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Grey-Taguchi and ANN optimization in CI Engines using acetylene & biodiesel blends for Low Emissions and Better Performance

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Abstract: This study aimed to reduce smoke and NOx emissions in a diesel engine fuelled with a 20% blend of Calophyllum inophyllum and Prosopis juliflora biodiesel (B20) with neat diesel, supplemented with acetylene at flow rates of 1, 2, and 3 liters per minute (lpm) in dual-fuel mode. Using the Grey-Taguchi method and an L9 (3^3) orthogonal array, the effects of compression ratio, fuel type, and acetylene flow rate were examined. Regression models were developed to predict brake thermal efficiency, smoke, and NOx emissions based on these controllable factors. The study found that the optimal individual values for NOx, brake thermal efficiency, and smoke were 2353 ppm, 31.52%, and 48.7 ppm, respectively. The best-combined results were achieved with a compression ratio of 17.5 and an acetylene flow rate of 3 lpm using the CI20 blend. The findings demonstrated significant improvements in output response factors when the optimal combination was applied, as validated by experimental and artificial neural network (ANN) simulations. The Grey-Taguchi approach proved effective in reducing emissions while enhancing engine performance.

Keywords: Grey-Taguchi approach, ANN, Regression, Acetylene, Calophyllum inophyllum, Prosopis Juli flora biodiesel.

1. Introduction

Diesel engines are used extensively to produce energy and provide power to transportation systems all over the globe. The huge volumes of smoke and nitrogen oxides that they produce continue to be a significant barrier to their advancement throughout the industry. When compared to other kinds of engines, gasoline engines may be distinguished by their higher thermal efficiency, improved torque capacity, and lower emissions of carbon monoxide and hydrocarbons. However, in addition to these benefits, they also emit huge quantities of smoke and nitrogen oxides, which means that they pose a serious risk to the environment. The deterioration of the environment, the depletion of fossil fuel reserves, and the need for energy security have all received an increasing amount of attention over the last twenty years. As a consequence of this, there has been a substantial emphasis placed on the search for alternative fuels. One of the key driving forces behind these tremendous developments is the growing use of fuels derived from petroleum. The excessive usage of petroleum fuels has been a contributing factor in the widespread destruction of the environment and is a contributor to the harm that it presents to the general public's health. The combustion of petroleum fuels is the principal source of gaseous air pollutants. These contaminants include carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (UHC), and nitrogen oxides (NOx). High amounts of these pollutants are released into the atmosphere. Several studies have shown the link between these pollutants and the development of lung cancers as well as cardiovascular problems In light of this, it is of the utmost importance to research alternative fuels that are not only renewable but also good for the environment, such as biofuels that are both green and sustainable [1-8].

As a result of the adoption of more stringent emission restrictions all around the globe, researchers have explored developing new and better methods for reducing harmful pollutants. Altering the injection time, recirculating exhaust gas, using water emulsification, utilizing exhaust catalysts, changing the combustion chamber, and minimizing ignition delay are only a few of the approaches that have been used extensively to reduce the amount of nitrogen oxide (NOx) emissions. This is because of the inverse trade-off that exists between NOx and smoke, which makes it difficult to reduce one of them without simultaneously increasing the other, and vice versa [9-11]. At the present moment, researchers are looking into a wide range of elements to achieve simultaneous reductions in NOx emissions and smoke density concentrations. One of the reasons for this is that there are several conflicting goals, including the decrease of emissions of both smoke and nitrogen oxides (NOx), while simultaneously maintaining optimum performance. As a result, it is of the utmost importance to develop scientific approaches that are capable of effectively regulating emissions while simultaneously reducing the effects on performance. Within the context of a dual-mode engine, this research work focused on the use of acetylene, which is a gaseous fuel, in combination with B20 blends. The emission of smoke and nitrogen oxides had to be reduced while the performance was to be kept at its highest possible level. Through the use of the GTM approach in conjunction with the conventional Taguchi design, the optimization was accomplished. Acetylene, compressed natural gas (CNG), biogas, and producer gas are some of the other gaseous fuels. Even though they represent an alternative to petroleum, gaseous fuels are not compatible with compression ignition engines. Because of their much higher autoignition temperature, gaseous fuels can be ignited at temperatures that are far lower than those that are encountered during the compression stroke. For spark ignition engines that run on gaseous fuels, the timing of the spark is very important and must be done with precision. To make optimal use of acetylene gas as a gaseous fuel in a diesel engine, it is essential to optimize the experimental test rig.

In 1836, Edmund Davy discovered that acetylene gas (C_2H_2) should be used. The hydrocarbon represented by this chemical is not conventional. In the year 1860, Marceline Berthelot was the first person to use the name "acetylene" when she discovered the substance under investigation. The production of acetylene gas was accomplished by first causing organic compounds, such as methanol and ethanol, to undergo thermal decomposition inside of a heated tube, and then collecting the emission that was produced as a consequence of this process. In order to generate electricity, it is possible to pass a current through a mixture of hydrogen and cyanogen. It is possible for acetylene gas to be produced when hydrogen moves between the poles of the carbon arc. A direct consequence of the reaction that takes place between water and calcium carbide, which ultimately leads to the production of acetylene, is the production of synthesis gas being produced. At the beginning of the nineteenth century, acetylene was used in the private homes of people in order to offer light. Acetylene is a substance that is characterized by its lack of color, its odor that is similar to that of garlic, and its high likelihood of becoming combustible. Because of the way it interacts with oxygen, it has the potential to produce temperatures that may escalate to as high as three thousand degrees Celsius. Because it is so simple to produce, acetylene may be synthesized without the need for complicated machinery. This is because it can be produced by mixing calcium carbide with water. Acetylene is produced in order to fulfill the supply of illumination that is required at mining sites. Acetylene is mostly used in welding operations and in light torches, since it has a restricted range of applications in industrial settings. Ether, also known as diethyl ether (DEE), is a chemical molecule that is characterized by its very low boiling point and the fact that it persists in a liquid form. Ether is a chemical that is a clear substance that is very combustible. An oxygen-generating agent is fed into diesel engines during the cold start phase of the engine's operation. Due to the fact that it has a low autoignition temperature, diethyl ether (DEE) functions as a catalyst and speeds up the ignition process. It is done in this manner in order to reduce the amount of nitrogen oxides (NOx) that are released by diesel engines [12].

The majority of engine designers have made modifications to the components of traditional internal combustion engines to permit dual-fuel combustion [13]. The transition to a dual-fuel engine (DFE) has a considerable impact on lowering emissions [14-15], but it does not have a major impact on performance. In addition, several studies have shown that DFE has a significant disadvantage, which is the emission of significant amounts of nitrogen oxides, regardless of the load it is being used for various forms of gaseous fuels, such as hydrogen, compressed natural gas, acetylene, biogas, and hydrogen, have been used by engine experts in the development of DFE engines.

