

## **Improving the Use of Biogas/Biohydrogen in Dual Fuel Engines Using Response Surface Methodology (RSM) and Artificial Neural Network (ANN)**

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### **ABSTRACT**

The escalating global energy demand and the urgent need to mitigate greenhouse gas emissions have intensified interest in alternative fuels as viable diesel substitutes, with biodiesel, biogas, and biohydrogen emerging as promising candidates. Biodiesel enhances combustion efficiency while reducing carbon monoxide (CO) and hydrocarbon (HC) emissions. Biogas offers economically feasible utilization, though its efficiency is compromised by CO<sub>2</sub> content. Biohydrogen promotes flame development, improves thermal efficiency, and substantially reduces carbon-based emissions. However, challenges such as abnormal combustion phenomena, decreased efficiency, and elevated nitrogen oxide (NO<sub>x</sub>) emissions at high substitution rates necessitate rigorous parameter optimization. This study employed Response Surface Methodology (RSM) and Artificial Neural Network (ANN) to evaluate and optimize the effects of load, compression ratio, ignition pressure, and gas flow rates on engine performance and emissions in dual-fuel configurations. RSM analysis identified load, ignition pressure, and biohydrogen concentration as critical factors influencing brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), CO, and NO<sub>x</sub> emissions, achieving optimal values of 40.55% BTE, 303.48 g/kWh BSFC, 2.35 g/kWh CO, and 869.78 ppm NO<sub>x</sub>. ANN models demonstrated superior predictive capability with  $R^2 > 0.99$ , exhibiting enhanced accuracy in emission trend prediction compared to RSM. The integration of RSM and ANN provides a robust hybrid optimization framework for dual-fuel diesel engines, facilitating improved efficiency, optimized fuel utilization, and reduced emissions for sustainable green energy applications. This study presents the first comprehensive RSM–ANN integrated approach for biogas/biohydrogen optimization in dual-fuel engines, offering practical implications for green energy transition and carbon reduction strategies.

**Keywords:** *Optimization, Dual-fuel engine, Emission reduction, Response Surface Methodology (RSM), Artificial Neural Network (ANN).*

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## **INTRODUCTION**

Growing energy consumption internationally and the need for more GHG emissions reductions create a focus on alternative diesel fuels. The primary energy source, fossil fuels, produces large emissions of greenhouse gases as well as damaging effects on the environment (Ahmad, Yadav, and Hasan 2024). In order to meet these problems and work For the SDGs 7 and 11, Which focus on the provision of clean and affordable energy and making the city and human settlements as safe, inclusive, resilient, and sustainable, it's therefore vital that alternative fuels, which are with reduced emissions (Das et al. 2024). To balance that issues, diesel engine researchers are looking for a replacement fuel that can improve the performance and lower the emission of the engine(Aydın, Uslu, and Bahattin Çelik 2020). Biofuels are one of the best replacement fuels for conventional fuels due to their simultaneous fuel characteristic for fossil energies and for their ability to produce fewer greenhouse releases of gas and smoke. Biofuels are liquid or gaseous fuel that is produced from biomass, i.e., plants, microalgae, and other organic

sources of material substance. Sources of sugar (sugar cane, starch and etc.), lipids (vegetable oils, animal fat and algae) and lignocellulose biomass (wood, crop and forestry residues, etc.) are the prime feedstock for the fuel production for automobiles (Lin and Lu 2021).

Biogas and bio-hydrogen can fuel diesel engines and enhance air blending functions, making them beneficial for internal combustion engines (Khan et al. 2024). The mixture of biogas and diesel provides low emission combustion, but the ignition delay adding by the presence of the carbon dioxide in the biogas adds excessive engine inefficiency (Khan and Goga 2023). It can be avoided while not having negative impacts on emissions, the application of bio-hydrogen in the biogas feedstock is a strategic alternative. Offering a bright approach (Xiumei Zhang et al. 2023). When implemented in natural gas or methane fueled engines already running hydrogen engines, such engines experience improved combustion characteristics mainly due to the combustion positive nature of the bio-hydrogen (Wei and Geng 2016).

The bio-hydrogen having no elements of carbon and providing water vapor upon combustion, allows one to reduce the carbon (Dewangan, Ahmad, and Yadav 2024). Bio-hydrogen, a product of biological reactions such as fermentation and anaerobic digestion, is a clean and a renewable energy source with high energy density. Because of the high diffusivity and low ignition energy of bio-hydrogen, it is a suitable supplementary fuel for internal combustion engines. This allows for a better and faster combustion process and an improvement in the engine's thermal efficiency and power generation (Deepalika, Kumar, and Choudhary 2023). Additionally, the use of bio-hydrogen application is also able to decrease NO<sub>x</sub> emissions by the reduced peak combustion temperatures achieved by hydrogen-enriched combustion. Bio-hydrogen is a prominent additive in the manufacture of sustainable and effective alternative diesel engine fuels because it enjoys the combined benefit of improved performance and decreased emissions (Li et al. 2024).

However, the extensive use of such renewable gases in diesel engines is limited by the technical limitations. The replacement of diesel by biogas tends to cause lower thermal efficiency and high cyclic variations and high rates of unburned hydrocarbons (UHC) and carbon monoxide (CO) emissions at high substitution rates (Kabeyi and Olanrewaju 2023). Bio-hydrogen, despite possessing very good combustion characteristics, also carries the risk of abnormal combustion such as knocking and more NO<sub>x</sub> emissions owing to the high value of the adiabatic flame temperature and high flame speed. Hence, the engine parameter optimality i.e ,injection timing, injection pressure, compression ratio, and gas flow rate is necessary for utilizing the full potential of such fuels and overcoming their limitations (Stępień 2021).

