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A comprehensive study on the performance and emission analysis in diesel engine via optimization of novel ternary fuel blends: Diesel, manganese, and diethyl ether

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ABSTRACT

Ecosystem degradation and fossil fuel depletion are the two foremost concerns to look for alternative fuels. Rapid population growth is primarily accountable for higher consumption of fossil fuel sources, although engine technology is achieving milestones in terms of fuel efficiency and lower exhaust emissions in order to contribute towards a sustainable environment. The main root cause of global warming is carbon dioxide emissions; therefore, it is imperative to assess the impact of alternative fuels in diesel engines with an aim to minimize carbon emissions. A current study deals with the reduction of carbon emissions and improvement of efficiency through addition of manganese nano-additive to di-ethyl ether and diesel fuel blend in particulate form. Fuel blends were formed by adding various proportions of manganese to high-speed diesel fuel and stirring the mixture while heating it for 10 min. The blends were then tested in diesel engines at two distinct loads and five engine speed ranges. Emission analyzer was used to ascertain the CO_2 output of engine. At higher loads for 10 % diethyl ether in diesel, the increase in brake thermal efficiency was 24.19, 28.17 and 26.86 % when the manganese amount in blend was changed as 250 mg, 375 mg and 500 mg respectively. On the other side CO_2 emissions increase by 11.57, 30.52 and 20.33 % for manganese concentrations of 250 mg, 375 mg and 500 mg respectively. Analysis performed with Design Expert 13 showed that the desirability was 0.796 for a blend of 375 mg manganese at 1300 rpm and 4500 W load with 33.0611 % BTE, 334.011kg/kWh BSFC, 67.8821Nm torque, and 6.072 % CO_2. Therefore, it can be deduced that manganese nanoparticle blends improved engine performance but CO_2 emissions also increase which can be responsible for global warming and it should be reduced through catalytic converters.

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1. Introduction

Over the last few decades, rapid industrialization and population growth have resulted in the exhalation of hazardous emissions and unprecedented global warming [1,2]. The previous decade was the hottest period in human history, reaching temperatures of 0.8 °C above the pre-industrial average [3]. It is projected that the overall global population is escalating at a pace of 83.1 million per year and the remaining life of fossil fuel reserves is 50 years at the present rate of fossil fuel consumption [4–6]. Diesel engines possess pre-dominant applications in the power sector, because of their high specific torque, efficiency, and low fuel consumption. Their reliability and durability are also cited as reasons for their usage in the transport sector, where downtime could be detrimental to business [7]. However, diesel engines predominantly contribute towards global warming, since up to 40 % of pollutant emissions originate from the transport sector. Diesel pollutants like particulate matter, SO_x, and NO_x directly cause respiratory diseases like asthma. NO_x and SO_x emissions are responsible for acid rain, and ground-level ozone [8]. Modern diesel engines have come a long way in terms of efficiency and emissions reduction [9]. Whereas older CI engines emitted significant black smoke and other odorous chemicals, the adoption of Diesel Particulate Filter (DPF) and Direct Injection (DI) technology have resulted in cleaner combustion of diesel fuel with considerably reduced emissions and odor-less tailpipe exhaust stream [10]. Despite this progress, the emissions caused by diesel engines remain a major environmental concern. Even Euro-VI compliant CI engines are drastically more harmful for living beings than the equivalent petrol engine due to partially combusted gaseous emissions. In the short term, emphasis must be placed on reducing the environmental impact of CI engines through improving efficiency and reducing emissions [11]. New developments in diesel engine technology possess potential to substantially improve efficiency and mitigate emissions. Techniques like turbocharging, supercharging and the addition of mild-hybrid components can greatly improve engine power and efficiency while reducing emissions. Upcoming vehicles are expected to use cutting-edge forced induction methods like variable geometry turbochargers to further improve

Table 1
Literature review.

Author	Experimental conditions	Engine specifications	Findings		
			Performance parameters	Emission characteristics	Combustion parameters
Srihari et al. [43]	Experiments was conducted using three fuel blends: DBD1 (5%DEE+20%cottonseedbiodiesel+75% diesel) DBD2 (10%DEE+20%cottonseedbiodiesel+70% diesel) DBD3 (15%DEE+20%cottonseedbiodiesel+65% diesel)	395CC diesel engine of 18CR	BSFC EGT↓↑ BTE↓ Cylinder pressure↑	NOx↓ CO↓ HC↓ Smoke↓	
Amr Ibrahim [44]	Experiments was conducted using three fuel blends: D95 (95%diesel+5%DEE) D90 (90%diesel+10%DEE) D85 (85%diesel+15%DEE)	232CC diesel engine of 22CR	BTE↑ BSFC↓	–	Specific heat ratio↓ Max cylinder pressure↑
Sivalakshmi and Balusamy [45]	DEE (5, 10 and 15 %v) in neem oil biodiesel (B100) named as BD5, BD10 and BD15 respectively	Diesel engine of 16.5CR	BTE↑ BSFC↓	CO↓ Smoke↓ NOx↑ HC↑	Peak cylinder pressure↑ HRR↑
Rakopoulos et al. [40]	Experiment was conducted at 8, 16 and 24 %vol DEE in diesel fuel	Diesel engine of 19.8CR	BSFC↑ BTE↓ EGT↑	CO↓ Smoke↓ NOx↓ HC↑	
Tudu et al. [46]	Experiments was conducted using four fuel blends: X1 (59%diesel+40%LFPO+1%DEE) X2 (58%diesel+40%LFPO+2%DEE) X3 (57%diesel+40%LFPO+3%DEE) X4 (56%diesel+40%LFPO+4%DEE)	Diesel engine of 17.5CR	BTE↑ BSFC↓	CO↑ Smoke↓ NOx↓ HC↑	ID↓ Peak cylinder pressure↑
Uslu and Aydin [47]	DEE (0, 5 and 10%v) in palm oil biodiesel	296CC diesel engine of 18CR	BTE↑ BSFC↓ EGT↑	CO↓ NOx↑ HC↓	
Barik and Murugan [48]	2,4, and 6 % DEE in karanja oil biodiesel	662CC diesel engine of 17.5CR	BTE↑ BSFC↓ EGT↑	CO↓ NOx↑ HC↓ Smoke↓	
Imtenan et al. [49]	Experiment was conducted using DEE (5–10 %) in jatropha oil biodiesel	2477 cc diesel engine of 21CR	BSFC↓ BSEC↓ BTE↑	NO↓ CO↓ Smoke↓	HRR↓ Incylinder pressure↓
Barik et al. [50]	DEE (5, 10,15, 20, and 25%v) blended in diesel as pilot fuel. Hydrogen was blended as 0.2LPM	551 cc diesel engine of 17.5CR	BTE↑ BSFC↓	HC↓ CO↓ CO_2↑ NOx↑	HRR↑ ID↓

power output and cut down emissions [12]. On the other hand, innovations in exhaust aftertreatment systems have the potential to appreciably reduce engine emissions. However, the usage of conventional diesel fuel is responsible for high emission levels [13]. Major research has gone into the development of alternative fuels like biodiesel [14,15], alcoholic fuels [16–19] and gaseous fuels (CNG, LPG and LNG) [20–22]. These studies offer a meaningful emissions reduction in comparison to conventional petroleum fuels, especially in terms of particulate matter, NO_x, and SO_x emissions. However, these fuels have major disadvantages in power output and production cost. Biodiesel also poses a threat to food security since their production requires crops to be cut down. Microalgae usually requires less land for its production as it can be grown in rough conditions like lower quality water, in sufficient sunshine, infertile land (unsuitable for cultivation of biofuel feedstocks and food producing crops along with higher yield rate) [23]. Moreover, emissions like CO, NOx, PM, PN can be significantly reduce in case of algae-based biodiesel at the cost of higher fuel consumption. However, the higher fuel consumption can be reducing at higher loading conditions [24,25]. Oxygen content significantly contributes in emission abatement. Therefore alcoholic fuels possess higher oxygen content which can contribute in lower emissions and improved engine performance [26]. Moreover, they possess higher lubricity and viscous nature which may result in better performance of oxygenated fuels without any cold start cranking issue [27]. Ethanol is most commonly used oxygenated fuel in the world. It is analyzed by Kannan et al. [28] that only 5 % addition of ethanol in jatropha biodiesel can reduce CO emission by 51 %, HC emission by 40 %, and smoke emission by 43 % respectively at the cost of 47 % higher NOx emission.

The emerging issues like gaseous pollutants, contamination in environment and the usage of conventional energy sources such as fuel has urged us to find a solution to cope up with this international calamity. It leads towards the search of better, renewable, and eco-friendly fuel for engines [29]. The fuel blends produce better combustion and can perform their role in mitigating pollution from the diesel engines without bad impacts on performance. Therefore, these blends considered as better alternates [30]. Alcohols because of their higher octane number is consuming at large scale as substitute fuel in SI engine and currently being considered as fuel blends for diesel engine as these blends includes oxygen containing fuels [31]. For diesel engines the prevalent types of alcohol ethanol and butanol are being extensively tested as possibly high oxygen containing fuel blends. But the fact which tells us that ethanol and butanol are not the most suitable types of alcohol for being consumed as fuel blends for diesel engines is their low cetane number. Cetane number of ethanol and butanol is lower than diesel fuel which suggests considering other alternates with high cetene numbers such as ethers. Diethyl ether due to its high cetene number and calorific values than both diesel and ethanol, butanol is under consideration [30,32]. Besides diethyl ether the other type is dimethyl ether which is also a substitute but in comparison with diethyl ether it is fluid at adjacent temperature while dimethyl ether is gaseous. Consequently, diethyl ether (DEE) is more appropriate as fuel blends in diesel engines without any modifications [33]. Diethyl ether has all prominent characteristics to be used as diesel engine fuel. it is highly oxygenated and needs low temperature to auto-start. Despite of high cetane number and volatility it has extensive restrictions on flammability and high miscibility with the diesel fuel [34]. Diethyl ether (DEE) can be preferred over dimethyl ether (DME) and used as fuel for the taciturn assistance of diesel engine because of lower autoignition temperature, slightly higher energy content per unit volume, higher vapor pressure and better compatibility with existing fuel infrastructure in comparison with dimethyl ether [35–38]. Sezer [39] found that brake power decreases about 32.1 and 19.4 % at 4200 rpm while BSFC increases about 47.1 and 24.7 % at 2200 rpm for DME and DEE, respectively. Thus, it is suggested that diethyl ether should only be use as fuel added substance instead of fuel for diesel engines [40]. Table 1 includes relevant literature regarding the impact of diethyl ether in diesel/biodiesel fuel blend on engine performance. Thus, from prior research it is determined that diethyl ether as a fuel added substance can be used to improve engine performance and decrease air pollutants. The metallic additives have been used in combustion engines for the improvement in combustion of the fuel. Magnesium, Iron, Aluminum, and other such metal particles are quite prominent [41,42]. These particles are also used in combination with biodiesel for the quest to improve engine efficiency.

