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Experimental Investigation of Combustion and Emission in a Diesel Engine Using a Blended Fuel of Pentanol With Oxygenated Additives

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Abstract

This study investigates the effects of oxygenated alcohol fuels blended with diesel on exhaust emissions, carbon particle morphology and nanostructure in a single-cylinder direct injection diesel engine. Blends incorporating n-pentanol, diethylene-glycol diethyl-ether (DE), diethylene-glycol dimethyl-ether (DM) and dimethyl carbonate (DMC) at varying concentrations were tested across different engine loads. These oxygenates, characterized by diverse chain lengths and ether functionalities, enhance fuel oxygenation, promoting more full combustion and altering soot formation mechanisms. Experimental results demonstrate significant reductions in brake specific fuel consumption (BSFC) compared to baseline diesel operation. The improved BSFC, particularly evident in DE and DM blends under high-load conditions, stems from superior fuel properties such as higher cetane numbers, better atomization and enhanced air-fuel mixing. Heat release rate analysis reveals shorter combustion durations and higher peak pressures, indicative of advanced ignition and efficient energy release. Emissions performance shows marked decreases in carbon monoxide (CO) and hydrocarbon (HC) levels across all blends, attributed to the oxygen content facilitating oxidation of unburnt fuel residues. Combustion efficiency gains lead to elevated NOx formation from higher flame temperatures, though overall energy utilization improves substantially. These findings establish foundational guidelines for oxygenated diesel blend formulations, emphasizing BSFC optimization and combustion enhancements to advance cleaner engine designs for future regulatory compliance.

Keywords: Diesel Engine, Diethylene Glycol Diethyl Ether, Diethylene Glycol Dimethyl Ether, Dimethyl Carbonate, Emissions.

Introduction

Biofuels are attracting more consideration, especially in the energy industry, because fossil fuels are running out quickly. Diesel engines are critical for modern life and help people get more done, but they also generate difficulties for individuals and the atmosphere. Diesel engines are a significant supplier to transportation exhaust, specifically nitrogen oxides (NOx) and particulate matter (PM), especially in heavy-duty transport sectors. Several studies have reported that diesel-powered vehicles contribute substantially to urban air pollution due to their higher NOx and PM emissions compared with gasoline engines. Fuel use is going up and stricter rules are in place. This means that more investigation needs to be done on biofuel for internal combustion engines. In the last few years, biofuels and alcohols have become quite popular (1). Consuming clean or fresh energy can help us use less energy and get better results (2). A lot of research in the US and other industrialized nations over the previous 20 years has verified that mixing oxygenated fuels with diesel can assist engines start up and cut down on emissions (3). Adding oxygenated fuel makes the burning process more complete, which means that less dangerous gases like CO and particulate matter (PM) are emitted. These harmful emissions are even lower when the percentage of oxygenated fuels is higher and the thermal efficiency doesn't change much (4, 5). The efficiency of engine blends collected of cottonseed oil biodiesel (COB, diethyl ether and diesel fuel inspected (6). Their research found that combining 20% cottonseed oil biodiesel(COB) with diesel fuel reduced the Brake Thermal Efficiency(BTE) by roughly 12.9%. This mix, on the other hand, did have some helpful effects on the environment. For example, Carbon dioxide (CO_2) emissions cutdown by around 17% while using