A. Mohite et al. (Mohite et al. 2024) proposed biogas- biodiesel dual-fuel CI engines as an environmentally friendly alternative for diesel, and the performance and emissions were reported. NO<sub>x</sub> emissions decreased with enriched CO<sub>2</sub> biogas, but the increase was seen for CO and UHC; combustion improved with more oxygen from the biodiesel. The principal parameters governing efficiency and emissions are compression ratio, pilot injection timing, and engine load. Optimization through RSM lowers the emissions from the CO, CO<sub>2</sub>, HC, and NO<sub>x</sub> and increases

the brake thermal efficiency. Optimized dual-fuel engines via the RSM method offer fuel flexibility, lowered emissions, and the improvement of efficiency.

S. Patnaik et al. (Patnaik, Khatri, and Rene 2024a) Characterized the environmental issues of fossil fuels and the potential for sustainable biodiesel. ANN models were trained for the forecasting of parameters like fuel consumption, energy consumption, thermal efficiency, exhaust gas temperature, smoke density, and absorption coefficient according to the outcomes of a single-cylinder CI engine. Models were of high accuracy, and the correlation coefficients were over 0.99, demonstrating the appropriateness of ANN for the optimization of expensive physical tests. Torque, brake power, and fuel consumption were confirmed by the outcomes of the sensitivity analysis as the drivers of performance. The results of the article demonstrate that waste cooking oil biodiesel can replace diesel efficiently, and ANN modeling improves efficiency, reduces emissions, and enables sustainable energy.

F. Khan et al. (Khan et al. 2025) Analyzed enhanced machine learning for biodiesel with biogas and bio-hydrogen for dual-fuel engines. It states that biodiesel and biogas can decrease energy density and increase NO<sub>x</sub> emissions, and bio-hydrogen reduces emissions and improves flame development. Experiments on a Kirloskar-AV1 diesel engine employed correlation analysis, Analytic Hierarchy Process (AHP), and weighted k-means clustering. Outcomes indicated an inverse relationship between BTE (brake thermal efficiency) and BSFC (brake specific fuel consumption), and positive association with CO and NO<sub>x</sub> emissions. AHP ranked BTE (51%) and NO<sub>x</sub> (24%), and determined the best configuration as 100% load, 19 CR, 220 IP-bar, 12% hydrogen, and 8% biogas, achieving 37.5% BTE, 220 g/kWh BSFC, 1.1 g/kWh CO, and 675 ppm NO<sub>x</sub>. In summary, biodiesel-biogas and bio-hydrogen promote sustainability and fossil fuel consumption minimization, although commercial applications on a large scale suffer from feedstock variability and storage expense.

A.A.M. Mohammedali et al (Mohammedali et al. 2025) Introduced a machine learning method for optimizing syngas-diesel dual-fuel engine thermal efficiency and emissions as a future direction. He trained four models (ANN, RF, SVR, XGBoost) on experimental datasets for the prediction of thermal efficiency, CO, and NO<sub>x</sub>. The highest performing model for NSGA-III multi-objective optimization was ANN. Optimization under the optimal scenario delivered 41.8% efficiency, 1970.5 ppm CO, and 746.5 ppm NO<sub>x</sub>. A graphical user interface was created for increasing clean, hydrogen-enriched syngas utilization.

Literature for the dual-fuel engine distinctly exhibits a lack of standardized multi-objective optimization for the application of biogas/bio-hydrogen. Performance emission tradeoffs were reported by the previous studies but employed few analyses in a non-homogenous manner without taking account of interactions in the factors such as the load, the injection time, and the gas substitution ratio. The application also did not yield much from the use of Response Surface Methodology (RSM) in a simultaneous manner for the purpose of optimization and Artificial Neural Networks (ANN) for the framework of prediction. The implication is the absence of a justified model capable of operating at maximum efficiency while keeping the emissions at a mere minimum and limiting optimized operating strategies for the corresponding renewable energy fuel.

The study focuses at the extensive application of biogas/bio-hydrogen in a dual-fuel engine by scientifically exploring important operating parameter impacts on engine effectiveness and emissions. It will adopt a twofold application of the RSM and ANN for the purposes of initially optimizing the system and subsequently setting up a forecasting relationship. A critical research gap identified in the literature is the absence of a standardized, multi-objective optimization framework that systematically addresses the complex interactions between key operational parameters—such as load, compression ratio, ignition pressure, and gas flow rates—for biogas/biohydrogen dual-fuel engines. Previous studies have often analyzed performance-emission trade-offs in a non-homogeneous manner, lacking a holistic approach to simultaneously optimize for efficiency and minimal emissions.

The urgency of this research is underscored by the global commitment to sustainable development goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities). The continued reliance on fossil fuels exacerbates environmental degradation and public health issues, necessitating an immediate transition to cleaner energy systems. Developing efficient strategies to utilize renewable gases like biogas and biohydrogen in existing engine technologies is therefore not merely an academic exercise but a pressing practical need to decarbonize the transportation and power generation sectors, contributing directly to climate change mitigation and energy security.

The novelty of this study lies in the pioneering integration of Response Surface Methodology (RSM) and Artificial Neural Networks (ANN) to form a robust hybrid optimization and predictive framework specifically for biogas/biohydrogen dual-fuel engines. While RSM and ANN have been applied individually in engine optimization, their combined application in this context, complemented by a Multi-Objective Genetic Algorithm (MOGA) for final optimization, represents a significant methodological advancement. This integrated approach is designed to overcome the limitations of single-method analyses by leveraging the strengths of both statistical modeling and machine learning for superior parameter optimization and emission trend prediction.

The purpose of this research is threefold: firstly, to utilize RSM for the experimental design and determination of optimal operating conditions that maximize brake thermal efficiency (BTE) while minimizing brake-specific fuel consumption (BSFC), carbon monoxide (CO), and NO<sub>x</sub> emissions. Secondly, to develop and calibrate an ANN model for the accurate prediction of engine performance and emission characteristics. Finally, to compare the efficacy of the RSM and ANN models and validate the optimization results using MOGA. The primary benefit of this work is the provision of a validated, data-driven framework that enables the practical and efficient utilization of biogas and biohydrogen in dual-fuel engines, thereby facilitating improved engine performance, optimized fuel consumption, and substantially reduced emissions for sustainable green energy applications.