Furthermore, compressed natural gas has been used in conjunction with hydrogen in other applications. Research on the many different types of fuels has been conducted by several researchers [16-19]. The majority of the investigations that have been conducted have focused on hydrogen and compressed natural gas, according to the most recent study. The use of hydrogen as an alternative energy source is seen as a viable option that can assist in the fight against the depletion of petroleum products and highlight possible future energy sources. In addition to having the ability to efficiently handle concerns such as reverse discharges, pre-ignition, and detonation, the Hydrogen Direct-Infusion (HDI) technique has the potential to greatly improve efficiency. On the other hand, this promise has not yet been fully realized [20]. When the diameter of the nozzle and the pressure of the hydrogen combustion increased, the combustion rate of the engine decreased. The engine's combustion qualities were enhanced as a consequence of the higher combustion pressure that it brought about. On the other hand, there have been very few studies carried out on the use of acetylene as a main fuel in compression ignition (CI) applications. According to the assertions made by several engine specialists [21-22], the use of acetylene has the potential to solve the issues of black emissions, condensation on engine walls, and decreased lubrication that are often seen in compression ignition (CI) engines.

In addition, acetylene is less hazardous than hydrogen and has a lower cost-effectiveness compared to hydrogen. There is the possibility that hydrogen might be used as an alternative fuel in internal combustion engines in a manner that is both efficient and viable. Additionally, several studies have hypothesized that it has the potential to take the place of diesel fuel in the not-too-distant future respectively [23].

An investigation was carried out with the purpose of optimizing the flow rate of acetylene in a direct injection (DI) engine that was running in dual fuel mode. They concluded that out of the four different flow rates that might be used for dual fuel operation. These flow rates are 5, 6, 7, and 8 liters per minute. It has been observed that increasing the flow rate of acetylene induction causes the maximum pressure inside the cylinder to increase until it hits a particular threshold, after which it starts to fall. This phenomenon continues until the pressure exceeds the threshold. This behavior has been seen rather often. Over time, it has been observed that the pace at which heat is emitted grows in direct proportion to the quantity of acetylene induction, and this rate is typically higher when compared to the operation of pure diesel. When the test rig is operating on both fuels at the same time, the amount of carbon monoxide (CO) emissions decreases, but the amount of nitrogen oxide (NOx) emissions increases [24]. Few studies have reported that a certain fuel has a wide variety of chemical and physical properties [25]. Making adjustments to the operational parameters is necessary in order to bring them into alignment with the particular qualities of the fuel. This is because the features of the fuel have an effect on the aspects of combustion. The compression ratio is an essential component that has a very significant impact on the performance of the engine. According to the current body of research, it is evident that acetylene has been acknowledged as a fuel that has the potential to be successful for both spark ignition (S.I.) and compression ignition (C.I.) engines when it is used in dual fuel mode operations. On the other hand, there are limited studies that have been published about the influence that compression ratio has on the operation of dual-fuel internal combustion engines' performance. To acquire the best possible performance from the engine, it is required to conduct a comprehensive investigation of the combustion behavior, performance, and emission characteristics of the engine. For this investigation, it is necessary to conduct trials at several different compression ratios.

Following an examination of the existing body of literature, the study has concentrated on lowering emissions of smoke or NOx by the use of a variety of alternative fuels. The number of efforts that were made to significantly reduce the emissions, which would ultimately affect BTE, was quite minimal. In recent years, numerous experimental and numerical studies have been conducted to evaluate the performance of diesel engines. However, a research gap remains in the measurement and optimization of performance and emissions. Motivated by this, the current study focuses on optimizing performance parameters such as compression ratio, type of fuel, and flow rate. These optimizations are conducted, Consequently, the findings of this research provide a method that is both scientific and novel, to reduce the amount of smoke and NOx emissions produced by diesel engines while simultaneously preserving their Brake Thermal Efficiency (BTE). Additionally, the investigation investigates the influence of factors such as compression ratio, flow rate, and type of fuel on the reduction of emissions that are associated with the process. At the same time as it reduces the number of experimental trials that are carried out, it offers dependable quality control [26-27]. Nevertheless, the Taguchi approach has a key disadvantage in that it can only solve problems that involve a single answer. This is a significant restriction since the majority of engineering-related problems that occur in real time include several responses. It is of utmost importance to combine all of these different responses into a single function that incorporates all of the components that contribute to the overall quality of the process. Previous studies that were conducted by several researchers were effective in adjusting key engine variables to reduce NOx levels while simultaneously reducing the impacts on smoke density and thermal efficiency [28-32]. The purpose of this study is to investigate the possibility of lowering emissions of smoke and nitrogen oxide (NOx) without compromising performance fuelled by a 20% blend of Calophyllum inophyllum and prospsis juliflora biodiesel with neat diesel (B20) added along with acetylene at various flow rates from 1lpm to 3lpm in a dual fuel mode.

The objectives of this work are:

I. To determine the optimum combination of factors such as compression ratio, flow rate, and type of fuel to reduce emissions of smoke and nitrogen oxides (NOx), with a marginal compromise on BTE without any alteration in the engine's hardware.

II. To investigate the multiple response combined effect of BTE, NOx & Smoke.

III. To study the most influential factor in lowering the emissions of nitrogen oxides and smoke of various biodiesel blends at various flow rates and compression ratios.

2. Materials & Methods

The experiments were carried out as per the test matrix designed using Taguchi's technique of design of experiments (DOE).

Figure 1 illustrates the flow chart of the experimentation procedure.

