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ANN And RSM Of Ternary Blends On Compression Ignition Engine

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Abstract
This study investigates the effectiveness of various alternative fuels and their emissions in an internal combustion engine. P3 (pentanol) exhibit its highest Brake Thermal Efficiency (BTE) during low to medium loads (25% to 75%). This indicates its potential to improve efficiency under mild to moderate operating conditions. When running under full load, DM1 and DMC1 displayed exceptional performance, suggesting their fit for high-demand jobs requiring best efficiency. The result showed that the DE1 regularly had the lowest NOx emissions under different load scenarios. This suggests that DE1 might be a good way to reduce environmental damage. This research assessed D100 and other gasoline blends (P1, P2, P3, DM1, DM2, DM3, DE1, DE2, DE3, DMC1, DMC2, DMC3) for their performance, combustion, and emission characteristics under varied load circumstances. At 75% load, P3 had a BTE of 33.05%, but DM1 earned the greatest BTE of 34.67% at full load. DE1 demonstrated the lowest NOx emissions at 570 ppm (75% load) and 330 ppm (50% load), while D100 recorded 685 ppm and 407 ppm, respectively. DE1 had the lowest smoke emissions (32.71% at maximum load), and surpassing D100's 44.75% smoke emissions.
Key words: *Pentanol: Diethylene glycol dimethyl ether: Diethylene glycol diethyl ether: Dimethyl carbonate*

1. INTRODUCTION

The enervation of the limited resources on Earth led to the hunt for alternative fuels to conventional ones. Because of their renewable qualities, biofuels are becoming more and more acknowledged as a potential substitute fuel. Biofuels can be utilized for dual or bi-fuelling purposes; however, they are typically mixed by petroleum diesel. The fuel possesses a superior cetane rating, resulting in improved cold starting and reduced static engine noise. The limitations of biodiesel stem from its unfavourable chemical characteristics. Therefore, it is imperative to address the limitations with the intention of enhance the successful integration of biodiesel in diesel engine applications. Engines powered by biodiesel fuel have incorporated various techniques, such as preheating, exhaust gas recirculation, and the utilization of fuel additives. Using the formulation approach is a highly effective strategy for addressing the limitations of biodiesel. The emulsion method is a highly effective technique used in the fuel composition process to decrease exhaust emissions in Compression Ignition (CI) engines. Studies have found the addition of biodiesel and diesel blends to alcohols. Hence, a comprehensive investigation found effect of higher alcohols on emission properties of pure biodiesel is planned to be conducted.

Hydrogen is becoming an essential element in the shift towards sustainable energy systems, providing considerable environmental advantages as a clean fuel that emits only water vapor upon use. Its adaptability enables many uses, including as fuel cells for transportation and energy storage systems. Furthermore, innovations in manufacturing techniques, such green hydrogen via electrolysis, improve its sustainability and economic feasibility. As worldwide investments and research in hydrogen technologies expand, its capacity to foster innovation and economic development in the clean energy industry markedly rises[1,2]. Extensive research is focused on addressing the drawbacks of mustard oil biodiesel through the adjustment of various factors. These include exhaust gas recirculation, compression ratio and variable timing, and the incorporation of different additives like oxygenated and metal-based compounds.[3–5]. The fuel formulation method proves to be highly effective in addressing the limitations associated with biodiesel operation, surpassing alternative approaches [6]. The emulsion process is a highly successful technology in the fuel formulation procedure for reducing exhaust emissions in CI engines. Therefore, using greater alcohols as additives in biodiesel during the emulsification procedure results in improved engine efficiency, reduced delay duration, and decreased emission levels. Blending higher alcohols has been discovered as an effective method to enhance engine performance and decrease emissions in biodiesel applications[7]. Datta and Mandal [8,9] conducted a study on a compression ignition engine using various biodiesel-alcohol mixes. They found that from the addition of alcohol leads to notable decrease in emissions. The ignition delay has been reduced in comparison to pure biodiesel. The researchers determined that the inclusion of methanol to jatropha biodiesel leads to substantial drop in all emissions. In addition, the utilization of methanol in biodiesel led to a reduction in the time it takes for ignition to occur. Su et al. [10] explored the effects of ethanol on mixtures of diesel and biodiesel. Researcher found a notable drop in NO_x emissions and specific fuel consumption. In inclusion, the addition of ethanol in diesel and biodiesel blends led to a drop in both peak pressure and temperature. Tongroon and Zhao [11] performed an investigation on the combustion and emission characteristics of alcohol-based fuels when combined with diesel and biodiesel blends. They noticed an improvement in thermal efficiency. In addition, it was found that alcohols have the impact of reducing the viscosity of fuel mixtures and decreasing the duration of delay. In their study, Imdadul et al. [12] explored the effects of more alcohol content on the efficiency, environmental impact, and combustion characteristics of biodiesel-diesel mixtures. They observed a notable drop in the delay period, as well as in the levels of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOX) emissions. After reviewing the literature, several studies have been accomplished utilizing lower alcohols in mixtures of bio-diesel and diesel. Utilizing antioxidants and oxidizing additives has demonstrated promise in significantly reducing CO and NOx emissions [13]. DEE and DME have been widely used as additives for diesel fuel and other fuel sources because of their shorter carbon-based chain composition and their potential to enhance ignition. Although the DME content is higher, it has similar properties to LPG (liquefied petroleum gas) when it comes to reducing both NOx and smoke emissions at the same time [14], it is presently not feasible to distribute larger amounts of gaseous fuels in an unmodified diesel engine. Furthermore, the production cost of DME in today's industrial context is significantly greater. The solution lies in utilizing DEE, which possesses the reflecting characteristics of DME, but in a liquid state at normal environmental conditions. This effectively overcomes the drawbacks of existing automobile technology and reduces the cost of fuel delivery. Additionally, DEE has a somewhat lower manufacturing cost and can be synthesized from ethanol, which can be derived from biomass [15] via a dehydration process.