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diesel fuel (D100) and CO emissions went down by amount 19%. The study also found that the amount of oxygen in COB (biodiesel) made NO_x emissions go up. When the engine was at full load, the ignition delay times were 2.37 crank angle for D100 and 1.02 crank angle (CA) for the 20% COB blend. The performance of diesel engine and their petrol consumption when operating on 100% COB examined (7).The analysis showed that the higher cylinder pressure for 100% COB was 22.6% lower than the pressure for D100 at full load. Researchers observed that the ignition delay period (IDP) was 10 degree of crank angle for diesel fuel and 11 degree of CA for COB. The engines BTE dropped by 15.3% when COB was used. The study indicated that emissions of NO_x went up by roughly 31%, while emissions of CO and HC went decreased by 21.2% and 30.4%, respectively. Study of biodiesel blends made from rice bran and cottonseed oil did a side-by-side (8). The study showed that a blend with 20% cottonseed biofuel lowered BTE by 17.1%. the amount of HC and CO that come out was 18.4% and 17.5% lesser than that traditional diesel fuel (TDF). But in the cottonseed biodiesel blend, NO_x emissions rose up by about 8% compared to TDF. The BTE in low-load diesel-ethane Conventional dual fuel (CDF) mode while decreasing HC and CO emissions improved (9). An experimental assessment contrasting CDF mode with traditional diesel combustion at a 25% load performed (10). They discovered that the CDF mode exhibited a BTE of 39.7% and lessened CO_2 emissions by 28.57%, while simultaneously increasing CH4 levels by 49%. The impact of Fe_2O_3 nanoparticles on a blend of d100, n-amyl alcohol and muhua biofuel investigated (11). They found that the levels of NO_x, CO and HC that were released have gone down. BTE, on the other hand, went up by 7.8% while BSFC, on the other hand, went down by 4.9%. A study of Nanoparticles of GO, GPNs and WCNT seen how it affects a mix of n-butanol(12). They found that the nanoparticles in the blend raised the cylinder pressure, which led to lower emissions of NO_x, HC and CO emissions. The effect of DMC and DEE alcohols worked with CNTs and TiO_2 nanoparticles effect was seen (13). The initial findings indicated that the mixture of 20% biofuel and 80% D100 with TiO_2 in three alignments resulted in a reduction of BSFC. The BTE of the 30% biofuel mix with D100 and DMC is 9.8% higher than the BTE of the other fuel that was tested. The ternary blend with DMC also had the highest decline in CO and HC emissions, while the blend with CNTs had the biggest drop in NO_x emissions associated to the 30% blend. An experiment to investigate a fuel blend of waste Simarouba glauca oil and chapor oil in a Comprssion Ignition (CI) engine was shown (14) . They found that the amounts of NO and CO_2 were related to the increased volumetric, exergy, BTE, sustainability index and cyclic changes. They also confirmed that the release of HC, CO and smoke into the air decreased. An experiment examining the amalgamation of polanga and camphor oil in a 5.2 kW CI engine was performed (15). They saw that the thermal competence, BTE, sustainability index, cyclic variations and emissions of NO and CO all increased up. They also noticed that the amount of smoke, HC and CO released, as well as the temperature of the exhaust gas, decreases. The study used a single-cylinder, naturally aspirated, 4-stroke, compression ignition engine within an experimental framework. The engine is tested with loads of 25%, 50%, 75% and 100%. Response surface methodology (RSM) and artificial neural networks (ANN) is employed to analyse the output response characteristics.

Methodology

This research uses diesel fuel as the reference fuel and alcohol fuels with varying carbon chain lengths, such as oxygenated DM, DE, DMC and n-pentanol (P) as the test fuels. Table 1 shows the many types of fuels and their qualities. We keep the oxygen level of the three mixes at roughly (P1, P2, P3, DE1, DE2, DE3, DMC1, DMC2, DMC3, DM1, DM2 and DM3) to make sure that the varied amounts of oxygen don't affect the characteristics of the elements. The alcohol is blended with diesel fuel before the fuel tank. After that, a magnetic stirrer in the fuel tank is used to agitate the combination even more until it is no longer stratified. Before the new test, the varied fuel was made to make sure that the combination was the same throughout. It is significant to note that these fuel qualities are a relative measure based on the volume ratio and only take some things into interpretation. The fuel blends were prepared on a volumetric basis according to the compositions listed in the Table 1, using diesel (D100) as the base fuel and oxygenated additives including n-pentanol, DM, DE and DMC.

Table 1: Volumetric Composition of Tested Fuel Blends

Fuel Blend	Diesel (%)	Pentanol (%)	Additive (%)	Additive Type
P1	70	30	–	Pentanol
P2	80	20	–	Pentanol
P3	90	10	–	Pentanol
DM1	72	8	20	Diglyme
DM2	76.5	8.5	15	Diglyme
DM3	81	9	10	Diglyme
DE1	72	8	20	Butylal
DE2	76.5	8.5	15	Butylal
DE3	81	9	10	Butylal
DMC1	72	8	20	Dimethyl Carbonate
DMC2	76.5	8.5	15	Dimethyl Carbonate
DMC3	81	9	10	Dimethyl Carbonate

Note: P: n-pentanol, DM: diethylene-glycol diethyl-ether, DE: diethylene-glycol dimethyl-ether, DMC: dimethyl carbonate.

The properties of fuel are given in Table 2. The blending ratios were selected to investigate the influence of oxygenated compounds on combustion and emission characteristics while maintaining comparable fuel properties. All blends were prepared immediately prior to testing using volumetric measurements to ensure accurate proportions and homogeneity. The blending process was carried out using a magnetic stirrer operated at 600 rpm for approximately 30 minutes at room temperature (25 ± 2 °C). After stirring, the fuel blends were visually inspected to ensure complete mixing and absence of stratification. To verify blend stability, each sample was stored in sealed glass containers for 24 hours and monitored for any signs of phase separation or sedimentation. No phase separation was observed during the storage period, confirming adequate blend stability for engine testing.

