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Experimental investigation of multi-additive fuel blend and its optimization for CI engine performance and emissions by the hybrid Taguchi- TOPSIS technique

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A R T I C L E I N F O

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A B S T R A C T

In recent years, the critical stage of air pollution and government stringent emission norms like Bharat Standard VI in 2020 in India and Euro VI in European countries, along with the promotion of electric vehicles, has made the future of diesel vehicles unpredictable. The present work correlates and tries to overcome the emission issue by improving fuel properties using a novel multi-additive fuel blend which can control engine emission, mostly NOx, without compromising efficiency and operating fuel economy. Using experimental and literature studies, three additives were identified for creating a novel multi-additive fuel blend, viz. dimethyl carbonate, 2-ethylhexyl nitrate and ethyl acetate. Using the Taguchi Design of Experiment method, sixteen test samples having different combinations of these additive were identified for experimental trials to create sufficient and suitable test data for the optimization process. Technique for Order of Preference by Similarity to Ideal Solution is a Multi Criteria Decision Making optimization process, is performed to identify the optimized multi-additive fuel blend coded as D8EH6E4. Blending the optimized multi-additive sample D8EH6E4 with diesel fuel reduced NOx formation by an average of 19 % while causing a substantial drop in smoke at higher load conditions without adversely affecting engine performance and fuel economy.

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Nomenclature

D	Decision matrix
P	Performance score
S	Separation values from ideal best S^{+} and idle worst S^{-}
V	Normalized response for all runs
w	Weightage value
X	Normalized response parameter
y	Normalized response parameter

Subscripts

i, j, k	ith, jth and kth values
m	No. of alternatives
n	No. of attributes

Superscripts

$^{+}$	Ideal best or maximum
$^{-}$	Ideal worst or minimum

Acronyms

ANOVA	Analysis of variance
BP	Brake power
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CAbTDC	Crank angle before top dead center
CI	Compression ignition
CO	Carbon monoxide
COHR	Centre of heat release
DMC	Dimethyl carbonate
DoE	Design of Experiments
EA	Ethyl acetate
EGR	Exhaust gas recirculation
EHN	Ethyl-hexyl nitrate
ESC	European stationary cycle
ETC	European transient cycle
GRA	Grey Relational Analysis
GRG	Grey relational grade
HC	Hydrocarbon
NOx	Oxides of nitrogen
OME	Oxy-methylene ethers
PCCI	Premixed charged CI engine
ppm	Parts per million
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

1. Introduction

Compression ignition (CI) engines, owing to their cost-effectiveness compared to petrol and their robust power-generation capabilities, find widespread utilization in heavy-duty vehicles and power generation, surpassing gasoline engines in these domains [1]. Despite their superior efficiency and fuel economy, CI engines are known sources of smoke and NOx emissions, which constitute significant contributors to air pollution. In response to the imperative of curbing air pollution and aligning with stringent emission regulations, researchers both in India and abroad have been diligently exploring methodologies to achieve homogeneous air-fuel mixture formation within compression ignition (CI) engines. This approach aims to mitigate the propensity for emissions formation during combustion. One particularly promising avenue is the enhancement of fuel properties, as it obviates the necessity for extensive engine design modifications and presents a user-friendly solution. Moreover, this strategy holds the potential for widespread implementation, thanks to collaborative efforts with the oil and gas industries. Such collaborations not only reduce costs but also facilitate the dissemination of these improvements through large-scale fuel distributors and dealers. A study conducted by Tiemin Xuan et al. [2] delved into the impact of blending hydrogenated catalytic biodiesel with methanol, with a focus on spray morphology and combustion characteristics such as ignition delay and flame lift-off. Their investigation revealed notable findings: pure biodiesel exhibited the swiftest spray penetration, followed by blends containing 15 % and 25 % methanol. Furthermore, their subsequent research into combustion properties, encompassing aspects such as liquid length and in-flame soot formation, highlights a more pronounced reduction in liquid length following ignition, a phenomenon that is notably more prominent in the blended fuels as compared to pure hydrogenated catalytic biodiesel (HCB). This can be attributed to the shorter lift-off length observed in the blended fuels [3]. In their study, Mujtaba et al. [4] discovered that incorporating primary and secondary alcohols into diesel fuel as an additive led to a reduction in nitrogen oxides (NOx) emissions. This drop in NOx was attributed to the reduced latent heat of the fuel blend, particularly when used in combination with 20 % biodiesel Mahmudal et al. [5] in their study on oxygenate observed that blending with n-butanol resulted in significant reductions in nitrogen oxides (NOx) by approximately 20 % and carbon monoxide (CO) by 3 %. But at this same time, this improvement in emissions control was accompanied by a slight drop in engine power, accounting to 11.1 %, and a drop in torque by 3.5 %. Palazzo et al. [6], studied and investigated the impact of oxygenate additives on soot formation and observed that inclusion of oxymethylene ethers (OME) additives led to a significant drop in particle concentration, achieving a notable decrease of approximately 36 %. Importantly, this reduction in soot concentration happened without showing any adverse effect on the local soot formation temperature. Ahmed I. EL Seesy et al. [7], in their comprehensive experimental investigation, the stability of both pure methanol and hydrous methanol was examined when blended with biodiesel, specifically n-octanol, across a temperature range from 10 °C to 30 °C. Their results consistently demonstrated the stability of these blends at all tested temperatures. Subsequent studies delved into the emissions and combustion characteristics of three distinct blend samples of Biodiesel with methanol and DEE. These investigations revealed that the blends exhibited lower values for several critical parameters, including the highest cylinder pressure, heat release rate, and pressure rise rate, in contrast to pure biodiesel. Zhixia He et al. [8] Conducted an experimental investigation focused on the blending of methanol with a diesel blend comprising n-octanol and DEE nanoparticles. Their study revealed that the blending of diesel exclusively with methanol exhibited unstable behaviour across varying temperatures. The outcomes of their research indicated that when DEE nanoparticles were introduced into the diesel-methanol blend, significant improvements were observed. Specifically, the maximum cylinder pressure (Pcyl.), heat release rate (HRR), and the rate of pressure rise (dp/dθ) decreased in comparison to pure diesel. Simultaneously, Brake Thermal Efficiency (BTE) declined while Brake Specific Fuel Consumption (BSFC) demonstrated enhancement for the test sample when compared to the baseline diesel. Radwan M. EL-Zohairy et al. [9] conducted a study examining the influence of adding DEE (diethyl ether) to biodiesel, along with an additional blend agent of jet fuel A1, within a lean pre-vaporized premixed system utilizing preheated air at 350 °C, all while maintaining a fixed equivalence ratio of 0.85 (lean condition). The results of this investigation unveiled a noteworthy reduction in emission gases and a higher maximum temperature when contrasted with other blends. Ahmed I. EL-Seesy et al. conducted an exhaustive experimental investigation to assess the impact of nitrogen-doped and amino-functionalized multiwall carbon nanotubes on a blend of diesel and n-decanol, with a focus on the performance and emissions parameters of a Compression Ignition (CI) engine. The experimental results indicated that the blend of waste cooking oil (WCO) diesel and decanol exhibited significant control over NOx emissions, resulting in an 8 % reduction, as well as a substantial decrease in smoke emissions by 44 % when compared to standard diesel. Remarkably, engine performance remained consistent in both cases. Conversely, the incorporation of multiwall carbon nanotubes (MWCNTs) in the blend had an adverse effect. It led to a 10 % drop in Brake Thermal Efficiency (BTE) and a 15 % increase in Brake Specific Fuel Consumption (BSFC) [10]. In a study by Jayabal et al. [11] the impact of injection timing was explored concerning two oxygenate blends: dimethyl carbonate (DMC) and n-butanol biodiesel. This investigation delved into their behavior in relation to combustion characteristics, specifically peak pressure and heat release rate. The results unveiled a gradual decline as the injection timing transitioned from 250° to 210° crank angle before top dead center (CAbTDC), alongside reduced engine emissions—namely, diminished smoke and NOx levels—when a 5 % Exhaust Gas Recirculation (EGR) was employed. C. Swaminathan et al. research [12] centered on the blending of sunflower methyl ester and Diethyl Ether (DEE) with diesel. The outcomes of this investigation indicated a notable 8 % enhancement in brake thermal efficiency, accompanied by a substantial reduction in NOx emissions—from 469 to 261 ppm—and a decrease in hydrocarbon (HC) emissions—from 200 to 130 ppm. This study demonstrates the potential for improving engine efficiency while simultaneously mitigating NOx and HC emissions through strategic fuel blending. In a study by Appavu et al. [13], it was asserted that the incorporation of a fuel additive in biodiesel, coupled with Exhaust Gas Recirculation (EGR), effectively reduced NOx formation. This reduction, though, came at the expense of compromises in terms of brake thermal efficiency and brake specific fuel consumption. This study emphasises the compromises made by NOx emission control strategies for engines powered by biodiesel. Oung et al. [14] in their study on the influence of 2-Ethylhexyl Nitrate (2EHN) combined with Exhaust Gas Recirculation (EGR) in Compression Ignition (CI) engines, it was observed that maintaining a constant combustion phase with the addition of 2EHN did not lead to an rise in NOx emissions. Further, this approach permits an extension of the dilution rate through EGR, effectively lowering NOx emissions without any adverse effect on combustion characteristics. Mei et al. [15] in their experimental investigation, studied the impact of a blend of diesel with 10 % DMC (dimethyl carbonate) for five different Center of Heat Release (COHR) modes. This study indicate a significant influence of COHR on combustion characteristics particularly, it is observed that carbon monoxide (CO) and hydrocarbons (HC) increases as COHR delayed. At the same time addition of DMC resulted in a notable reduction in particulate matter (PM) emissions, albeit with a slight increase in NOx. by Abdalla et al. [16], in their literature review work recommended that DMC (dimethyl carbonate) could serve as a valuable oxygenated additive for Compression Ignition (CI) engines and highlighted the DMC's unique characteristic of inducing pyrolysis, which can leads to the generation of carbon dioxide prior to carbon monoxide—an attribute not commonly observed in other oxygenated fuels. The study recommend, DMC's potential as an effective additive for lowering carbon monoxide emissions in CI engines. A comprehensive review of the pertinent literature on this study underscores a notable observation: individual additives do not possess the capacity to positively influence the thermal performance of an engine while concurrently achieving a reduction in exhaust emissions [17]. The literature reviewed above underscores a important imperative to identify and optimize a multi-additive fuel blend within diesel fuel that can effectively enhance engine thermal performance while simultaneously effecting reductions in NOx, smoke, and particulate matter (PM) emissions [18,19]. When exploring the blending of gasoline with JP-8 fuels in heavy-duty military vehicles equipped with 5 %