Direct injection (DI) diesel engines play a significant role in emerging nations as they provide power for agricultural pumps, small power tillers, light surface transport vehicles, and other machinery. The issue of escalating need for substantial brake power and the rapid exhaustion of fossil resources necessitates stringent power regulation and a high degree of fuel efficiency. A multitude of modern technologies are being created to address these issues. An optimization strategy must be implemented to ensure that the engine's efficiency is not compromised. Regarding internal combustion engines, the optimization of design and operational characteristics is crucial for achieving high thermal efficiency and minimizing emissions.

2. MATERIAL AND METHODOLOGY

2.1. Test fuel and characteristics

Initially, three sets of blends are created using a Diesel to Pentanol ratio of 70:30, 80:20, and 90:10 accordingly. All combustion and emission factors are taken into account, and the best mix is determined out of the three blends. The combination is mixed with three distinct oxygen additives: Diethylene Glycol Dimethyl Ether (Diglyme), Diethylene Glycol Diethyl Ether (Butylal), and Dimethyl Carbonate (DMC). The blend contains varying amounts of oxygen additions, specifically 30%, 20%, and 10%. The remaining portion, 70%, 80%, and 90%, consists of a mixture of diesel and pentanol in a ratio of 90:10. Figure 1 indicates detail Volume percentage of Diesel, Pentanol and Oxygen additives in each blend. The table 1 indicates the characteristics of the fuels.

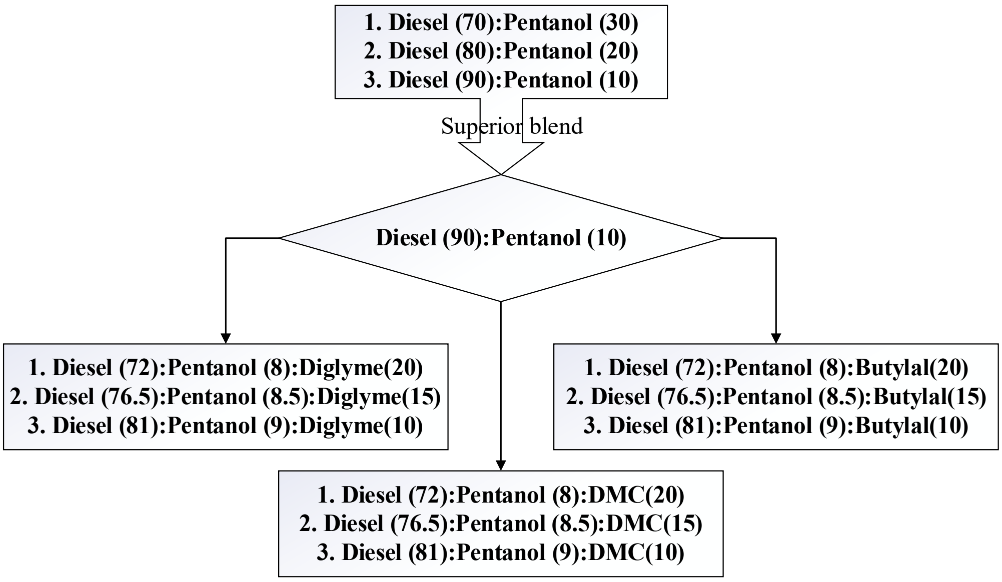

Figure 1. Fuel blend volume %.

Table 1. Characteristics of fuel.