The oxygen mass fraction of each blend was estimated using the known elemental composition of the oxygenated additives and their volumetric fraction in the diesel mixture. The oxygen content of the blend was calculated using the weighted contribution of oxygen from each component according to Equation [1]:

$$\mathrm{O_{blend}} = \sum(\mathrm{X_i} \times \mathrm{O_i}) \qquad [1]$$

Where X_i represents the volume fraction of component i in the blend and O_i denotes the oxygen mass fraction of that component obtained from literature data.

Diesel fuel was assumed to contain negligible oxygen content. This approach ensured that the overall oxygen concentration of the tested blends remained within a comparable range, enabling meaningful comparison of combustion characteristics. The increase in cetane number observed in the blended fuels is primarily attributed to the presence of oxygenated additives such as diethylene glycol ethers and dimethyl carbonate, which possess inherently higher ignition quality compared with conventional diesel. These additives promote faster ignition and shorter ignition delay periods, thereby increasing the overall cetane rating of the blended fuel.

Table 2: Properties of Tested Fuel Blends with Diesel Fuel

Fuel	Density @20^{0}C (kg m^{-3})	Viscosity @40^{0}C (cSt)	Lower calorific value (kJ/kg)	Flash point (^{0}C)	Cetane No.	Oxygen content (%)
DE1	818	3.9	39,480	72	66	~7
DE2	820	3.7	40,548	70	63	~5
DE3	827	3.4	40,985	68	61	~4
DM1	831	3.5	41,862	65	54	~9-11
DM2	826	3.7	41,354	67	58	~8
DM3	821	3.8	41,025	70	61	~6
DMC1	811	3.8	41,250	69	62	~12
DMC2	823	3.6	41,380	65	58	~9

DMC3	832	3.5	41,910	63	53	~6
P1	828	3.8	41,542	75	62	5.46
P2	832	3.5	41,854	72	59	3.64
P3	838	3.4	42,110	69	52	1.82
D100	840	3.3	42,700	68	48	-

Note: P: n-pentanol, DM: diethylene-glycol diethyl-ether, DE: diethylene-glycol dimethyl-ether, DMC: dimethyl carbonate.

Figure 1 illustrates the experimental setup used for the present investigation, while the detailed operating conditions are provided in Table 3 and the uncertainty analysis is summarized in Table 4. The experiments were conducted on a single-cylinder, four-stroke, direct-injection diesel engine equipped with a water-cooling system as depicted in Figure 1. Before conducting the tests, the engine was allowed to run until it reached stable operating conditions. Performance and emission parameters were recorded under different engine load conditions ranging from 25% to 100% and the final values were obtained by averaging five repeated measurements.

Figure 1: Investigation Setup

Table 3: Engine Specification

Specification	**Values**
Stroke length and bore	110 mm and 87.5 mm
Compression ration	18:1
Speed	1500 rpm
Cylinder	one
Cooking	Water
Injector	Multi hole
Power	3.5 kW
Connecting rod length	234.00 (mm)

Table 4: Uncertainty of Setup

Specification	**Values (%)**
Temperature sensor	±0.15
Speed sensor	±1.0
Load cell	±0.5
CO	±0.5
HC	±0.5
Pressure sensor	±0.5
Crank angle encoder	±0.2
CO_2	±1.0

Results and Discussion

Heat Release Rate

The heat release rate is employed to determine the initiation of the combustion process, the quantity of fuel consumed and any variation in fuel combustion rate. Figure 2 displays the heat release rate variations under full-load settings for diesel and all mixtures. The maximum heat release rate of D100, P1, DE1, DE2, P2, P3, DE3, DMC1, DM1, DM2, DM3, DMC2 and DMC3 are 20.1981, 25.4181, 25.6481, 20.4281, 23.5981, 25.2981, 20.3281, 23.3781, 23.4981, 21.0781, 21.8781, 23.0781 and 23.2581 J/degree respectively. The enhanced combustion, decreased delay duration and increased heat release rate of all blends can be attributed to its greater oxygen concentration along with cetane number (16, 17).

Combustion in a compression ignition engine typically occurs in two main phases: the premixed combustion phase and the diffusion combustion phase. The premixed phase occurs immediately after ignition delay, where the accumulated fuel–air mixture burns rapidly, resulting in a sharp heat release peak. The diffusion phase follows as the remaining fuel burns progressively as it mixes with air. The presence of oxygenated additives enhances fuel atomization and oxygen availability, reducing ignition delay and shifting the peak heat release rate closer to top dead centre.

