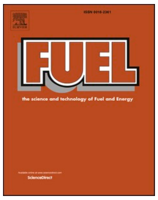
ARTICLE IN PRESS

Fuel xxx (xxxx) xxx

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel



Full Length Article

Optimization and investigation the effects of using biodiesel-ethanol blends on the performance and emission characteristics of a diesel engine by genetic algorithm

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ARTICLE INFO

Keywords:
Ethanol
Biodiesel
Performance
Exhaust Emissions
Optimization
Diesel Engine

ABSTRACT

The purpose of this research is to investigate the combined effects of biodiesel-ethanol fuel blends on the performance and emission parameters of a diesel engine by the response surface methodology (RSM). The genetic algorithm was also applied for optimizations of the parameters. According to the results, the brake power and torque were decreased by approximately 30% with increasing the amount of ethanol in the fuel mixture. On the other hand, the BSFC of fuel blends enhanced around 16% with a higher percentage of ethanol as a result of the lower calorific value of ethanol compared with biodiesel. However, higher viscosity and density of biodiesel cause more fuel injection; so there is no notable difference in BSFC values for all blends. About emission parameters, the more percentage of ethanol resulted in less amount of smoke level and NOx emission around 38% and 17%, respectively due to the high level of oxygen in the molecular structure of ethanol. However, there is an approximately 44% decrease in CO emissions for a high percentage of biodiesel contained blends. According to the GA optimization, the results showed that the biodiesel percentage in the fuel mixture, RPM, and engine load were converged to 94.65%, 2800, and 65.75%, respectively as the optimal conditions. It is concluded that ethanol is more effective to improve the emission characteristics than that of the performance characteristics.

1. Introduction

Based on growing demands for energy especially in Asia and the Middle East and gaseous pollutant issues, it is necessary to find alternative energy sources and solutions for internal combustion engines [1]. Therefore, biomass sources mostly biofuels such as biodiesel and bioethanol are receiving more attention these years [1–3]. Vegetable origin biofuels were considered to be advantageous among the sources due to their high biodegradability and lubricity, which has been the main concern in modern engine combustion [4,5]. Biodiesel is a form of diesel fuel derived from plants or animals and consisting of long-chain fatty acid esters. Bioethanol is an oxygen content fuel that can be produced from agricultural waste and molasses feedstock [6,7]. Bioethanol is an oxygen content fuel that can be produced from agricultural waste and molasses feedstock [8–10]. However, lower cetane index and poor solubility of ethanol compared with diesel fuel cause many technical limitations to the direct use of ethanol in cold weather conditions [7,9,11].

Regulated emissions such as nitrogen oxide (NOx), carbon monoxide (CO), and smoke number are the main kinds of emissions in the exhaust of diesel engines. Carbon monoxide is toxic to humans and animals when encountered in higher concentrations. Nitric oxide (NO) and nitrogen dioxide (NO_2) as NOx emissions formed during the combustion of fuels in motor vehicles, residential, engines, and other equipment. There are many studies related to the optimization of the performance and emission characteristics of diesel engines fueled with biodiesel-diesel blends [12–18]. Some of them are reported in the below lines:

Abbreviations: B, Biodiesel; E, Ethanol; D, Diesel; CO, Carbon monoxide; NOx, Nitrogen oxides.

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https://doi.org/10.1016/j.fuel.2020.119753
Received 23 July 2020; Received in revised form 29 September 2020; Accepted 11 November 2020

Please cite this article as: Alireza Shirneshan, *Fuel*, https://doi.org/10.1016/j.fuel.2020.119753

Singh et al. [19] investigated the effect of Jatropha biodiesel through transesterification reaction with the use of a heterogeneous catalyst. The results showed that the performance of the engine fuelled with B20 was almost comparable to that of diesel fuel. Moreover, a significant decrease in HC emissions (14.3%) compared to diesel, and a slight increase in NOx emissions (2%) was also observed.

Engine operating parameters optimization has been executed using the central composite design method (CCD) by Elkelawy et al. [20] to achieve an optimum break thermal efficiency of a lone cylinder DI-engine fueled by biodiesel-diesel mixtures. RSM optimizer results indicated that the best possible values of BTE, UHC, and NOx were 13.656%, 120.7748 ppm, and 234.8926 ppm, respectively, at the maximum value of biodiesel mixture of 70% and break the power of 2.05 kW.