SI. No.	Fuel	Density @20^{0}C (kg m^{-3})	Viscosity @40^{0}C (cSt)	Lower calorific value (kJ/kg)	Flash point (^{0}C)	Cetane No.
1.	D100	840	3.3	42,700	68	48
2.	P1	828	3.8	41,542	75	62
3.	P2	832	3.5	41,854	72	59
4.	P3	838	3.4	42,110	69	52
5.	DM1	831	3.5	41,862	65	54
6.	DM2	826	3.7	41,354	67	58
7.	DM3	821	3.8	41,025	70	61
8.	DE1	818	3.9	39,480	72	66
9.	DE2	820	3.7	40,548	70	63
10.	DE3	827	3.4	40,985	68	61
11.	DMC1	811	3.8	41,250	69	62
12.	DMC2	823	3.6	41,380	65	58
13.	DMC3	832	3.5	41,910	63	53

2.2. Test rig

Figure 2 illustrates the engine test apparatus and the conditions that are related to it. The study utilizes a single-cylinder, four-stroke, naturally aspirated water cooled CI engine in an experimental setting and specification in Table 2. Upon initiating the engine, an adequate duration was allowed for the engine to reach its optimal operating temperature. The system eventually achieved a state of equilibrium. The engine underwent testing at load settings of 25%, 50%, 75%, and 100%. Prior to starting the engine with a fresh fuel combination, a 15-minute period was designated for operation. Once the engine achieved a steady operational state, the gas analyzer was employed to quantify the levels of emission.

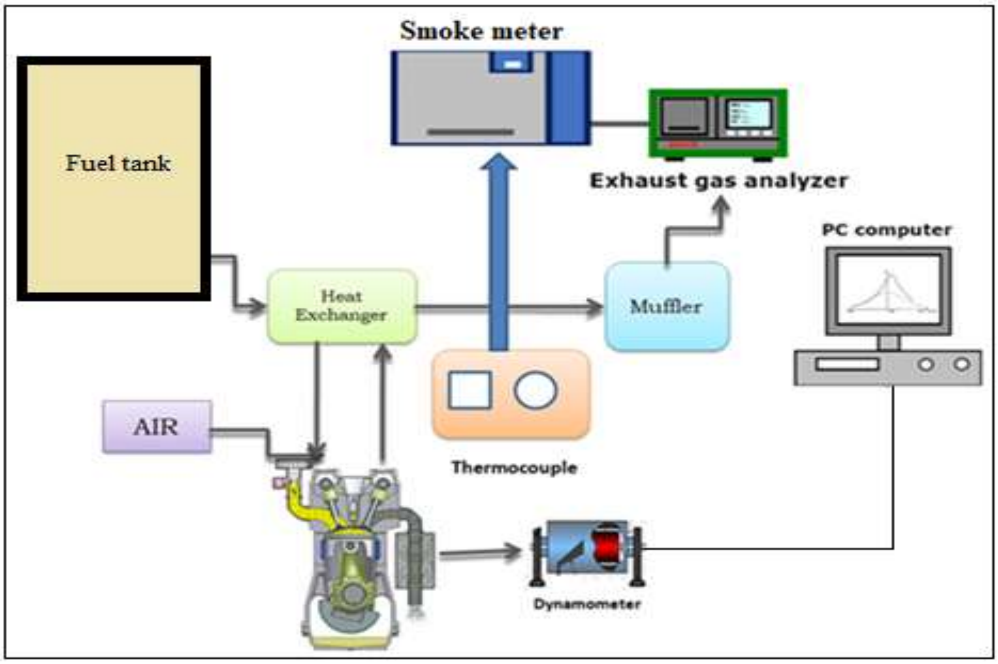

Figure 2. Engine setup.

Table 2. Engine specification.

specification	values
Stroke and bore	110 mm and 87.5 mm
Compression ration	18:1
Speed	1500 rpm
No. of cylinder	1
Cooking	Water
Injector	Multi hole
Power	3.5 kW
Connecting rod length	234.00 (mm)

2.3. Uncertainty

Uncertainty analysis involves a set of organized and balanced processes used to determine the errors in experimental data. The square root approach was employed to assess the proportion of uncertainty associated with multiple unique factors. Equation 1 was employed to get the total percentage of data uncertainty [16]. The level of uncertainty has been calculated to be 3.9%.

$$\delta = \sqrt{(\delta_{Load}^2 + \delta_{BP}^2 + \delta_{BSFC}^2 + \delta_{Temp}^2 + \delta_{HC}^2 + \delta_{CO}^2 + \delta_{NO_X}^2 + \delta_{Smoke}^2)} \quad (1)$$

2.4. Optimization and analysis

An analysis of the output response characteristics was conducted using the response surface methodology (RSM) to develop a prediction model. The Response Surface Methodology (RSM) is a powerful computational and analytical technique used to analyze the relationship between the output response and the input parameters. It helps determine an objective function that accurately measures this relationship. Various load circumstances were tested to evaluate their impact on engine emissions and performance parameters [17]. To assess the neural network model, we made use of MATLAB's nntool, a user-friendly graphical interface found in the Deep Learning Toolbox. This program streamlines the process of designing, training, and simulating neural networks with minimal scripting required. A regression plot illustrates the visual representation of the relationship between the network's outputs and the actual targets. Here are the following steps that outline the procedure [18]. The artificial neural network model as shown in figure 3. The remaining 15% (approximately 8 data points) was reserved as unseen data to test the reliability and generalization capability of the ANN model after training shown in Table 3.

