responses in the process which is not convincing as different system weights various levels of prominence on response variables [15, 16]. In the earlier investigations much work was not concentrated on multi-response optimization that assigned with different weights during the optimization of parameters of compression ignition (CI) engines.

Geetha and Pappula [17] used the Analytical Hierarchy Process (AHP) and Weighted Euclidean Distance (WED) based integrated approach to choose the parameters involved in the spark ignition (SI) engine for optimization. Emission and performance analysis of a CI engine is performed based on Taguchi optimization technique integrated with AHP method to sort out the influencing parameters among various engine variable and found 15% of butanol diesel blends is more appropriate [18-20]. Using the Taguchi method, it has been determined that rotation is the key factor in stabilizing flow patterns [21]. Similarly, many researchers have used the Taguchi technique for optimization. However, it is notable that the Taguchi-Grey method combined with the Analytic Hierarchy Process has not been specifically implemented in performance and emission analysis of CI engines. The selection of AHP-GRA is selected based on their proven ability in literature to handle complex criteria interactions and variability, essential for achieving global optimization. These methods offer robust frameworks: AHP-GRA combines hierarchical criteria weighting (AHP) with robustness assessment (GRA), while Taguchi methods optimize performance against variations, ensuring reliable results across diverse scenarios. For the first time, in engine research, a hybrid approach is adopted to optimize the engine design factors along with different anti-oxidants. This hybrid methodology is competent in recognizing the best combination of process parameters to enhance the performance and ease the emission in the CI engine.

In this work, the main aim is to ease the nitrogen dioxide emission in a CI engine powered with an algae biodiesel blend. The injection timing (IT) and antioxidants are considered for this investigation. For the first time in this area of research, a hybrid optimization approach is employed to determine the optimum process parameters for the engine. The most influencing factor is identified and verified by Taguchi grey relational techniques.

EXPERIMENTAL DETAILS AND PROCEDURES

Design of Test Matrix

Injection timing and anti-oxidants were chosen as factors for the investigation and selection of levels of injection timing and anti-oxidants were elaborated in the author's earlier investigations [22, 23]. The orthogonal array (OA) based design methodology is adopted in this work to run the experiment in a single cylinder, air cooled, vertical and direct injection diesel engine. The statistical approach is used to perform required mathematical operations and the response values are acquired. The three factors considered for this investigation are injection timing (IT), PY, and BHT. As modifying the injection timing by more than 3 crank angle degree (CAD) from the conventional CAD was not preferable, 23 BTDC, 26BTDC and 20 BTDC was the three levels for the injection timing [22, 23]. As reported in the earlier investigations, maximum preferable amount of anti-oxidant was chosen as 500 ppm and by adding two more levels, 0,250 and 500 ppm were selected as the three levels for the BHT and PY [22, 23]. Table 1 shows the factors along with their levels. The L_9 OA is selected for the experimental design and it is specified in Table 2. Taguchi L_9 orthogonal array, a robust experimental design, facilitates biodiesel engine research by optimizing parameters efficiently. It systematically examines three crucial factors with three levels each, offering comprehensive insights into biodiesel combustion dynamics. This design minimizes the number of experiments required while maximizing the information gained, saving time and resources in the research process. By varying factors, the Taguchi L9 array enables researchers to identify the most influential variables for optimizing engine performance and emissions. Its structured approach aids in accelerating advancements in sustainable energy technology and enhancing the viability of biodiesel as a renewable fuel source [22, 23] Based on the levels of the factors from Table 1, the values are assigned to the different columns of L9 and the test matrix was designed and presented in Table 3.

Preparation of Biodiesel Blends

Universally accepted B20 blend (20 % of biodiesel with 80 % of diesel on volume basis) was selected as a fuel blend for the investigation. The total quantity of each sample is fixed to the blend of 500 ml of which 400 ml of diesel and 100 ml of algae biodiesel. The properties of fuel used in this work such as diesel, algae oil, and biodiesel are given in Table 4a. The antioxidants are measured using the weighing machine and prepared with the aid of a homogenizer. The antioxidant properties of PY and BHT are given in Table 4b.