In another study [21], the effects of using B20 and B50 blends of diesel-biodiesel fuels mixed with three different concentrations of the Acetone as an oxygenated organic compound were investigated in a diesel engine. The results obtained for B20 with 2% acetone showed that the Brake Thermal Efficiency (BTE) was enhanced by 12.64% when compared with the commercial diesel fuel. Besides, there are a reduction of 18.09% and 11.22% for the exhaust gas temperature and specific energy consumption, respectively. Carbon monoxide (CO), Carbon dioxide (CO_2), UHC, and Particulate matter emissions were reduced dramatically by 63.38%, 22.69%, 47.76%, and 40.84%.

Elkelawy et al. [22] prepared three diesel-biodiesel Blends with Mn (II) supramolecular complex nanoparticle emulsions. The results showed that the operations of the engine in the presence by using nanofluid emulsions improved the thermal brake efficiency by 15–20% compared with diesel fuel. Furthermore, CO and HC emissions are significantly decreased by 49–62% and 15–61% compared to pure diesel fuel, respectively. It is observed that the NOx emissions for all nanofluids combustion increase by 30–68% and the smoke emissions reduce by 32–44% in comparison with pure Diesel.

However, a little research was done on the use of biodiesel/ethanol blends in diesel engines. Wei et al. [23] investigated the effects of biodiesel-n-butanol and biodiesel-ethanol blends on performance and emissions of a DI diesel engine. The results showed that biodiesel-ethanol blends have more adverse effects on engine performance than that on biodiesel-n-butanol blends, especially at low engine loads. Moreover, the fuel blends increase CO emission; but reduces NOx emission. Besides, the biodiesel-ethanol blends are more effective to reduce PM and NOx emissions but the biodiesel-n-butanol blends produced lower HC and CO emissions. Yilmaz and Sanchez [8] investigated the effect biodiesel-methanol and biodiesel-ethanol blends on performance and emission characteristics of a two-cylinder diesel engine under various loads. The results showed that biodiesel-alcohol blends in comparison with neat diesel reduced NOx emissions while enhanced CO and HC emissions at engine loads below 70%. The results also showed that biodiesel-ethanol blend is more effective than biodiesel-methanol to reduce pollutant emissions. Zheng et al. [24] performed research to investigate the impacts of biodiesel-n-butanol, biodiesel-ethanol, and biodiesel-2,5-dimethylfuran blends on the combustion and emissions on a diesel engine. The results showed that the ITE of an engine fueled with biodiesel-diesel blends was lower than that of diesel fuel at low engine loads. The authors reported that biodiesel-diesel blends had higher ITE than that of neat diesel fuel, especially with increasing engine load at EGR rates. The results also showed that neat biodiesel, n-butanol, and 2,5-dimethylfuran blends produced higher NOx emissions compared to neat diesel, while ethanol had lower NOx emissions. The results of this research also indicated that thermal efficiency and smoke improved at high engine load by increasing the amount of biodiesel, n-butanol, and 2,5-dimethylfuran. Zheng et al. [25] investigated the effect of n-butanol, 2,5-dimethylfuran, and ethanol blends on the emissions and combustion characteristics of an RCCI diesel engine. The results showed that biodiesel-ethanol blends had longer ignition delay than the other fuels and this fuel blend indicated a lower NOx and soot emissions. On the other hand, biodiesel-n-butanol produced the highest indicated thermal efficiency under RCCI combustion. Shamun et al. [26] investigated the effect of diesel-biodiesel-ethanol blends on the net indicated efficiency and emissions of a light-duty CI engine. The results indicated that fuel blend with a higher proportion of ethanol caused a higher net indicated efficiency compared to diesel. About the emissions, the soot-NOx reduced notably when the fuel blend included a higher amount of ethanol. The results showed that the THC and CO emissions increased for the ethanol and biodiesel included blends than for the diesel at lower engine loads. Tutak et al. [27] performed a study to compare the effect of combustion, emission and, the performance of diesel-ethanol and biodiesel-ethanol fuel blends with the volumetric fraction up to 45% for ethanol on a one-cylinder diesel engine. The results showed that the highest ITE value was achieved for the diesel-ethanol blend, blend included 35% of the ethanol. Moreover, the maximum value of NOx was obtained for the diesel-ethanol blend included 70% of diesel. The results also indicated that THC emissions enhanced up to around 40% of the ethanol proportion in the fuel mixture. Madiwale et al. [9] presented an experimental study to investigate the effect of ethanol addition to biodiesel-diesel blends on the performance of a single-cylinder engine. The results of performance showed that brake power and BTE improved by the addition of ethanol to biodiesel-diesel blends while BSFC increased at various loads. Hu et al. [28] presented an experimental study to evaluate the emissions characteristics of a diesel engine fueled with the ethanol-biodiesel-diesel blends. The results of volatile organic compounds emissions showed that ethanol-biodiesel-diesel mixture increased total emissions around 85% at the maximum power but it decreased by 15% and 21% at 10% and 50% engine loads, respectively compared with diesel. The volatile organic compounds emissions of the ethanol-biodiesel-diesel blend were improved compared to neat diesel at medium and low engine loads. Pidol et al. [29] conducted a study of the properties of ethanol-blended fuels and evaluates their behavior in conventional diesel combustion and advanced combustion such as low-temperature combustion. The results showed that the addition of ethanol into diesel fuel affects some properties such as blend stability, cetane number, and flash point. The results also showed that there is a combined reduction of smoke levels and NO*x* emissions, with higher fuel consumption. Moreover, these biofuels lead to an improved maximum power output.