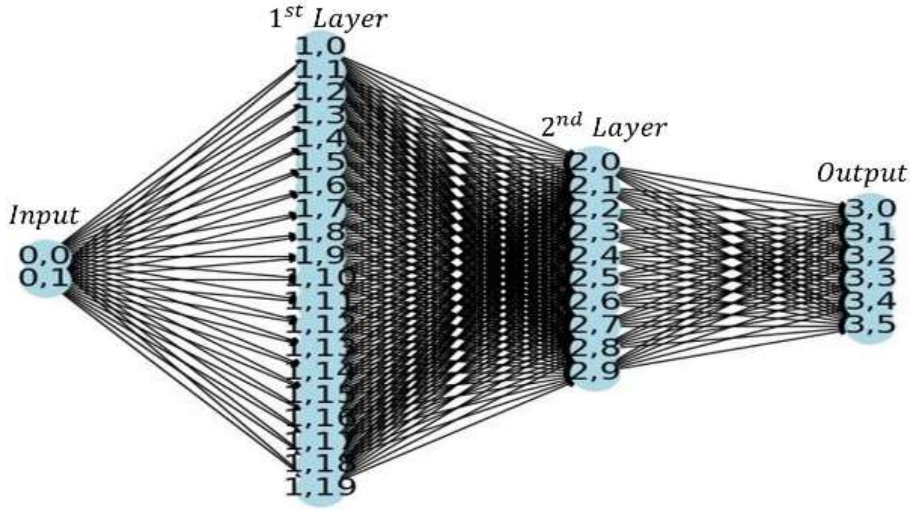

Figure 3. Artificial neural network model.

Table 3. Testing data of ANN.

load	blend	BTE	NOx	Smoke
75	7	31.1	640	41.51
100	10	31.27	892	41.15
75	13	31.4	694.75	35.6
100	4	32.87	976	49.51
75	8	29.9	570.25	32.03
25	11	22.8	271	46.2
75	5	32.9	622	41.93
25	3	21.95	271	45.67

3. RESULT AND DISCUSSION

3.1. Cylinder pressure

The attainment of maximum pressure in a compression ignition (CI) engine is determined by the rate of combustion, that affected by the quantity of fuel burned during the premixed combustion period. Figure 4 displays the relationship between pressure plus crank angle under full-load circumstances for all blends and diesel. The engine exhibits a consistent in-cylinder pressure pattern across all test fuels. All blends exhibit higher peak pressure levels contrast to diesel because of alcohol presence in the blends. The viscosity of all blends exceeds that of diesel, resulting in a protracted ignition delay. This leads to increased fuel consumption, uneven combustion, and greater peak pressure [19].The reduced calorific value of blends is another factor contributing to their greater peak pressure. According to Devarajan et al. (2017) [20], fuel having a lesser calorific value necessitates a larger amount of fuel during combustion. The peak pressure at full load for the D100, P1, P2, P3, DM1, DM2, DM3, DE1, DE2, DE3, DMC1, DMC2, and DMC3 are 84.67, 89.89, 90.12, 84.9, 88.07, 89.77, 84.8, 87.85, 87.97, 85.55, 86.35, 87.55, and 87.73 bar respectively.

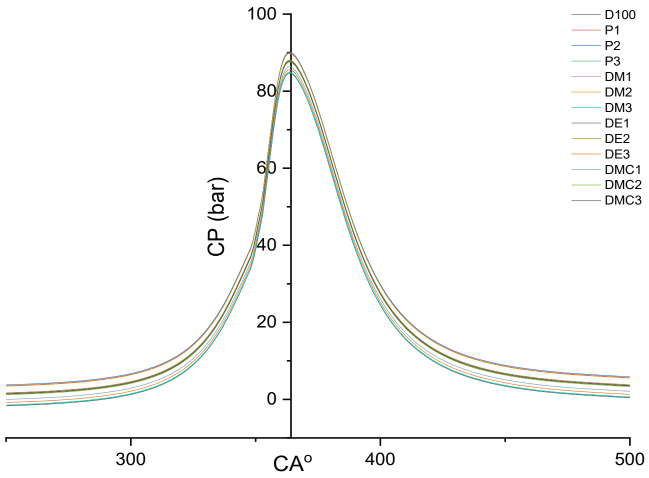

Figure 4. Cylinder pressure(bar) vs Crank angle(degree).