Table 2. L_9 Orthogonal Array (OA) [22, 23]

Experiments	Factor 1	Factor 2	Factor 3
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 1. Factors and levels [22, 23]

S.No	Factors	Levels		
		1	2	3
1	Injection Timing (IT)	23° BTDC (Default injection)	26° BTDC (Advanced injection)	20° BTDC (Retarded injection)
2	Antioxidant 1 (PY)	0 ppm	250 ppm	500 ppm
3	Antioxidant 2 (BHT)	0 ppm	250 ppm	500 ppm

Table 3. Experimental trails [22, 23]

Experiments	Injection Timing (IT)	Pyrogallol (PY)	Butylated Hydroxy Toluene (BHT)
1	23	0	0
2	23	250	250
3	23	500	500
4	26	0	250
5	26	250	500
6	26	500	0
7	20	0	500
8	20	250	0
9	20	500	250

Table 4. a Fuel properties [3]

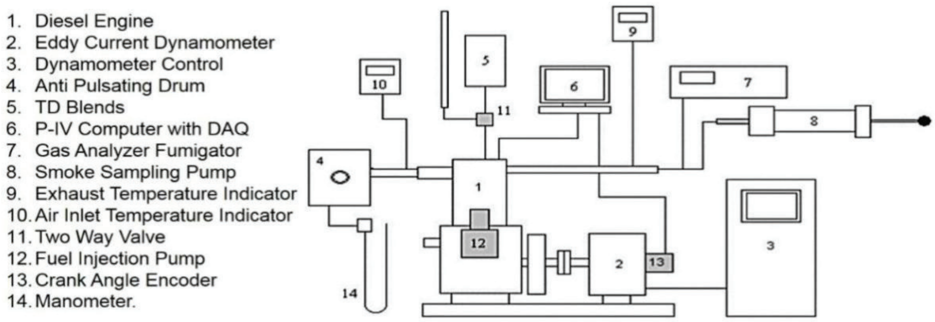
Fuel property	Instrument	Algae oil	Diesel	Biodiesel
Density at 15 °C (Kg/m³)	Hydrometer	918	836	840
Viscosity at 40 °C (mm²/s)	Rotational viscometer	31.5	2.9	3.3
Calorific Value (MJ/Kg)	Bomb calorimeter	38.9	42.3	41.7
Flash point (°C)	Flashpoint apparatus	131	64	72
Fire point (°C)	Pour point apparatus	-9	-19	-15
Cetane number	-	55	60	47

Table 4. b Properties of antioxidants

Properties	PY	BHT
Chemical structure	$C_6H_6O_3$	$[(CH_3)_3C]_2C_6H_2(CH_3)OH$
Molecular weight (g/mol)	126.11	220.35
Assay	98 %	99 %
Flash point (close cover) (°C)	164	127
Auto ignition point (°C)	309	470

Engine Setup

The direct injection diesel engine is used for the experimental investigation and the details of its parts are shown in Figure 1. The engine is attached to a dynamometer and develops 4.4 kW power at 1500 rpm. The inlet passage is mounted with an internal air heater, anti-pulsating drum, and resistance type thermocouple devices. At the exhaust, the engine is equipped with a smoke sampler, thermometer to measure exhaust gas temperature (EGT), and exhaust gas analyzers



1. Diesel Engine, 2. Eddy current Dynamometer, 3. Dynamometer Control, 4. Anti-pulsating Drum, 5. TD blends, 6. P-IV computer with DAQ, 7. Gas Analyzer Fumigator, 8. Smoke sampling pump, 9. Exhaust temperature indicator, 10. Air inlet temperature indicator, 11. Two way valve, 12. Fuel Injection Pump, 13. Crankangle encoder, 14. Manometer.

Figure 1. Schematic representation of engine test setup.