## **METHOD**

The research employed an experimental and quantitative modeling approach to investigate and optimize the performance and emission characteristics of a dual-fuel engine operating on

biogas and biohydrogen blends. Controlled experiments were conducted on a single-cylinder compression ignition (CI) engine, which provided the primary dataset for analysis. The dataset comprised 30 experimental runs systematically designed using Response Surface Methodology (RSM) with a Central Composite Design (CCD) to capture the effects of key input parameters across the operational range.

The engine test bed consisted of a Kirloskar-AV1 diesel engine equipped with transducers, sensors, and analyzers for precise data acquisition. Measurements included engine load, compression ratio, ignition pressure, and the respective biogas and biohydrogen flow rates, while emissions of carbon monoxide (CO) and nitrogen oxides (NO<sub>x</sub>) were recorded using an exhaust gas analyzer. Real-time data were collected under each CCD-defined condition to obtain brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), CO, and NO<sub>x</sub> as performance indicators.

Data analysis integrated statistical and artificial intelligence techniques. The RSM was first applied to develop second-order polynomial models, validated through Analysis of Variance (ANOVA). Subsequently, an Artificial Neural Network (ANN) with a single hidden layer was trained on 70% of the dataset and tested on the remainder to predict engine responses. The predictive performance of RSM and ANN models was evaluated using the coefficient of determination ( $R^2$ ), mean square error (MSE), and mean absolute percentage error (MAPE). A Multi-Objective Genetic Algorithm (MOGA) was then applied to both validated models to determine the Pareto-optimal engine parameters that maximized BTE while minimizing BSFC and NO<sub>x</sub> emissions.

## RESULT AND DISCUSSION

### Modeling Development, Verification and Optimization of Response Surface Methodology

For establishing five independent variables of the four responses, RSM modeling was performed by following various steps, i.e., model determination, factor levels, design selection, evaluation, validation, and optimization. The DoE is the single most important component of RSM by virtue of which statistically dispersed data in the input domain is achieved (Gammoudi et al. 2021).

An empirical correlation was also obtained after achieving the DoE data from the inputs and the responses. It was followed by the analysis by means of RSM, to obtain the desired output. Also, the four responses' variations, i.e., BTE, BSFC, CO and NO<sub>x</sub>, were experimented. Table 1 depicts the values by employing Central Composite Design (CCD) of the input parameters, whereas the ANOVA analysis is displayed in Table 2. Results showed how the input, the square of it, and interaction helped in output analysis. They showed that the characteristics under consideration were important in assessing the model. Table 2 indicates that BTE has an F-value of 100.41 with P-value of <0.05. This showed that the model terms with P-values less than 0.05 were significant, indicating the appropriate reputation of the implemented experimental parameters.

Table 2 also demonstrated the value of the developed model in optimizing performance of BTE. From the ANOVA table, the load (%), ignition pressure (bar) and Bio-hydrogen (%) were

the most significant variables affecting BTE. This showed that the BTE model was forecasted by employing Equation (13). From these outcomes, the equation is accountable for highlighting the different parameters that affect BTE. In the analysis, A, B, C, D and E denoted the load, compression ratio, ignition pressure, and Bio-hydrogen and Bio-flow rate respectively.

$$\text{BTE (\%)} = +32.19 + 4.36 A - 0.3055 B + 2.39 C + 1.10 D - 0.4990E \quad (13)$$

Table 2 also provides the ANOVA test of BSFC, for which the F-value and P-value of 32.22 and <0.05 were noted, respectively. It was revealed that load was the ordered list of parameter that affected BSFC. It was also revealed from the F-value of 32.22 that the model was significant, and Equation (14) was the resulting system for BSFC prediction.

$$\text{BSFC (g/kWh)} = +251.89 - 20.17A - 0.8642B - 13.68C - 10.51D + 3.28E - 3.54AB - 12.22AC + 18.49AD + 1.05AE + 12.22BC - 20.23BD + 1.81BE - 3.65CD + 1.55CE - 3.58DE \quad (14)$$

Table 2 also reveals the ANOVA test of CO whose F-value and P-value of 65.86 and <0.05 were, respectively, noted. It revealed that the load, ignition pressure (bar) and Bio-hydrogen (%) were significant model terms. In addition, Equation (15) represented the developed model for CO emission.

$$\text{CO (g/kWh)} = + 1.59 - 0.3471A + 0.0047B - 0.2403C - 0.1166D + 0.0553 E \quad (15)$$

Table 2 also shows the ANOVA analysis for NOx, where the F-value and P-value of 30.34 and <0.05 were observed, respectively. From this context, all the P-values were 0.0001 and closer to 0, proving the high significance level of the model. The F-value of 30.34 also implied that the model was significant, with Equation (16) representing the NOx emission.

$$\text{NOx (ppm)} = + 690.55 - 57.87A - 8.75B - 22.02C - 12.40D + 5.29E + 4.52AB - 29.85AC + 49.99AD - 11.97AE + 10.76BC - 38.24BD + 8.10BE - 44.10CD + 26.67CE - 25.84DE + 9.54A^2 + 19.12B^2 + 51.05C^2 + 10.91D^2 + 22.98E^2 \quad (16)$$