3.2. Brake thermal efficiency

Brake thermal efficiency (BTE) is a measure of the engine's efficiency in converting the fuel's energy into mechanical work [20]. The higher the BTE, the more efficient the engine is shown in Figure 5. During a low load condition of 25%, the D100 exhibits the lowest BTE at a value of 20.01%. P3 demonstrates the best BTE at 22.5%, demonstrating superior efficiency compared to D100 and other fuel blends. DMC1 exhibits superior performance (22.8%), with DM1 closely trailing behind (22.1%), among the available alternative fuels. When operating at half load, the D100 exhibits a BTE of 24.02%. P3 exhibits exceptional performance with a Back-End Efficiency (BTE) of 28.3%, suggesting a consistent level of efficiency under various load circumstances [19-20]. DM1 (28.2%) and DMC1 (28.1%) exhibit superior performance, attaining significantly better BTE compared to D100. Under heavy load conditions (75%), the D100 has a BTE of 29.83%. P3 consistently maintains its exceptional performance, achieving a BTE of 33.05%. DM1 and DMC1 demonstrate superior efficiency, surpassing that of D100. Under the condition of maximum load, the D100 achieves a BTE of 33.57%. DM1 exhibits the highest BTE of 34.67%, suggesting that it outperforms other blends, such as Diesel and Diethylene Glycol Dimethyl Ether, when operating at maximum capacity. The DMC1 also has a notable BTE of 34.47%, indicating that the Dimethyl Carbonate blend improves efficiency.

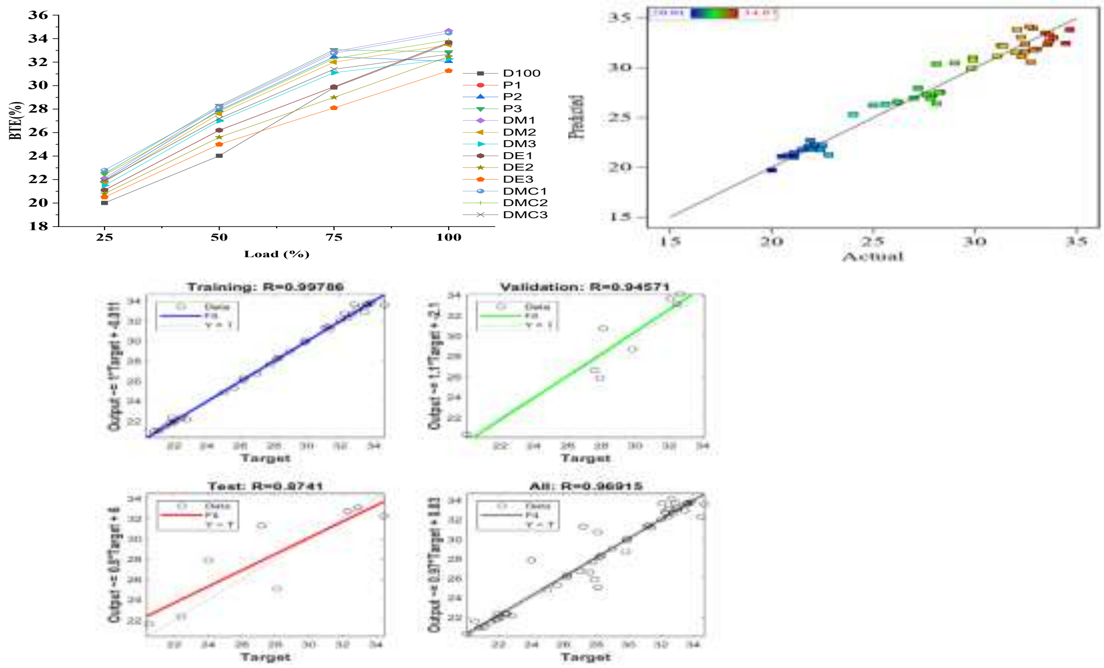

Figure 5. a) BTE VS Load, b) RSM actual vs predicted of BTE, c) ANN regression of BTE.

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3.3. Nitrogen oxides (NOx)

Figure 6 illustrates the NOx emissions of an internal combustion engine operating at different load settings utilizing different fuels. NOx emissions are a crucial contaminant linked to combustion processes, and it is imperative to decrease them in order to comply with environmental requirements [21-22]. Under low load conditions (25%), the D100 exhibits NOx emissions of 256 ppm. DE1 demonstrates superior environmental performance compared to D100 and other mixes, since it produces the lowest NOx emissions at 242 ppm. DE3 has superior performance among the alternative fuels, with a concentration of 256 ppm, closely followed by P1 with a concentration of 261 ppm. Under a medium load condition (50%), the D100 exhibits NOx emissions of 407 ppm. The DE1 exhibits exceptional performance, achieving NOx emissions as low as 330 ppm. DM1 (365 parts per million) and DM2 (372 parts per million) likewise exhibit excellent performance, producing notably reduced NOx emissions compared to D100.Under high load conditions (75%), the D100 achieves NOx emissions of 685 ppm. The DE1 consistently maintains its performance, exhibiting NOx emissions of 570.25 parts per million. DM1, with a concentration of 622 ppm, and DM2, with a concentration of 633.25 ppm, exhibit superior environmental performance compared to D100.Under full load conditions, namely at 100% capacity, the D100 exhibits NOx emissions of 980 ppm. The DE1 fuel blend demonstrates superior performance in decreasing NOx emissions, with a recorded level of 827 ppm, the lowest among all tested fuels at full load. DM1 and DM2 have comparatively modest levels of NOx emissions, measuring at 896 ppm and 911 ppm respectively.