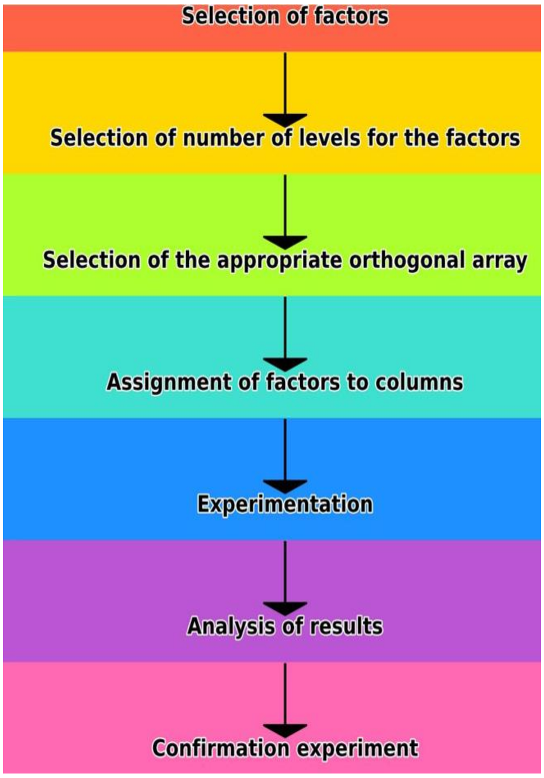

Figure 1. Experimental Procedure

2.1 Calophyllum inophyllum plant and Prosopis Juli flora Blends

Based on the transesterification technique, the oil that was obtained from the seeds of the Calophyllum inophyllum plant and Prosopis Juli flora was employed in the production of calophyllum inophyllum methyl ester (CIME) and Prosopis Juli flora methyl ester (JFME). In the subsequent phase of this experiment, CIME was used as a biodiesel. In the experiment, a fuel diesel and 20% CIME, 80% diesel, and 20% JFME, and it was also combined with acetylene (C_2H_2) that was stored in a cylinder. A high combination of Calophyllum inophyllum biodiesel (CI20) and Prosopis Juli flora (JF20) was used. This fuel mixture is composed of 80% pressure maintained in storage cylinders for acetylene, and a pressure reducer was used in combination with a pressure controller to bring the pressure down to the level that was wanted. To solve the problem of backfiring that was brought about by the increased flammability constraints of acetylene, flame arrestors were used. The flow rate of acetylene was found to be the rate. Using a suitable flowmeter. Table 1 illustrates the properties of test samples used in this investigation: Acetylene gas was injected into the intake manifold of the engine, which allowed it to function effectively in a dual-fuel arrangement. To ensure safety, a flame arrester and a flame trap containing water were incorporated into the acetylene conduit. A control valve was employed to modulate the discharge rate of acetylene. The flow rate of biodiesel and diesel was measured and monitored by the installation of a burette in the panel, which was outfitted with the appropriate valves. The crank's angle and the pressure within the cylinder were both measured. Utilizing a mechanical angle encoder and a Kistler piezoelectric transducer. The AVL. 437°C smoke meter is intended to measure the the opacity of smoke produced by an engine.

The AVL Digas 444N gas analyzer was employed to measure the emissions of CO, HC, and NOx. The specifications of a diesel engine are illustrated in Table 2. The accuracy and range of various instruments and uncertainty analysis in the present investigation are illustrated in Table 3. The uncertainties in the measured parameters are illustrated in Table 4.

3. Results & Discussions

The engine was subjected to nine tests, each utilizing a different combination of input parameters.

3.1 Analysis of variance (ANOVA) for BTE, Smoke, and NOx

To determine the influence of the input parameters that were provided, specifically, analysis of variance (ANOVA) was used. The type of fuel, the compression ratio, and the flow rate of acetylene are some of the parameters that influence the BTE, as well as smoke and nitrogen oxide emissions. ANOVA is a powerful statistical tool for comparing group means and identifying significant differences [36].

Table 1. Properties of Fuel Samples [33-35].

Properties	ASTM D6751	Diesel	CI20	JF20	Acetylene
Density (kg/m^3)	-	840	851	860	1.092
Kinematic Viscosity (cSt)	1.9-6.0	3.35	1.86	1.72	-
Flashpoint(°c) **Fire point(°c)**	>110 -	68 60	44 53	47 55	-
Calorific value (MJ/kg)	>43	43.5	41.40	41.60	48.5
Cetane number	-	51	53	50.4	-
Auto Ignition temperature		180-220	-	-	300-330
Molecular Weight (g/mol)	-	210	-	-	-

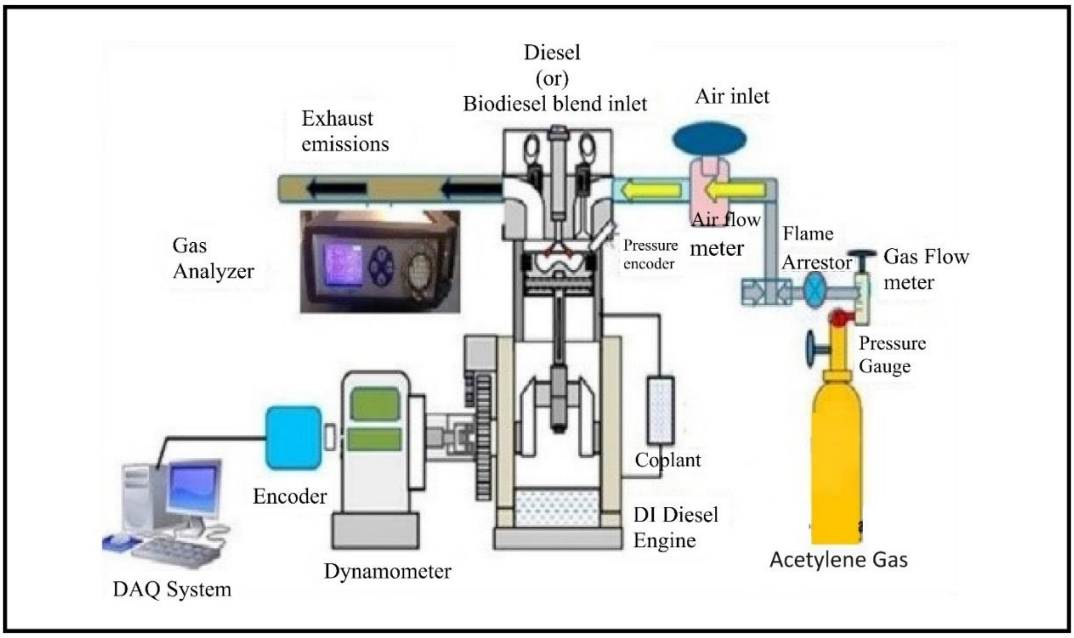

Figure 2. Experimental Set-up

Table 2. Engine Specifications

Make and Model	Kirloskar TV1 single-cylinder 4-stroke diesel engine
Number of cylinders	Single
Rated brake power and speed	5.2 kW and 1500 rpm
Compression Ratio	17.5:1
Stroke × Bore (mm)	110 × 87.5
Cooling system	Water Cooled
Standard FIT & FIP	23° bTDC and 210 bar
Dynamometer	Eddy current dynamometer

Table 3. Accuracy and range of the various instruments

Instrument	Measuring range	Accuracy
AVL Gas analyzer		
Carbon monoxide (CO)	0-9% Vol	0.01% Vol
Hydrocarbon (HC)	0-1000 ppm	1 ppm
Oxides of Nitrogen (NOx)	0-5000 ppm	1 ppm
AVL Smoke meter		
Smoke density	0-9.99 HSU	0.01 HSU

Table 4. The uncertainties in the measured parameters

Parameter	Symbol	Uncertainty in %
Load	L	0.6
Pressure	P	1.1
Speed	N	1.2
Brake power	BP	0.5
Break Thermal Efficiency	BTE	0.4
Brake-Specific Energy Consumption	BSEC	0.3
Hydro Carbon	HC	0.2
Carbon monoxide	CO	0.6
Smoke opacity	SO	0.3
Nitrogen Oxides	NOx	0.5