exhaust gas recirculation (EGR), researchers observed a reduction in nitrogen oxides (NOx) and nanoparticle emissions, albeit with a minor decrease in performance. In a similar context, testing the same vehicle with various biodiesel fuels, such as Algae, Karanja, and Jatropha oil, along with CeO2 as a fuel additive, yielded slightly diminished engine power output but a notable reduction in both NOx and nanoparticle emissions when compared to baseline diesel fuel. These results highlight the potential for achieving improved emission characteristics, albeit with a marginal trade-off in engine performance [20–24]. In a study conducted by Vishal Kumbhar and colleagues, a statistical approach involving multiple linear regression analysis (MLR) was employed to establish mathematical models aimed at predicting specific properties based on the fatty acid composition (FAC) of various biodiesel samples. Notably, the models created for cetane number and viscosity demonstrated a high degree of success in predicting values that closely aligned with existing literature data. However, it's important to note that the models developed for kinematic viscosity and heating value exhibited limited accuracy in predicting the corresponding data points. This analysis underscores the varying degrees of predictability associated with different properties based on FAC composition in biodiesel samples [25]. In the present study, three additives were meticulously selected based on their potential utility for crafting test samples of multi-additive fuel blends. These formulations were accomplished through the systematic application of the Taguchi Design of Experiments (DoE) methodology. Subsequently, the prepared multi-additive fuel blend samples underwent rigorous testing and optimization employing the Grey Relational Analysis (GRA) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) techniques. The optimized multi-additive fuel blend sample was then subjected to experimental testing, and its performance and emission attributes were compared with those of baseline diesel fuel using a Compression Ignition (CI) Engine test rig. The ensuing results were meticulously scrutinized to discern the improvements facilitated by the optimized multi-additive test sample in terms of both performance and emission characteristics. The optimized multi-additive fuel sample, developed through innovation, is engineered to reduce emissions, specifically targeting NOx formation, while maintaining engine performance. This sample can be readily and cost-effectively distributed to vehicle owners through a network of fuel dealers for use in diesel fuel.

2. Selection of multi-additives for fuel blend

As highlighted in the preceding section, individual additives often lack the capacity to comprehensively enhance fuel properties and all combustion parameters [26]. Prior research has explored the potential of multi-additive fuel blends to overcome this limitation, but achieving optimal results necessitates a thorough investigation and optimization of the blending process [15,16]. In the current study, a novel multi-additive fuel blend was identified and formulated, comprising three distinct classes of additives: dimethyl carbonate as an oxygenate, 2-ethylhexyl nitrate as a cetane improver, and ethyl acetate (EA) serving as a fuel stabilizer [16,27]. To streamline the experimentation and data collection processes, the Taguchi method of experimental design (DoE) was employed to determine the correct and sufficient combinations of additives for sample preparation. The range of additive proportions was thoughtfully chosen to ensure that the minimum value would have a minimal but noticeable effect on combustion, while the highest blend proportion was selected to maintain fuel properties within acceptable limits and prevent any adverse changes. These ranges were subsequently divided into four parts to strike a balance – avoiding excessively small blend proportions that might not yield noticeable effects while also preventing overly large proportions that could bypass the significant blending levels for fuel optimization. Given that there are three key design factors (additives), each with four concentration levels, the Taguchi Design of Experiments (DoE) method recommended the use of an L16 array. This implies that sixteen unique additive combinations were considered for preparing test samples, as delineated in Table 1. The numerical values assigned to the additives in Table 1 represent the design levels within the Taguchi DoE framework, signifying the percentage concentration of additives mixed with diesel fuel on a volume basis for each experimental trial [17–20].

To facilitate experimentation and gather data pertaining to engine performance and emission parameters, sixteen distinct test samples were formulated based on the mixing configuration outlined in Table 1. Subsequently, the resulting dataset was harnessed for the optimization process, aimed at enhancing both emission levels and engine performance. Analytical formulas were applied to

Table 1
Composition of multi-additive fuel blend sample using Taguchi L16 array.

Sample no.	Sample used	Composition of Sample (v/vs. v)
1	D4EH2E1	DMC 4 %, 2EHN 2 %, Ethyle acetate 1 %
2	D4EH4E2	DMC 4 %, 2EHN 4 %, Ethyle Acetate 2 %
3	D4EH6E3	DMC 4 %, 2EHN 6 %, Ethyle Acetate 3 %
4	D4EH8E4	DMC 4 %, 2EHN 8 %, Ethyle Acetate 4 %
5	D8EH2E2	DMC 8 %, 2EHN 2 %, Ethyle Acetate 2 %
6	D8EH4E1	DMC 8 %, 2EHN 4 %, Ethyle Acetate 1 %
7	D8EH6E4	DMC 8 %, 2EHN 6 %, Ethyle Acetate 4 %
8	D8EH8E3	DMC 8 %, 2EHN 8 %, Ethyle Acetate 3 %
9	D12EH2E3	DMC 12 %, 2EHN 2 %, Ethyle Acetate 3 %
10	D12EH4E4	DMC 12 %, 2EHN 4 %, Ethyle Acetate 4 %
11	D12EH6E1	DMC 12 %, 2EHN 6 %, Ethyle Acetate 1 %
12	D12EH8E2	DMC 12 %, 2EHN 8 %, Ethyle Acetate 2 %
13	D16EH2E4	DMC 16 %, 2EHN 2 %, Ethyle Acetate 4 %
14	D16EH4E3	DMC 16 %, 2EHN 4 %, Ethyle Acetate 3 %
15	D16EH6E2	DMC 16 %, 2EHN 6 %, Ethyle Acetate 2 %
16	D16EH8E1	DMC 16 %, 2EHN 8 %, Ethyle Acetate 1 %

ascertain crucial properties of these test samples. For instance, chemical balancing and molar mass calculations were employed to determine the Air-Fuel (A/F) ratio for each test sample. Additionally, mass and energy balancing techniques were utilized to compute and document the density and heating value of the samples. These calculated properties are comprehensively presented in Table 2 for reference and further analysis.

3. Experimental procedure

Within the existing literature, a plethora of test cycles have been proposed and recommended for experimental testing of Compression Ignition (CI) engines. These include well-established cycles such as the European Stationary Cycle (ESC), the European Transient Cycle (ETC), and the Constant Speed Variable Load Cycle, among others. These test cycles serve as essential tools for assessing and evaluating the performance and emissions characteristics of CI engines in a controlled and systematic manner [28]. In this study, the constant speed variable load cycle methodology is chosen and applied due to its practical suitability and alignment with the research objectives. This approach is deemed most feasible for the current research endeavour, facilitating an in-depth exploration of the impact of various multi-additive fuel blends, when compared to baseline diesel fuel, on engine performance, encompassing thermal characteristics and emissions. Importantly, this methodology enables the examination of these effects under diverse load conditions characteristic of CI engines [29–31]. The experimentation work for this study was conducted at a test facility provided by Apex Innovation Pvt. Ltd., India. The actual test setup is depicted in Fig. 1. The test rig employed for this study is fully computerized, offering the capability to manipulate various engine operating parameters such as compression ratio, fuel injection timing, fuel injection pressure, and exhaust gas recirculation, among others. This sophisticated setup allows for the comprehensive investigation of the effects of both conventional and non-conventional fuels. A total of sixteen test samples, detailed in Table 1 were subjected to testing using the engine test facility. These experiments were conducted at a constant speed of 1500 rpm, encompassing a wide spectrum of load conditions, ranging from the engine's idle load condition to an overload condition at 125 % of the rated power at compression ratio of 18. The experimental outcomes, including data pertaining to Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), NOx emissions, and smoke levels, were meticulously recorded and analysed. Further technical specifications of the experimental setup are documented in Table 3 for reference.