**Table 1. Results of DoE based on Centered Composite Design (CCD)**

Run order	BTE Actual (%)	BTE Predicted (%)	BSFC Actual (g/kwh)	BSFC Predicted (g/kwh)	CO Actual	CO Predicted	NOx Actual (ppm)	NOx Predicted (ppm)
1	25.2	25.14	290	285.73	2.2	2.24	850	849.93
2	26	24.64	280	288.18	2.1	2.29	820	835.29
3	24.8	24.15	295	290.64	2.3	2.35	880	866.59
4	28.5	28.63	270	268.96	2	1.88	810	804.16
5	27.8	28.13	265	269.38	1.9	1.94	780	790.34
6	26.7	27.63	275	269.80	2.1	1.99	830	822.47
7	29.2	27.83	260	272.06	1.8	1.94	760	757.96
8	31	29.42	245	244.42	1.6	1.77	740	738.04
9	32.4	31.82	240	237.76	1.5	1.53	720	726.14
10	34.5	35.08	230	233.39	1.3	1.30	710	710.59
11	36	35.18	225	225.30	1.2	1.29	690	703.08
12	38.5	38.45	215	211.71	1.1	1.06	680	684.36
13	39	40.55	210	207.87	1	0.8346	670	674.62
14	40.2	39.24	205	201.84	0.9	0.9500	660	658.44
15	33.2	32.39	250	245.95	1.4	1.54	700	710.51

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Run order	BTE Actual (%)	BTE Predicted (%)	BSFC Actual (g/kwh)	BSFC Predicted (g/kwh)	CO Actual	CO Predicted	NO <sub>x</sub> Actual (ppm)	NO <sub>x</sub> Predicted (ppm)
16	34.1	31.89	240	251.03	1.3	1.60	690	700.92
17	37.5	38.64	220	213.65	1.1	1.01	675	667.05
18	31.7	31.60	265	255.55	1.7	1.66	715	705.70
19	22.3	24.53	305	303.48	2.5	2.25	870	862.15
20	28.9	30.11	280	278.66	2	1.83	800	802.24
21	29.6	29.30	270	267.29	1.9	1.89	770	765.21
22	36.5	35.68	225	224.06	1.2	1.24	695	673.99
23	37.8	38.05	215	218.29	1.1	1.07	685	691.75
24	38.9	38.64	210	213.65	1	1.01	675	667.05
25	23.5	23.84	300	303.13	2.4	2.35	860	869.78
26	35.2	33.87	235	237.85	1.4	1.54	710	708.80
27	33.5	33.79	240	241.69	1.5	1.42	735	732.60
28	25	27.02	285	278.77	2.2	2.00	815	812.13
29	31.4	33.59	265	262.47	1.6	1.47	755	755.16
30	39.5	39.55	205	212.45	0.9	0.9453	660	662.92

Table 2 (a-b): The ANOVA Results for BTE, BSFC, CO and NO<sub>x</sub> Emission

Source	BTE					BSFC				
	Sum of Square	Df	Mean Square	F-value	P-value	Sum of Square	Df	Mean of Square	F-value	P-value
Model	781.84	5	156.37	100.41	< 0.0001	26402.61	15	1760.17	32.22	< 0.0001
Load	248.26	1	248.26	159.43	< 0.0001	2355.18	1	2355.18	43.11	< 0.0001
Compression Ratio	1.17	1	1.17	0.7500	0.3950	5.81	1	5.81	0.1063	0.7492
Ignition pressure	41.39	1		26.58	< 0.0001	683.15	1	683.15	12.50	0.0033
Bio-hydrogen	11.71	1	11.71	7.52	0.0114	359.81	1	359.81	6.59	0.0224
Bio-flow rate	5.05	1	5.05	3.25	0.0842	148.60	1	148.60	2.72	0.1214
Residuals	37.37	24	1.56			764.89	14	54.60		
Cor total	819.21	29				27167.50	29			

(a)

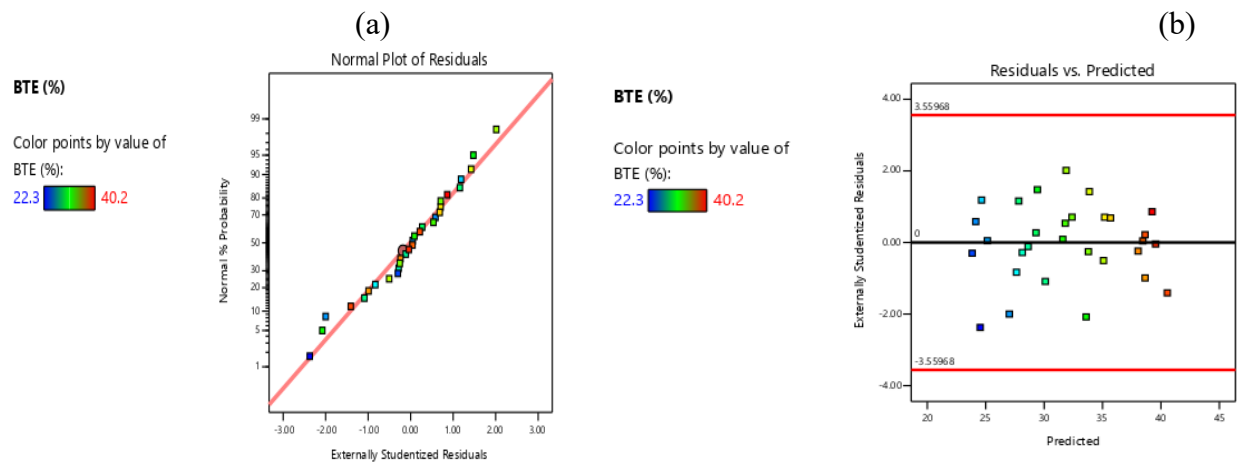
Source	CO					NO <sub>x</sub>				
	Sum of Square	Df	Mean Square	F-value	P-value	Sum of Square	Df	Mean of Square	F-value	P-value
Model	6.30	5	1.26	65.86	< 0.0001	1355E+05	20	6776.00	30.34	< 0.0001
Load	1.57	1	1.57	82.08	< 0.0001	15898.08	1	15898.08	71.18	< 0.0001
Compression Ratio	0.0003	1	0.0003	0.0143	0.9059	364.56	1	364.56	1.63	0.2334