Table 5. ANOVA analysis for BTE

Source Variation	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value	Percent Contribution (%)
Regression	3	24.6056	8.2019	40.34	0.001	96.03%
CR	1	13.8017	13.8017	67.88	0.000	53.86%
FR	1	10.7246	10.7246	52.75	0.001	41.85%
TF	1	0.0793	0.0793	0.39	0.560	0.309%
Error	5	1.0166	0.2033			3.967%
Total	8	25.6222				

The findings of the analysis of variance (ANOVA) are shown in Tables 5, 6, and 7 respectively, for brake thermal efficiency, NOx, and smoke. The investigation was carried out with a ninety-five percent confidence level and a five percent significance level. The following elements are included in the analysis of variance table: degrees of freedom, sum of squares, mean square, F ratio, P value, and percentage of contribution all have their respective components.

The analysis of variance (ANOVA) is a statistical test that is often used to explain the importance of certain model coefficients. An analysis of variance was performed to determine the importance of each component by calculating its F value. When the F contribution of a component is higher, the influence that it has on the response ratio is also higher.

The response ratio is defined as the ratio of the mean square to the mean square of experimental error. The fact that the p-value for the term in the model is lower than 0.05 indicates that the term is statistically significant rather than insignificant. In these models, the compression ratio and flow rate are two very important factors. The compression ratio was responsible for 53.86 %, while the flow rate was responsible for 41.85 % and the type of fuel was responsible for 0.3096 % contribution on BTE. According to the findings, the most influential component was the compression ratio, which had a percentage of 53.86 %. The flow rate and the type of fuel came in second and third, respectively. 3.967% is the percentage of error that is measured for the BTE, which is satisfactory [37-38].

It is estimated that the compression ratio is responsible for 79.83%, with a flow rate of 6% and the type of fuel was 0.014% contribution on NOx. It was determined that the Compression ratio, which had a value of 79.83%, was the most significant component, followed by the flow rate and the type of fuel. The level of error for NOx is quite low, coming in at 14.14 %.

The compression ratio was responsible for 32.18%, while the flow rate was responsible for 25.66 % and the type of fuel was responsible for 25.87 % contribution on smoke. According to the findings, the most influential component was the compression ratio, which was 32.18 %. The type of fuel and the flow rate came in second and third, respectively [39].

3.2 Regression equations of brake thermal efficiency (BTE), smoke, and nitrogen oxides (NOx)

Regression equations help to quantify the relationship between dependent variables (NOx emissions, smoke density, BTE) and independent variables (factors such as fuel, the compression ratio, and the flow rate of acetylene.)

The regression equations are as follows:

$$\mathrm{BTE} = 1.50 + 1.517\,\mathrm{CR} + 0.2917\,\mathrm{FR} - 0.115\,\mathrm{TF} \quad (1)$$

$$\mathrm{NOx} = -213 + 162.0\,\mathrm{CR} + 9.70\,\mathrm{FR} - 2.2\,\mathrm{TF} \quad (2)$$

$$\mathrm{SMOKE} = 129.0 - 4.35\,\mathrm{CR} - 0.848\,\mathrm{FR} + 3.90\,\mathrm{TF} \quad (3)$$

Regression analysis yields the following coefficients for the BTE emissions model:

- The coefficient for the compression ratio (CR) is 1.5, indicating that an increase in the compression ratio leads to an increase in BTE.
- The coefficient for flow rate (FR)is 0.29, suggesting that an increase in flow rates increases BTE
- The coefficient for the type of fuel (TF) is -0.1, implying that fuel with a higher calorific value increases BTE.

R-squared is a crucial metric in regression analysis, used to assess the goodness-of-fit of a model. It ranges from 0 to 1, where higher values indicate a better fit. Based on the regression equations, the following regression statistics are obtained for the BTE: R-squared = 96.03%, Adjusted R-squared= 93.65%, and Predicted R-squared = 87.38%. These Values indicate that the models indicate a better fit.

Table 6. ANOVA analysis for NOx

Source Variation	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value	Percent Contribution (%)
Regression	3	169344	56448	10.12	0.015	85.85%
CR	1	157464	157464	28.22	0.003	79.83%
FR	1	11851	11851	2.12	0.205	6.00%
TF	1	28	28	0.01	0.946	0.014%
Error	5	27901	5580			14.14%
Total	8	197244				

Table 7. ANOVA analysis for the Smoke

Source Variation	Degree of Freedom	Adj SS	Adj MS	F-Value	P-Value	Percent Contribution (%)
Regression	3	295.32	98.44	8.58	0.020	83.73%
CR	1	113.53	113.53	9.89	0.026	32.18%
FR	1	90.53	90.53	7.89	0.038	25.66%
TF	1	91.26	91.26	7.95	0.037	25.87%
Error	5	57.38	11.48			16.26%
Total	8	352.70				