(EGA). Also, it is equipped with a petroleum consumption meter to determine the consumption rate of prepared fuel. A 64-bit data acquisition system is mounted to collect the data like the crank angle and cylinder pressure. The technical details of the engine and the instruments involved in the study are provided in Table 5 and Table 6 respectively. To apply the load, a swinging field electrical dynamometer of a 5-kVA AC alternator (220 V, 1500 rpm) was used.

The engine is operated at full load conditions. A strain gauge is used to measure the torque developed by the reaction accurately. To release the power developed, the water rheostat with height-adjustable immersion electrodes is provided. The thickness of the shim is varied to change the injection timing. The engine was tested with the combinations of factors shown in Table 3 and emission parameters and performance parameters were recorded for each combination of testing. Two replicates were made for each responses and the average of the two responses obtained for testing Taguchi L_9 experimental design are shown in Table 7.

Table 5. Engine specification

Rated Power	**4.4 KW**
Rated Speed	1500 rpm
Bore Diameter	87.5 mm
Stroke	110 mm
Compression Ratio	17.5:1
Orifice Diameter of injector	13.6 mm
Coefficient of discharge	0.62
Fuel injection system	Direct injection
Intake system	Naturally aspirated
Combustion Chamber	annular

Analysis and Optimization

The theoretical charter of the planned hybrid methodology is shown in Figure 2. In this work, based on experts' opinions the weightage is calculated and assigned for responses. The obtained data are incorporated for further processing to attain the grey relational grades (GRG).

AHP method

AHP is a powerful yet simple method based on mathematics and psychology for organizing and analyzing complex decisions. Initially, the problems in the system are identified and converted into a hierarchical structure. Then the objective function is considered for further evaluation. The procedures followed in the AHP method are discussed below.

Comparison of responses pairwise

Initially, responses for the system are identified and structured. Then a comparison is made on one over others based on the objective. A minimum of ten expert's opinions collected for the collective views. The collected results are converted into a square matrix (V_l) acquired from l^{th} expert (l=1, 2,….,L). According to the Saaty scale, each element (a_{ijl}) represents a score collected from the expert based on the importance of the response i and j [24] as shown in

Table 6. Range, accuracy and percentage uncertainties of instruments used

Instrument	Measured Quantity	Range	Accuracy	Uncertainties, %
AVL DIGAS 444 Exhaust gas analyzer	NOx	0 - 5000 ppm	±10 ppm	0.2
AVL 437C Smoke meter	Smoke opacity	0 – 100%	±2 %	1.0
Burette	Fuel quantity	0 – 1000 cc	±0.1 cc	1.0
Digital stopwatch	Time		±0.6 s	0.2

Table 7. Taguchi L_9 Experimental design and its response variables

Experiments	IT	PY	BHT	NOx PPM	Smoke %	BTE %
1	23	0	0	1476	43	32.21
2	23	250	250	1273	49	30.4
3	23	500	500	1220	56	34.81
4	26	0	250	1324	53	31.65
5	26	250	500	1243	62	31.65
6	26	500	0	1316	56	30.4
7	20	0	500	1188	78	32.91
8	20	250	0	1150	69	31.65
9	20	500	250	1094	86	30.38