Manganese nanoparticles, when used as a fuel additive, are often included to improve fuel combustion attributes and potentially improve engine performance (higher combustion efficiency, reducing emissions, and increasing fuel economy). Manganese nanoparticles act as catalyst and promotes effective fuel combustion. However, there are some concerns about the potential detrimental effects of these nanoparticles on engine parts such as injectors, pistons, and cylinders. These detrimental impacts can be reduced through proper fuel dispersion and smaller size particles [51,52]. The utilization of copper and manganese (Cu–Mn) along with conventional fuel declined the temperature of regeneration to 420 °C [53,54]. In CI engine, manganese from organic based were suspended within diesel fuel in various percentages. The physio-chemical properties showed reduction in flash point and increment in heating value. With diesel, organic-based manganese was added at four different weights in a CI engine. The ignition delay was found at 13.2° of cranking angle which produced a cylinder pressure of 62.7 bar. Furthermore, carbon monoxide, smoke and hydrocarbon, were declined by 25.3, 6.5 and 6.6 % percent, respectively, with a 25.5 % rise in oxides of nitrogen [55].

Anh Tuan Hoang [56] performed the experimentation on a CI engine using CeO_2 metal-based nanoparticles. Results showed that it has valence transformation ability and has good thermal properties such that it enhances the combustion properties of diesel and biodiesel and improves emission (NO_X, CO, and HC). A. Prabu [57] also experimented with nanoparticles such as CeO_2 and Al_2O_3 with diesel and biodiesel in diesel engine. He found improvement of 13 % in BTE along with reduction of 30 %, 60 %, 44 %, 38 % in NOx, CO, HC and smoke emission respectively. M. Anish et al. [58] performed experimentation using three types of biofuels using TiO_2 and ZnO nanoparticles. They observed around 16 % higher BTE along with 32, 62, 48 and 40 % reduction in NOx, CO, HC, and smoke respectively. MA Lenin et al. [59] used CuO nanoparticles in diesel. The solution was prepared using the sol-gel method. Results using the most effective blends found that emissions of NOx and particulate matter decreased marginally, while BTE increased by 4 %. The most effective blends showed a decrease of 5 % in CO_2. Junshuai Lv, Su Wang and Beibei Meng [60] used the following nanoparticles: Zinc Oxide, Cerium oxide, Titanium dioxide in conjunction with biodiesel. However, TiO_2 proved to be the most effective in decreasing NOx pollutant (22.57 % reduction). Selvaganapathy et al. [61] conducted an empirical study on the impact of ZnO nanoparticle on emission and engine performance. Results found an increase in thermal efficiency as 37 % BTE for blended fuel and 35.825 % BTE in

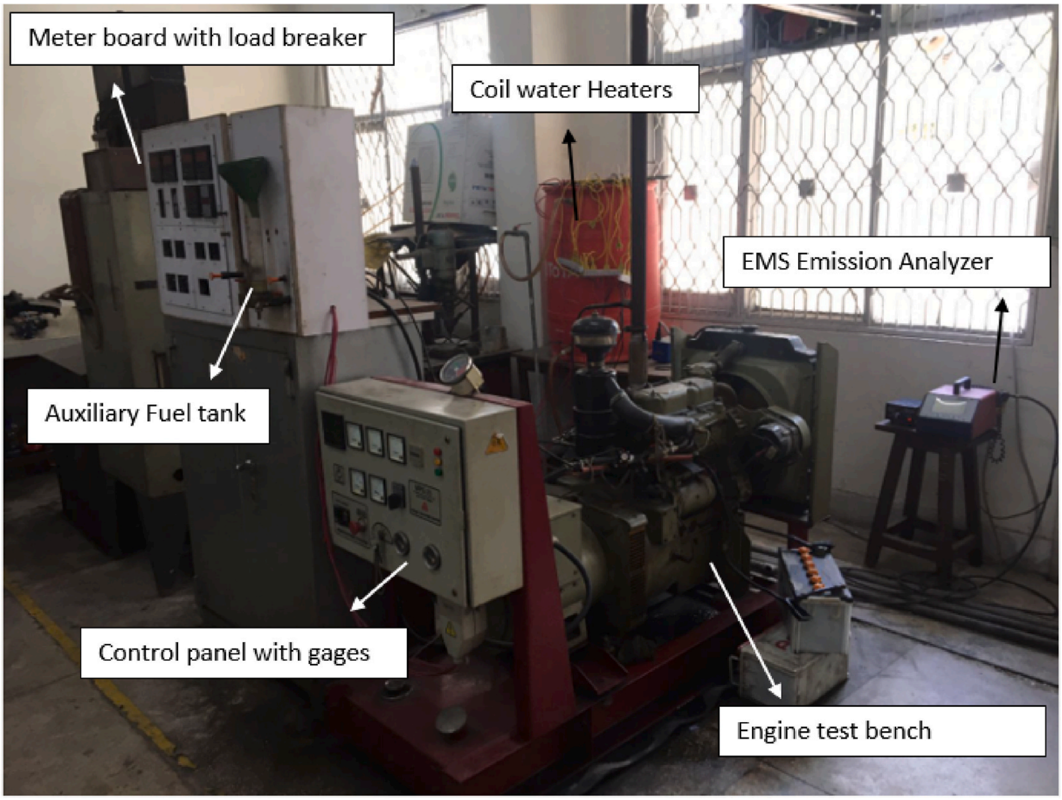

Fig. 1. Real time image of experimental test bench of engine.

Table 2
Engine characteristics.

Parameters	Values
Bore x Stroke (cm)	9.14 × 12.7
No of Storke	04
No of Cylinders	03
Nature of cooling	Water type
Lubricant capacity (L)	6.17
Displacement (L)	2.5
Compression ratio	16.5

case of diesel. Sajeevan et al. [62] experimentally found that the performance of diesel engine is enhanced by blending cerium oxide with diesel. They found 6 % increase in BTE for blended fuels. Mehmet Celik H. Serdar Yucesu, Metin Guru [55] used manganese as nanoparticle with biodiesel and evaluated that the addition of manganese in biodiesel enhanced fuel properties by decreasing the emissions. Carbon monoxide went down by 25.28 %, while HC and smoke emissions declined by 6.64 % and 6.5 % respectively. On the other hand, NOx emissions rose by 25 %. Nano additives, like transition metal particles, offer an effective way of reducing engine emissions and improving efficiency at a comparably low production cost [42]. These work as a catalyst and reduce the activation energy of combustion as well as the ignition delay. Secondly, these improve the exothermic value of fuel combustion resulting in higher power output and efficiency. Their catalytic nature also allows for reduced emissions of particulate matters, NO_x, and SO_x [63]. Manganese was chosen as a nanoparticle for this study due to their lower price compared to Cerium and Magnesium, and their excellent catalytic abilities.

A detailed review of literature revealed that the impact of manganese (Mn) and diethyl ethers (DEE) separately investigated in diesel engine fueled with diesel/biodiesel. However, a current study used the novel combination of manganese and diethyl ethers (DEE) in diesel. A novelty of the current study is the application of response surface methodology (RSM) technique in order to optimize the engine performance fueled with unique combination of manganese and diethyl ether blend in diesel. RSM developed regression models and performed analysis of variance (ANOVA) for each parameter.

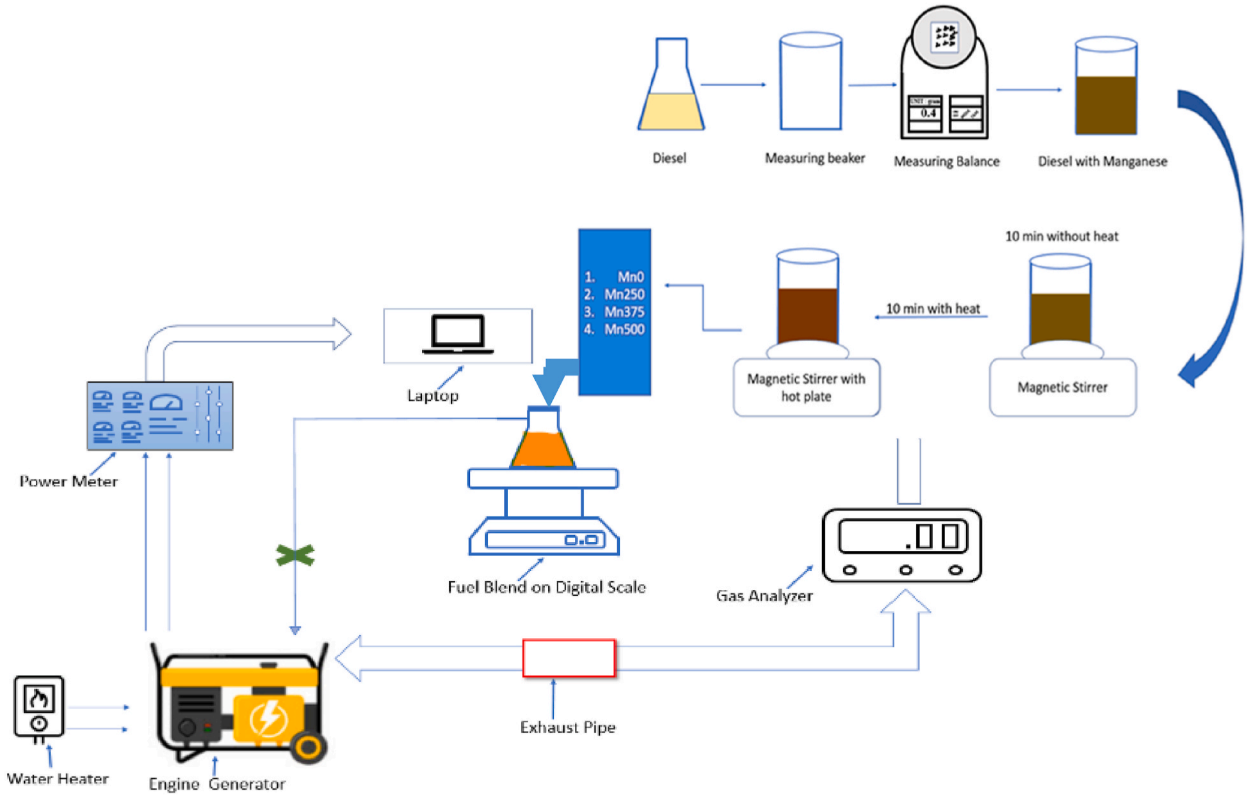

Fig. 2. Schematic of experiment set up.