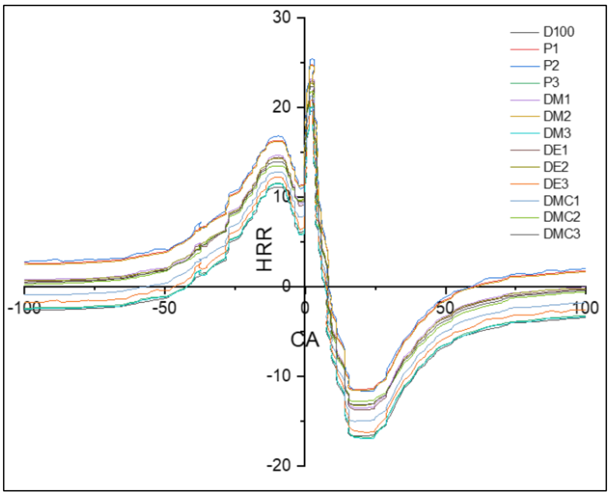

Figure 2: Heat Release Rate VS Crank Angle (°)

Brake Specific Fuel Consumption (BSFC)

Figure 3A displays the BSFC values of an internal combustion engine operating at varying load circumstances with different fuels. BSFC is a metric that quantifies the fuel efficiency of an engine by measuring the quantity of fuel used to generate one kilowatt-hour (kWh) of energy. Lower BSFC readings are indicative of greater fuel efficiency. Under less load circumstances (25%), the diesel (D100) exhibits a BSFC of 0.64 kg/kWh. DE3 demonstrates the most favourable BSFC at 0.65 kg/kWh, suggesting a somewhat superior efficiency compared to D100 and other fuel combinations. The DM has the best presentation of the alternative fuels, at 0.61 kg/kWh and P1 is very close behind, at 0.61 kg/kWh. The D100 has a BSFC of 0.49 kg/kWh while it is under a medium load of 50%. DE3 has a remarkable performance, with a BSFC of 0.51 kg/kWh. P1 and P3 both works quite well, using 0.43 kg/kWh and 0.31 kg/kWh of fuel, respectively. The D100 gets a BSFC of 0.39 kg/kWh when it is heavily loaded (75%). The DE3 engine keeps up its presentation with a BSFC of 0.47 kg/kWh. P1 and DM3 are more efficient than D100, which uses 0.4 kg/kWh of fuel. The D100 engine may use 0.34 kg/kWh of fuel when it is successively at full power. The DE3 blend works better at full load, as seen by its very low BSFC of 0.45 kg/kWh. Both DM3 and P1 have a BSFC of 0.35 kg/kWh, which is rather low.

The results show that DE3, P1 and DM3 are some alternative fuels that have lower BSFC values than D100 at all the loads. It looks like some mixtures work better for fuel efficacy. As a rule, the BSFC values go down as the load goes up, no matter what fuel is used. This common trend can also be observed in Figure 3B, which illustrates the correlation between actual and predicted BSFC values. This is a common trend because engines typically work better when they have more weight on them (17-19). Among the tested blends, DE3, P1 and DM3 demonstrated comparatively lower BSFC values at several load conditions. However, the relative performance varied depending on engine load. P1 and DM3 also have lower BSFC values, which means they can help increase fuel efficiency in a variety of circumstances. When compared to D100, the pentanol blends (P1, P2 and P3) and diethylene glycol dimethyl ether blends (DM1, DM2 and DM3) had lower values of BSFC. This indicates that these alternative fuels could improve fuel efficiency.The developed ANN model predictive power is demonstrated by regression. The training data as demonstrated in Figure 3C provides a good correlation between the predicted and experimental BSFC values at a correlation coefficient is R = 0.9356 which implies that it effectively learns the underlying patterns.