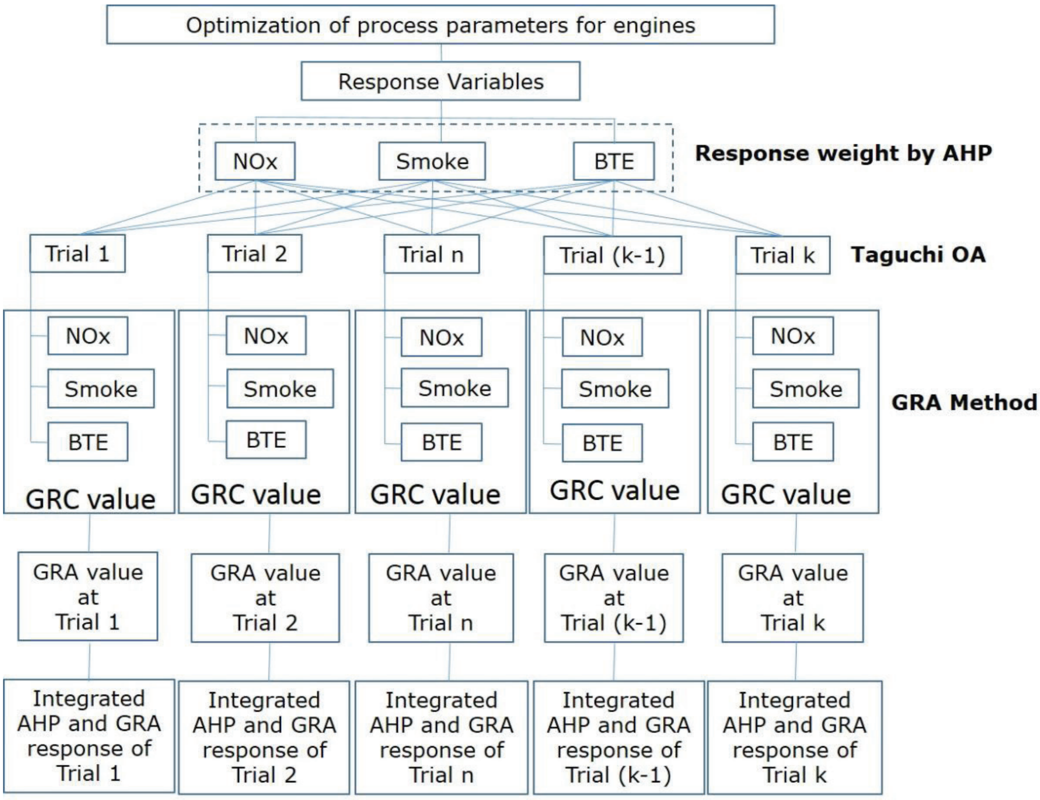


Figure 2. Methodology adopted for optimization.

Table 8. The square matrix used for determining the value is given in Equation (1).

$$V_l = \begin{pmatrix} a_{11l} & a_{12l} & \cdots & a_{1nl} \\ a_{21l} & a_{22l} & \cdots\cdot & a_{2nl} \\ \cdots\cdot & \cdots\cdot & \cdots\cdot & \cdots\cdot\cdot \\ a_{n1l} & a_{n2l} & \cdots\cdot\cdot & a_{nnl} \end{pmatrix} \quad \text{Where, } a_{ijl} = 1/a_{jil} \text{ and } i=1,\ldots,n, j=1,\ldots,n, l=1,\ldots,L \tag{1}$$

Estimation of the geometric mean from expert's opinion

The expert's view is always different from one another so to evade the influence scores are solicited independently. Then, the score is calculated in the following steps. The most commonly adopted technique to estimate the total score is shown in Equation (2) [25]. In Equation (3), the matrix required to calculate the aggregate score is presented.

Table 8. Importance scale for pair-wise comparison

Importance	Description
1	"*i*" and "*j*" are equally important
3	"*i*" is slightly more important than "*j*"
5	"*i*" is important than "*j*"
7	"*i*" is much important than "*j*"
9	"*i*" is absolutely important than "*j*"
2, 4, 6, 8	Intermediate values

$$b_{ij} = \sqrt[L]{\prod_{l=1}^{L} a_{ijl}} \quad \forall i, j \text{ and } i, j \in k \tag{2}$$

$$V = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots\cdot & b_{2n} \\ \cdots\cdot & \cdots\cdot & \cdots\cdot & \cdots\cdot\cdot \\ b_{n1} & b_{n2} & \cdots\cdot\cdot & b_{nn} \end{pmatrix} \tag{3}$$