4. Taguchi-Grey Relational Analysis (GRA) DoE

The challenge of conducting trials and experiments at different load conditions for various fuel test samples necessitates the transformation of this multi-response problem into a single response objective. To achieve this, the Grey Relational Analysis (GRA) method is employed. Initially, the Grey Relational Coefficient for all response parameters, encompassing both performance and emission metrics, is computed across the different load scenarios. These coefficients are subsequently transformed into Grey Relational Grade (GRG) values for all load conditions, employing a weighted approach. Subsequently, these GRG values serve as the response parameters within the Taguchi analysis framework, facilitating the generation of Signal-Noise (S/N) plots for the designated design elements. S/N plots play a pivotal role in discerning the impact of variations in design factor levels on the selected response variables. To construct these plots, a 'Lower is Better' approach is adopted for responses that require reduction, while a 'Higher is Better' approach is employed for response variables that demand improvement. This methodological approach allows for the creation of S/N plots for a diverse array of selected design elements, enhancing our understanding of their influence on the response variables [32,33].

Fig. 2 serves as a representation of the influence of altering the levels of individual design factors on the response, employing a Signal-Noise ratio as a metric. This ratio enables a comparison of the desirability of the signal level against the background noise level, shedding light on the significance of these factors in shaping the responses of interest, including NOx, smoke, BSFC, and others. It becomes evident from the Signal-Noise (S/N) plot in Fig. 2a that dimethyl carbonate (DMC) exerts a substantial influence on all additives, manifesting a steep incline across the board. This steep incline signifies that any alteration in the levels of DMC within the

Table 2
Physio-chemical properties by analytical method.

Sample no.	Density (kg/m3)	A/F ratio	Heating value (kJ/Kg)
1	0.8382	14.25	41729.46
2	0.8396	14.15	41065.34
3	0.8411	14.06	40422.16
4	0.8424	13.97	39798.93
5	0.8428	13.98	40898.91
6	0.8437	13.95	40668.69
7	0.8455	13.81	39653.74
8	0.8463	13.78	39437.44
9	0.8472	13.73	40115.10
10	0.8485	13.65	39512.21
11	0.8489	13.68	39678.69
12	0.8501	13.60	39088.90
13	0.8514	13.50	39374.20
14	0.8522	13.47	39164.76
15	0.8530	13.45	38957.58
16	0.8538	13.43	38752.62

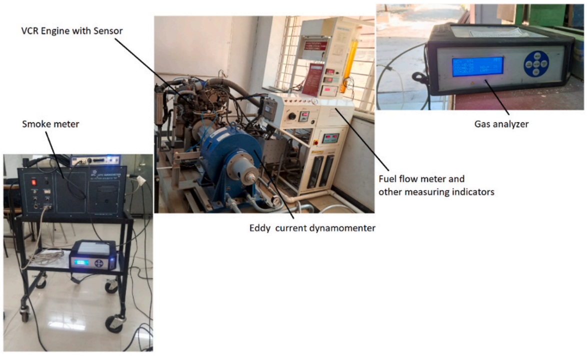
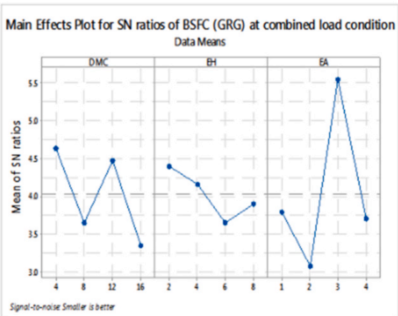


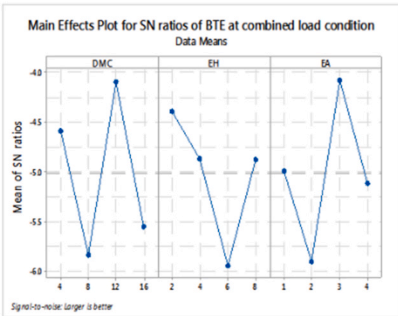
Fig. 1. Experimental test setup.

Table 3
Experimental test setup technical data.

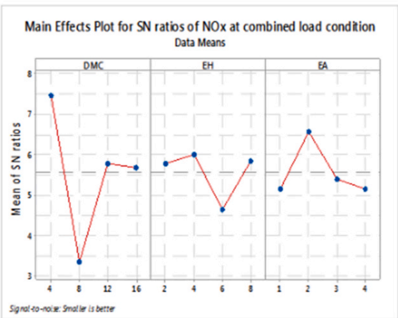
Engine Make and model	Make Kirloskar 240,
Engine Specification	Single cylinder, Multi-fuel, VCR [12–18], 4 stroke, DI, water cooled, 3.5 kW @ 1500 rpm,
Dynamo meter	Eddy current and water cooled
Pressure	Piezo Sensors, (0–350) bar, ± 1 %
Load Cell	Strain Gauge, (0–50) kg, ± 0.25 % F.S.
Temperature	RTD, PT 100, (−50 to 400)°C, Thermocouple K type, (0–360)°C, ± 0.5 %
Fuel Flow transmitter	Differential pressure Trans., (0–240) mm WC, ± 0.1 %
Crank angle Sensor	Resol. 1°, Speed 5500 rpm with TDC pulse.
RPM Indicator	PNP Type, (4.00–9999) RPM, ± 0.05 % F.S.
Data acquisition device	NI USB-6210, 16-bit, 250 kS/s.
Gas Analyzer	AVL DIGI GAS 444
Smoke Meter	AVL 437 Smoke Meter



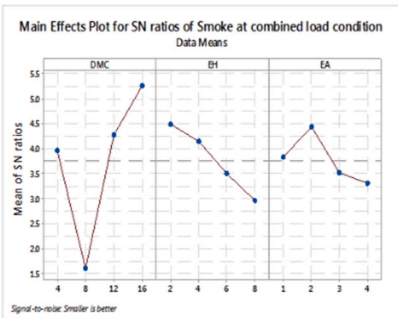
(a) S/N Plot for BSFC



(b) S/N Plot for BTE



(c) S/N Plot for NOx emission



(d) S/N Plot for Smoke

Fig. 2. S/N plots for various response parameters: (a) BSFC, (b) BTE, (c) NOx emission, (d) smoke.

fuel blend results in a noteworthy change in the S/N ratio, indicative of its profound impact on responses. Furthermore, the S/N plot for Brake Thermal Efficiency (BTE) in Fig. 2b underscores the dominance of DMC, with ethyl acetate following as the next most significant factor. Likewise, the S/N plot for NOx in Fig. 2c highlights the pre-eminence of DMC, with the remaining additives exhibiting negligible effects when their levels are adjusted. A similar trend is observed in the case of smoke, as depicted in Fig. 2d. Collectively, these findings underscore the pivotal role of DMC as the primary component within a multi-additive fuel blend, asserting its substantial influence on engine performance and emissions. Any modifications to its composition are poised to engender significant repercussions across multiple response parameters.

5. Interaction study on effect of multi-additive fuel blend vs. performance and emission parameters

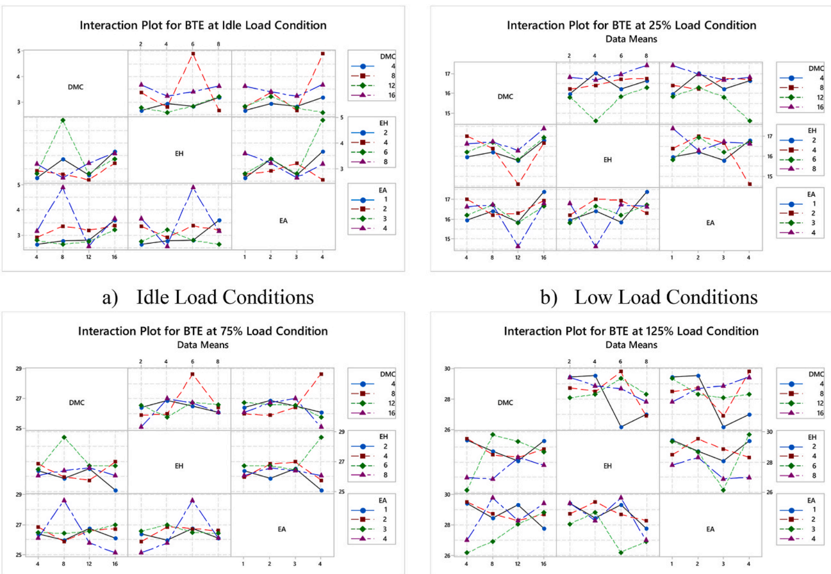
Interaction plots serve as visual tools for elucidating how the value of a second categorical factor modulates the relationship between one categorical factor and a continuous response. In these plots, nonparallel lines indicate the presence of an interaction, while parallel lines signify the absence of such interaction. The extent of interaction strength corresponds to the degree of non-parallelism observed between the lines. In the context of this study, we have assessed and graphically presented the interaction strength between the three selected additives across diverse performance and emission parameters under varying load conditions. This analysis aims to provide a comprehensive understanding of how these additives interact and influence the outcomes of interest [34].