Table 3
Design of experiment of the study.

Speed Range/Step Size	DEE/Percentage Variations	Mn/Concentration Variations	Load
1000-1800 (with the steps of 200 rpm)	0-15 (with a step of 5 % by volume)	0-250-375-500 (mg)	1500 W and 4500 W

Table 4
Physicochemical properties of diesel and diethyl ether.

Properties	Diesel	Diethyl ether
Chemical composition	$C_{12}H_{23}$	$C_4H_{10}O$
Density (kg/m^3)	833.1	710
Calorific value (MJ/kg)	42.5	28.4
Autoignition temperature (K)	530	433.15
Cetane Number	51	125

2. Methodology

The apparatus used for the preparation of fuel blend were magnetic stirrer, measuring flask, measuring beaker and measuring balance. The engine test bench consisted of a diesel engine with fuel tank, a set of water heaters and meter board with different load breakers (Fig. 1). The generator of the test bench provided the voltage and current to the water heater. A Perkins/AD 3.152 direct injection 2500 cc diesel engine was used in the experiment. Further specification of test engine is displayed in Table 2. A schematic arrangement of test engine along with all auxiliaries has been mentioned in Fig. 2.

An engine testing was performed by incrementing engine speed from 1000 to 1800 rpm with interval of 200 rpm along with variation of engine load (1500 and 4500 W). At first, the engine was powered on using pure diesel until reaching steady-state operation. The fuel blends, engine speed and the applied load were the input parameters, whereas the output parameters were voltages and current which was obtained by the volt and ampere meter. The exhaust gas emission (CO_2) was measured using EMS emission analyzer.

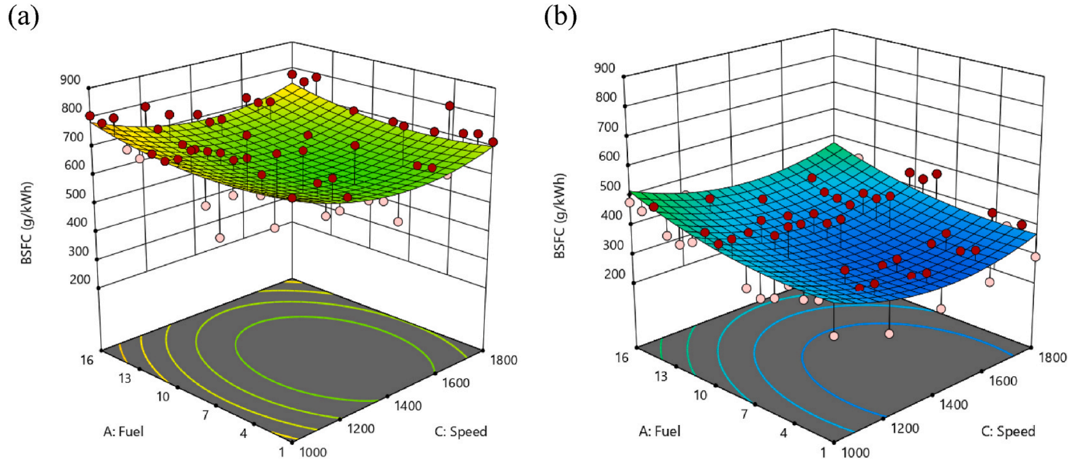

Fig. 3. Brake specific fuel Consumption (BSFC) at (a) lower load and (b) higher load.

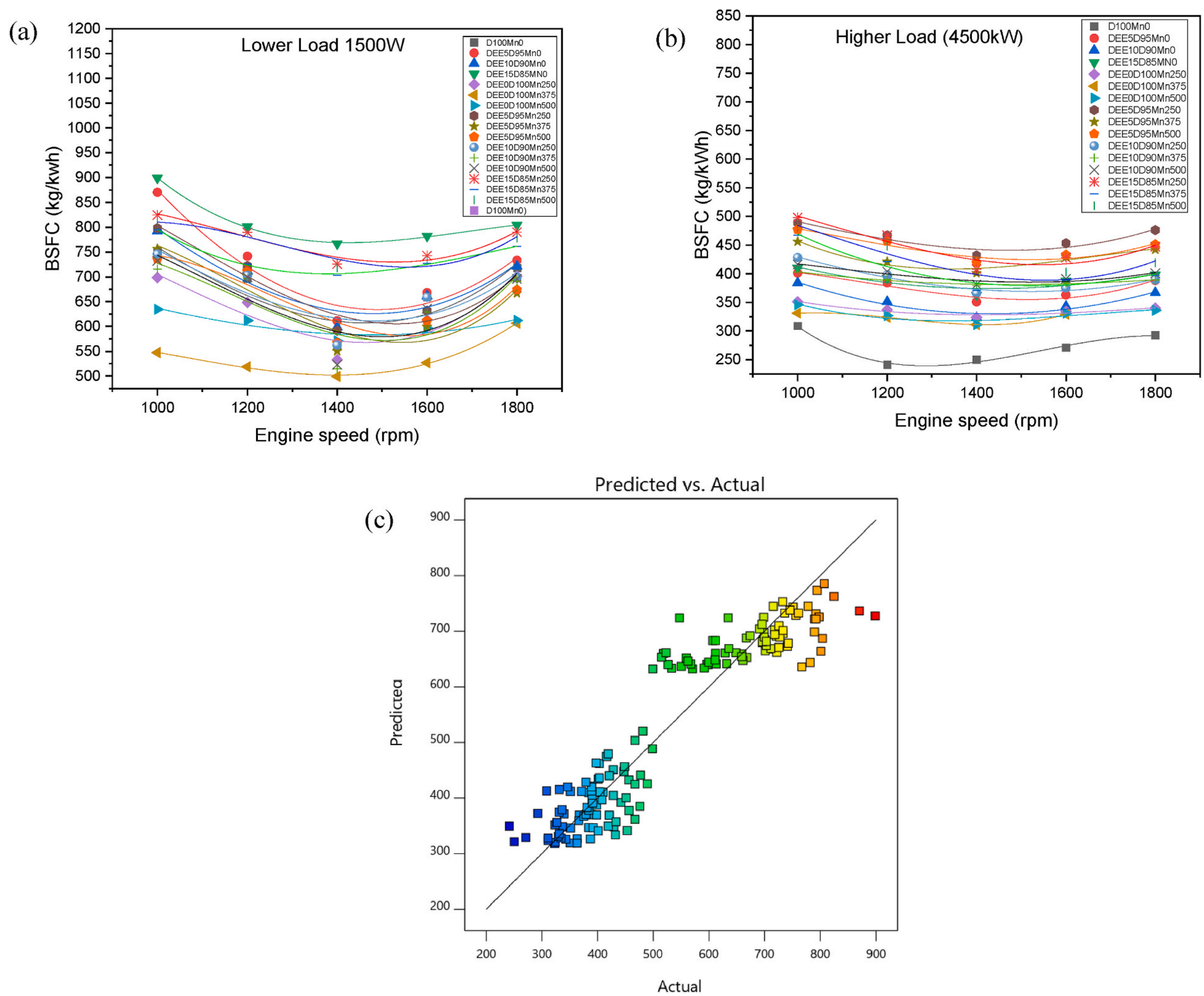

Fig. 4. BSFC (a) variation wrt engine speed at lower load, (b) variation wrt engine speed at higher load and (c) Predicted and Actual values comparison.

Table 5
ANOVA results for reduced regression model (BSFC).

Source	Sum of Squares	df	Mean Square	F-value	p-value		PC (%)
Model	3851000.00	6.00	641800.00	173.42	<0.0001	Significant	87.2
A-Fuel	84277.44	1.00	84277.44	22.77	<0.0001		1.91
B-Load	3550000.00	1.00	3550000.00	959.23	<0.0001		80.4
C-Speed	32984.46	1.00	32984.46	8.91	0.00		0.75
AB	15875.80	1.00	15875.80	4.29	0.04		0.36
A^2	25528.86	1.00	25528.86	6.90	0.01		0.58
C^2	142200.00	1.00	142200.00	38.42	<0.0001		3.22
Residual	566200.00	153.00	3700.97				12.8
Cor Total	4417000.00	159.00					

The predicted R^2 of 0.8603 followed fair compliance with Adjusted R^2 of 0.8668. The adequate precision ratio of 36.721 shows appropriate signal. A regression equation for BSFC is given as:

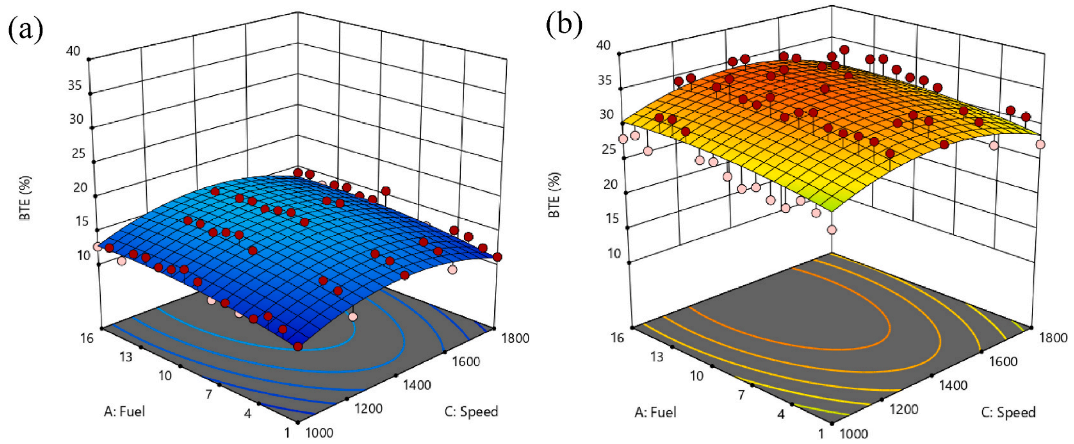

Fig. 5. BTE at (a) lower load and (b) higher load.

2.1. *Preparation of fuel blends*

In terms of fuel blends there were sixteen types of blends prepared such that manganese used in milligrams and di ethyl ether in percentage by volume as per the scheme shown in Table 3. The physicochemical characteristics of diesel and diethyl ether are mentioned in Table 4.