Normalization of obtained data

The geometric mean value is normalized using Equation (4) and the matrix required to represent the normalized matrix is presented in Equation (5).

$$p_{ij} = \frac{b_{ij}}{\sqrt{\sum_{i=1}^{n} b_{ij}^2}} \quad \forall i, j \tag{4}$$

$$W = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots\cdot & p_{2n} \\ \cdots\cdot & \cdots\cdot & \cdots\cdot & \cdots\cdot\cdot \\ p_{n1} & p_{n2} & \cdots\cdot\cdot & p_{nn} \end{pmatrix} \tag{5}$$

Determination of weight

The following equation is necessary to determine the weight of each response are given in equation (6). The prominence of one response over other responses such as Injection timing and antioxidants to improve the engine performance is represented as weight.

$$w_i = \frac{\sum_{i=1}^{n} p_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij}} \quad \forall i \in k \;\; i = 1,2,\ldots,K \tag{6}$$

Check for consistency

Consistency Ratio (*CR*) must be less than 0.1 for the matrix involved in the study according to Saaty [24]. If it is higher than 0.1, the matrix needs to be revised and bring it to a consistent level. To get a successful output, the matrix needs to adhere to the principle of transitivity [26].

$$CR = \frac{CI}{RI} \mathrm{W} \tag{7}$$

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{8}$$

Where, λ_{max}– Eigen value of matrix V_n

Using equation (7), the RI can be determined for criteria *n* over the number of elements of a similar direction of reciprocal matrix. Principle Eigen value is determined using Equation (9).

$$\lambda_{\max} = \frac{\sum_{j=1}^{n} b_{ij} w_j}{w_i} \tag{9}$$

Taguchi grey relational analysis

In this method, controllable process parameters are identified to reduce the variation in a system to minimize the effects of noise factors. Noise factors can only be controlled during experimentation. To minimize the effects of the errors, the values of (signal to noise) S/N ratio are identified and modified as required. The multi-response optimization problem cannot be solved in the traditional Taguchi method, hence it is combined with GRA. In the year 1982, Deng proposed the GRA theory based on the grey set by linking the model's to various theories such as system, space, and control theory [25]. For all response conditions, whether "smaller the better" or "larger the better," Grey Relational Analysis estimates and consolidates the Grey Relational Coefficient (GRC) [27, 28]. GRA is a universally accepted technique to optimize multiple systems in many of automobile applications particularly in engine research [29–31]. The steps to evaluate the GRG using the Taguchi GRA method is as follows.

Calculation of signal to noise ratio

Based on the output, the Taguchi classifies the S/N ratio into various categories they are larger-the-better, smaller-the-better, and nominal-the-better. Each condition has their approach to determine the S/N ratio. In this work, two conditions maximize and minimize used to calculate S/N ratio with the aid of Equations (10&11) respectively.

$$x_k^0(i) = -10\log_{10}\left(\frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_{k(i)}^2}\right) \tag{10}$$

$$x_k^0(i) = -10\log_{10}\left(\frac{1}{n}\sum_{k=1}^{n} y_{k(i)}^2\right) \tag{11}$$

Where,

n - Total number of experimental trials

$y_k(i)$ - observed value of variable *i* (*i*=1, 2, …., *h*) obtained from experiment *k* (*k*=1, 2, ….., *n*).

Normalizing the obtained data

Normalizing the obtained data is required to get the dimensionless unit and its aid to integrate different conditions into one single value. Normalization of data is figure based on the condition of whether to be maximized or minimized using equation (12&13).

$$x_k^*(i) = \frac{x_k^o(i) - \min x_k^o(i)}{\max x_k^o(i) - \min x_k^o(i)} \tag{12}$$

$$x_k^*(i) = \frac{\max x_k^o(i) - x_k^o(i)}{\max x_k^o(i) - \min x_k^o(i)} \tag{13}$$

Where,

$maxx_k^o(i)$ is the Maximum of response i and $\min x_k^o(i)$ is the minimum of response i in L9 experiment.