Aydin and İlkılıç [30] used ethanol as an additive to research the possible use of higher percentages of biodiesel in an unmodified diesel engine. 20% biodiesel and 80% diesel fuel and 80% biodiesel (BE20) and 20% ethanol were used in a single-cylinder diesel engine. The effect of test fuels on engine torque, power, and brake specific fuel consumption, brake thermal efficiency, exhaust gas temperature, and CO, CO_2, NO*x*, and SO_2 emissions was investigated. The experimental results showed that the performance of the CI engine was improved with the use of the 80% biodiesel and 20% ethanol fuel blend in comparison to 20% biodiesel and 80% diesel fuel blend. Besides, the exhaust emissions for BE20 were fairly reduced.

According to the literature review, normally the amount of ethanol in diesel-biodiesel-ethanol blend is 5 to 20%, however, some researchers used 30 to 50% ethanol in diesel-biodiesel-ethanol blend [26,31,32]. Also, some studies used 50 to 80% ethanol in ethanol-diesel blends [33,34]. But the maximum amount of ethanol in the biodiesel-ethanol blends is 45% as was mentioned in the introduction.

To overcome high expense, costly, and time-consuming experimental approach exhorts, the use of the fuzzy logic system and artificial neural network and RSM techniques help in the proper prediction of data with high accuracy that delineate the actual results [35–37].

Response surface methodology is a gathering of the statistical-based mathematical methods which is among the most relevant multivariate techniques for engine modeling. Response surface methodology also measures the assembly among the governing engine input factors and the resulting output responses of the engine [38]. Moreover, several optimization techniques have been developed and used in engine performance and emission parameters optimization. It is a well-known fact that classical optimization techniques impose several limitations on solving mathematical programming models. Based on this motivation, nature-inspired algorithms such as Genetic Algorithm (GA), Simulated Annealing (SA), and Tabu Search (TS) can be given more attention.

Literature reviews showed that there are so far no researches focused on the investigation of the combined effects of using biodiesel-ethanol blends and various engine speeds and loads on the performance and emission characteristics of a diesel engine. Moreover, there is not any discussion about optimization in these studies that considers ethanol and biodiesel percentage in the fuel mixture, engine speed, and load. As an innovation, no research works were described in engine studies with a high percentage of ethanol (50%) in the fuel mixture. Therefore, the objective of this research paper is the optimization and investigation of the effects of biodiesel-ethanol blends on the performance and emission characteristics of a diesel engine. Response Surface Methodology (RSM) was applied to develop mathematical relationships between independent variables and brake power, torque, BSFC, CO, NOx emissions, and smoke level as the responses. Moreover, the Genetic Algorithm was employed to find the optimal conditions which lead to higher brake power and brake torque and lower BSFC, smoke level, CO, and NOx emissions. Moreover, thermo-physical properties and engine in-cylinder pressure for various fuel blends were investigated and compared with each other. Finally, the performance and emission parameters of the engine fuelled with a biodiesel-ethanol blend and neat diesel were compared.