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<b>Ignition pressure</b>	0.4175	1	0.4175	21.82	< 0.0001	1452.77	1	1452.77	6.50	0.0312
<b>Bio-Hydrogen</b>	0.1324	1	0.1324	6.92	0.0146	388.75	1	388.75	1.74	0.2196
<b>Bio-flow Rate</b>	0.0622	1	0.0622	3.25	0.0840	275.51	1	275.51	1.23	0.2955
<b>Residuals</b>	0.4592	24	0.0191			2010.05	9	223.34		
<b>Cor total</b>	6.76	29				1375E+05	29			

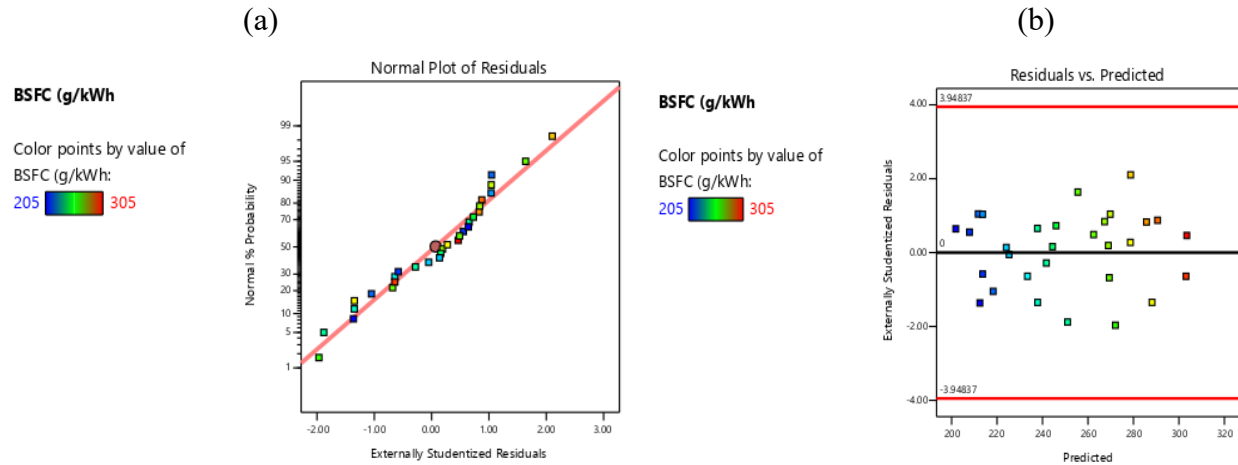
(b)

The model was subsequently tested for abnormality and data adequacy through the use of normal plots of residuals and outliers. An acceptable model, in this case, is not likely to exhibit any trend or sequence, and the points should be near enough to a straight line. Figure 1, shows the plot of residuals and outliers for BTE. From Figure 1a, it is seen that all the data points were randomly dispersed and showed no sequence, thus verifying the predictability of the model. From Figure 1b, also shown is the chart of outliers for BTE, in which all data points outside the permissible range of  $\pm 3.55968$  were deemed to be abnormal. Also, Figure 2b showed that all data points were classified within the allowable range. The residual and the outlier plot for the BSFC model are also shown in Figure 2a and Figure 2b, respectively. From Figure 3a and 3b, all of the data points showed no pattern and no sequence and were classified within an allowable range of  $\pm 3.94837$ . Also, the residual and the outlier plot of CO were shown in Figure 3a and figure 3b, correspondingly. And figure 4a and figure 4b, all of the data point had no pattern and sequence and were classified under acceptable range of  $-4.63979$  to  $+4.63979$  and the residual and outlier plot for  $\text{NO}_x$  are given in figure 4a and figure 4b, respectively.