Calculate grey relational coefficient

GRC helps to express the association amongst the normalized value with the ideal value and the same is given in the Equation (14).

$$\gamma_k(i) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_k(i) + \zeta\Delta_{\max}} \tag{14}$$

Where,

ζ - distinguishing coefficient of range 0-1 (0.5 prefered)

$\Delta_k(i)$- Difference of normalized value and reference sequence for i^{th} response

Δ_{max} - maximum values of $\Delta_k(i)$

Δ_{min} – minimum values of $\Delta_k(i)$

$$\Delta_k(i) = \left| x_o^*(i) - x_k^*(i) \right| \tag{15}$$

Where, $x_o^*(i)$- maximum value of $x_k^*(i)$

Calculate grey relational grade

It is a mean value of GRC added included with weight obtained by AHP method of all the response variables.

$$\delta_k = \sum_{i=1}^{h} w_i \gamma_k(i) \tag{16}$$

RESULTS AND DISCUSSION

After identification of the variable factors and responses, the opinion from the experts were gathered to rank the response and the weight for each of the responses are calculated. The objective was to optimize the engine parameters to obtain maximum efficiency and low emission. The eight experts with specialization in engine research were invited to correlate the prominence of one parameter over others to derive the weight as defined in Table 8. The values obtained from the experts were used to form the matrix using the geometric mean method as mentioned in Equation 2. The expert's pairwise comparison matrix is given in Table 9.

Table 9. Pairwise comparison matrix based on expert's opinion

Response variable	A	B	C
NOx (A)	1	1	2
Smoke (B)	1	1	1
BTE (C)	0.5	1	1

Table 10. Rank of response variables

Response variable	Weight	Rank
A	0.413	1
B	0.327	2
C	0.26	3

The obtained matrix is normalized using equation 4 and then using equation 6 the weight of the responses were ranked. In table 10, the rank and weight of the response variables are presented.

According to Khanna et al. [26], From Equation 7, the CR value must be less than 0.1, in this AHP analysis CR value is equal to 0.056, which is less than the value of 0.1. Thus, the pair-wise comparison for the response variables obtained from experts satisfies the condition thus the optimization can be progressed. From the results obtained using AHP analysis showed in Table 10, it is observable that the most significant response for the engine is NOx, which is followed by Smoke and brake thermal efficiency.

The S/N ratio for the responses obtained is derived from the equation 10&11 based on the conditions larger the better or smaller the better. Then, the equation 12&13 are used to determine the normalized value of S/N ratio. Then, the values between 1 (best) and 0 (worst) are provided for the individual data. Table 11 shows the S/N ratio and the normalization value of each experiment. From the normalization data, the grey relational coefficient is developed. The numerical values of normalization value after conversion and the GRC are given in Table 12.

Finally, GRC values are integrated with the weight obtained from AHP analysis to estimate GRG. The GRC value after incorporating the weight, GRG and the rank of each experiment are shown in Table 13. It is observed from the results that based on GRG value the optimized combination is IT of 23 degree, PY of 0 PPM, and BHT of 0 PPM. The optimized trail is denoted by IT1-PY1-BHT1. On the

Table 11. S/N ratio and Normalization values of responses

Experiments	S/N ratio			Normalization		
	NOx	Smoke	BTE	NOx	Smoke	BTE
1	-63.381	-32.669	30.159	1.000	0.000	0.430
2	-62.096	-33.803	29.657	0.506	0.188	0.005
3	-61.727	-34.963	30.834	0.364	0.381	1.000
4	-62.437	-34.485	30.007	0.637	0.302	0.301
5	-61.889	-35.847	30.007	0.426	0.528	0.301
6	-62.385	-34.963	29.657	0.617	0.381	0.005
7	-61.496	-37.841	30.346	0.275	0.859	0.588
8	-61.210	-36.777	30.007	0.167	0.682	0.301
9	-60.780	-38.690	29.651	0.000	1.000	0.000