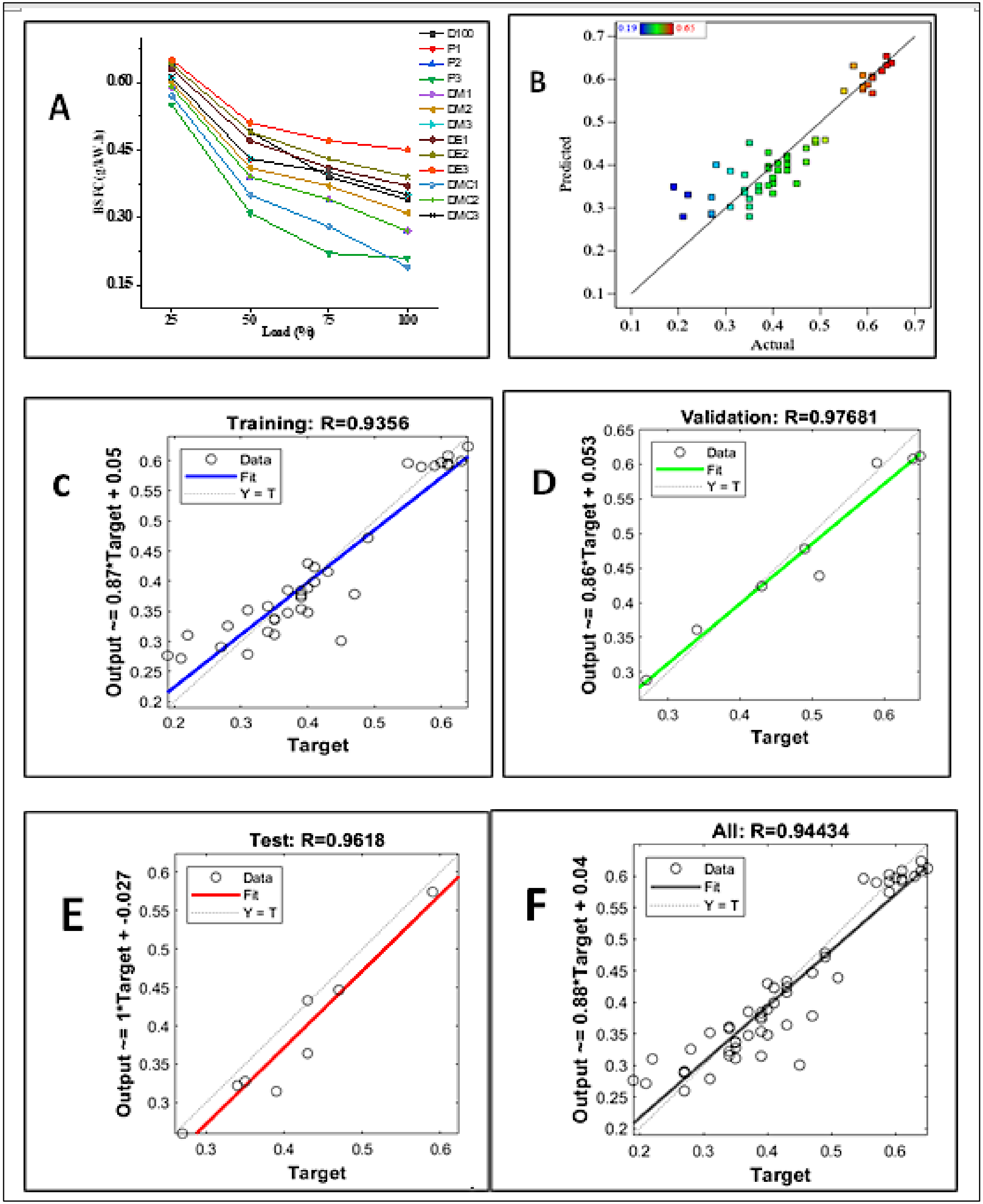

Figure 3: (A) Variation of BSFC With Engine Load for Different Fuel Blends, (B) Actual Versus Predicted BSFC Values Obtained Using the RSM Model, (C) ANN Regression Performance for the Training Dataset, (D) ANN Regression Performance for the Validation Dataset, (E) ANN Regression Performance for the Test Dataset, (F) ANN Regression Performance for the Overall Dataset

Figure 3D shows that validation data (validation data) has a very high generalization performance and its correlation coefficient of R = 0.9768 is high indicating that overfitting is minimal. In the same way, Figure 3E indicates excellent compliance to the test data with R = 0.9618 that confirms the predictive capacity of the model to unknown data. Lastly, Figure 3F shows the general regression performance with a correlation coefficient of R = 0.9443 indicating the strength and dependability of the built ANN model in all the datasets.

CO Emission

Figure 4A illustrates the variation of CO emissions for diesel and oxygenated fuel blends under different engine load conditions. When there is more pentanol, CO emissions go reduced. Because there is more oxygen in the combinations, oxygen additives and pentanol blends burn totally, which lower CO emissions (20, 21). This relationship between experimental and predicted CO emissions is further illustrated in Figure 4B. When the load is low (25%), the D100 lets out 0.028364% of CO emissions. DE1 has a far lower CO emissions rate of 0.021%, which shows that it burns more efficiently than D100 and other blends. P1 (0.031%) and DM1 (0.035%) are two of the substitute fuels that produce the least amount of CO emissions. When the D100 is under a medium load (50%), it lets out 0.038% of CO. The DE1 works fairly well, with CO emissions as low as 0.024%. P1 (0.044%) and DM1 (0.052%) complete better than D100 because they produce lower CO emissions. The D100 model has a carbon monoxide emission rate of 0.048354%. DE1 shows constant performance with CO emissions of 0.016%, which is far lower than D100 and other environment by 0.037% and the DM1 is better by 0.058%. when the engine is running at maximum capacity, the D100 releases CO at a rate of 0.0764%. the P3 releases the least amount of CO emissions, only 0.0293%. this means that the pentanol blend works best at reducing CO emissions when it is running at full capacity. P1 and DM2 have relatively modest levels of CO emissions, at 0.0533% and 0.0493%, respectively.