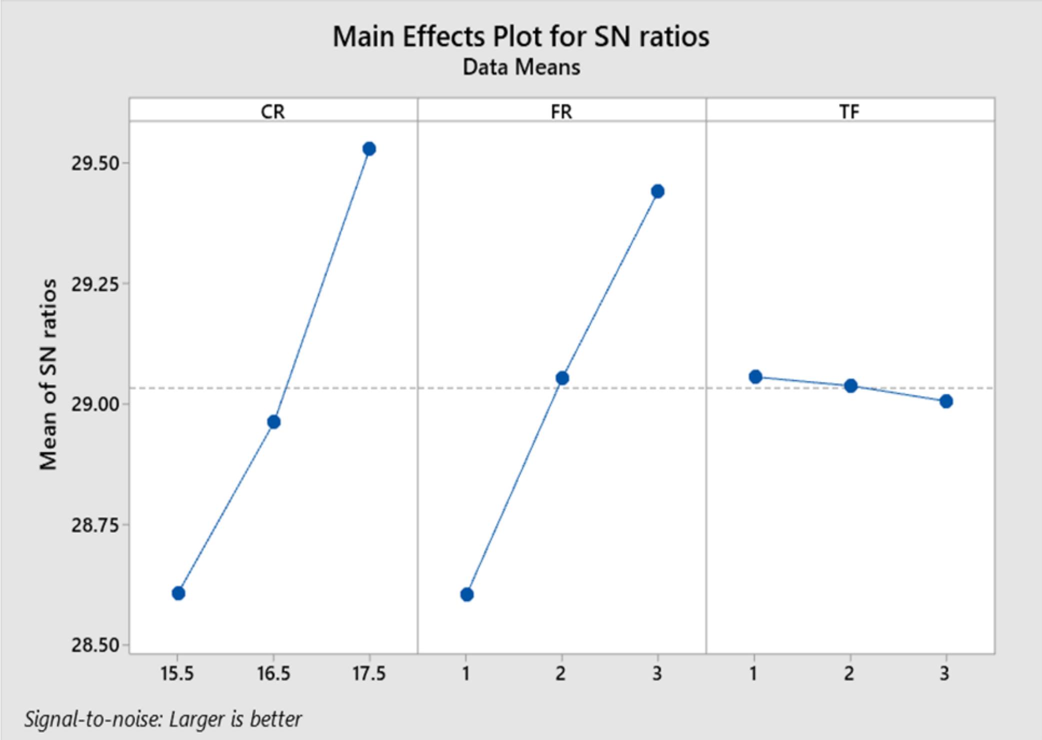

Figure 3. S/N plot for BTE at full load

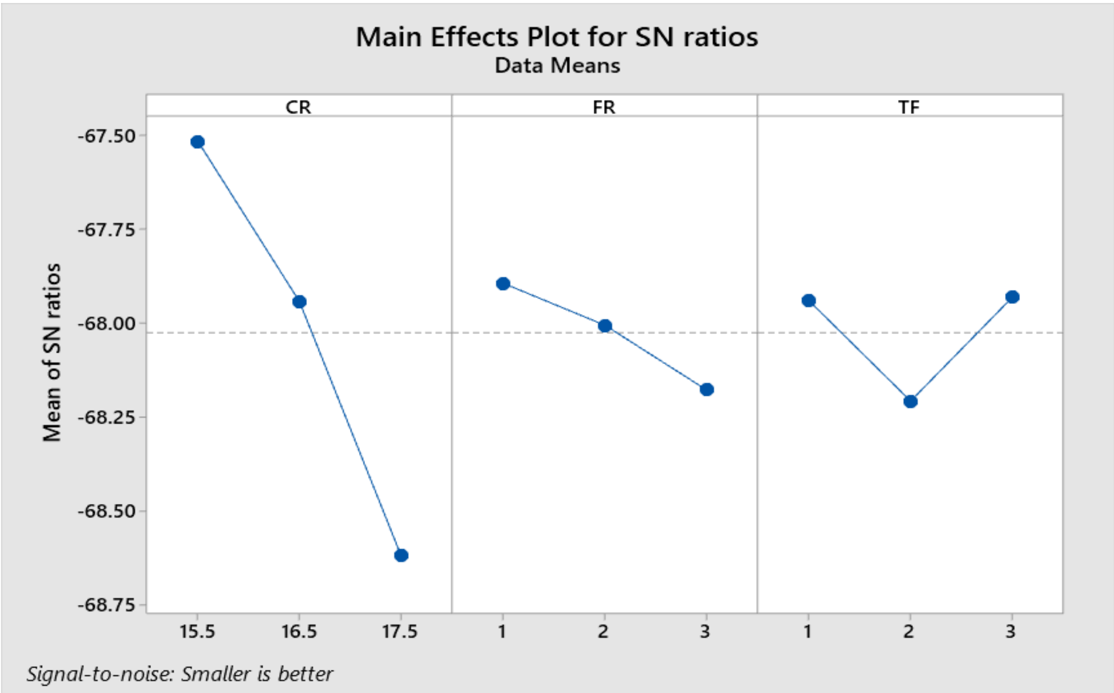

Figure 4. S/N plot for NOx at full load

3.3 Analysis of the S/N ratio for BTE, Smoke, and NOx

The objective of this study was to achieve the highest possible Brake Thermal Efficiency (BTE) while simultaneously reducing the amount of smoke and nitrogen oxides (NOx) that were released into the atmosphere. The characteristic of "larger is better" was picked for BTE, whereas the attribute of "smaller is better" was selected for NOx and smoke. This was done to achieve the objective that was set out. The main effects plot of BTE can be seen in Figure 3. The main effects plot of NOx and Smoke is shown in Figures 4 & 5 respectively.

In an era where quality and reliability are paramount, the Taguchi method offers a systematic approach to design optimization [38].