2. Materials and methods

2.1. Biodiesel preparation and fuel properties

In the present investigation, biodiesel was supplied from Tarbiat Modares University Biofuel Lab. In this laboratory, biodiesel was produced from waste cooking oil by transesterification reaction using methanol and potassium hydroxide (KOH) tablets as the alcohol and catalyst respectively. Titration was performed to determine the amount of KOH needed to neutralize the free fatty acids in waste cooking oil. The amount of KOH needed as a catalyst was determined as 0.98 mg/g Oil. The biodiesel was obtained at a reaction temperature of 55 °C, 6:1 alcohol to oil molar ratio, and reaction time of 85 min.

Also, ethanol used in this study was purchased from a local supplier with 99% purity. The fuels were mixed by hand in the containers. The important properties of cooking oil methyl ester (biodiesel) and ethanol and fuel blends obtained from the ASTM method are shown in Tables 1 and 2, respectively.

2.2. Test engine

A direct-injection and water-cooled diesel engine has been used for the experimental tests. The specifications of the engine are presented in Table 3. The engine run with various biodiesel-ethanol blends at the different engine speeds and loads according to the matrix of experiments. Fig. 1 shows a schematic diagram of the engine setup and control panel. The engine was coupled to an eddy current dynamometer (E400) and an AVL gas analyzer (DiCom 4000) was used to measure emission parameters. Smoke meter AVL Di Smoke 4000 is used to measure the filter smoke level. The engine was allowed to run a few times until the cooling water and the lubricating oil temperature reach 80 °C and then the data were recorded. The pressure sensor (Kistler) was utilized to measure the combustion pressure (Table 4). The cylinder pressure data were recorded in 1°crank-angle increment. For each operating point, the cylinder pressures of 50 cycles were collected.

Table 1
Properties of biodiesel and ethanol fuels used for the present study.

Property	Method	Units	Biodiesel	Ethanol
Kinematical viscosity, 40 °C	ASTM-D445	mm^2/s	4.15	1.2
Density at 20 °C	–	kg/m^3	850	800
Lower calorific value	ASTM-D240	kJ/kg	38,800	26,800
Cetane number	ASTM-D613	–	63	8
Oxygen content	–	wt%	11	34.8
Carbon content	–	wt%	77	52

Table 2
Thermo-physical properties of the fuel blends.

Property	unit	B50E50	B60E40	B75E25	B90E10
Kinematic viscosity (40°C)	Mm^2/s	2.4	2.62	3.17	3.58
Density	g/cm^3	825	830	838	845
Lower calorific value	kJ/kg	32,800	34,000	35,800	37,600
Cetane number	–	38	43	50	59

Table 3
Engine specifications.

Engine type	Diesel OM314
Cylinder number	4
Compression ratio	16:1
Stroke(mm) × Bore(mm)	128 × 97
Maximum Power	82 kW at 2800 RPM
Maximum Torque	350 N.m at 1800 RPM

2.3. Design of experiment and analysis

The Experimental design performed by Design-Expert software v7 according to the RSM using the central composite design (CCD) to report the relationship between the response and independent variables. The independent parameters were defined as the biodiesel percentage in fuel mixture (X_1), engine speed (X_2), and engine load (X_3) according to Table 5. The six responses (Y) were power, torque, brake specific fuel consumption, NOx, CO emission, and smoke level. Based on the RSM method (CCD) for three independent variables α is 1.682, and in the experimental data matrix (Table 5), the rows 6,7,8,15,19 and 20 of should be repeated. The response functions were extracted according to the second-order polynomial equation based on Eq. (1) [38]:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_{11}{}^2 + b_{22}x_{22}{}^2 + b_{33}x_{33}{}^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \tag{1}$$

Subscripts 1, 2, 3 indicate the percentage of biodiesel in the ethanol-biodiesel mixture, engine speed, and engine load, respectively.