Figures 4C to Figure 4F show the developed ANN model performance with respect to regression. As indicated in Figure 4C, the training data has a high correlation between estimated and experimental values with the correlation coefficient of R = 0.9698 meaning that the underlying patterns are effectively learned. In Figure 4D, the validation data indicates that there is a moderate correlation with R = 0.7638, which indicates that there is variability in the generalization performance. On the same note, Figure 4E illustrates the test data with R = -0.6462, which means finite correlation accuracy of an unknown data. Lastly, Figure 4F displays the regression result of the overall with R = 0.8306 and thus we can conclude that the model predicts the general trend but with less accuracy than the BSFC prediction.

Hydrocarbon Emissions

Figure 5A shows the hydrocarbon (HC) emissions of an internal combustion engine under different load conditions using various fuel blends. Imperfect ignition causes HC emissions and smaller amount mean that ignition is completer and more efficient (22-25). The relationship between experimental and predicted HC emission values obtained from the developed RSM model is illustrated in Figure 5B. The D100 has HC emissions of 0.8% when the load is low, like when it is 25% full. P1 has far inferior HC emissions (0.7%) than D100 and other combinations, which show that, are burns additional proficiently. One of the alternative fuels, DE1, has a low level of HC emissions at 0.8% while it is under a load of 50%, which is called a medium load. The D100 measurement shows that the HC emissions are 0.9%. P1 works quite well, with HC emissions as low as 0.7%. Both DE1 and D100 perform better than D100, with lower HC emissions. When the load is high, the D100 has a level of HC emissions of 1.2%. P1 continuously completes well, with HC emissions of 0.9%, which is far lower than those of D100 and other fuels. In terms of ecological presentation, DE1 (1.2%) is better than D100. When the load is at its highest (100%). The D100 lets off 1.6% of HC emissions. P1 has the smallest amount of HC emissions, which is 1.2%. this means that the pentanol mix works better at reducing HC emissions when it is running at full capacity. DM1 and DE1 have comparatively low amounts of HC emissions, at 1.5% and 1.6%, correspondingly.

The predicted performance of the developed ANN model in predicting the HC emission is shown in Figure 5C to Figure 5F. Figure 5C reveals that training set demonstrates a great prediction and experimental correlation with the correlation coefficient of R = 0.9823, which suggests that the learning capacity is high. The validation dataset presented in Figure 5D also supports the satisfactory generalization performance because R equals 0.8847. Figure 5E illustrates that the test data has moderately good predictive performance with R = 0.7084, which means a certain variation in the case of unseen data. Lastly, Figure 5F shows the overall regression performance of R = 0.9336, which confirms that ANN model is reliable to reflect the overall trend of HC emissions at all the operating conditions.