First, diesel and diethyl ether were poured in the decided percentage in the measuring beaker the manganese particles were added, and the solution was stirred for 10 min without heat. Then, the solution was heated along with the magnetic stirrer for 10 min in order to ensure the dispersion of manganese nanoparticle in diethyl-ether and diesel fuel blend. A proper dispersion of manganese nanoparticle is effective for reduction of detrimental effect of manganese. Moreover, the manganese nanoparticle size of 50 nm was used in proportion of 250, 375 and 500 mg, as this smaller concentration is considered safe to be used in engines without any major detrimental impact. The total time needed for the preparation of the fuel blend was 20 min.

After that the sample was tested in the engine test bench and noted the readings of the voltages and current and values of CO_2 from the emission analyzer. Total 9 heaters were used in order to apply load on engine as each heater of 500 W. For 1500 W loading condition, the 3 heaters were powered from the engine. However, the 9 heaters were powered from engine for 4500 W loading condition. The engine was set at specified rpm and measurement of the flowrate of fuel for 20 ml of consumption was taken. Next, the values of voltages and current were recorded from the meter board and value of the CO_2 from the EMS analyzer at a specified rpm. Then, the performance was made on all the other combinations of load, rpm and fuel blends as shown in Table 3. For performance evaluation, torque, brake thermal efficiency (BTE), and brake specific fuel consumption (BSFC) were measured. The optimization of the experimentation was performed using response surface methodology in Design Experts software. Then, an optimal solution was found with the best desirability.

3. Results and discussions

3.1. *Impact on engine performance*

Fig. 3(a) depicts the variation in BSFC for distinct fuel blends of diesel, diethyl ether and manganese when the load is kept at a lower setting. The results show that there is an increase in BSFC as the percentage of DEE goes on increasing from 0 to 15 % in the fuel blends

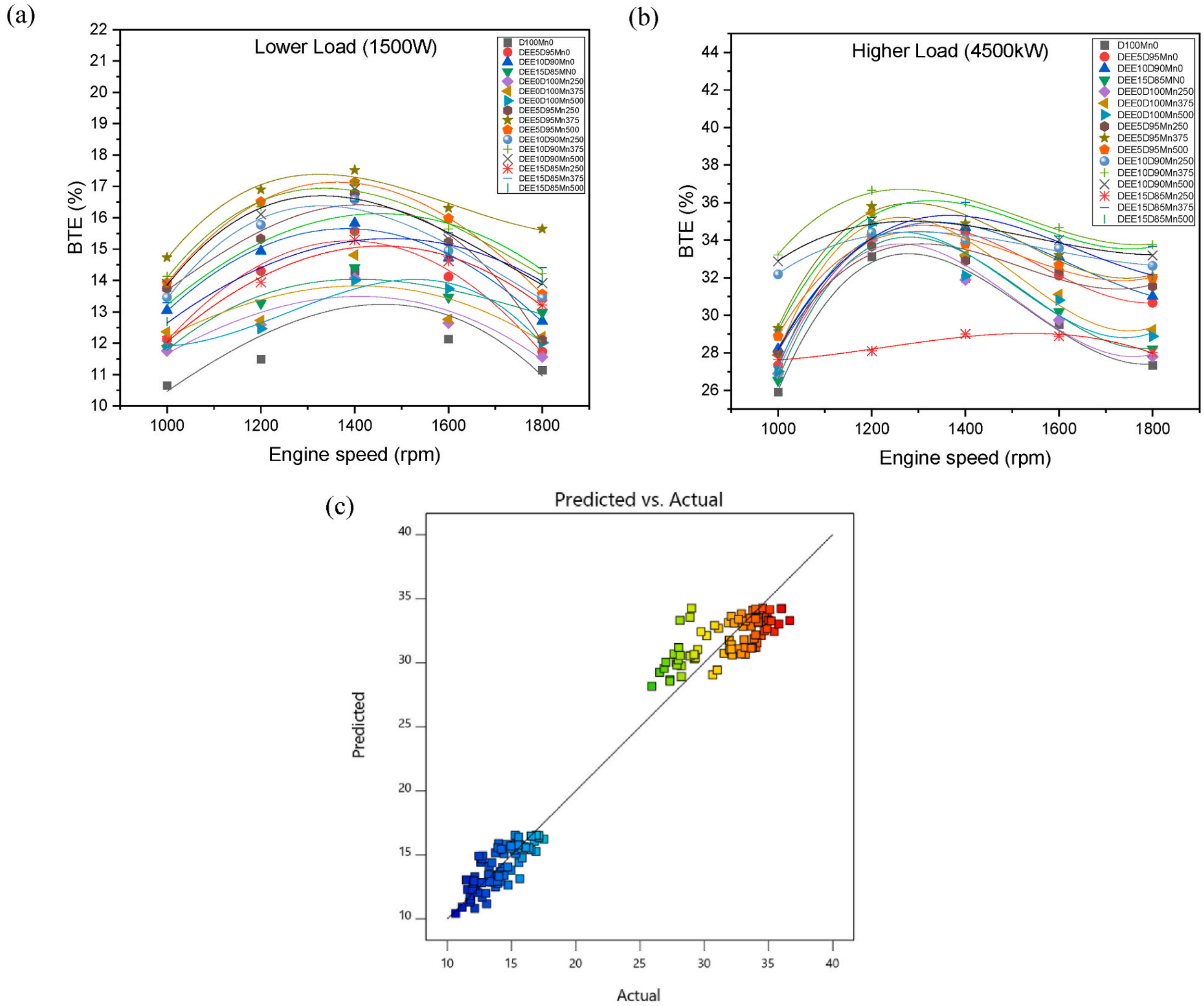

Fig. 6. BTE (a) variation wrt engine speed at lower load, (b) variation wrt engine speed at higher load and (c) Actual and predicted values comparison.

Table 6
ANOVA results for reduced regression model (BTE).

Source	Sum of Squares	df	Mean Square	F-value	p-value		PC (%)
Model	13003.82	5	2600.76	972	<0.0001	Significant	96.93
A-Fuel	86.81	1	86.81	32.45	<0.0001		0.65
B-Load	12584.91	1	12584.91	4703.45	<0.0001		93.81
C-Speed	4.97	1	4.97	1.86	0.175		0.04
A^2	16.34	1	16.34	6.11	0.0145		0.12
C^2	310.78	1	310.78	116.15	<0.0001		2.32
Residual	412.05	154	2.68				3.07
Cor Total	13415.87	159					

of diesel, diethyl ether and manganese because of the lower calorific value when DEE is used in higher concentration. The decrease in the response surface curve at lower loads shows an abrupt change for BSFC as compared to the high load setting as shown in Fig. 3(b). The increasing decreasing trend of BSFC for various fuels blends when the load is kept at higher setting. The least value of BSFC for all the fuel blends occurred at 1000 rpm when the load is kept at lower setting and at 1800 rpm when the load is kept at higher setting. So, at higher load the engine power output is greater as higher load produced lower BSFC.

Fig. 4(a) and (b) indicate that BSFC is lower at higher loading condition due to production of higher power. The dip in the curve of BSFC indicates the most optimum region from 1400 to 1600 rpm engine speed range. At this region, the fuel consumption is least. After

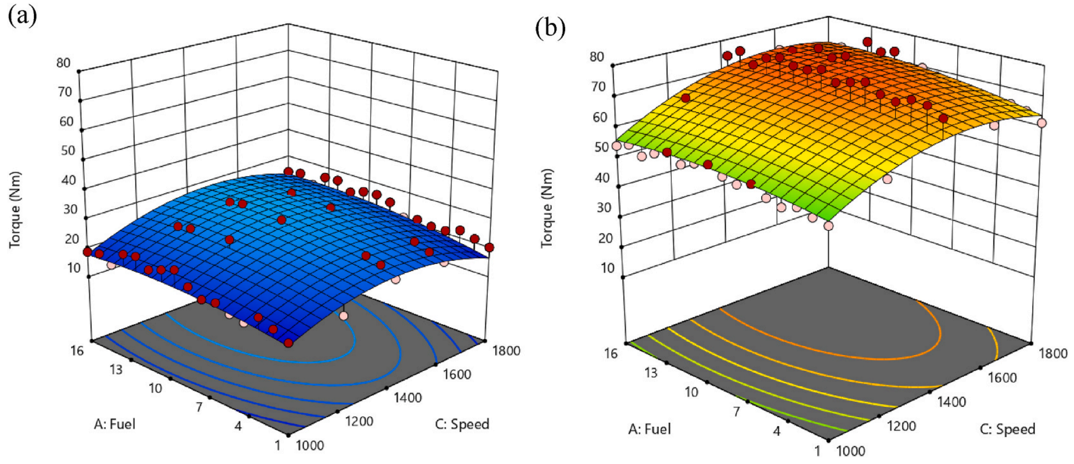

Fig. 7. Torque at (a) lower load and (b) higher load.

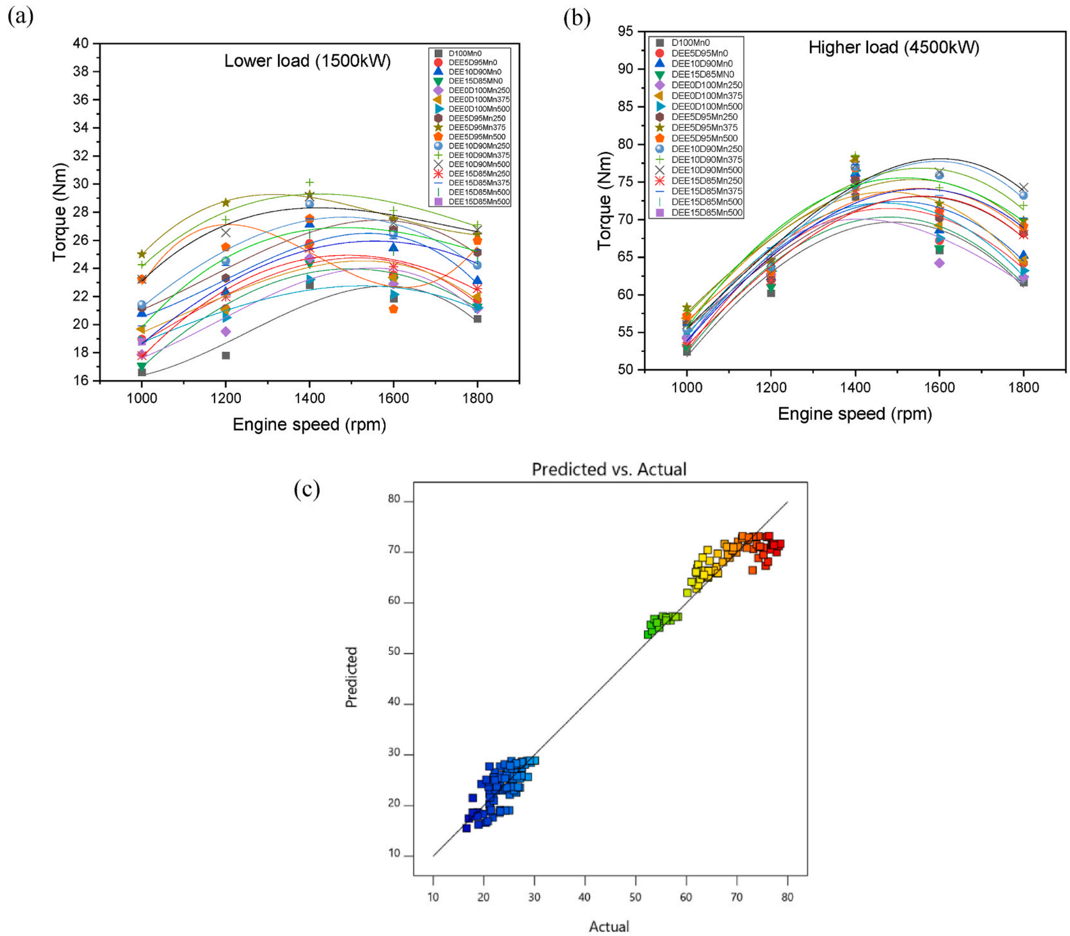

Fig. 8. Torque (a) variation wrt engine speed at lower load, (b) variation wrt engine speed at higher load and (c) Actual and predicted values comparison.