Moreover, Design-Expert software was applied to develop the mathematical models and study the following regression analyses and analyses of variance. Based on the models, the performance and exhaust characteristics of the engine were calculated and plotted in the plots.

2.4. Uncertainty analysis

The uncertainties of the experimental parameters are affected by different error sources, namely, the random fluctuation of employed instruments, the calibration of the test bed, and the observation accuracy [4]. For directly measured parameters, the measurement uncertainties are defined by the accuracies of the experimental instruments. For computed parameters, the measurement uncertainties are determined based on the principle of the root-mean-square method and the measurement accuracies of the measured parameters [39,40]:

$$e_R = \left[\left(\frac{\partial f}{\partial X_1}e_1\right)^2 + \left(\frac{\partial f}{\partial X_2}e_2\right)^2 + \cdots + \left(\frac{\partial f}{\partial X_n}e_n\right)^2\right]^{\frac{1}{2}} \tag{2}$$

The uncertainty of measured parameters is presented in Table 6. It is necessary to mention that the uncertainty in the computation as an example is given for the B75E25 blend at 1900 engine speed and load of 62.5%.

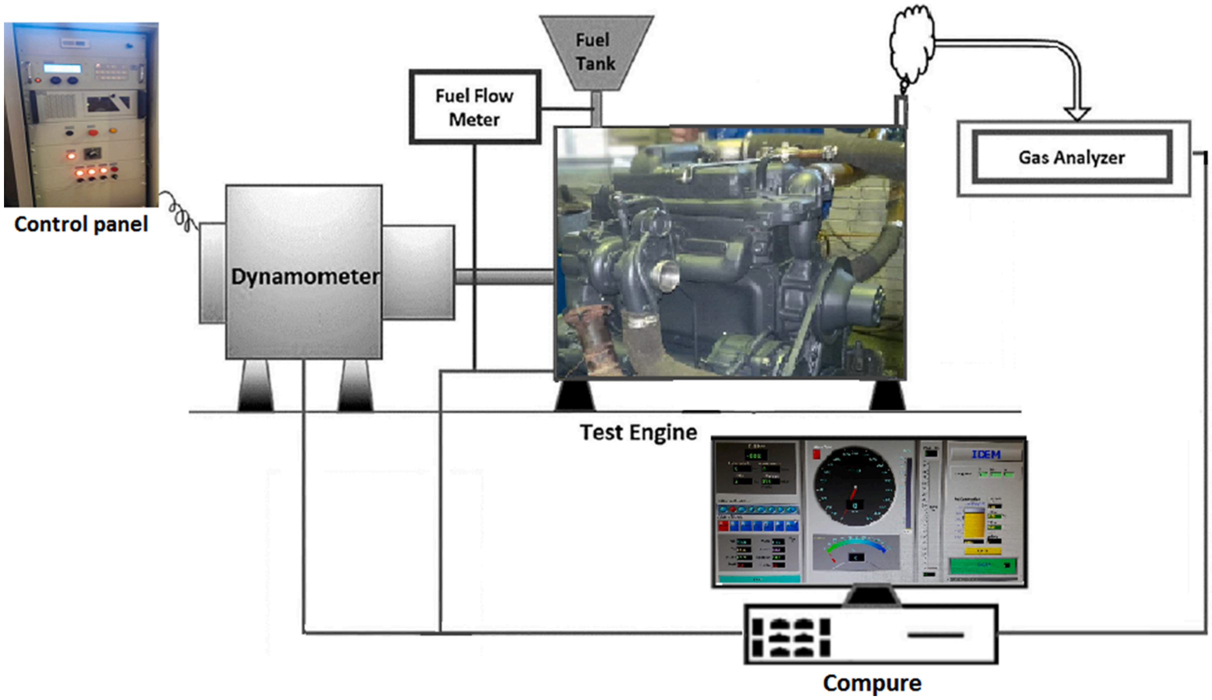

Fig. 1. The schematic diagram of the engine set up and control panel.