5.1. Interaction study for BTE

Fig. 3 presents interaction plots that elucidate the influence of various additives on Brake Thermal Efficiency (BTE) across various load conditions. In Fig. 3a, we observe an interaction plot depicting different additive levels' impact on BTE during idle load conditions. Notably, the DMC-EHN line exhibits pronounced nonlinearity, signifying their strong interaction effect resulting in the highest BTE. Specifically, the most significant interaction occurs at level '8′ of DMC and level '6′ of EHN, a pattern consistent across all load conditions. Similarly, the interaction between DMC and EA yields its most substantial impact on BTE during the highest load conditions, notably when DMC operates at level '8′ and interacts with EA at level '4'. This interaction pattern persists consistently across all remaining load conditions, as evidenced by the plot lines' relatively flat trajectory. Furthermore, it becomes apparent that as we progress to higher load conditions, the effect of interaction between additive concentrations on BTE becomes increasingly sensitive. At medium load conditions, the interaction effect of DMC is prominently observed with EHN at level '4′ and EA at level '4' (Fig. 3b). However, at higher and overload conditions, this interaction dynamic shifts to EHN at level '6′ and EA at level '4' (Fig. 3c and d), further highlighting the evolving nature of these interactions with varying load conditions.

5.2. Interaction study for BSFC

Fig. 4 exhibits interaction plots elucidating the influence of various additives on Brake Specific Fuel Consumption (BSFC) across a spectrum of load conditions. Notably, these interaction plots manifest pronounced nonlinearity, with the most conspicuous effects occurring during idle and high load conditions, indicative of their substantial impact on BSFC. Conversely, the interaction effects appear relatively weaker for low load and overload conditions, as evidenced by the relatively flatter trajectory of the plot lines. Lowest BSFC levels are observed under low load conditions, primarily attributed to the pronounced interaction between DMC at level '8′ and



a) Idle Load Conditions b) Low Load Conditions

c) High Load Condition d) Overload Condition

Fig. 3. Interaction plot for BTE at different load conditions: (a) idle load, (b) low load, (c) high load, (d) overload.

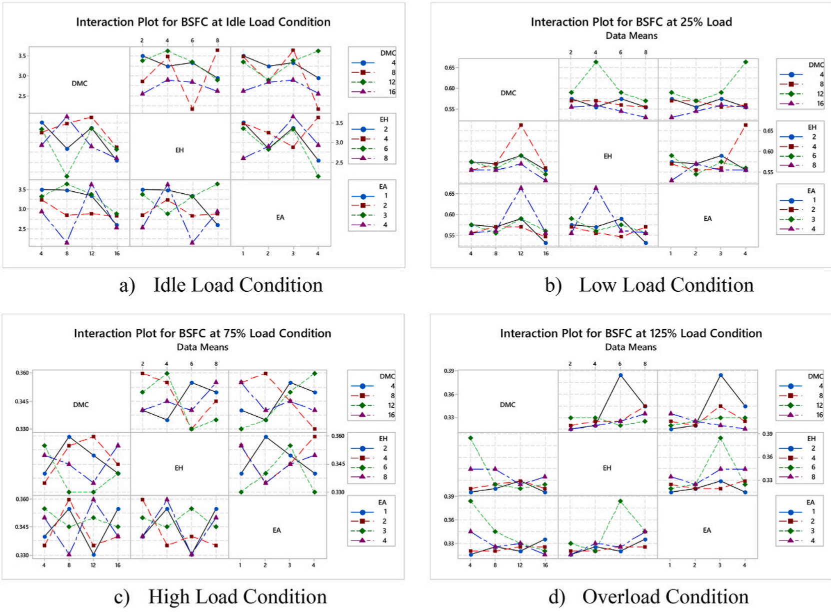


Fig. 4. Interaction plots for BSFC at different load conditions: (a) idle load, (b) low load, (c) high load, (d) overload.

EHN at level '6'. However, as load conditions escalate, the most significant interaction arises with a higher level of DMC at level '12'. Notably, the interaction between DMC and EA attains its zenith at level '4′ of EA when DMC operates at level '8′ across most load conditions (Fig. 4 a, b, c). This dynamic shifts to DMC operating at level '16,' as depicted in Fig. 4d. One plausible explanation for this shift could be the need for a richer fuel blend during overload conditions, necessitating a greater oxygen supply for combustion—an aspect effectively provided by DMC.

5.3. *Interaction study for NOx emissions*

Fig. 5 presents interaction plots of the effects of various additives on NOx emissions at several load conditions. The interaction plot line between DMC and EHN is highly linear for most load conditions, showing a weaker interaction effect on NOx. The lowest NOx formation is observed for the interaction of level '8' DMC with level '6' EHN and level 4 EA with level '8' DMC. The same behaviour is observed for most load conditions (Fig. 5 b-d), except at idle load (Fig. 5 a), where minimum NOx formation is represented by the

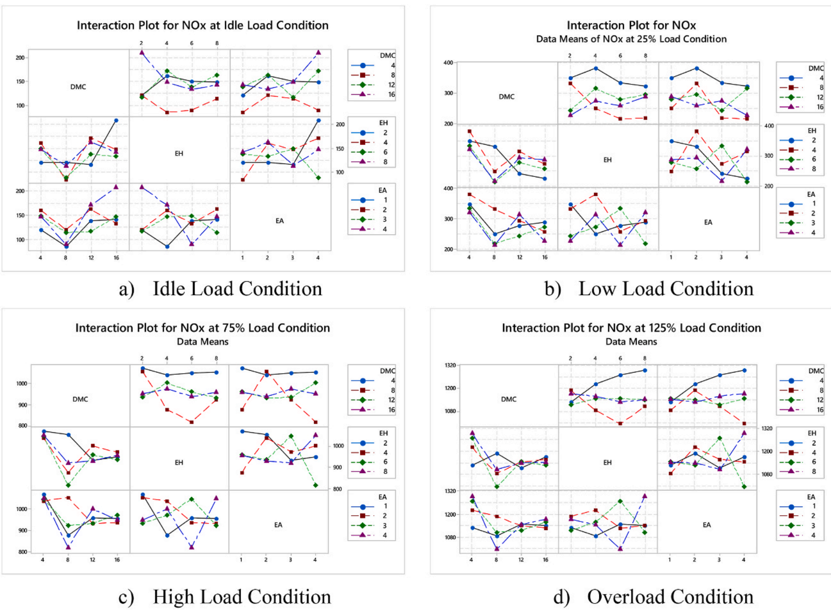


Fig. 5. Interaction plots for NOx at different load conditions: (a) idle load, (b) low load, (c) high load, (d) overload.

interaction of level 8 DMC with level '4' EN. The interaction effect between EA and EHN on NOx is visible from the non-parallelism of plot lines. Minimum NOx formation for the interaction of EA and EHN is observed at levels '6' of EHN and '4' of EA for most load conditions. In Fig. 5, the minimum NOx is observed for the interaction of DMC at level '8', EHN at level '6', and EA at level '4' for most load conditions.

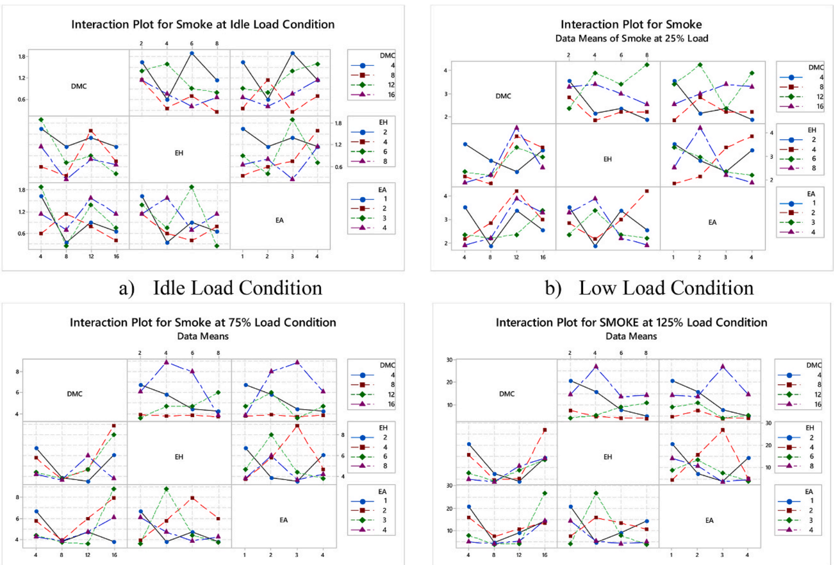
5.4. *Interaction study for engine exhaust (smoke)*

Fig. 6 presents an interaction plot of different additives for smoke emission for different load conditions. These plots indicate how any change of percentage of additives in composition affects the response factor i.e smoke. Here, a more inclined line of any additive indicates a significant effect on smoke formation. Note that this is a behavioural plot and based on experimental results of additives. Smoke has the unit of % opacity but here, since it is a behavioural representation of effect of additive on smoke, it is not included. The nonlinearity of the interaction plot line between DMC, EHN, and EA shows their interaction effect on smoke formation. The interaction line between DMC and EHN is flat, showing weaker strength, so changing the level of DMC and EHN in the blend will have little effect on smoke formation. The minimum smoke formation happens for the interaction of DMC at level '8' with EH at level 4, which changes to level '6' of EH at overload conditions (Fig. 6 d). The interaction plot lines between DMC and EA are highly nonlinear, indicating a strong effect of changes in blend proportion on smoke formation. A minimum smoke level is observed for the interaction of DMC at level '8' with EA at level '4 'for all load conditions (Fig. 6 b, c) except idle load condition (Fig. 6 a) where it changes to EA at level '3'. The interaction plot between EA and EHN is much chewed, indicating the strongest interaction strength between them. The slightest change in level will greatly impact the smoke formation and needs to be controlled carefully in blending. The change in EA blending can suddenly trigger smoke formation due to its effect on combustion.