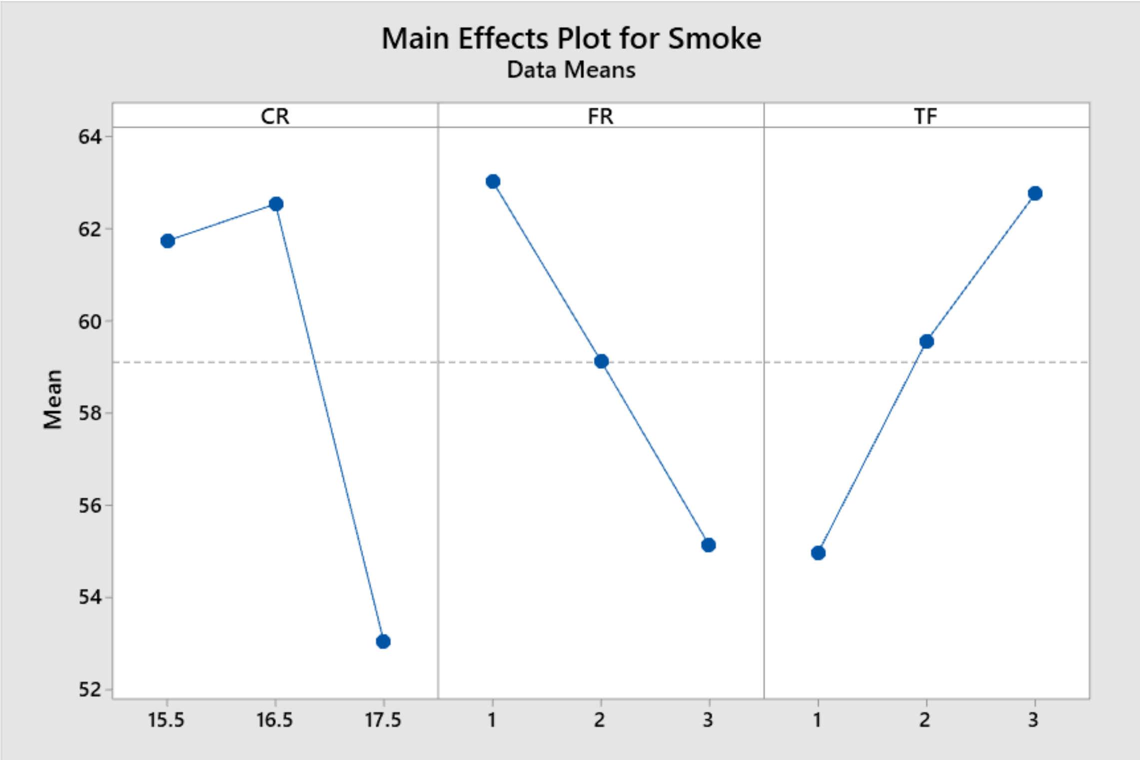

Figure 5. S/N plot for Smoke at full load

Table 8. Data Normalization

	BTE		NOX		SMOKE	
Expt	S/N Ratios	Normalized	S/N Ratios	Normalized	S/N Ratios	Normalized
1	35.22	0.00	-60.44	0.00	-28.82	0.75
2	35.58	0.21	-60.56	0.07	-28.90	0.78
3	36.00	0.45	-60.57	0.08	-28.75	0.73
4	35.55	0.19	-60.99	0.33	-29.49	1.00
5	35.97	0.43	-60.97	0.32	-29.45	0.99
6	36.34	0.64	-60.90	0.27	-27.74	0.36
7	36.02	0.46	-61.28	0.51	-28.67	0.70
8	36.58	0.79	-61.51	0.65	-26.76	0.00
9	36.96	1.00	-62.10	1.00	-26.94	0.06

Table 9. The findings of GRC & GRG Variables

Expt	BTE	NOx	SMOKE	Grade	Rank
1	0.33	0.33	0.67	0.27	9
2	0.39	0.35	0.70	0.29	7
3	0.48	0.35	0.65	0.29	6
4	0.38	0.43	1.00	0.36	3
5	0.47	0.42	0.97	0.37	2
6	0.58	0.41	0.44	0.29	8
7	0.48	0.50	0.63	0.32	5
8	0.70	0.59	0.33	0.32	4
9	1.00	1.00	0.35	0.47	1

Developed by Genichi Taguchi, this method emphasizes the importance of robust design, focusing on making products and processes resilient to variations. The key instruments in this method are response graphs and S/N ratios, which minimize variability and enhance performance. Which help identify optimal settings The S/N ratio is a cornerstone of the Taguchi method, serving as a measure of robustness by evaluating the influence of noise factors on the response variable. The primary objective is to maximize the S/N ratio, thereby achieving a design that performs consistently under varying conditions. Depending on the nature of the quality characteristic, different forms of S/N ratios are employed. Response graphs, also known as main effect plots, are visual representations of the influence of different factors on the response variable. In the context of the Taguchi method, these graphs help in identifying the optimal levels of control factor.

3.4 Grey–Relational Analysis (GRA)

The Grey–Relational Analysis (GRA) is a multifaceted technique in the domain of quality engineering and decision-making. Originating from the gray system theory, GRA is particularly effective for handling systems with incomplete and uncertain information. Modern engineering and manufacturing processes often involve multiple response variables that must be optimized simultaneously. Traditional optimization methods can struggle with the complexity and interdependence of these responses [40-41]. The Gray Relational approach offers a robust solution to this challenge, enabling effective multi-response.

Optimization by transforming multiple responses into a single relational grade. Table 8 & 9 represent Data Normalization and the findings of GRC & GRG Variables.

Methodology of Gray Relational Analysis

The Gray Relational Approach involves several systematic steps:

Step-1: Data Normalization

Before applying GRA, data must be normalized to ensure comparability. This process transforms different measurement scales into a dimensionless form.

For larger-the-better responses:

$$Xi'(k) = Xi(k) - min\ (Xi(k)) / \ max\ (Xi(k)) \ - min\ (Xi(k)) \quad (4)$$

$$Xi'(k) = max\ (Xi(k)) \ - min\ (Xi(k)) / max\ (Xi(k)) \ - Xi(k) \quad (5)$$

Step-2: Reference Sequence Determination:

Define a reference sequence, usually the best performance among the normalized data.

Step-3: Gray Relational Coefficient Calculation:

Calculate the Gray Relational Coefficient (GRC) to express the relationship between the reference and comparability sequences.

$$\xi i(k) = \Delta min + \zeta \Delta max \ / \ \Delta i(k) + \zeta \Delta max \quad (6)$$

Here, $\Delta i(k)=|X0'(k)-Xi'(k)|$ is the absolute difference between the reference and actual sequence, Δmin and Δmax are the minimum and maximum values of $\Delta i(k)$ respectively, and ζ is the distinguishing coefficient, typically set to 0.5.

Step-4: Gray Relational Grade Calculation:

Compute the Gray Relational Grade (GRG) to aggregate the multiple GRCs into a single metric:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad (7)$$

The GRG represents the overall performance across multiple responses, with higher values indicating better performance [42].