Table 4
Technical specifications of the in-cylinder pressure sensor.

Model	6613CA
Measurement range	0–250 bar
Sensitivity	10 mV/bar
Sensitivity to acceleration	0.001 bar/g

Table 5
The central composite experimental design matrix.

Experiment number	Percentage of biodiesel in the biodiesel-ethanol mixture (%) X_1	Engine speed(rpm) X_2	Engine load (%) X_3
1	60	1365	40
2	90	1365	85
3	75	1900	25
4	100	1900	62.5
5	90	2435	85
6	75	1900	62.5
7	75	1000	62.5
8	75	1900	62.5
9	75	1900	62.5
10	75	1900	100
11	60	1365	85
12	50	1900	62.5
13	90	1365	40
14	90	2435	40
15	75	1900	62.5
16	60	2435	40
17	75	2800	62.5
18	60	2435	85
19	75	1900	62.5
20	75	1900	62.5

2.5. Optimization

The Genetic Algorithm (GA) is a *meta*-heuristic optimization method inspired by the natural selection mechanism of evolution [41]. Due to its coding capability, the GA can be implemented to real optimization problems with sophisticated fitness functions. Also, high-dimensional and multi-objective optimization problems can be easily solved by the GA. Furthermore, the multi-modal optimization problems can be solved by the GA due to the random processes of the initialization, selection, cross-over, and mutation. The GA is also a metaheuristic method for solving almost all types of optimization problems having large search spaces, especially within multi-variable spaces. Finally, it should be noted that GA can be applied to non-convex optimization problems. Therefore, the GA seems an interesting method for global optimization [42,43]. Since the GA is a global, stochastic, and robust search method, it was preferred for the current problem.

Table 6
The accuracies and uncertainties of the measurements and calculated parameters.

Measured parameter	Measurement range	Accuracy of measurement
Speed	0–2500 rpm	±1 rpm
Fuel flow rate	–	±0.1%
CO	0–10%	0.01 vol%±
NO_X	0-5000PPM	±5% reading
HC	0-2000PPM	±3% reading
Soot opacity	0–100%	±0.1%
Torque	0–400Nm	±0.5%
Calculated parameter		Uncertainty in the computation
Brake power	–	±0.263 kW
BSFC	–	±1.216 gr/kWh

In this method, a population consisting of random individuals is generated[44]. Then an evolution process starts in which individuals with better fitness values are more likely to be selected. A new generation is stochastically formed from the previous generation based on bio-inspired operators such as selection, cross over, and mutation. In other words, the new generation is randomly formed from the previous one while the dominant individuals have more chance to be reproduced. The iterative process continues until convergence is attained. The GA algorithm is illustrated in Fig. 2. Due to its encoding capability from the search space into the genetic representation space, the GA is appropriate for finding the global optimum points in nonlinear optimization problems. Hence, the GA has shown acceptable performance in a variety of optimization problems until now. In this paper, the GA was employed to