6. Regression analysis

This methodology establishes a mathematical model that correlates the components of a multi-additive fuel blend with their impact on engine response parameters, gauged through a grey relational grade computed via the GRA method. In the realm of regression analysis, researchers often have the latitude to choose a confidence level, which can range from 90 % to 99 %. A confidence level of 90 % implies a scenario where more data points deviate from the established trend, while a 99 % confidence level signifies a stricter adherence to the trend. In the context of this specific problem, the presence of various external factors influencing engine performance renders a 99 % confidence level impractical, while a 90 % confidence level offers a more generalized trend. Therefore, a prudent choice has been made to employ a two-sided interval with a confidence level of 95 %, signifying that 95 % of the samples within the population will align with the confidence interval. Subsequently, this model is employed to conduct an analysis of variance (ANOVA) employing the sum of squares, which serves as a measure of variation or deviation from the mean. This ANOVA analysis adopts a type II test without any data transformation [34]. This condition is input to statistical software, and then an ANOVA is performed using statistical software. The mathematical relation achieved between engine response parameters, viz. BSFC, BTE, NOx, smoke, and fuel additives, are represented as follows:

$$\text{BSFC} = 0.585 + 0.00525\text{DMC} + 0.0067\ \text{EH} - 0.0131\text{EA} \quad (1)$$



a) Idle Load Condition b) Low Load Condition

c) High Load Condition d) Overload Condition

Fig. 6. Interaction plots for smoke at different load conditions: (a) idle load, (b) low load, (c) high load, (d) overload.

$$BTE = 0.592 - 0.00216DMC - 0.0082\,EH + 0.0163EA \quad (2)$$

$$NOx = 0.449 + 0.00240DMC + 0.0057\,EH + 0.0165EA \quad (3)$$

$$Smoke = 0.645 - 0.01258DMC + 0.0198\,EH + 0.0185EA \quad (4)$$

In above equation, DMC, EH and EA denote % concentration of respectively dimethyl carbonate, 2EHN and ethyl acetate in the diesel fuel sample on a volume basis.

7. Technique for Order of Preference by similarity to ideal solution optimization (TOPSIS)

TOPSIS stands as a robust and adept multi-criteria decision-making technique, well-suited for resolving intricate decision-making challenges. It finds its applicability in domains where a multitude of criteria, alternatives, and their interdependencies hold significant sway, exerting substantial influence on the overall process. The TOPSIS technique boasts computational efficiency, rendering it an accessible means to evaluate and select the optimal set of parameters from a predefined array of alternatives [19,35]. A widely recognized technique for ranking alternatives in order of preference, TOPSIS places paramount emphasis on positioning the favoured solution as closely as possible to the ideal positive solution while distancing it from the ideal negative solution. In essence, the ideal solution aims to maximize the criteria that denote benefits while simultaneously minimizing those representing the least desirable attributes. To put it differently, the ideal solution encompasses the highest values of the favourable criteria, while the negative ideal solution encompasses the lowest values of the undesirable criteria. An inherent advantage of this approach lies in its capacity to yield robust rankings for alternatives when dealing with absolute data for each indicator. Some scholars have also advocated the integration of this method with other approaches, positing that such amalgamations can offer more efficient and adaptable problem-solving solutions [11,36–39].

7.1. Decision matrix

The identification of a decision matrix containing 'n' attributes and 'm' alternatives is the first step in TOPSIS optimization process, as represented by the matrix equation [5].

$$|D_m| = \begin{bmatrix} X_{11} & X_{12} & .. & X_{1n} \\ X_{21} & . & . & . \\ . & . & . & . \\ X_{m1} & . & . & X_{mn} \end{bmatrix} \quad (5)$$

7.2. Normalization matrix of response

Prior to commencing the optimization process, it is imperative to normalize all response parameters. Normalization is a vital step as it standardizes the response parameters, bringing them to a uniform scale ranging from '0′ to '1'. To address the disparate dimensions of various criteria, two commonly employed normalization methods are linear normalization and vector normalization. Typically, the normalization procedure is carried out on a column-by-column basis, enabling a meaningful comparison of alternatives based on each attribute. Consequently, the normalized values for each attribute fall within the positive range of 0–1.The following equation Eqn 6 is used for linear normalization:

$$x_i = \frac{y_{i(k)}}{\sqrt{\sum y_{i,k}^2}} \quad (6)$$

Response parameters are converted into normalized response parameters, and sample calculations results for the 50 % load condition are tabulated in Table 4.

Table 4
Normalization of response matrix.

Sample No	BSFC	NOx	Smoke	BTE
1	0.251	0.244	0.314	0.251
2	0.247	0.264	0.270	0.257
3	0.255	0.275	0.205	0.243
4	0.247	0.280	0.198	0.248
5	0.247	0.257	0.182	0.249
6	0.247	0.235	0.175	0.250
7	0.259	0.219	0.177	0.263
8	0.247	0.239	0.172	0.250
9	0.259	0.241	0.165	0.239
10	0.247	0.248	0.219	0.250
11	0.247	0.248	0.219	0.251
12	0.247	0.247	0.279	0.251
13	0.247	0.254	0.284	0.251
14	0.247	0.251	0.414	0.251
15	0.247	0.244	0.372	0.250
16	0.255	0.247	0.177	0.244

7.3. Weighted normalized matrix of response

First, each repository must assign weightage to each response depending on its priority in the problem statement. Each response value is multiplied with weightage based on its significance:

$$Y_i(k) = y_i(k) * w_k \tag{7}$$

where $Y_i(k)$ is weightage response value of kth response for ith run number and w_k is importance weightage value for kth response.

In the context of the current study and in alignment with the problem statement's objectives and requirements, weight values (wk) have been systematically assigned to different performance parameters. Specifically, NOx has been assigned a weight of '0.4,' signifying a 40 % importance in the optimization process, while smoke has been assigned '0.3,' indicating a 30 % importance. Furthermore, Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) have been assigned '0.15′ each, collectively representing 15 % importance during the optimization process. These weightages (w_k) serve as a quantifiable representation of the significance attributed to each design parameter within the optimization framework. By employing these weightage values in conjunction with the respective normalized responses, we can derive a weighted normalized response. This weighted normalized response encapsulates the weighted relative closeness coefficient for each response observed in each experimental run. The specific responses corresponding to these weightages are comprehensively documented in Table 5.

7.4. Selection of ideal best and ideal worst

If it is required to minimize the response, the minimum value will be considered the ideal best, while the maximum value will be considered the ideal worst, as shown Table 6.

Here, Ideal Best V^+ = Minimum of Normalized Response for all runs (for responses to minimize) and Ideal Worst V^- = Maximum of Normalized Response for all runs (for responses to maximize).

7.5. Separation of each response from ideal best and ideal worst

The departure of each alternative from the 'positive ideal' answer is calculated by

$$S^+ = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^+ \right)^2} \tag{8}$$

The departure of each alternative from the 'negative ideal' answer is calculated by

$$S^- = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^- \right)^2} \tag{9}$$

Using equations (8) and (9), separation values from ideal best S^+ and ideal worst S^- is calculated for each response parameter and tabulated as shown in Table 7. If it is required to minimize the response, the minimum value will be considered the ideal best, while the maximum value will be considered the ideal worst.

7.6. Ranking of experimental sequence

The relative nearness of a particular alternative to the model solution is calculated using Equation Eqn 10 and expressed as P_i. That is,

Table 5
Weighted normalized response matrix.

Sample No	BSFC	NOx	Smoke	BTE
1	0.038	0.098	0.094	0.038
2	0.037	0.106	0.081	0.039
3	0.038	0.110	0.061	0.037
4	0.037	0.112	0.059	0.037
5	0.037	0.103	0.054	0.037
6	0.037	0.094	0.052	0.038
7	0.039	0.088	0.053	0.039
8	0.037	0.096	0.052	0.037
9	0.039	0.096	0.050	0.036
10	0.037	0.099	0.066	0.038
11	0.037	0.099	0.066	0.038
12	0.037	0.099	0.084	0.038
13	0.037	0.102	0.085	0.038
14	0.037	0.100	0.124	0.038
15	0.037	0.098	0.112	0.038
16	0.038	0.099	0.053	0.037

Table 6
Selection of ideal best and ideal worst.

	BSFC	NOx	Smoke	BTE
Ideal Best V+	0.037	0.088	0.050	0.039
Ideal Worst V-	0.039	0.112	0.094	0.036

Table 7
Separation value of responses from Ideal Best and Ideal Worst.