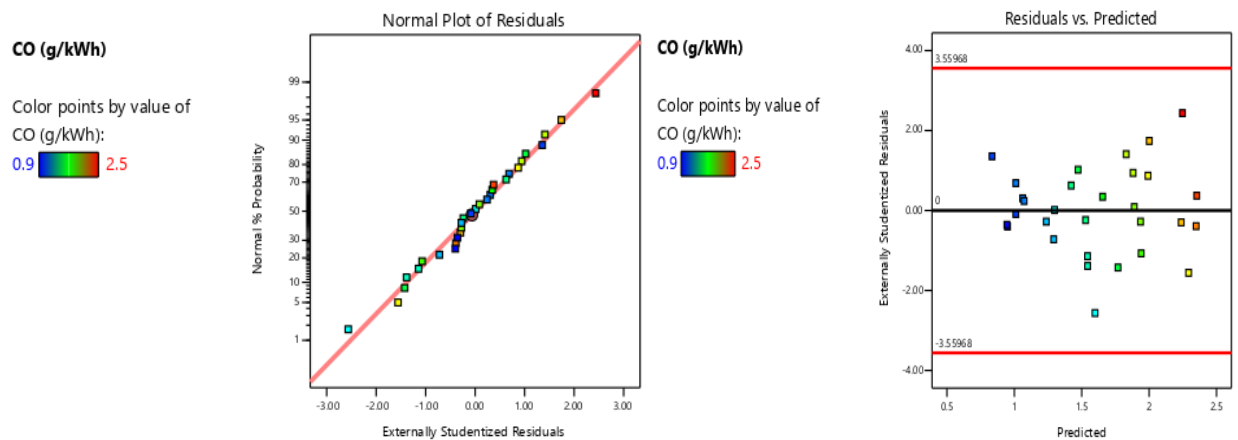


**Figure 1:** The normal plot of residuals (a) and Residual vs Predicted (b) for BTE (%)

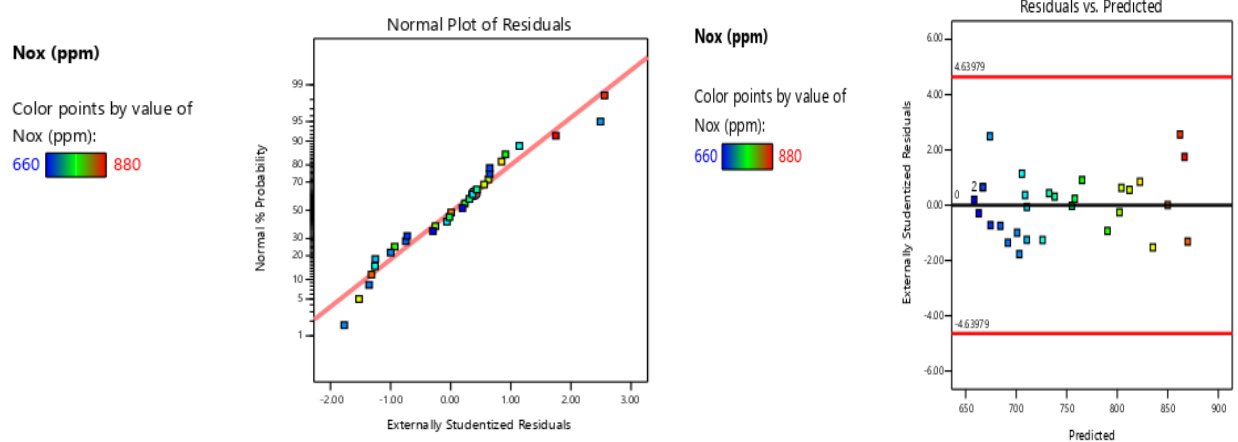
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**Figure 2:** The normal plot of residuals (a) and Residual vs Predicted (b) for BSFC (g/kWh)



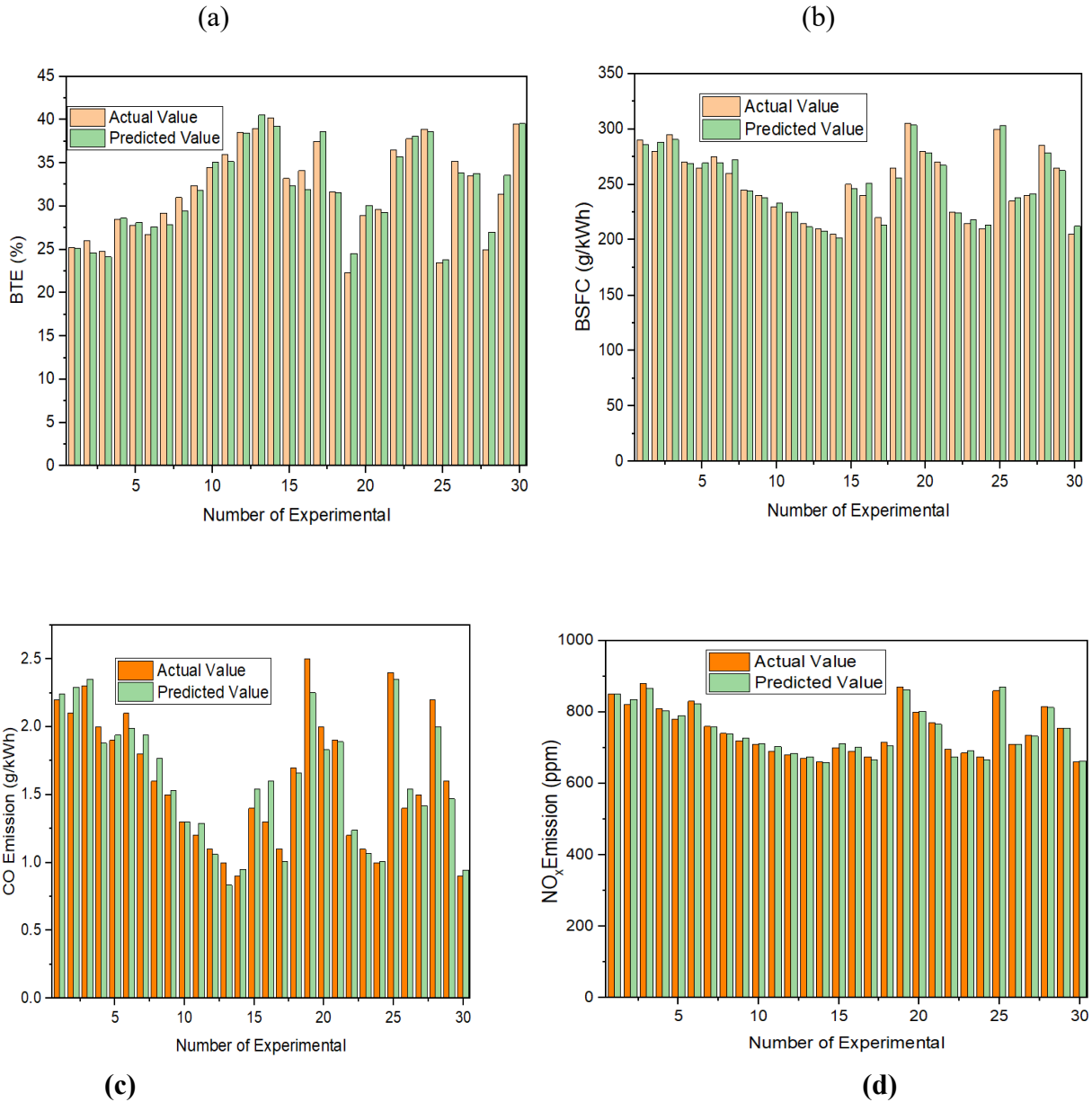
**Figure 3:** The normal Plot of Residuals (a) and Residuals vs Predicted (b) for CO Emission



**Figure 4:** The Normal Plot of Residuals (a) and Residuals vs Predicted (b) for NO<sub>x</sub> Emission

Verification and validation procedure was the last observation step performed by the RSM technique, showing comparisons of the Equations 13-16 with experimental data. In it, the

comparison graph between the experimental data and the predictions is seen from the **figure 5(a-d)**. From the results, the RSM technique's models of BTE, BSFC, CO and NO<sub>x</sub> were employed to find the engine's performance and emission control.