this region, the BSFC was increased drastically in order to meet higher power requirement. Di-ethyl ether percentage (10 %) in diesel fuel proved to be the most optimum blend ratio. At lower loading condition (1500 W), the BSFC was decreased by 3.30, 6.81 and 5.69 % for 250 mg, 375 mg and 500 mg concentration of manganese in diethyl-diesel blend (10 %) respectively. However, the BSFC was

Table 7
ANOVA results for reduced regression model (Torque).

Source	Sum of Squares	df	Mean Square	F-value	p-value		PC (%)
Model	77020.46	7	11002.92	1111.68	<0.0001	significant	98.08
A-Fuel	329.95	1	329.95	33.34	<0.0001		0.42
B-Load	73249.02	1	73249.02	7400.72	<0.0001		93.28
C-Speed	1267.17	1	1267.17	128.03	<0.0001		1.61
AC	40.51	1	40.51	4.09	0.0448		0.05
BC	417.29	1	417.29	42.16	<0.0001		0.53
A^2	94.42	1	94.42	9.54	0.0024		0.12
C^2	1622.1	1	1622.1	163.89	<0.0001		2.07
Residual	1504.43	152	9.9				1.92
Cor Total	78524.89	159					

The impact of load values on engine were greater as compared to the fuel blends concentration and speed showing the PCs of 93.28 %, 0.42 % and 1.61 % respectively. The adequate precision ratio of 82.051 indicates appropriateness of data signal. The best fitting regression (quadratic) model is chosen from the inadequate linear and cubic models. The aliased nature and inadequate fit of the cubic and linear models, respectively, the best fitting quadratic model from the fit summary was chosen. In addition to allowing for the assessment of the individual effects of fuel blend, speed and load on Torque, the aliased regression model also permits for the interaction of input data set and the analysis of their additive effects on Torque. The regression equation for Torque is given as:

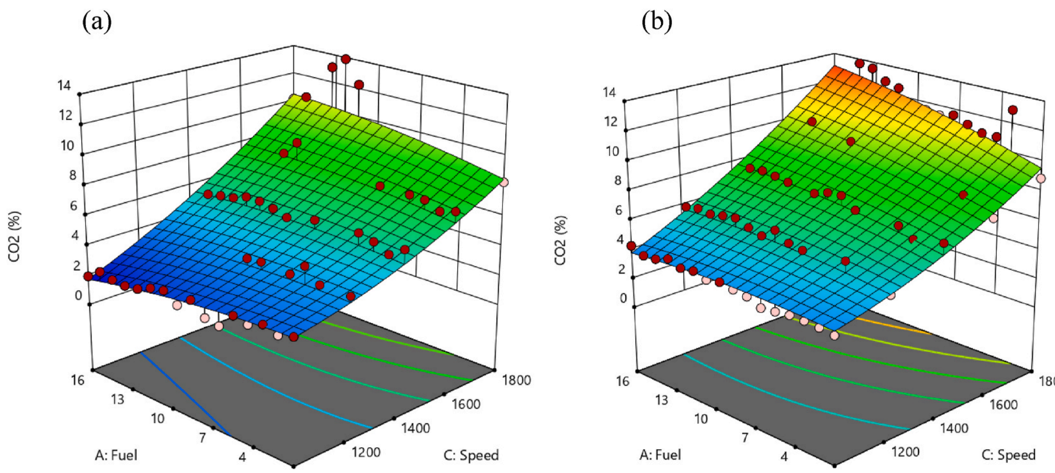

Fig. 9. Carbon dioxide (CO_2) at (a) lower load and (b) higher load.

10.62, 10.01 and 12.70 % higher for the above blended fuels at higher loading conditions.

Fig. 4(c) depicts the comparative analysis amid actual engine generated and the predicted RSM based BSFC which shows a little scattering of data from the regression line. The actual BSFC was calculated using the equipment manually which may be the reason behind the scattering of data. But this disorderliness is not so huge, and the regression model is useable. This less disorderliness of predicted data of RSM proves that these values are best fit of regression model. Table 5 shows the ANOVA results for reduced regression model for BSFC. The reduced quadratic model is significant having F value of 173.42, also p-value is small indicating that the model terms are significant and R^2 (0.8718) which is approximately equal to 1. Only 0.01 % chance exist for higher F-value occur because of noise. In case of BSFC, the p value for model is less than 0.0001, which gives a reasonable fact that we do not have verification to show that data fitting lacks in reduced quadratic model. Also, from Table 5, the impact of load values on engine were greater as compared to the fuel blends concentration and speed showing the percentage contribution (PC) of 80.4 %, 1.91 % and 0.75 % respectively.

$$\boldsymbol{BSFC = +486.22 + 37.34 \times Fuel - 148.96 \times Load - 20.31 \times Speed + 16.21 \times Load \times Fuel + 37.60 \times Fuel^2 + 71.26 \times Speed^2}$$

Fig. 5(a) depicts the variation BTE behavior for different fuel blends of diesel, diethyl ether and manganese when the load is kept at lower setting. Generally, the basic purpose of BTE is to show the conversion efficiency of fuel into BP. At lower load there is an increasing decreasing trend of BTE is obtained. Fig. 5 (a) shows that when the DEE is 5 % in the fuel blends then the greater value of BTE is attained. At higher load settings the more obvious trend for BTE is conspicuous as shown in Fig. 5 (b). 3D contour plot depicts the red color region which shows the greater engine BTE with positive points along the fuel blends and load axis. Fig. 6(a) and (b) show the distinction in BTE wrt engine speed at lower and higher loading conditions respectively. It can be noticed that BTE is lower in the beginning than it starts increasing to maximum value and ultimately BTE curve falls down. Increased in BTE is caused by isochoric ignition and decreased disassociation losses. But there is decrease in BTE at higher engine speed which is due to the abrupt burning of fuels blends. The higher fuel consumption when the 15 % DEE is used reduces the BTE for the fuel blends. BTE contour plots depict the

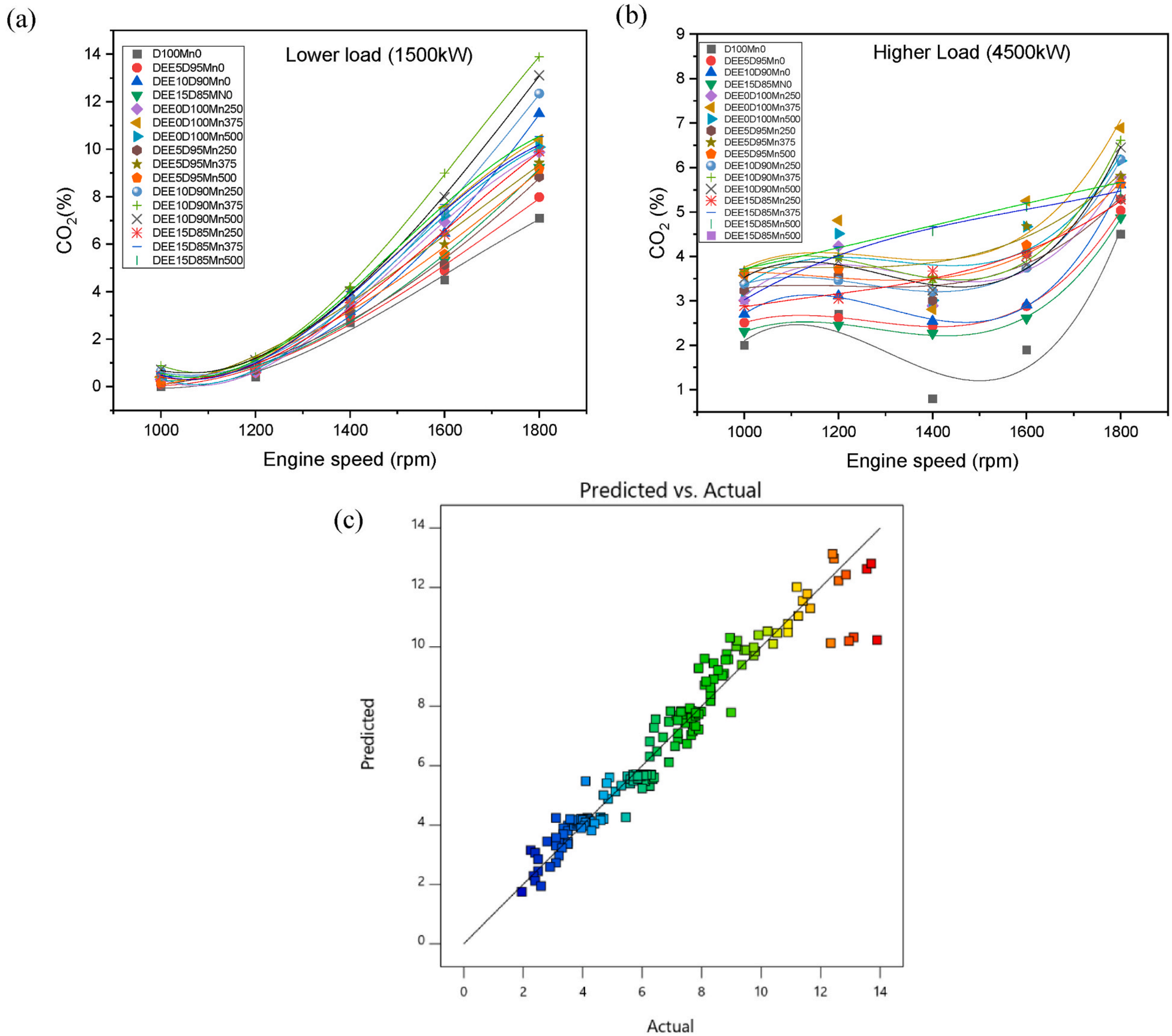

Fig. 10. CO_2 (a) variation wrt engine speed at lower load, (b) variation wrt engine speed at higher load and (c) Actual and predicted values comparison.

inverse relation with BSFC and calorific value, hence, BTE increases as there is lower heat dissipation. The catalytic property of manganese (Mn) results in a modest increase in the BTE of engine. The fuel blend with 10 % DEE showed the maximum BTE value as compared to other fuel blends. At higher load for 10 % DEE, the increase in the BTE is 24.19 %, 28.17 % and 26.86 % when the Mn amount in blend is changed as 250, 375, and 500 mg respectively. However, the BTE at lower loading condition was 4.17, 8.75 and 6.89 % higher for manganese concentration 250, 375, and 500 mg respectively.