Run No	BSFC	NOx	Smoke	BTE	Ideal Best S^+	Ideal Worst S^-
1	0.038	0.098	0.094	0.038	0.046	0.091
2	0.037	0.106	0.081	0.039	0.036	0.099
3	0.038	0.110	0.061	0.037	0.025	0.111
4	0.037	0.112	0.059	0.037	0.026	0.113
5	0.037	0.103	0.054	0.037	0.016	0.109
6	0.037	0.094	0.052	0.038	0.007	0.105
7	0.039	0.088	0.053	0.039	0.004	0.101
8	0.037	0.096	0.052	0.037	0.008	0.107
9	0.039	0.096	0.050	0.036	0.010	0.109
10	0.037	0.099	0.066	0.038	0.020	0.101
11	0.037	0.099	0.066	0.038	0.020	0.102
12	0.037	0.099	0.084	0.038	0.036	0.094
13	0.037	0.102	0.085	0.038	0.038	0.096
14	0.037	0.100	0.124	0.038	0.076	0.092
15	0.037	0.098	0.112	0.038	0.063	0.089
16	0.038	0.099	0.053	0.037	0.012	0.108

$$P_i = \frac{S^-}{(S^- + S^+)} \tag{10}$$

The P_i values were ranked in descending order to find the alternatives with the most favoured and least favoured solutions, as listed in Table 8.

So from Table 8 and it is observed that run No. '7' achieved the rank '1," which represent the most favourable result, hence the multi-additive fuel blend used for run number 7 will be best suited for optimizing performance and emissions. The D8EH6E4 used in test run number '7′ is the most suitable composition for the proposed optimized multi-additive fuel blend based on the TOPSIS optimization process. The test sample code D8EH6E4 represent 8 % of DMC, 6 % of 2EHN and 4 % of ethyl acetate for 1 L of diesel fuel sample.

8. Comparison of performance and emission results of optimized multi-additive fuel blend with baseline diesel fuel

In this section, performance and emission characteristics of an engine by the blend of diesel fuel with optimized multi-additive fuel blend D8EH6E4 is compared with that by baseline diesel fuel and a discussion on possible reasons is performed.

8.1. Effect of multi-additive fuel blend on engine performance: brake thermal efficiency vs. load

Brake thermal efficiency (BTE) is an indicator of engine health and economy. In Fig. 7, brake thermal efficiency for both baseline diesel fuel and diesel fuel with additive is plotted against load condition to study the effect of the proposed multi-additive fuel blend on engine performance. In Figure 7, the Brake Thermal Efficiency (BTE) performance of an engine using the proposed multi-additive fuel blend test sample is highlighted. At an idle load of 0.1 kW, the BTE is recorded at 4.9 %, increasing to 16.7 % at 0.9 kW, further to 24.5 % at a half-load condition of 1.8 kW, and reaching 28.7 % at 2.6 kW. At a full load condition of 3.5 kW, the BTE peaks at 30.6 %, and it remains at 29.8 % at a 125 % load condition of 4.4 kW. Comparing this BTE with that of the baseline diesel fuel reveals significant improvements. Particularly at idle load, there is a notable enhancement of 24.8 %. The improvement is less pronounced at low load conditions, ranging from 0.9 kW to 1.8 kW, with a modest increase of 1 %. However, for load conditions ranging from 2.6 kW to 4.4 kW, there is a consistent average improvement of 7.2 % in BTE. Several factors contribute to this enhanced performance. Increased brake power, resulting from extended ignition delay, leads to a rapid energy release [2]. The presence of the additive (2EHN) effectively reduces heat loss, while the improved homogeneity of the air-fuel mixture results in faster, premixed combustion. Moreover, the test mixture boasts a 1.62 % higher density compared to the baseline fuel, resulting in a greater mass fraction of carbon fuel within the air-fuel mixture. This increased carbon fraction releases more energy during combustion. However, it's important to note that at low load conditions, specifically at a brake power of 0.9 kW and 1.8 kW, there is no substantial improvement in BTE when compared to the baseline fuel. This is attributed to the lean mixture and the limited impact of additional oxygen in the combustion process. Conversely, at high load conditions, ranging from 75 % to 125 % of rated brake power (2.6 kW–4.4 kW), BTE exhibits a significant improvement of 6–7%. This improvement can be attributed to a higher proportion of fuel being burned in the premixed mode, resulting in more efficient combustion and greater energy release [40,41].

Table 8
Relative closeness and ranking of sequence for idle load condition.

Run No.	Performance Score	Rank Order
1	0.665	14
2	0.732	11
3	0.814	9
4	0.810	10
5	0.872	6
6	0.938	2
7	0.963	1
8	0.927	3
9	0.919	4
10	0.837	7
11	0.837	8
12	0.724	12
13	0.714	13
14	0.547	16
15	0.586	15
16	0.900	5

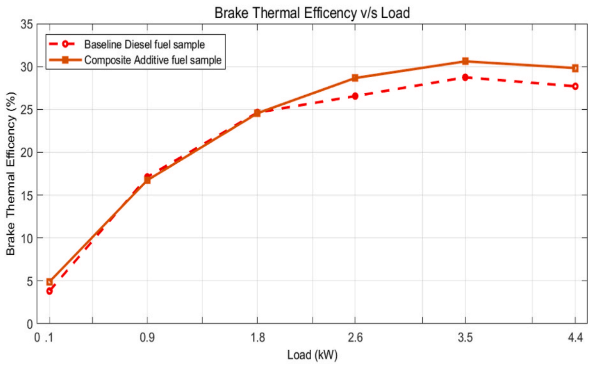


Fig. 7. Brake thermal efficiency vs. load (brake power).

8.2. *Effect of multi-additive fuel blend on engine performance: brake specific fuel consumption (BSFC) vs. load*

From Fig. 8, the Brake Specific Fuel Consumption (BSFC) for the multi-additive fuel blend sample exhibits various values under different load conditions, as follows: 2.15 kg/kWh at an idle load of 0.1 kW, 0.56 kg/kWh at a load of 0.9 kW, 0.38 kg/kWh at 1.8 kW, 0.33 kg/kWh at 2.6 kW, 0.335 kg/kWh at 3.5 kW, and 0.325 kg/kWh at an overload condition of 4.4 kW. A comparison of these BSFC values with those of the baseline diesel fuel reveals a marginal decrease at idle load conditions (0.1 kW), with limited or no improvement observed for the remaining load conditions. This decline in BSFC during idle conditions can be attributed to improvements in both the premixed and diffusive combustion phases, facilitated by extended ignition delay and oxygen enrichment [2]. Additionally, the presence of the 2EHN additive may enhances combustion by aligning the start of combustion and in-cylinder peak pressure closer to top-dead center. This improvement in ignition quality compensates for the lower heating value of the fuel blend, thus maintaining BSFC levels similar to baseline diesel at high load conditions. Furthermore, increased density of the fuel blend from 0.8320 kg/m^3 to 0.8455 kg/m^3 may results in reduced volumetric fuel consumption, further contributing to the maintenance of BSFC

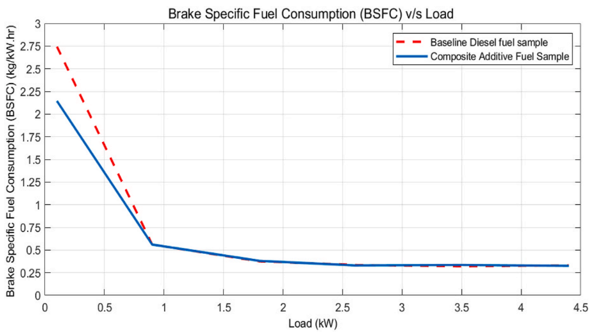


Fig. 8. Brake thermal fuel consumption (BSFC) vs. load (brake power).

close to that of baseline diesel. This effect is driven by the relatively lower heating value of the optimized fuel blend, which stands at 94 % of that of baseline diesel due to the inclusion of fuel additives in the multi-additive fuel blend [40,42].

8.3. Effect of multi-additive fuel blend on engine emission: smoke formation vs. load

Smoke formation within the engine is monitored using a smoke meter, quantified in terms of opacity, and the results are presented in Fig. 9 across various load conditions. The smoke opacity for the multi-additive fuel blend sample exhibits the following values: 0.7 % at idle load (0.1 kW), 2.2 % at 0.9 kW, 3.4 % at 1.8 kW, 3.85 % at 2.6 kW, 5 % at full load, and 6.1 % at overload conditions (4.4 kW). Comparing this smoke opacity with that of an engine running on baseline diesel fuel reveals a significant increase, approximately 34 %, up to the half-load condition of 1.8 kW brake power. However, at higher load conditions, specifically beyond the half-load point of 2.6 kW, smoke formation in the proposed multi-additive fuel blend undergoes a substantial reduction of around 30 %, reaching a maximum reduction of 39 % at overload conditions (4.4 kW brake power). This observed decrease in smoke formation at higher loads may be attributed to the presence of additional oxygen in the richer mixture, which aids in mitigating localized rich hot spots responsible for incomplete combustion [43]. 2-EHN enhances ignition quality, ensuring a controlled and stable combustion process, resulting in more efficient and complete fuel combustion. Meanwhile, the presence of DMC, functioning as an oxygenate, further improves combustion by facilitating the complete oxidation of fuel [40,41]

8.4. Effect of multi-additive fuel blend on engine emission: NOx formation vs. load

Referring to Fig. 10, the formation of NOx in an engine utilizing the proposed multi-additive fuel blend exhibits varying levels: 116 ppm at an idle load of 0.1 kW, 214 ppm at a 0.9 kW load, 537 ppm at 1.8 kW, 819 ppm at 2.6 kW, 1015 ppm at full load (3.5 kW), and 1038 ppm under overload conditions. A comparison of these NOx formation values with those of an engine running on baseline diesel fuel reveals a reduction of 19.9 % at overload conditions (4.4 kW) and a substantial decrease of 41.2 % at idle load conditions (0.1 kW). This decrease in NOx formation persists across the remaining load conditions, ranging from 0.9 kW to 3.5 kW brake power, with a consistent reduction of approximately 31 %–33 %, as depicted in Fig. 10. Notably, it is observed that the reduction in NOx formation diminishes as the load increases from idle load conditions to 125 % load conditions, with reductions ranging from 54 % to 19.9 %.