Table 12. Normalization values conversion and calculation of GRC

Experiments	Converting Normalized Value			Calculating GRC		
	NOx	Smoke	BTE	NOx	Smoke	BTE
1	0.000	1.000	0.570	1.000	0.333	0.467
2	0.494	0.812	0.995	0.503	0.381	0.334
3	0.636	0.619	0.000	0.440	0.447	1.000
4	0.363	0.698	0.699	0.579	0.417	0.417
5	0.574	0.472	0.699	0.466	0.514	0.417
6	0.383	0.619	0.995	0.566	0.447	0.334
7	0.725	0.141	0.412	0.408	0.780	0.548
8	0.833	0.318	0.699	0.375	0.611	0.417
9	1.000	0.000	1.000	0.333	1.000	0.333

Table 13. Weight integrated GRC, GRG and rank of each experiment

Experiments	Weight			GRG	Rank
	NOx	Smoke	BTE		
1	0.410	0.109	0.121	0.213	1
2	0.206	0.125	0.087	0.139	9
3	0.180	0.146	0.260	0.196	2
4	0.238	0.136	0.108	0.161	5
5	0.191	0.168	0.108	0.156	6
6	0.232	0.146	0.087	0.155	7
7	0.167	0.255	0.142	0.188	3
8	0.154	0.200	0.108	0.154	8
9	0.137	0.327	0.087	0.183	4

other hand, the least performance obtained from the combination is IT1-PY2-BHT2.

The usage of fuel and power output of an engine are increased as the speed of an engine is increased. The percentage of biodiesel in diesel is increased, BTE is decreased. The load of an engine increases, BTE reaches maximum and then starts to decrease. The speed of an engine is less, leads to high heat loss and high usage of fuel. As compared the biodiesel with diesel, biodiesel possesses lesser thermal efficiency, restricted volatility, poor combustion behavior, and improved kinematic viscosity. The density and volatility of biodiesel causes reduction in BTE as compared to the diesel [31]. The total amount of oxygen, temperature of cylinder, and duration of residence are affected the development of NOx. The lean and rich air-fuel mixture is exhibited at the engine is working at low load and high load respectively. The temperature of the engine cylinder is increased which increases the NOx. The turbulence effect of the cylinder and the speed of an engine are increased, causes developing a rich amount of air-fuel mixture. The percentage of methyl ester is increased, NOx is also increased. The fuel consumption and engine speed are increased which results in the increasing smoke emissions [32]. Due to the high oxygen content at the low engine speed, the formation of smoke is reduced and the low oxygen content at the high engine speed, the formation of smoke is increased. The smoke emission is decreased due to the percentage blend of biodiesel in diesel is increased. The presence of oxygen content in methyl ester played a major role to reduce the smoke emissions. The methyl ester blended with the diesel developed less amount of smoke as compared with the diesel fuel. The increase of oxygen content in biodiesel increased the combustion characteristics and decreased the smoke emissions [33].

Significant Process Parameter

To find the influences of factors on the variables, the mean value of grey relational analysis is utilized by considering all the trials. The rank of responses based on control variables are shown in Table 14.

From the response table, it is witnessed that the best combination is when IT is at 23 ^{0}, PY is 0 PPM, and BHT

Table 14. Response table for GRG

Responses	Level 1	Level 2	Level 3	Best	Optimal Condition	Max-Min	Rank
IT	0.182	0.157	0.175	0.182	A1	0.026	2
PY	0.188	0.150	0.161	0.188	B1	0.038	1
BHT	0.174	0.178	0.180	0.180	C3	0.019	3

Table 15. Confirmation test

	Initial setting	Prediction	Experimental	Improvement
Setting level				%
NOx	1476	-	1386	6
Smoke	43	-	48	10
BTE	32.38	-	33.56	3.6
GRG	0.225	0.273	0.249	3.68

is 500 PPM, which is represented by the combination IT1-PY1-BHT3. The Max-Min value in Table 14 designates the responses with supreme impact. Thus, PY is the peakleading parameter followed by IT and BHT.