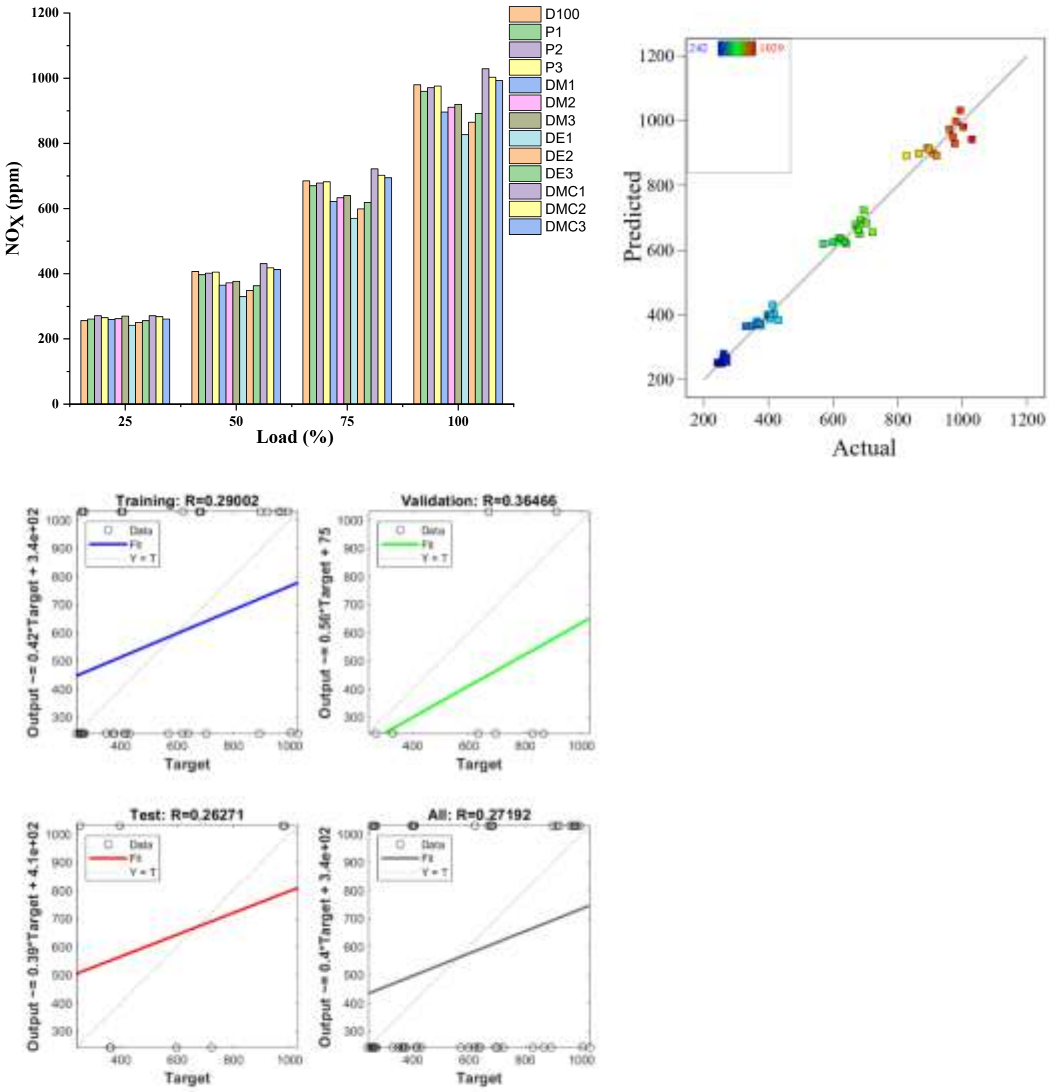

Figure 6. a) NO_x vs load, b) RSM actual vs predicted of NO_x, c) ANN regression of NO_x.

3.4. Smoke emission

The provided data presents the smoke emissions of an internal combustion engine under various load conditions using different fuel blends. Smoke emissions, measured in percentage, indicate the amount of particulate matter produced during combustion, with lower values representing cleaner combustion. At Low Load Condition (25%). D100 has smoke emissions of 45.02%. P1 shows slightly lower smoke emissions at 44.21%, indicating better combustion efficiency compared to D100. DE1 exhibits the lowest smoke emissions at 42.01%, suggesting significantly cleaner combustion among all fuels. At Medium Load Condition (50%). D100 shows smoke emissions of 42.04%. P1 has lower smoke emissions at 40.42%. DE1 again shows the lowest emissions at 36.02%, indicating a notable reduction in particulate matter. At High Load Condition (75%). D100 achieves smoke emissions of 41.06%. P1 demonstrates superior performance with smoke emissions of 38.63%. DE1 continues to perform best with smoke emissions at 32.03%. At Full Load Condition (100%). D100 reaches smoke emissions of 44.75%. P1 shows reduced smoke emissions at 41.51%. DE1 stands out with the lowest emissions at 32.71%, indicating excellent combustion efficiency even under full load. The results show that certain alternative fuels, especially specific blends of Pentanol and Diethylene Glycol Diethyl Ether, achieve lower smoke emissions compared to standard diesel (D100) across all load conditions. This indicates that these blends are more efficient in terms of reducing particulate matter. For most fuels, smoke emissions increase with higher loads. This trend is typical because higher loads generally lead to richer air-fuel mixtures, promoting the formation of particulate matter.