Fig. 6 (c) depicts the actual engine generated and the predicted RSM based BTE comparison. The minimal BTE is represented by the color blue which is 10.64 %, while the maximum BTE is represented by the color red which is 36.66 %. This less disorderliness of predicted data of RSM proves that these values are best fit of regression model.

Table 6 shows the ANOVA results for reduced regression model for BTE. The reduced quadratic model is significant having F value of 972, also p-value is small indicating that the model terms are significant and R^2 (0.9693) which is approximately equal to 1. An adequate consistency is obtained between the predicted and adjusted R^2. The predicted R^2 of 0.9670 shows fair compliance with adjusted R^2 of 0.9683. Only 0.01 % chance exist for higher F-value in case of BTE mainly because of noise. In case of BTE, the p value for model is less than 0.0001, which shows proper data fitting in reduced quadratic model. The p values of load, concentration of fuel blends and speed from Table 6 depicts that these three factors have a noteworthy impact on engine parameters. The impact of load values on engine were greater as compared to the fuel blends concentration and speed showing the PCs of 93.81 %, 0.65 % and 0.04 % respectively.

The adequate precision ratio of 75.277 indicates appropriateness of data signal. Aliased nature and inadequate fit of the cubic and

Table 8
ANOVA results for reduced regression model in case of CO_2.

Source	Sum of Squares	df	Mean Square	F-value	p-value		PC (%)
Model	1196.37	8	149.55	288.67	<0.0001	significant	93.86
A-Fuel	13.16	1	13.16	25.4	<0.0001		1.03
B-Load	98.52	1	98.52	190.17	<0.0001		7.73
C-Speed	1034.32	1	1034.32	1996.57	<0.0001		81.15
AB	8.81	1	8.81	17.01	<0.0001		0.69
AC	26.12	1	26.12	50.41	<0.0001		2.05
BC	1.51	1	1.51	2.91	0.09		0.12
A^2	1.76	1	1.76	3.4	0.0672		0.14
C^2	12.18	1	12.18	23.51	<0.0001		0.96
Residual	78.23	151	0.518				6.14
Cor Total	1274.6	159					

The p values of load, concentration of fuel blends and speed from Table 8 depict that these three factors have a predominant impact on the engine parameters. The impact of speed values on engine were greater as compared to the fuel blends concentration and load showing the PCs of 81.15 %, 1.03 % and 7.73 % respectively. The adequate precision ratio of 66.686 indicates appropriateness of data signal. The best fitting regression (quadratic) model is chosen from the inadequate linear and cubic models. The aliased nature and inadequate fit of the cubic and linear models, respectively, the best fitting quadratic model from the fit summary was chosen. In addition to allowing for the assessment of the individual effects of fuel blend, engine speed, and load on CO_2, the aliased regression model also permits for the interaction of input data set and the analysis of their additive effects on CO_2 emission content. The regression equation for BSFC is given as:

Table 9
Optimization Set up.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A: Fuel	is in range	1	16	1	1	3
B: Load	is in range	1500	4500	1	1	3
C: Speed	is in range	1000	1800	1	1	3
BSFC	minimize	241.502	898.89	1	1	3
BTE	maximize	10.6492	36.66	1	1	3
Torque	maximize	16.606	78.55	1	1	3
CO_2	minimize	1.95	13.89	1	1	3

linear models, the best fitting quadratic model from the fit summary was chosen. In addition to allowing for the assessment of the individual effects of speed, load, and fuel blends on BTE, the aliased regression model also permits for the interaction of input data set and the analysis of their additive effects on BTE. A regression equation for BTE is given as:

$$BTE\ (\%) = +25.03 + 1.20 \times Fuel + 8.87 \times Load + 0.2492 \times Speed - 0.9515 \times Fuel^2 - 3.33 \times Speed^2$$

Fig. 7 (a) depicts the behavior of Torque for distinct fuel blends of diesel, diethyl ether and manganese when the load is kept at lower setting. There is an increase in torque as the DEE proportion rises in fuel blends. But torque decreased after a certain increase in the amount of DEE because of lower calorific value. Fig. 7 (b) depicts the trend of Torque for fuels blends when the load is kept at higher setting. From Fig. 7 (a) and (b) it is apparent that all the fuel blends at higher load setting show greater torque as compared to the fuel blends at lower load setting when the speed is greater. For higher load and speed, the overall increase in the trend of torque is due to the rapid burning of fuel blends.

Fig. 8(a) and (b) depicts the trend in torque with respect to engine speed at lower loading condition and higher loading condition respectively. It can be observed that generally torque increase to maximum value and afterwards decrease. The speed range 1400–1600 rpm can be considered as most optimum region as the speed surpass from this region, the torque starts declining. Moreover, it can be observed that higher torque produces by blended fuels at higher loading conditions. The torque at lower loading condition was increased by 5.39, 15.43 and 11.88 % for 250 mg, 375 mg and 500 mg concentration of manganese in 10 % diethyl ether in diesel fuel. However, the torque 18.38, 28.33 and 23.89 % for 250 mg, 375 mg and 500 mg concentration of manganese in diethyl-diesel blend (10 %) respectively. Fig. 8 (c) depicts the comparison between the actual engine generated and the predicted RSM based Torque. The minimal torque is represented by the color blue which is 16.606 Nm, while the maximum torque is represented by the color red which is 78.55 Nm. This less disorderliness of predicted data of RSM proves that these values are best fit of regression model.

Table 7 shows ANOVA results for reduced regression model for Torque. The reduced quadratic model is significant having F value of 1111.68, also p-value is small indicating that the model terms are significant and R^2 (0.9808) which is approximately equal to 1. An adequate consistency is obtained between the predicted and adjusted R^2. A predicted R^2 of 0.9791 is in fair compliance with adjusted R^2 of 0.9800 i.e., Only 0.01 % chance exists for larger F-value in case of BTE because of noise. In case of Torque, the p value is less than 0.0001, which gives a reasonable fact that we do not have verification for lack of data fitting in reduced quadratic model. The p values of load, concentration of fuel blends and speed from Table 7 depict that they predominately impact on the engine performance.

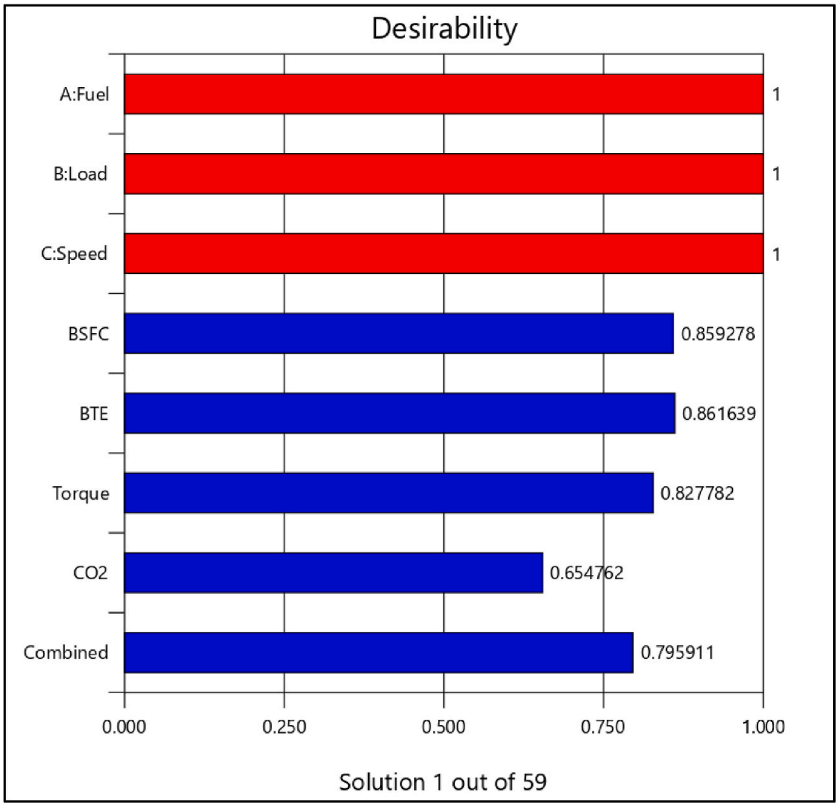

Fig. 11. Desirability chart.

$$Torque = +49.71 + 2.34 \times Fuel + 21.40 \times Load + 3.98 \times Speed + 1.16 \times Speed \times Fuel + 2.28 \times Load \times Speed - 2.29 \times Fuel^2 - 7.61 \times Speed^2$$

3.2. Impact on exhaust emission

Fig. 9 (a) depicts the behavior of CO_2 emissions for distinct fuel blends of diesel, diethyl ether and manganese when the load is kept at lower setting with the speed variations from 1000 to 1800 rpm. The figure shows that at 1000 rpm the value CO_2 emission is low when DEE ranges between 5 % and 15 % and manganese added in the fuel blends in high amount. Fig. 9 (b) depicts the CO_2 emissions trend for distinct fuels blends when the load is kept at higher setting and the speed is ranging from 1000 rpm to 1800 rpm. At 1800 rpm the CO_2 emission content is greater than for diesel fuel.