Confirmation Test

After the determination of required data from the experiment, a validation or confirmation test is required to analyse the accuracy of obtained data. From Table 14, the GRG value needs to be predicted by using Equation 17.

$$\delta_{pre} = \delta_{tot} + \sum_{i=1}^{n}\left(\delta_{opt} - \delta_{tot}\right) \tag{17}$$

Where,

δ_{tot}- total mean of GRG

δ_{opt} - mean of GRG at the optimum level.

From the calculation, it is derived that the predicted GRG is 0.273. Table 15 shows the data obtained from the confirmation test using the best combination determined with the help of AHP-GRA hybrid technique. Based on the results, clearly understand that GRG is improved from 0.225 to 0.249 i.e. improvement of 3.68 %. The response values are improved from 1476, 43, 32.38 to 1386, 48, 33.56 respectively. The NOx and BTE improved by 6% and 3.6%, respectively, with a compromise of a 10% increase in smoke.

CONCLUSION

In this research work, the novel hybrid technique is adopted successfully to optimize the parameters of biodiesel powered CI engine. The following conclusions are drawn from these investigations:

1. A hybrid technique in optimization to perform a multi response system has been productively employed for the first time in biodiesel powered CI engine. The optimum levels of process parameters are IT is at 23^0, PY is at 0 PPM, and BHT is at 500 PPM (IT1-PY1-BHT3).
2. The confirmation test revealed a 3.68% enhancement in GRG value, with improvements of 6% and 3.6 % observed in NOx and BTE respectively, compared to the optimal combination identified from the L_9 orthogonal array.
3. The Taguchi-Grey-AHP methodology has enhanced the promising results envisioned for biodiesel-powered CI engines. Consequently, this approach could potentially be extended to optimize various systems or industrial processes, ensuring enhanced quality, quantity, and efficient resource utilization within the sector.

Future Scope

The present developed model will be used to develop the CI engine operating by the biodiesel and enhance their performance and emission characteristics.

NOMENCLATURE

λ_{max}	Eigen value of matrix V_n
n	Total number of experimental trials
$y_k(i)$	Observed value of variable i (i=1, 2, …., h) obtained from experiment k (k=1, 2, ….., n).
$max x_k^o(i)$	The maximum of response i
$\min x_k^o(i)$	The minimum of response i in L9 experiment.
ζ	Distinguishing coefficient of range 0-1 (0.5 prefered)
$\Delta_k(i)$	Difference of normalized value and reference sequence for i^{th} response
Δ_{max}	Maximum values of $\Delta_k(i)$
Δ_{min}	Minimum values of $\Delta_k(i)$
Where, $x_o^*(i)$	Maximum value of $x_k^*(i)$
δ_{tot}	Total mean of GRG
δ_{opt}	Mean of GRG at the optimum level.

Abbreviations

BHT	Butylated Hydroxy Toluene
GRA	Grey Relational Analysis
GRC	Grey Relational Coefficient
GRG	Grey Relational Grade
IT	Injection Timing
PY	Pyrogallol
WED	Weighted Euclidean Distance
AHP	Analytical Hierarchy Process
EGT	Exhaust Gas Temperature
EGA	Exhaust Gas Analyzers
CR	Consistency Ratio
S/N	Signal to Noise
OA	Orthogonal Array
BTDC	Before Top Dead Center
BTE	Brake Thermal Efficiency

AUTHORSHIP CONTRIBUTIONS

Krishnamoorthy Natarajan: Investigation, Writing-Original draft, Conceptualization, Methodology, **Saravanan Subramani:** Visualization, Data preparation, Reviewing and Editing, **Ravi Govindasamy:** Software, Formal analysis, **PaulDurai Kumar:** Resources**,** Software Validation

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

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

ETHICS

There are no ethical issues with the publication of this manuscript.

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