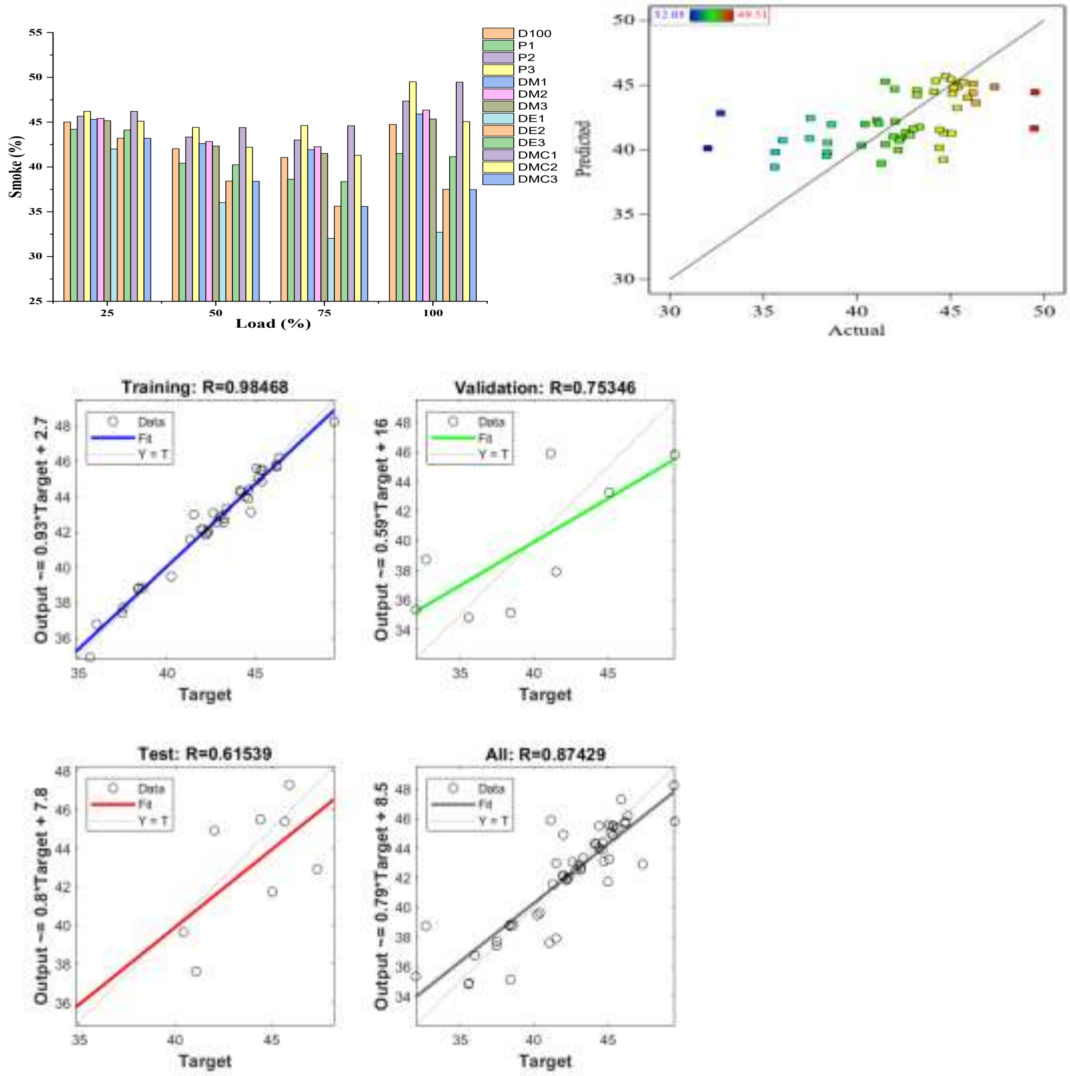

Figure 7. a) Smoke VS load, b) RSM actual vs predicted of smoke, c) ANN regression of smoke.