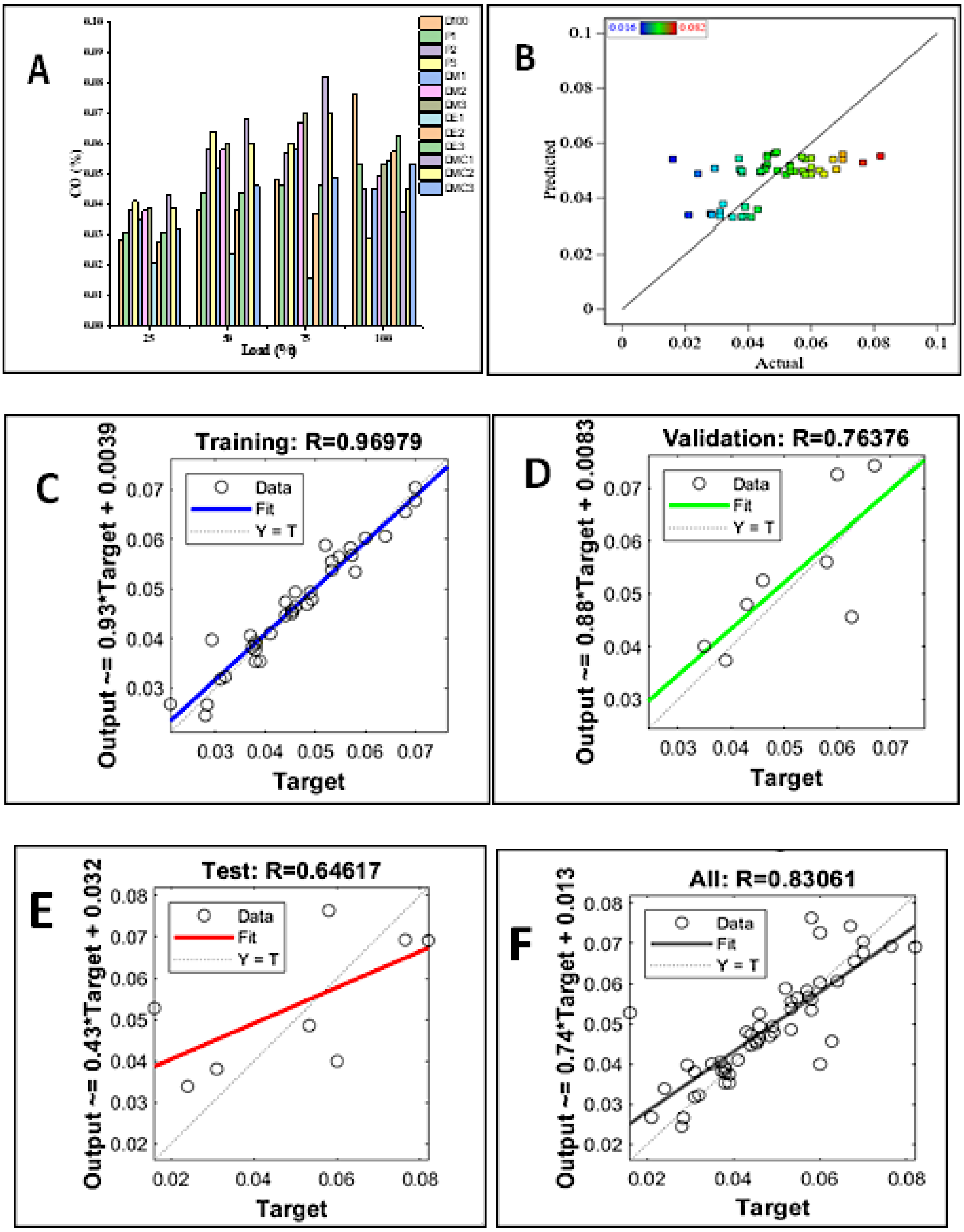

Figure 4: (A) Variation of CO Emission with Engine Load for Different Fuel Blends, (B) Actual Versus Predicted CO Emission Values Obtained Using the RSM Model, (C) ANN Regression Performance for the Training Dataset, (D) ANN Regression Performance for the Validation Dataset, (E) ANN Regression Performance for the Test Dataset and (F) ANN Regression Performance for the Overall Dataset