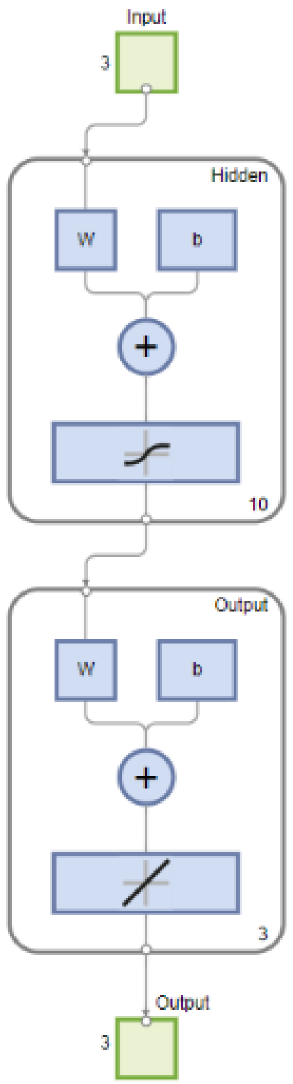

Figure 6. ANN Training Network

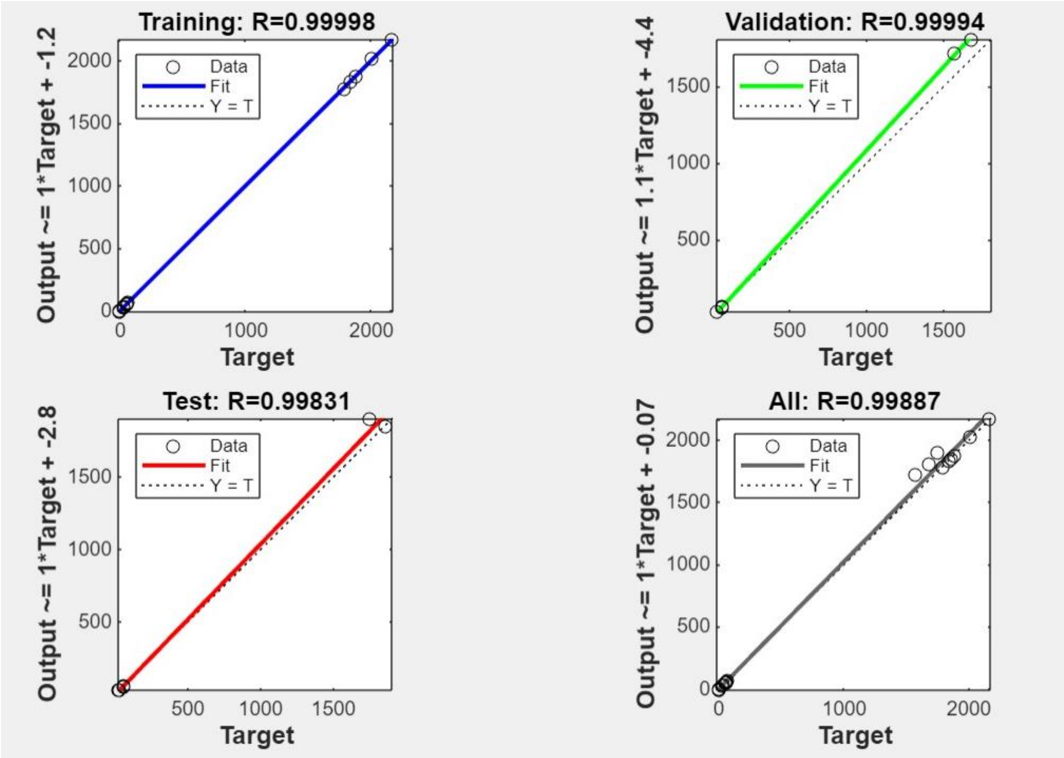

Figure 7. Regression Analysis of ANN

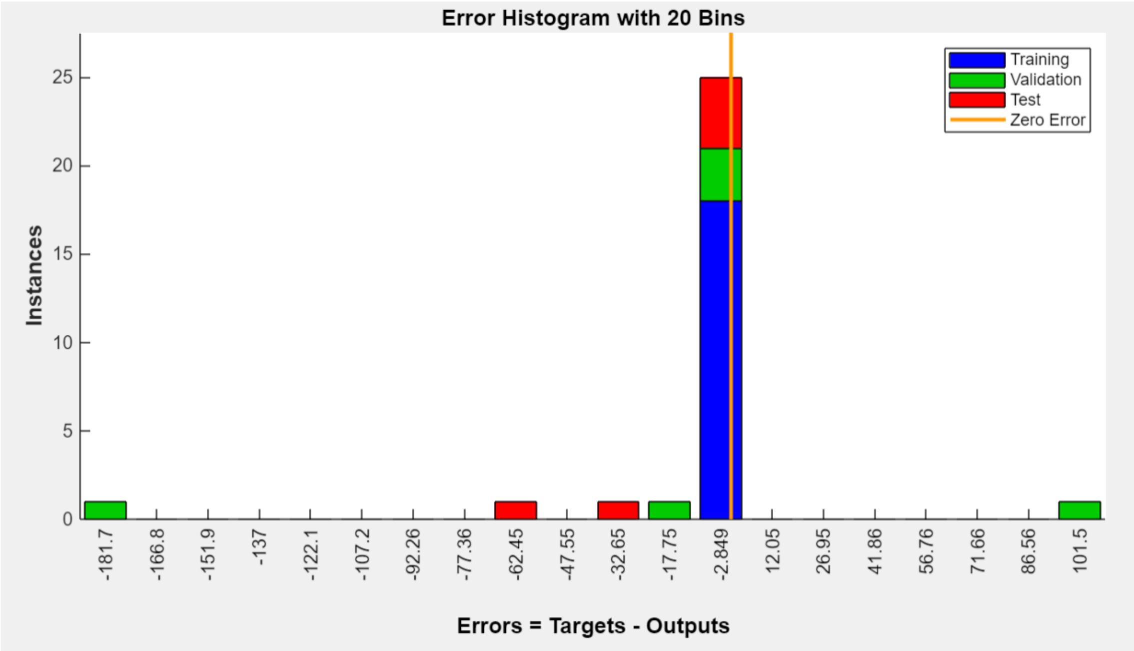

Figure 8. Error Histogram

3.5 Experimental Validation

To validate the regression model, we compared the predicted engine responses with the experimental data, as shown in [Figure 9(a, b, c, d, e)]. The graph illustrates the predicted values of various model responses alongside the actual experimental values, differentiated by colors. The errors were generally within 5%, the graph demonstrates that the predicted results are very close to the actual targets, indicating that the model has strong predictive capabilities.

Figure 7 presents the regression analysis of the ANN's predictions versus the actual target values across training, validation, test, and overall datasets.

Figure 8: error histogram displays the distribution of errors (difference between targets and outputs) in the ANN model. Most errors are clustered around zero, showing that the ANN performs well, with minimal deviation between predicted and actual values.