Fig. 10(a) and (b) show the general increasing trend of CO_2 emission with respect to engine speed at higher and lower loading conditions. A fuel blend with 10 % diethyl ether content in diesel fuel produced maximum CO_2 emission mainly because of improved combustion. CO_2 emissions were increased by 11.57, 30.52 and 20.33 % for manganese concentrations of 250 mg, 375 mg and 500 mg respectively at lower loading conditions. On the other side, CO_2 emissions were increased by 18.38, 28.33 and 23.89 % for manganese concentrations of 250 mg, 375 mg and 500 mg respectively at higher loading conditions. Fig. 10(c) depicts the comparison between the actual engine generated and the predicted RSM based CO_2 emission. The minimal CO_2 emission is represented by the color blue which is 1.95 %, while the maximum CO_2 emission is represented by the color red which is 13.89 %. This less disorderliness of predicted data of RSM proves that these values are best fit of regression model.

Table 8 shows ANOVA results for reduced regression model for CO_2. The reduced quadratic model considered significant having an F value of 288.67, also p-value is smaller than 0.0001 and R^2 (0.9386) which is approximately equal to 1. An adequate consistency is obtained between the predicted and adjusted R^2. The predicted R^2 of 0.9303 possess fair compliance with the adjusted R^2 of 0.9354. Only 0.01 % chance exists for higher F-value in case of BTE because of noise. In case of CO_2, the p value for model is less than 0.0001, which gives a reasonable fact that we do not have verification to show that data fitting lack in reduced quadratic model.

$$CO_2 = +6.49 + 0.46 \times Fuel + 0.78 \times Load + 3.60 \times Speed + 0.38 \times Load \times Fuel + 0.92 \times Fuel \times Speed + 0.13 \times Load \times Speed - 0.31 \times Fuel^2 + 0.65 \times Speed^2$$

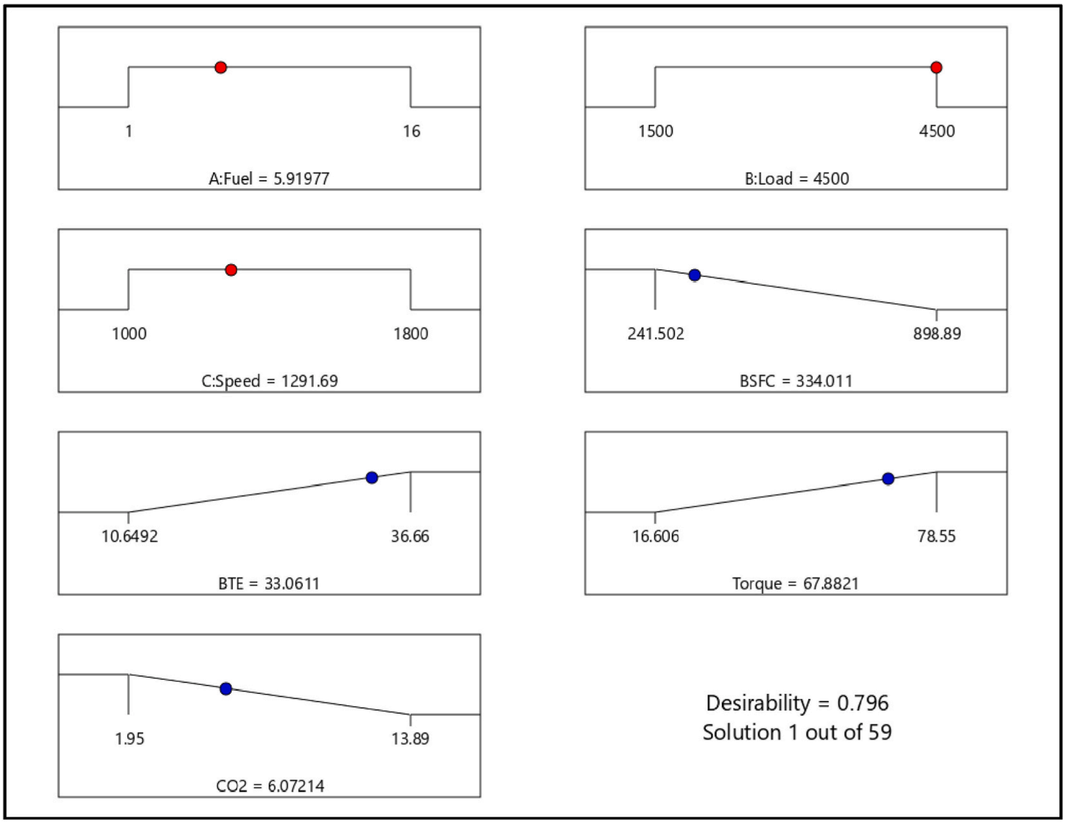

Fig. 12. Identified optimum values.

3.3. RSM-based optimization

This optimization is a vigorous way for the identification of optimized values for required desirable output by altering the input values. For the detailed understanding of trends of variables, the RSM-based optimization is helpful by providing the relationship between response and input factors. The present study entails the performance parameters of engine and emission are optimized. As in Table 9, the main objective is to maximize the BTE only, while for other parameters like BSFC and CO_2 minimum criteria is selected. The operating conditions of engine recognized by the optimization were at 4500 engine load and blend of diesel with DEE and manganese with 5.919 concentration. The response factors, with correspondence to the optimized operating factors, were 33.0611 % BTE, 334.011 (kg/kWh) BSFC, 67.8821 Nm torque and 6.072 % CO_2 as shown in Fig. 11. With the use of composite desirability (D), the statistical validity of optimization results against overall responses was examined. This value ranges between 0 and 1 and unit less, the most effective factor represented by this chart is close to 1.

In the present study, the composite desirability is 0.795 as shown in Fig. 12. It is prominent from the figure that d is largest for the BTE which is 0.861 and lowest for CO_2 which is 0.654. For torque and BSFC the value of d is 0.827 and 0.859 respectively.

4. Conclusion

The prime objective of present study was to evaluate the effect of different blends of diesel with diethyl ether and manganese (Mn) on engine performance parameters and emissions. The engine speed (1000–1800 rpm), load (1500 and 4500 W), and blend percentages (5–15 %) were the changing factors. The main conclusions of the research are given below:

All the results showed by ANOVA analysis give suitable fits for quadratic model. At higher load there is an increase of 29.98 % in BSFC when only DEE is added in the blend in comparison with blends when only diesel and Mn are the part of it. The increased in BTE as compared to the diesel fuel when higher percentage of DEE is included in the fuel at higher speed. At higher load for 10 % DEE, the increase in the BTE is 24.19 %, 28.17 % and 26.86 % when the Mn amount in blend is changed as 250, 375, and 500 mg respectively. However, the BTE at lower loading condition was 4.17, 8.75 and 6.89 % higher for manganese concentration 250, 375, and 500 mg respectively.

Di-ethyl ether percentage (10 %) in diesel fuel proved to be the most optimum blend ratio. At lower loading condition (1500 W), the BSFC was decreased by 3.30, 6.81 and 5.69 % for 250 mg, 375 mg and 500 mg concentration of manganese in diethyl-diesel blend (10 %) respectively. However, the BSFC was 10.62, 10.01 and 12.70 % higher for the above blended fuels at higher loading conditions.

The torque at lower loading condition was increased by 5.39, 15.43 and 11.88 % for 250 mg, 375 mg and 500 mg concentration of manganese in 10 % diethyl ether in diesel fuel. However, the torque 18.38, 28.33 and 23.89 % for 250 mg, 375 mg and 500 mg concentration of manganese in diethyl-diesel blend (10 %) respectively. CO_2 emissions were increased by 11.57, 30.52 and 20.33 % for manganese concentrations of 250 mg, 375 mg and 500 mg respectively at lower loading conditions. On the other side, CO_2 emissions were increased by 18.38, 28.33 and 23.89 % for manganese concentrations of 250 mg, 375 mg and 500 mg respectively at higher loading conditions.

The overall impact of manganese on engine emission and performance was good as desirability of 0.796 was obtained when 375 mg of Mn was used at 1300 rpm. It is revealed from the optimization that the composite desirability is 0.795 with 33.0611 % BTE, 334.011kg/kWh BSFC, 67.8821Nm torque and 6.072 % CO_2.

Although CO_2 is the product of complete combustion but it is a greenhouse gas and mainly responsible for global warming. In future, such techniques need to be developed which can perform their role in the abatement of CO_2 emissions.

CRediT authorship contribution statement

Hafiz Hamza Fayyaz: Data curation, Investigation, Writing – original draft. **M.A. Mujtaba:** Conceptualization, Formal analysis, Project administration, Writing – review & editing, Supervision. **Saad Jahangir:** Formal analysis, Software, Writing – review & editing. **Shahid Imran:** Project administration, Writing – review & editing. **Muhammad Ali Ijaz Malik:** Methodology, Software, Validation, Writing – review & editing. **H. Fayaz:** Funding acquisition, Writing – review & editing. **C Ahamed Saleel:** Funding acquisition, Writing – review & editing. **Uqba Hassan:** Writing – review & editing. **Saifullah Quershi:** Data curation, Writing – review & editing. **Hamza farooq:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M.U. Hassan, et al., Tribological analysis of molybdenum disulfide (MOS2) additivated in the Castor and mineral oil used in diesel engine, Sustainability 14 (17) (2022), 10485.
[2] M. Usman, et al., Experimental assessment of regenerated lube oil in spark-ignition engine for sustainable environment, Adv. Mech. Eng. 12 (7) (2020), 1687814020940451.
[3] H.D. Matthews, K. Caldeira, Stabilizing climate requires near-zero emissions, Geophys. Res. Lett. 35 (4) (2008).
[4] M.A. Ijaz Malik, et al., Response surface methodology application on lubricant oil degradation, performance, and emissions in SI engine: a novel optimization of alcoholic fuel blends, Sci. Prog. 106 (1) (2023), 00368504221148342.
[5] M.A.I. Malik, et al., Use of methanol-gasoline blend: a comparison of SI engine characteristics and lubricant oil condition, J. Chin. Inst. Eng. 45 (5) (2022) 402–412.
[6] M.A. Ijaz Malik, et al., Experimental evaluation of methanol-gasoline fuel blend on performance, emissions and lubricant oil deterioration in SI engine, Adv. Mech. Eng. 13 (6) (2021), 16878140211025213.
[7] R.M.G. Marrero, R.M. Lorenzo-Alegría, G.A. Marrero, A dynamic model for road gasoline and diesel consumption: an application for Spanish regions, Int. J. Energy Econ. Pol. 2 (4) (2012) 201–209.
[8] S. Kuczyński, et al., Experimental investigations and operational performance analysis on compressed natural gas home refueling system (CNG-HRS), Energies 12 (23) (2019) 4511.
[9] F. Leach, et al., The scope for improving the efficiency and environmental impact of internal combustion engines, Transport Eng. 1 (2020), 100005.
[10] J. Zhang, Particle Matter Emission Control and Related Issues for Diesel Engines, University of Birmingham, 2011.
[11] B. Guan, et al., Review of the state-of-the-art of exhaust particulate filter technology in internal combustion engines, J. Environ. Manag. 154 (2015) 225–258.
[12] R.K. Maurya, R.K. Maurya, Luby, Characteristics and Control of Low Temperature Combustion Engines, Springer, 2018.
[13] A.C. Lloyd, T.A. Cackette, Diesel engines: environmental impact and control, J. Air Waste Manag. Assoc. 51 (6) (2001) 809–847.
[14] M. Gad, et al., A comprehensive review on the usage of the nano-sized particles along with diesel/biofuel blends and their impacts on engine behaviors, Fuel 339 (2023), 127364.
[15] M. Elkelawy, et al., A comprehensive review on the effects of diesel/biofuel blends with nanofluid additives on compression ignition engine by response surface methodology, Energy Convers. Manag. X 14 (2022), 100177.
[16] E. Ahmed, et al., Application of ANN to predict performance and emissions of SI engine using gasoline-methanol blends, Sci. Prog. 104 (1) (2021), 00368504211002345.
[17] M. Usman, et al., Acetone–Gasoline blend as an alternative fuel in SI engines: a novel comparison of performance, emission, and lube oil degradation, ACS Omega 8 (12) (2023) 11267–11280.
[18] M. Usman, et al., Comparative assessment of ethanol and methanol–ethanol blends with gasoline in SI engine for sustainable development, Sustainability 15 (9) (2023) 7601.
[19] A. Atmanli, Comparative analyses of diesel–waste oil biodiesel and propanol, n-butanol or 1-pentanol blends in a diesel engine, Fuel 176 (2016) 209–215.
[20] M. Usman, et al., Enviro-economic assessment of HHO–CNG mixture utilization in spark ignition engine for performance and environmental sustainability, Energies 15 (21) (2022) 8253.
[21] M. Usman, et al., Experimental assessment of performance, emission and lube oil deterioration using gasoline and LPG for a sustainable environment, Case Stud. Therm. Eng. 49 (2023), 103300.
[22] B. Zhang, Y. Jiang, Y. Chen, Research on calibration, economy and PM emissions of a marine LNG–diesel dual-fuel engine, J. Mar. Sci. Eng. 10 (2) (2022) 239.