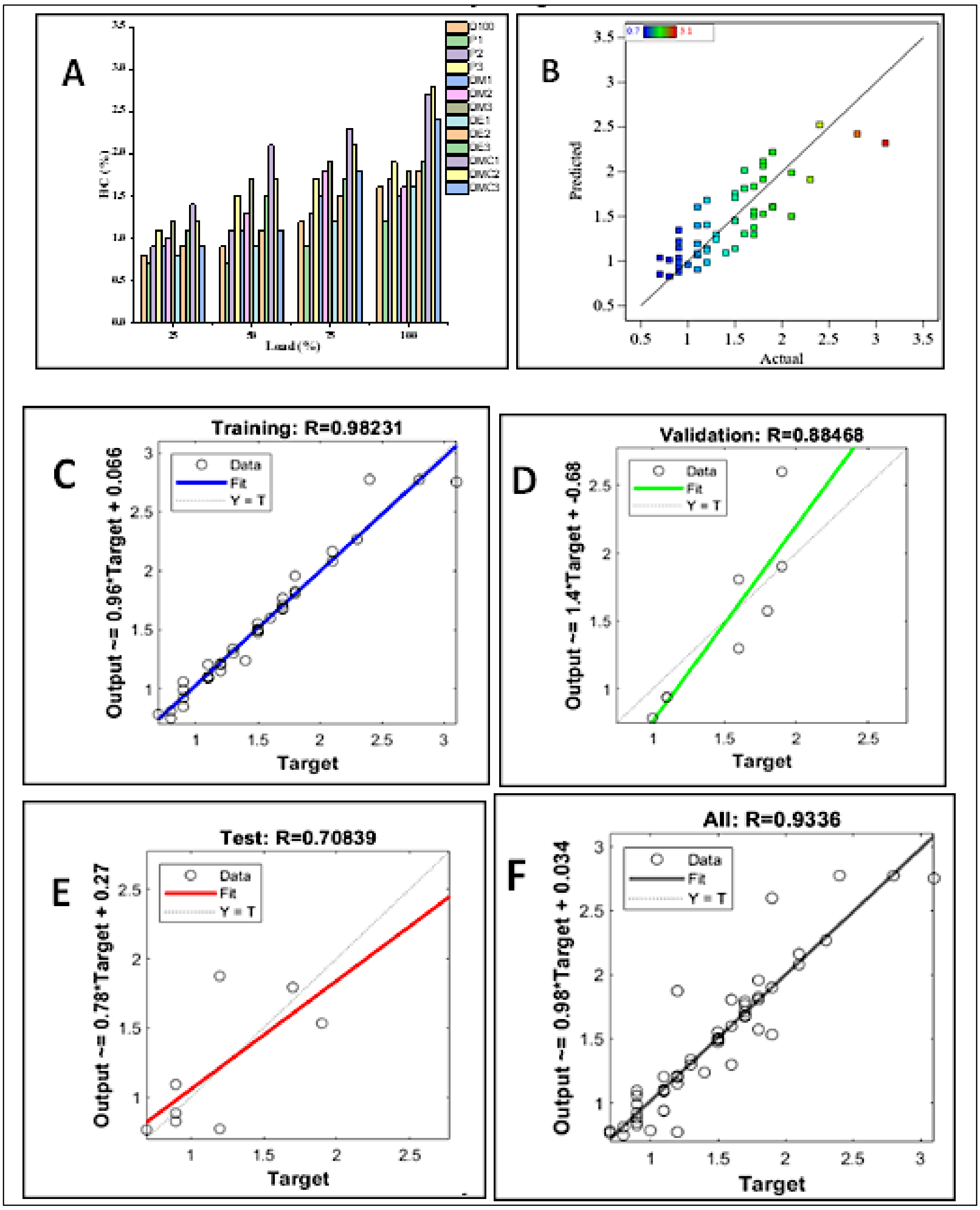

Figure 5: (A) Variation of HC Emission with Engine Load for Different Fuel Blends, (B) Actual Versus Predicted HC Emission Values Obtained Using the RSM Model, (C) ANN Regression Performance for the Training Dataset, (D) ANN Regression Performance for the Validation Dataset, (E) ANN Regression Performance for the Test Dataset and (F) ANN Regression Performance for the Overall Dataset

Table 5: Model Performance Metrics

Model	R^2	RMSE	MAE	MAPE
RSM	0.94	0.018	0.012	3.6
ANN	0.97	0.012	0.008	2.1

The predictive performance of RSM and ANN models was evaluated using statistical indicators including coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE) and mean absolute percentage error (MAPE). As shown in Table 5, the ANN model demonstrated higher predictive accuracy compared with the RSM model, by achieving a higher R^2 value and lower error metrics (RMSE, MAE and MAPE), indicating its superior capability in predicting engine emission characteristics.

Conclusion

Experiments were carried out at different engine load conditions to examine the emission behaviour and performance of diesel-pentanol fuel blends supplemented with three oxygenated additives (DM, DE and DMC). The following conclusions drawn.

a) DE1 has the lowest BSFC at 75% load, 0.41Kg/kW-h.DE1's efficiency and density lower fuel consumption for similar power output. At 25% and 50% loads, P3 has lower BSFC than diesel. Improved fuel characteristics increase combustion efficiency and minimize fuel consumption. DE and DM blends have lower BSFC than diesel at varied engine loads. These mixes burn better, improving fuel efficiency.
b) DE1 consistently demonstrates decreased CO and HC emissions under different loads. DE1 enhances combustion efficiency, resulting in a reduction of imperfect ignition by-products such as CO and HC.
c) DE1 always has the least amount of smoke approaching out, no matter what the load is high or low. The DE1 technology makes ignition additional efficient and adds more oxygen, which means less emission.
d) The results show that substitute fuels, especially DE1 and DM1 are more efficient and produce less emission. This is because they injury better and have additional oxygen than D100 fuel.
e) Future research may investigate the effects of additional oxygenated additives not examined in this work, such as ethanol or methanol blends, on the presentation and emissions of diesel-pentanol combinations to find optimum combinations for numerous engine formations. Long-term performance tests of the selected substitute fuels in a variety of functioning situations world yield valuable information regarding their permanence, efficiency and potential influence on engine wear over extended periods.

Abbreviations

CDF: Conventional Dual Fuel, CH4: Methane Gas, CNT: Carbon Nano Tubes, D100: Pure Diesel, FE2O3: Ferric Oxide, GO: Graphene Oxide, GPN: Graphene Nano Particles, TDF: Traditional Diesel Fuel, TiO_2: Titanium Oxide, WCNT: Wall Carbon Nano Tubes.

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Author Contributions

J Paul Rufus Babu: Conceptualization, Methodology, Investigation, writing – original draft preparation, C Sivarajan: Supervision, writing – review and editing, B Durga Prasad: writing – review and editing, Karthikeyan S: writing – review and editing. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Artificial Intelligence (AI) Assistance Process

The authors declare that they did not use AI assisted tools (ChatGPT, OpenAI) during the writing process. The authors take full responsibility for the content's originality, interpretation and accuracy.

Ethics Approval

Not Applicable.

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