As Fig. 10 illustrates, the escalation in NOx reduction at higher load conditions can be attributed to the elevated flame temperature resulting from increased load conditions. The formation of NOx is particularly critical when the burn gas temperature reaches its zenith, occurring between the onset of combustion and shortly after the peak pressure occurrence. Mixtures that ignite early in the combustion process hold significant importance because they undergo compression to higher temperatures, thus intensifying the rate of NO formation as the combustion progresses and cylinder pressure rises. The governing factor for the ignition process's evolution is the chemistry of the parent fuel, given that the temperature experiences rapid decline due to expansion and pool formation. This observation aligns with the hypothesis that 2-ethylhexyl nitrate (RO-NO2) undergoes uni-molecular decomposition early in the injection process, providing a reliable mechanism for OH production through the reaction involving H + NO2 + OH + NO. In the initial phases of the injection event, in the absence of the additive, no other dominant OH-generating reactions occur, and the formation of the radical pool is delayed [40,43]

9. Conclusions

This investigation yields several significant conclusions. The primary findings and corresponding conclusions are as follows:

- The outcome of this research culminates in the formulation of the multi-additive fuel blend sample denoted as D8EH6E4, comprising 8 % DMC, 6 % 2EHN, and 4 % ethyl acetate. This blend effectively controls NOx emissions across all load conditions while simultaneously mitigating smoke formation, particularly at higher loads. Furthermore, the proposed additive contributes to maintaining engine efficiency and Brake Specific Fuel Consumption (BSFC) at levels comparable to those of baseline diesel.
- The unique characteristics of this blend, such as higher latent heat vaporization and lower mean gas temperatures, facilitate combustion in a low-temperature environment. Consequently, NOx formation is significantly reduced, reaching a 54 % reduction at low load conditions and stabilizing at a 19.9 % reduction under engine overload conditions. The diminishing NOx reduction with increasing load can be attributed to the rising flame temperature accompanying higher loads.

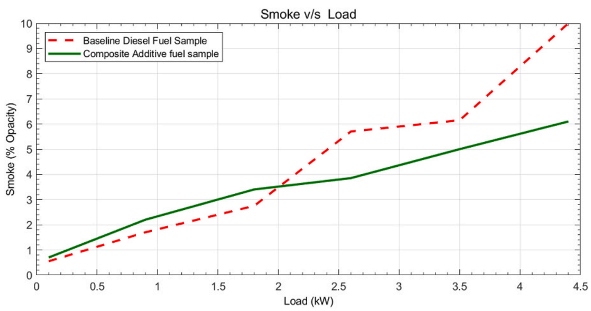


Fig. 9. Smoke vs. load (brake power).

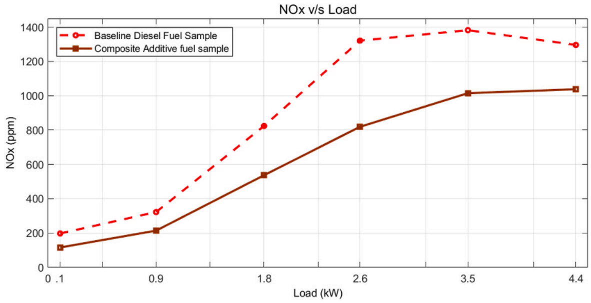


Fig. 10. NOx vs. load (brake power).

- Smoke formation initially increases with the test fuel sample due to its higher density and equivalence ratio. However, beyond 50 % load conditions, smoke emissions decline by approximately 30 %. This reduction is attributed to the presence of the DMC additive, which effectively controls the thermal cracking of constituents responsible for soot formation. Simultaneously, 2EHN maintains the cetane number of the mixture, enhancing ignition quality.
- While the test fuel samples exhibit limited improvement in BSFC at idle load conditions and no significant improvement at other load conditions, this can be attributed to the fuel sample's lower heating value and elevated local equivalence ratio. The presence of the 2EHN additive enhances combustion ignition quality, thereby preserving the BSFC of the fuel sample on par with baseline diesel.

Overall, the proposed multi-additive fuel blend exhibits no adverse effects on engine performance parameters or economy. This study can be extended to further experiments or tests involving an engine operating at a constant speed of 1500 rpm with the multi-additive fuel blend, both with and without Exhaust Gas Recirculation (EGR). This comparative analysis can provide insights for optimizing fuel injection pressure and timing for the multi-additive fuel blend. The novel multi-additive sample, named "D8EH6E4," has demonstrated substantial improvements from both performance and emissions perspectives. In addition to the optimization method used in this study, the sample was also subjected to another optimization method of AHP for confirmation and combustion characterizations, further confirming its positive outcomes. This novel sample can be easily and economically produced and made available through networks of oil manufacturers and resellers, allowing end-users to utilize it in a wide range of diesel engines. This application has the potential to effectively reduce emissions from diesel vehicles, contributing to a reduction in overall air pollution and making it a practical solution for environmental improvement.

Author statement

All authors have equal contribution.

Declaration of competing interest

We have no conflict of interest.

Data availability

Data will be made available on request.

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References

[1] M. Elkelawy, A.E. Kabeel, E.A. El Shenawy, H. Panchal, A. Elbanna, H.A.E. Bastawissi, et al., Experimental investigation on the influences of acetone organic compound additives into the diesel/biodiesel mixture in CI engine, Sustain. Energy Technol. Assessments 37 (2020), 100614, https://doi.org/10.1016/j.seta.2019.100614.
[2] T. Xuan, Z. Sun, A.I. EL-Seesy, Y. Mi, W. Zhong, Z. He, et al., An optical study on spray and combustion characteristics of ternary hydrogenated catalytic biodiesel/methanol/n-octanol blends; part I: spray morphology, ignition delay, and flame lift-off length, Fuel 289 (2021 Apr 1), 119762.
[3] T. Xuan, Z. Sun, A.I. EL-Seesy, Y. Mi, W. Zhong, Z. He, et al., An optical study on spray and combustion characteristics of ternary hydrogenated catalytic biodiesel/methanol/n-octanol blends; part II: liquid length and in-flame soot, Energy 227 (2021 Jul 15), 120543.
[4] M.A. Mujtaba, H. Muk Cho, H.H. Masjuki, M.A. Kalam, M. Farooq, M.E.M. Soudagar, et al., Effect of primary and secondary alcohols as oxygenated additives on the performance and emission characteristics of diesel engine, Energy Rep. 7 (2021 Nov 1) 1116–1124.
[5] H.M. Mahmudul, F.Y. Hagos, R. Mamat, A.A. Abdullah, Impact of oxygenated additives to diesel-biodiesel blends in the context of performance and emissions characteristics of a CI engine, in: IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, 2016.