3.5. Comparative study

To contextualize the findings of this investigation, a comparison with analogous studies using various gasoline additives and engine configurations is included in Table 4. The chart delineates engine specs, fuel additives, and critical performance and emission metrics, including Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), and emissions of NOx, CO, HC, along with smoke levels. Comparative analysis of research indicates that fuel additives, including alcohols (pentanol, butanol) and oxygenates (diethyl ether, dimethyl carbonate), often enhance combustion efficiency and reduce emissions. The precise effect of each additive is contingent upon the engine layout, injection method, and operating circumstances. The incorporation of dimethyl carbonate in Study 4 and Study 5 led to substantial decreases in NOx and smoke emissions, presumably owing to its increased oxygen content, which facilitates more thorough burning. Comparing the findings of this study with previous research indicates that the use of oxygenated fuel mixes, as examined herein, corresponds with the prevailing trend of using alternative fuel additives to enhance engine performance and diminish detrimental emissions. The result indicates the possibility for enhanced optimization and use of mixed fuels in commercial diesel engines.

Table 4. Comparison of current study to previous study.

Engine Specification	**Alcohol/ additive**	**BTE**	**BSFC**	**NOx**	**CO**	**HC**	**Smoke**	**Ref.**
4-cylinder 2.0-L-displacement supercharged intercooled electronically controlled high-pressure common rail engine.	n-pentanol	↑	↓	↑	↓			[21]
Single cylinder, naturally aspirated, air-cooled type, four-stroke, direct injection diesel engine (TAF1, Kirloskar model).	1-pentanol 1-butanol	↑	↓	↑	↑	↓	↓	[22]
4-stroke, direct-fueled Kirloskar TV1 engine (1-cylinder) with water cooling and natural air intake facility and it has a peak power of 3.5 kW at 1500 rpm.	diethyl ether	↓	↑	↓		↓		[23]
single-cylinder common-rail diesel research engine originating from a Daimler 2.2 L common-rail direct injection four-cylinder in-line engine of type OM646 (EU4).	Dimethyl carbonate	↓		↓		↓		[24]
A water-cooled research diesel engine of rated power 8.4 kW was subjected to performance and emission testing when coupled to an eddy-current dynamometer	Dimethyl carbonate	↑	↓	↑	↓	↓	↑	[25]

4. CONCLUSION

Engine operated at 4 different load level to analyse the Diesel and pentanol blend emission and performance parameters along with 3 different oxygen additives Di ethylene Glycol Di methyl Ether (DM), Diethylene glycol diethyl ether (DE) and Dimethyl carbonate (DMC). In the ANN model, 13 distinct fuel mixes were evaluated, each including various fractions of the fuels used in the experiment.

- Diethylene Glycol Dimethyl Ether (DM1) is found at a concentration of 34.67% under full load conditions. The increased oxygen levels in DM1 promote more effective combustion, leading to improved efficiency. P3 demonstrates enhanced Brake Thermal Efficiency (BTE) relative to diesel (D100) across load levels of 25%, 50%, and 75%. Pentanol demonstrates an enhanced calorific value and oxygen content, thereby improving the efficiency of combustion. All fuels exhibit enhanced Brake Thermal Efficiency (BTE) relative to diesel, particularly when subjected to heavy loads. The inclusion of oxygenates in these fuels optimizes the combustion process, resulting in improved thermal efficiency.
- DE3 exhibits reduced NOx emissions at 25% and 50% loads in comparison to diesel. Oxygenates present in DE3 contribute to the reduction of peak combustion temperatures, hence decreasing the generation of NOx.
- DE1 consistently exhibits the lowest levels of smoke emissions under all load circumstances. The DE1 system enhances combustion efficiency and increases the oxygen content, resulting in less production of particulate matter.
- The results highlight those alternative fuels, particularly Diethylene Glycol Diethyl Ether (DE1) and Diethylene Glycol Dimethyl Ether (DM1), provide enhanced efficiency and decreased emissions. This is due to their enhanced combustion characteristics and increased oxygen concentration relative to normal diesel fuel.

Nomenclatures

D100	Diesel (100%)
P1	Diesel (70%) + Pentanol (30%)
P2	Diesel (80%) + Pentanol (20%)
P3	Diesel (90%) + Pentanol (10%)
DM1	Diesel (72%) + Pentanol (8%) +Diglyme (20%)
DM2	Diesel (76.5%) + Pentanol (8.5%) +Diglyme (15%)
DM3	Diesel (81%) + Pentanol (9%) +Diglyme (10%)
DE1	Diesel (72%) + Pentanol (8%) + Butylal (20%)
DE2	Diesel (76.5%) + Pentanol (8.5%) + Butylal (15%)
DE3	Diesel (81%) + Pentanol (9%) + Butylal (10%)
DMC1	Diesel (72%) + Pentanol (8%) + Dimethyl Carbonate (20%)
DMC2	Diesel (76.5%) + Pentanol (8.5%) + Dimethyl Carbonate (15%)
DMC3	Diesel (81%) + Pentanol (9%) + Dimethyl Carbonate (10%)
RSM	Response surface methodology.
ANN	Artificial neural network
BTE	Brake thermal efficiency
NOx	Nitrogen oxides

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Conflicts of interest
The authors declare no conflicts of interest.
Ethical approval
The research work does not contained any studies with human and animals.

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