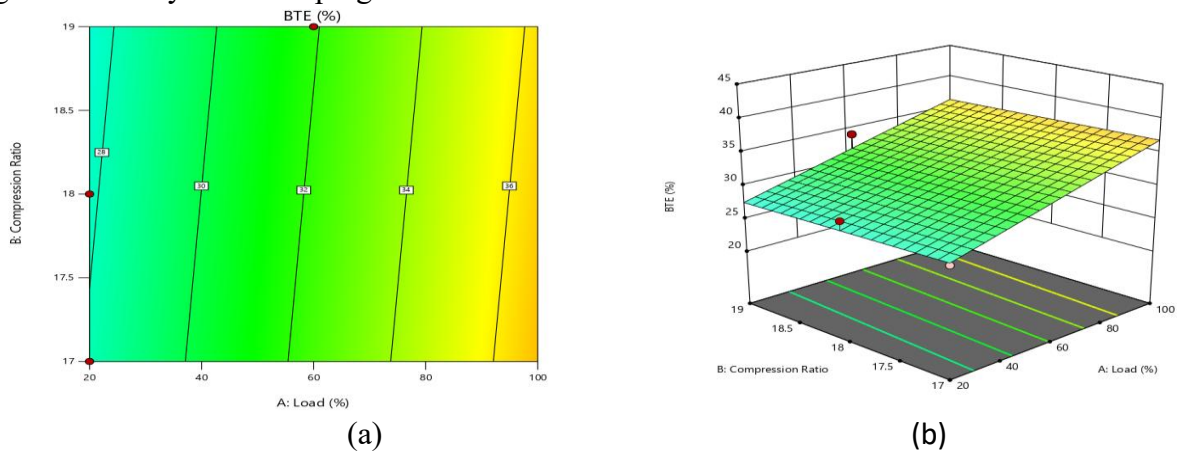


**Figure 5:** Validation of RSM Model for Optimize Performance and Minimize Emission for (a) BTE, (b) BSFC, (c) CO and (d) NO<sub>x</sub>

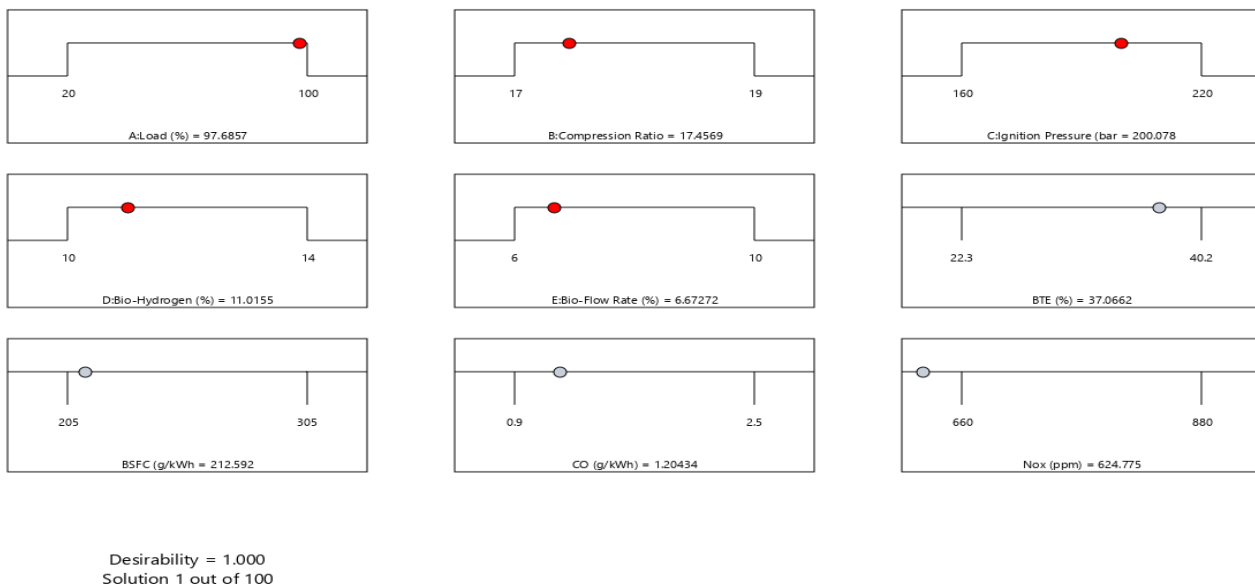
**Figure 6 (a-h)** display the 2D and 3D contour plots are based on Response Surface Methodology (RSM) and are descriptive of interactions between major operating parameters of compression ratio, load, ignition pressure, and Bio-flow/Bio-hydrogen rate with engine efficiency and combustion outcomes. The plots indicate that, the engine brake thermal efficiency (BTE) is

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superior with optimized load and optimized compression ratio, and brake specific fuel consumption (BSFC) is less with comparable conditions. In the same manner, Bio-hydrogen enrichment with optimized flow rates is superior with combustion, and CO emission is less. In general, the plots support that multi-variable optimization is very crucial for optimizing dual-fuel engine efficiency while keeping undesirable combustion outcomes minimal.



**Figure 6:** The 2D and 3D Surface Contour Plots by RSM Correlated for BTE, BSFC, CO and NO<sub>x</sub> Emission on the impact of (a) load and compression ratio, (b) load and ignition pressure, (c) load and Bio-Hydrogen, (d) load and Bio-Flow Rate, (e) compression ratio and load (f) Bio-Hydrogen and load, (g) compression ratio and load, and (h) ignition pressure and load.