[6] N. Palazzo, L. Zigan, F.J.T. Huber, S. Will, Impact of oxygenated additives on soot properties during diesel combustion, Energies 14 (1) (2021 Jan 1).
[7] A.I. EL-Seesy, M.S. Waly, Z. He, H.M. El-Batsh, A. Nasser, R.M. El-Zoheiry, Influence of quaternary combinations of biodiesel/methanol/n-octanol/diethyl ether from waste cooking oil on combustion, emission, and stability aspects of a diesel engine, Energy Convers. Manag. 240 (2021 Jul 15), 114268.
[8] A.I. EL-Seesy, M.S. Waly, Z. He, H.M. El-Batsh, A. Nasser, R.M. El-Zoheiry, Enhancement of the combustion and stability aspects of diesel-methanol-hydrous methanol blends utilizing n-octanol, diethyl ether, and nanoparticle additives, J. Clean. Prod. 371 (2022 Oct 15), 133673.
[9] R.M. EL-Zohairy, A.S. Attia, A.S. Huzayyin, A.I. EL-Seesy, Effect of diethyl ether addition to waste cooking oil biodiesel on the combustion and emission characteristics of a swirl-stabilized premixed flame, Energy Convers. Manag. 286 (2023 Jun 15), 117052.
[10] A.I. EL-Seesy, M.S. Waly, H.M. El-Batsh, R.M. El-Zoheiry, Enhancement of the waste cooking oil biodiesel usability in the diesel engine by using n-decanol, nitrogen-doped, and amino-functionalized multi-walled carbon nanotube, Energy Convers. Manag. 277 (2023 Feb 1), 116646.
[11] R. Jayabal, L. Thangavelu, S. Subramani, Combined effect of oxygenated additives, injection timing and EGR on combustion, performance and emission characteristics of a CRDi diesel engine powered by sapota biodiesel/diesel blends, Fuel 276 (2020), 118020 [Internet], https://www.sciencedirect.com/science/article/pii/S0016236120310164.
[12] C. Swaminathan, J. Sarangan, B.S. Michael, Investigation of performance and emission characteristics of IC engine using sunflower oil methyl ester as fuel with oxygenated additive and EGR, Biofuels 10 (5) (2019) 583–589, https://doi.org/10.1080/17597269.2016.1221300 [Internet].
[13] P. Appavu, V.R. Madhavan, H. Venu, A. Mariadoss, Effect of fuel additives and exhaust gas recirculation in biodiesel fuelled CI engine: a review [Internet], Int. J. Ambient Energy 42 (15) (2021), https://doi.org/10.1080/01430750.2019.1614995, 1803–9.
[14] R. Oung, A.-G. Morin, F. Foucher, Study on the effects on diesel LTC combustion of 2-EHN as cetane improver, in: WCX SAE World Congress Experience, SAE, 2020.
[15] D. Mei, S. Yue, X. Zhao, K. Hielscher, R. Baar, Effects of center of heat release on combustion and emissions in a PCCI diesel engine fuelled by DMC-diesel blend, Appl. Therm. Eng. 114 (2017) 969–976 [Internet], https://www.sciencedirect.com/science/article/pii/S1359431116341333.
[16] A. Abdalla, D. Liu, Dimethyl carbonate as a promising oxygenated fuel for combustion: a review, Energies 11 (6) (2018 Jun 14) 1552.
[17] M. Elkelawy, E.A. El Shenawy, H.A.-E. Bastawissi, M.M. Shams, H. Panchal, A comprehensive review on the effects of diesel/biofuel blends with nanofluid additives on compression ignition engine by response surface methodologyEnergy, Convers. Manag. X (2022), 10017718.
[18] A.R. Patil, R.S. Bindu, A.M. Pawar, N.D. Pagar, B.D. Nandre, Experimental investigation on the effect of optimized dimethyl carbonate on CI engine performance & Emissions at various engine operating parameters using Taguchi method, in: 9th National Conference on Recent Developments in Mechanical Engineering [RDME 2021] AIP Conf Proce, 2022, 020030.
[19] A.R. Patil, A.D. Desai, Optimization of application of 2-ethyl-hexyl-nitrate on partial substitution of ethanol in CI engine for fuel economy and emission control using MADM method, SN Appl. Sci. 1 (2) (2019 Feb 17) 166.
[20] V. Kumbhar, A. Pandey, C.R. Sonawane, H. Panchal, Ü. Ağbulut, Numerical and experimental investigation of the influence of various metal-oxide-based nanoparticles on performance, combustion, and emissions of CI engine fuelled with tamarind seed oil methyl ester, Energy 265 (2023 Feb 15), 126258.
[21] A.K. Pandey, M. Nandgaonkar, A. Varghese, C. Sonawane, R. Kohil, A. Warke, Comparison and evaluation of engine wear, engine performance, NOx reduction and nanoparticle emission by using gasoline, JP-8, Karanja oil methyl ester biodiesel, and diesel in a military 720 kW, heavy-duty CIDI engine applying EGR with turbo charging, in: SAE Technical Papers, SAE, 2023.
[22] A.K. Pandey, M. Nandgaonkar, C. Sonawane, V. Kumbhar, A. Varghese, Experimental investigation of the effect of gasoline fuel on engine performance, NOx reduction, and engine wear of a 38.8L military heavy duty CIDI diesel engine applying EGR, in: SAE Technical Papers, 2022.
[23] A. Pandey, M. Nandgaonkar, A. Varghese, S. Sambasivan, C. Sonawane, Evaluation and comparison of performance, combustion characteristics, NOx and particle emission of gasoline, JP-8 and diesel fuel in a military heavy duty 38 liters CIDI engine applying EGR, in: SAE Technical Papers, 2021.
[24] Pandey, A., Suresh, S., Nandgaonkar, M., Sonawane, C. et al., "Comparison and Evaluation of Performance, Combustion and Particle Emissions of Diesel and Gasoline in a Military Heavy Duty 720 kW CIDI Engine Applying EGR," SAE Technical Paper 2020-01-2057, 2020, https://doi.org/10.4271/2020-01-2057.
[25] V. Kumbhar, A. Pandey, C.R. Sonawane, A.S. El-Shafay, H. Panchal, A.J. Chamkha, Statistical analysis on prediction of biodiesel properties from its fatty acid composition, Case Stud. Therm. Eng. 30 (2022 Feb 1), 101775.
[26] T. Li, M. Suzuki, H. Ogawa, Effects of ethyl tert-butyl ether addition to diesel fuel on characteristics of combustion and exhaust emissions of diesel engines [Internet], Fuel 88 (10) (2009), 2017–24, https://www.sciencedirect.com/science/article/pii/S0016236109001070.
[27] L. Yongqi, W. Yanxia, Diesel engine emission improvements by the use of EGM-DMC-diesel blends fuel, in: 5th WSEAS Int Conf on ENVIRONMENT, ECOSYSTEMS and DEVELOPMENT, Tenerife, 2007 [Internet], http://jtxy.sdut.edu.cn/.
[28] A. Jaworski, H. Kuszewski, A. Ustrzycki, K. Balawender, K. Lejda, P. Woś, Analysis of the repeatability of the exhaust pollutants emission research results for cold and hot starts under controlled driving cycle conditions, Environ. Sci. Pollut. Res. 25 (18) (2018 Jun 20) 17862–17877.
[29] D.C. Caputo, P.G. Cavataio, V.C. Fonteriz, R.E. Ferreira, G.A. Receloglu, Processing of internal combustion engine test data using the indicated cycle provided model, in: Transportation Research Procedia, Elsevier B.V., 2018, pp. 20–27.
[30] Anaveerappa, M.C. Navindgi, Effect of cetane improver on the performance and emission characteristics of biodiesel fueled DI diesel engine with exhaust gas recirculation technique, Int. J. Eng. Dev. Res. [Internet 5 (3) (2017) 1064–1069. www.ijedr.org.
[31] A. Bragadeshwaran, N. Kasianantham, S. Ballusamy, K.R. Tarun, A.P. Dharmaraj, M.U. Kaisan, Experimental study of methyl tert-butyl ether as an oxygenated additive in diesel and Calophyllum inophyllum methyl ester blended fuel in CI engine, Environ. Sci. Pollut. Res. 25 (33) (2018) 33573–33590, https://doi.org/10.1007/s11356-018-3318-y [Internet].
[32] S. Yessian, P.A. Varthanan, Optimization of performance and emission characteristics of catalytic coated IC engine with biodiesel using grey-taguchi method, Sci. Rep. 10 (1) (2020).
[33] C. Ramakrishnan, P.K. Devan, R. Karthikeyan, Experimental study on the performance and emission characteristics of jojoba oil fueled DICI engine, Environ. Prog. Sustain. Energy 36 (1) (2017).
[34] A.R. Patil, A.D. Desai, Parametric optimization of engine performance and emission for various n-butanol blends at different operating parameter condition, Alex. Eng. J. 59 (2) (2020 Mar 1) 851–864.
[35] S. Tripathy, D.K. Tripathy, Multi-attribute optimization of machining process parameters in powder mixed electro-discharge machining using TOPSIS and grey relational analysis, Eng. Sci. Technol. an Int. J. 19 (1) (2016 Mar 1) 62–70.
[36] G. Dehdasht, M. Salim Ferwati, R.M. Zin, N.Z. Abidin, A hybrid approach using entropy and TOPSIS to select key drivers for a successful and sustainable lean construction implementation, PLoS One 15 (2) (2020 Feb 1).
[37] G. Sakthivel, R. Sivakumar, N. Saravanan, B.W. Ikua, A decision support system to evaluate the optimum fuel blend in an IC engine to enhance the energy efficiency and energy management, Energy (2017) 140.
[38] G. Sakthivel, M. Ilangkumaran, A. Gaikwad, A hybrid multi-criteria decision modeling approach for the best biodiesel blend selection based on ANP-TOPSIS analysis, Ain Shams Eng. J. 6 (1) (2015).
[39] A. Gharehghani, H.R. Abbasi, P. Alizadeh, Application of machine learning tools for constrained multi-objective optimization of an HCCI engine, Energy (2021) 233.
[40] T. Ramesh, A.P. Sathiyagnanam, MV De Poures, P. Murugan, A comprehensive study on the effect of dimethyl carbonate oxygenate and EGR on emission reduction, combustion analysis, and performance enhancement of a CRDI diesel engine using a blend of diesel and prosopis juliflora biodiesel, in: G.L. Balaji (Ed.), Int J Chem Eng, vol. 2022, 2022, 5717362, https://doi.org/10.1155/2022/5717362 [Internet].
[41] G.D. Zhang, H. Liu, X.X. Xia, W.G. Zhang, J.H. Fang, Effects of dimethyl carbonate fuel additive on diesel engine performances, Proc. Inst. Mech. Eng. - Part D J. Automob. Eng. 219 (7) (2005) 897–903, https://doi.org/10.1243/095440705X28358 [Internet].
[42] L. Razzaq, M.A. Mujtaba, M.A. Shahbaz, S. Nawaz, H. Mahmood Khan, A. Hussain, et al., Effect of biodiesel-dimethyl carbonate blends on engine performance, combustion and emission characteristics, Alex. Eng. J. 61 (7) (2022 Jul 1) 5111–5121.
[43] R. Li, Z. Wang, P. Ni, Y. Zhao, M. Li, L. Li, Effects of Cetane Number Improvers on the Performance of Diesel Engine Fuelled with Methanol/biodiesel Blend, vol. 128, Elsevier, Fuel, 2014, pp. 180–187.