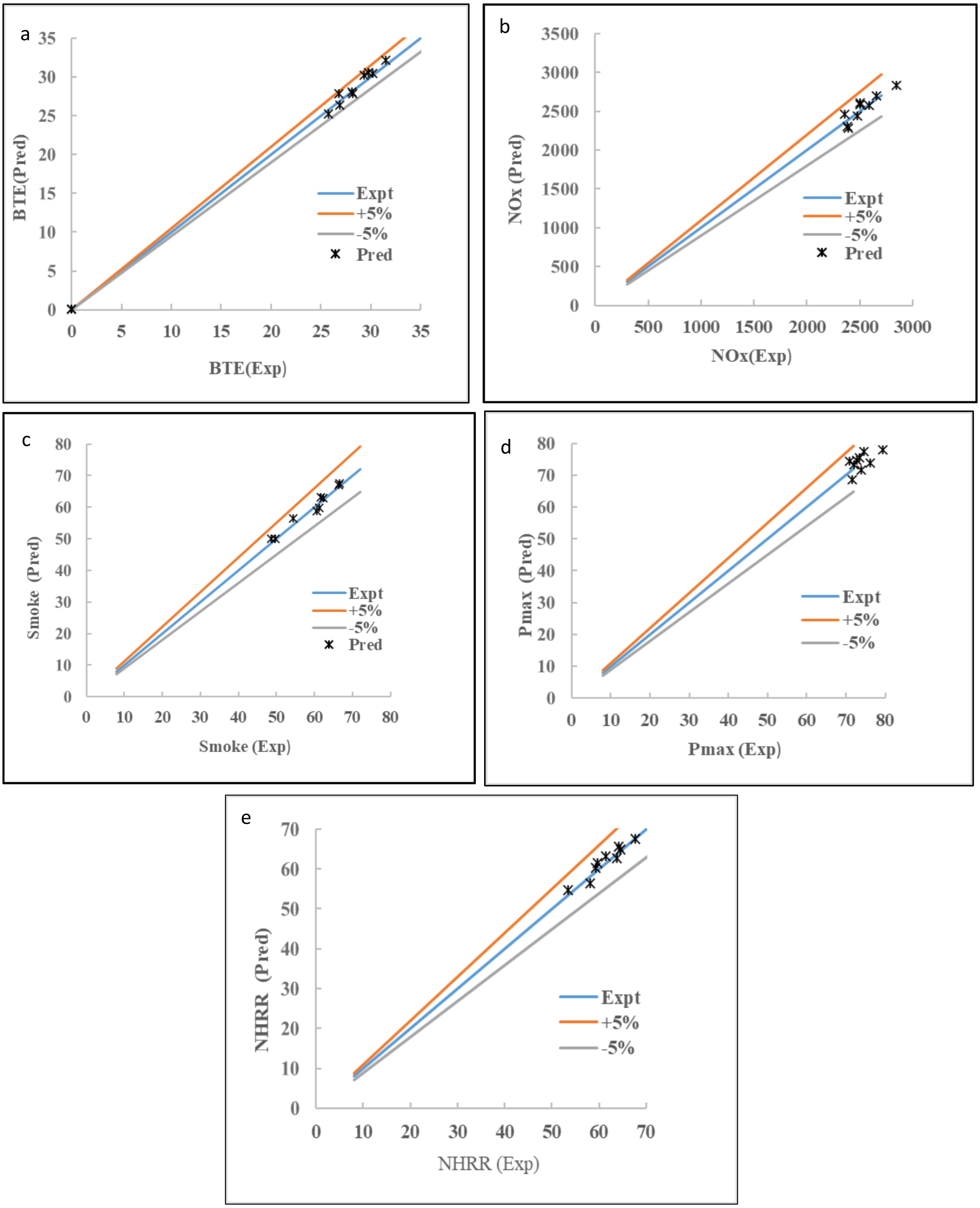

Figure 9. Experimental Vs Predicted value a) (BTE), b) (NOx), c) (Smoke), d) (Pmax), e) (NHRR)

3.6 Confirmation Test

After the successful completion of the confirmation experiment the most appropriate combination of factors that influence the outcome, is presented in the table. The experiment was carried out under ideal settings, and the outcomes were evaluated by comparing them to the original conditions via the use of the were obtained by experimentation with a higher S/N ratio of -33.75 compared with the initial condition of -35.80.

Table 10. Results of confirmation tests regarding BTE, NOx, smoke, and the combined effect

Responses	Initial Conditions				Optimal Conditions	
BTE	CR=15.5	FR=1	TF=Diesel	CR=17.5	FR=3	TF=BD1
	Prediction	Expt	S/N Ratio	Prediction	Expt	S/N Ratio
	25.19	25.78	28.22	29.80	31.51	29.96
NO_X	CR=15.5	FR=1	TF=Diesel	CR=15.5	FR=1	TF=Diesel
	Prediction	Expt	S/N Ratio	Prediction	Expt	S/N Ratio
	2486	2353	-67.43	2486	2353	-67.43
SMOKE	CR=15.5	FR=1	TF=Diesel	CR=17.5	FR=2	TF=Diesel
	Prediction	Expt	S/N Ratio	Prediction	Expt	S/N Ratio
	63.02	61.7	-35.80	51.94	48.7	-33.75
Multiple Response Combined Effect of BTE. NOX & Smoke				CR=17.5	FR=3	TF=BD1
				Gray Relational Grade	= 0.47.	

Table 10 illustrates the combined impact of BTE, NOx, and smoke by using a grey relation grade of 0.4 throughout the analysis. [43-45] NOx emissions have been found to increase with a rise in compression ratio (CR) in dual-fuel (DF) mode, this increase is attributed to higher combustion and cylinder temperatures [46]. As signal-to-noise ratio formula. The parameters CR, FR, and TF have ideal values of 17.5, and 3 lpm fuelled Calophyllum inophyllum blend (CI20) respectively, for BTE. The values of 31.51% were obtained by experimentation with a higher S/N ratio of 29.96 compared with the initial condition of 28.22. Using an orthogonal array, the Taguchi method determined the optimum condition for NOx, which was shown to be connected with the first experimental condition (Table 8). CR, FR, and TF have ideal values of 17.5, and 2 lpm fueled neat diesel respectively, for smoke. The values of 48.7% CR increases, the combustion chamber temperature rises, resulting in a decrease in smoke emissions. The addition of acetylene reduces the amount of pilot fuel required, leading to rapid combustion due to the formation of a homogeneous mixture, which further decreases smoke levels [47]. The rise in NOx emissions when using acetylene with diesel was mitigated by operating with a blend of hydrogen and B20 biodiesel at a reduced compression ratio. This reduction in emissions came with a slight compromise in engine brake thermal efficiency, additionally, the calorific value of the fuels plays a crucial role in these outcomes. Higher calorific value fuels have resulted in increased energy release and higher temperatures during combustion, contributing to the observed trends in NOx and smoke emissions.

4. Conclusions

The following findings were made as a result of the experimental investigation.

A maximum brake thermal efficiency of 31.51% was achieved with 17.5 CR, FR=3lpm, TF=BD1. Among the three dependent variables that were investigated.CR was found to be the most significant influential factor on brake thermal efficiency, NOx & Smoke, with a degree of confidence of 95%. This was accomplished by incorporating process parameters. Based on Multiple responses combined effect of BTE. NOx & Smoke were found to be 17.5 CR. an acetylene flow rate of 3 lpm fuelled Calophyllum inophyllum blend (CI20) respectively with a grey relational grade of 0.47 according to the Taguchi Gray analysis. The comparison of experimental findings with the expected results from the Artificial Neural Network (ANN) reveals that the ANN approach can be used successfully to estimate the emission, combustion, and performance characteristics of I.C. engines. Is demonstrated by the validation of experimental results with the predicted results from the Artificial Neural Network (ANN). This can be accomplished by reducing the number of trials and eradicating the necessity for a comprehensive experimental study. Consequently, both the engineering effort and the associated costs are reduced.

5. Nomenclature

Compression-Ignition CI

Variable compression ratio VCR

Pmax Peak Cylinder-Pressure

Liter per minute: lpm

Oxides of nitrogen emissions: NOx

Brake thermal efficiency: BTE

GRC Grey relational coefficient

GRD Grey relational grade

ANN Artificial Neural Network

ASTM American society for testing and material

CV calorific value

DOE design of experiment

S/N ratio signal to noise ratio

ANOVA Analysis of variance

PPM Part Per Million

SO- Smoke Opacity

CI20-Calophyllum Inophyllum B20 blend

JF20- Prosopis Juliflora B20 blend

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Anil Kumar B- Investigation, Formal analysis, Conceptualization, Writing – original draft. Ramana S V: Methodology, Validation, Writing – review & editing, Supervision. Hadya B: Validation, Methodology, Writing – review & editing, Supervision.

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

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