[23] M.M. Rahman, et al., Particle emissions from microalgae biodiesel combustion and their relative oxidative potential, Environ. Sci. J. Integr. Environ. Res.: Process. Impacts 17 (9) (2015) 1601–1610.
[24] F.M. Hossain, M.N. Nabi, R.J. Brown, Investigation of diesel engine performance and exhaust emissions of microalgae fuel components in a turbocharged diesel engine, Energy Convers. Manag. 186 (2019) 220–228.
[25] F.M. Hossain, et al., Investigation of microalgae HTL fuel effects on diesel engine performance and exhaust emissions using surrogate fuels, Energy Convers. Manag. 152 (2017) 186–200.
[26] A. Zare, et al., Engine performance during transient and steady-state operation with oxygenated fuels, Energy Fuel. 31 (7) (2017) 7510–7522.
[27] B.J. Mitchell, et al., Engine blow-by with oxygenated fuels: a comparative study into cold and hot start operation, Energy 140 (2017) 612–624.
[28] D. Kannan, M.N. Nabi, J.E. Hustad, Influence of Ethanol Blend Addition on Compression Ignition Engine Performance and Emissions Operated with Diesel and Jatropha Methyl Ester, SAE Technical Paper, 2009.
[29] İ. Sezer, A review study on the using of diethyl ether in diesel engines: effects on NOx emissions, Int. J. Adv. Eng. Technol. 7 (4) (2018) 164–183.
[30] J. Devaraj, Y. Robinson, P. Ganapathi, Experimental investigation of performance, emission and combustion characteristics of waste plastic pyrolysis oil blended with diethyl ether used as fuel for diesel engine, Energy 85 (2015) 304–309.
[31] M. El-Adawy, A. Ibrahim, M. El-Kassaby, An experimental evaluation of using waste cooking oil biodiesel in a diesel engine, Energy Technol. 1 (12) (2013) 726–734.
[32] A. Ibrahim, M. El-Adawy, M. El-Kassaby, The impact of changing the compression ratio on the performance of an engine fueled by biodiesel blends, Energy Technol. 1 (7) (2013) 395–404.
[33] A. Ibrahim, Performance and combustion characteristics of a diesel engine fuelled by butanol–biodiesel–diesel blends, Appl. Therm. Eng. 103 (2016) 651–659.
[34] D.C. Rakopoulos, C.D. Rakopoulos, E.G. Giakoumis, Impact of properties of vegetable oil, bio-diesel, ethanol and n-butanol on the combustion and emissions of turbocharged HDDI diesel engine operating under steady and transient conditions, Fuel 156 (2015) 1–19.
[35] D.C. Rakopoulos, et al., Influence of properties of various common bio-fuels on the combustion and emission characteristics of high-speed DI (direct injection) diesel engine: vegetable oil, bio-diesel, ethanol, n-butanol, diethyl ether, Energy 73 (2014) 354–366.
[36] B. Mohan, et al., Numerical analysis of spray characteristics of dimethyl ether and diethyl ether fuel, Appl. Energy 185 (2017) 1403–1410.
[37] I. Sezer, Thermodynamic, performance and emission investigation of a diesel engine running on dimethyl ether and diethyl ether, Int. J. Therm. Sci. 50 (8) (2011) 1594–1603.
[38] A. Ciftci, et al., Dimethyl ether, diethyl ether & ethylene from alcohols over tungstophosphoric acid based mesoporous catalysts, Chem. Eng. J. 207 (2012) 85–93.
[39] I. Sezer, Theoretical analysis the use of dimethyl ether and diethyl ether in a diesel engine, Catalyst 3 (2) (2011) 2.
[40] D.C. Rakopoulos, et al., Characteristics of performance and emissions in high-speed direct injection diesel engine fueled with diethyl ether/diesel fuel blends, Energy 43 (1) (2012) 214–224.
[41] M. Norhafana, et al., A review of the performance and emissions of nano additives in diesel fuelled compression ignition-engines, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2018.
[42] M.E.M. Soudagar, et al., The effect of nano-additives in diesel-biodiesel fuel blends: a comprehensive review on stability, engine performance and emission characteristics, Energy Convers. Manag. 178 (2018) 146–177.
[43] S. Srihari, S. Thirumalini, K. Prashanth, An experimental study on the performance and emission characteristics of PCCI-DI engine fuelled with diethyl ether-biodiesel-diesel blends, Renew. Energy 107 (2017) 440–447.
[44] A. Ibrahim, Investigating the effect of using diethyl ether as a fuel additive on diesel engine performance and combustion, Appl. Therm. Eng. 107 (2016) 853–862.
[45] S. Sivalakshmi, T. Balusamy, Effect of biodiesel and its blends with diethyl ether on the combustion, performance and emissions from a diesel engine, Fuel 106 (2013) 106–110.
[46] K. Tudu, S. Murugan, S. Patel, Effect of diethyl ether in a DI diesel engine run on a tyre derived fuel-diesel blend, J. Energy Inst. 89 (4) (2016) 525–535.
[47] S. Uslu, M. Aydın, Effect of operating parameters on performance and emissions of a diesel engine fueled with ternary blends of palm oil biodiesel/diethyl ether/diesel by Taguchi method, Fuel 275 (2020), 117978.
[48] D. Barik, S. Murugan, Effects of diethyl ether (DEE) injection on combustion performance and emission characteristics of Karanja methyl ester (KME)–biogas fueled dual fuel diesel engine, Fuel 164 (2016) 286–296.
[49] S. Imtenan, et al., Effect of n-butanol and diethyl ether as oxygenated additives on combustion–emission-performance characteristics of a multiple cylinder diesel engine fuelled with diesel–jatropha biodiesel blend, Energy Convers. Manag. 94 (2015) 84–94.
[50] D. Barik, et al., Exploration of the dual fuel combustion mode on a direct injection diesel engine powered with hydrogen as gaseous fuel in port injection and diesel-diethyl ether blend as liquid fuel, Int. J. Hydrogen Energy (2023).
[51] M. Çelik, H. Solmaz, H.S. Yücesu, Examination of the effects of organic based manganese fuel additive on combustion and engine performance, Fuel Process. Technol. 139 (2015) 100–107.
[52] A. Fayyazbakhsh, V. Pirouzfar, Investigating the influence of additives-fuel on diesel engine performance and emissions: analytical modeling and experimental validation, Fuel 171 (2016) 167–177.
[53] A. Konstandopoulos, et al., Ceramic particulate traps for diesel emissions control—effects of a manganese–copper fuel additive, SAE Trans. (1988) 37–53.
[54] W.M. Draper, et al., Impact of a Ceramic Trap and Manganese Fuel Additive on the Biological Activity and Chemical Composition of Exhaust Particles from Diesel Engines Used in Underground Mines, SAE Technical Paper, 1987.
[55] M. Celik, H.S. Yucesu, M. Guru, Investigation of the effects of organic based manganese addition to biodiesel on combustion and exhaust emissions, Fuel Process. Technol. 152 (2016) 83–92.
[56] A.T. Hoang, Combustion behavior, performance and emission characteristics of diesel engine fuelled with biodiesel containing cerium oxide nanoparticles: a review, Fuel Process. Technol. 218 (2021), 106840.
[57] A. Prabu, R. Anand, Production and application of biodiesel–A case study, Int. J. Eng. Res. Dev. 2 (2) (2012) 28–41.
[58] M. Anish, et al., An evaluation of biosynthesized nanoparticles in biodiesel as an enhancement of a VCR diesel engine, Fuel 328 (2022), 125299.
[59] M. Lenin, M. Swaminathan, G. Kumaresan, Performance and emission characteristics of a DI diesel engine with a nanofuel additive, Fuel 109 (2013) 362–365.
[60] J. Lv, S. Wang, B. Meng, The effects of nano-additives added to diesel-biodiesel fuel blends on combustion and emission characteristics of diesel engine: a review, Energies 15 (3) (2022) 1032.
[61] A. Selvaganapthy, et al., An experimental investigation to study the effects of various nano particles with diesel on DI diesel engine, ARPN J. Sci. Technol. 3 (1) (2013) 112–115.
[62] A.C. Sajeevan, V. Sajith, Diesel engine emission reduction using catalytic nanoparticles: an experimental investigation, J. Eng. 2013 (2013).
[63] S.H. Hosseini, et al., Effect of added alumina as nano-catalyst to diesel-biodiesel blends on performance and emission characteristics of CI engine, Energy 124 (2017) 543–552.