**Figure 7:** The Ramps Function of RSM Optimization.

### ANN modelling

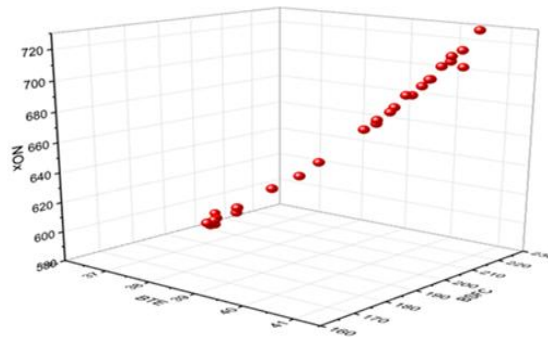
Like the RSM modelling, the ANN analysis also serves for finding the association between the five inputs and the four output variables. The steps applied for this analysis involve the collection of information, development as well as configuration of the network, initialization of

the weights and biases, training, testing, and also validation. The optimum regression parameter (R) for the minimum MSE is also anticipated for getting the optimally chosen neurons. The ANN modelling applied for this research had 5 inputs, 1 hidden layer with the number of neurons equal to 10, and the target outputs equal to 4.

Based on the results, the regression (R) coefficient near 1 established a highly accurate trend line. The blue line (training state) accurately contacted all points on the graph, with an R-value of 0.99. The training, validation, test, and total trend line regression coefficients were all 0.99. This illustrated several correlation coefficients between the ANN and regression model at all stages. The histogram of error shows the discrepancy between target and estimated values after training the feed forward neural network. The error values are the target and anticipated rate patterns, and the graph of the training shows the best possible validation efficiency for the network. When the MSE of the validation rises, the training automatically stop. The variation during training of the gradient coefficient is tracked using epochs. The training, validation, and test data had corresponding MSEs and regressions of 404.0711 & 0.9987, 320.7569 & 0.9984, and 2.0735e+03 & 0.9972. This verifies the fact that all the prediction data for the output had a value for regression of nearly 1, at 0.99744. For the estimation of BTE, BSFC, CO and NO<sub>x</sub> target data, the experimental Equation model was  $\text{Output} = 0.96 * \text{Target} + 1.3$ . This also followed the performance plot where the best validation performance is 320.7569 at epoch 1. The actual data vs. RSM and ANN value correlation plot. While estimating brake thermal efficiency (BTE), the Artificial Neural Network (ANN) as well as the Response Surface Methodology (RSM) presented trends which significantly matched the actual observed values, thus meaning that both methods presented a good model for estimating the BTE. In the case of the brake specific fuel consumption (BSFC), the nitrogen oxide (NO<sub>x</sub>) and the carbon monoxide (CO) predictions, the Artificial Neural Network surpassed the Response Surface Methodology when it came to accuracy. This better capability of ANN for estimating the BTE, BSFC, the NO<sub>x</sub> and the CO may well be due to the excellent regression statistics which reached an R<sup>2</sup> value to 0.99.

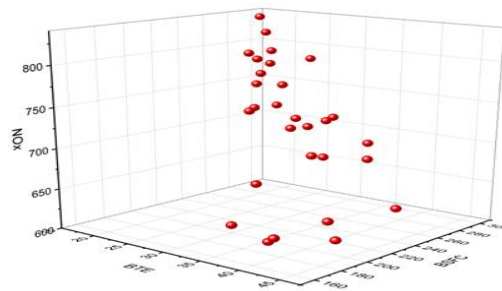
### **MOGA Optimization**

MOGA analysis was conducted through the utilization of MATLAB software, to derive Pareto graphs of the three objective functions, i.e., BTE, BSFC, and NO<sub>x</sub> emission. The optimization was also conducted through estimation obtained from DoE, i.e., Equations (13)-(16). These three objective values were maximized engine efficiency and minimize the emission. In addition, the input values of load, compression Ratio, Ignition Pressure, Bio-Hydrogen and Bio-flow rate were determined regarding the previous experimental data. From the outcomes, the optimization carried out with the DoE equation is represented through Figure 8. From this indication, it could be witnessed that the Pareto graph generated the highest values of 40.82%, 221.96 g/kWh, and 729.92 ppm of BTE, BSFC and NO<sub>x</sub> emission with the minimum at 36.64%, 170.23g/kWh, and 595.17 ppm correspondingly.



**Figure 8.** 3D plot of DoE MOGA optimization.

The developed network function also accurately predicted the BTE, BSFC, and NOx values. From the results, the developed function of the ANN process was utilized as a fitness characteristic during the optimization process. For the choice of the population and optimization process, a Pareto graph was utilized as shown in Figure 9. From the optimization with the prediction equation from the ANN-based approach, the optimum maximum values of BTE, BSFC and NOx were the values of 45.03%, 294.5 g/kWh and 834.4 ppm while the optimum minimum were 17.96%, 167.9 g/kWh and 616.7 ppm correspondingly. Thus, both the ANN and the DoE-based equation optimization process were similar with regard to output ranges



**Figure 9:** 3D plot of ANN MOGA optimization.

## CONCLUSION

The simultaneous application of biogas and biohydrogen in dual-fuel diesel engines, optimized using Response Surface Methodology (RSM) and Artificial Neural Network (ANN), significantly enhanced engine performance and reduced emissions. RSM identified load, ignition pressure, and biohydrogen concentration as the most influential parameters affecting brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), CO, and NOx emissions, while ANN demonstrated superior predictive accuracy with a regression coefficient of 0.99. Additionally, Multi-Objective Genetic Algorithm (MOGA) optimization confirmed that both models effectively increased efficiency (BTE up to 45%) while reducing fuel consumption and emissions. Future research should explore real-time adaptive control systems integrating RSM–ANN–MOGA frameworks to optimize engine operation under varying load and fuel conditions for broader industrial application.

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