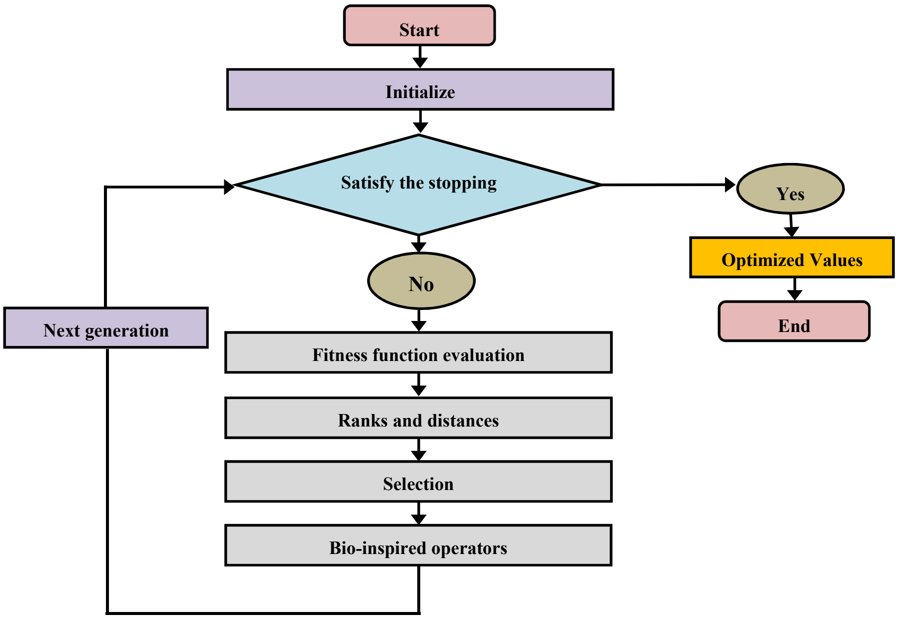

Fig. 2. The GA algorithm.

find the optimal conditions which lead to higher brake power and brake torque and lower BSFC, smoke level, CO, and NOx emissions.

3. Analysis and results

3.1. Changes in different thermo-physical properties with the biodiesel-ethanol blends relative to neat biodiesel fuel

Figs. 3 to 6 show the changes in kinematic viscosity, density, lower calorific value, and cetane number properties with the biodiesel-ethanol blend relative to neat biodiesel fuel, respectively.

The results indicated that the addition of ethanol in the fuel mixture reduces the entire thermo-physical properties of the blends. Based on the results the kinematic viscosity decreases by around 42% when the amount of ethanol in the fuel mixture is 50% in comparison with B100. However, there is a 14% reduction for B90E10 compared with neat biodiesel. According to the results, the minimum reduction (0.6%) in density belongs to B90E10 while the maximum decrement (3%) occurs for B50E50 relative to neat biodiesel fuel. Moreover, the minimum and maximum reduction in lower calorific value belong to B90E10 and B50E50 fuel blends with the amount of 3 and 16% compared with neat biodiesel, respectively. The results indicate that B50E50 has the highest reduction (40%) in cetane number and the lowest decrease (6.5%) in this property belongs to the B90E10 blend with respected to B100. As the results show, the addition of ethanol has more influence on kinematic viscosity and cetane index in comparison with the other two

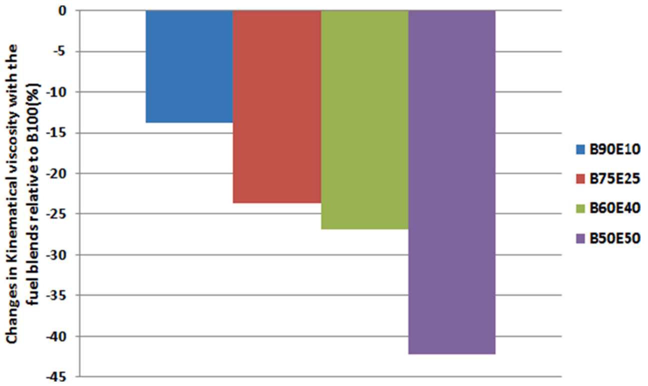

Fig. 3. Changes in kinematic viscosity with the biodiesel-ethanol blends relative to neat biodiesel.

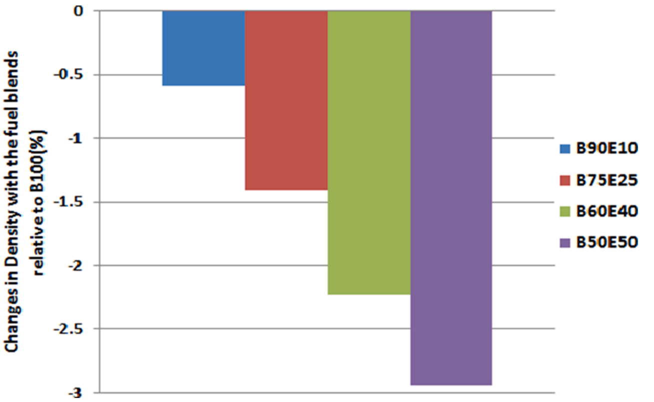

Fig. 4. Changes in density with the biodiesel-ethanol blends relative to neat biodiesel.

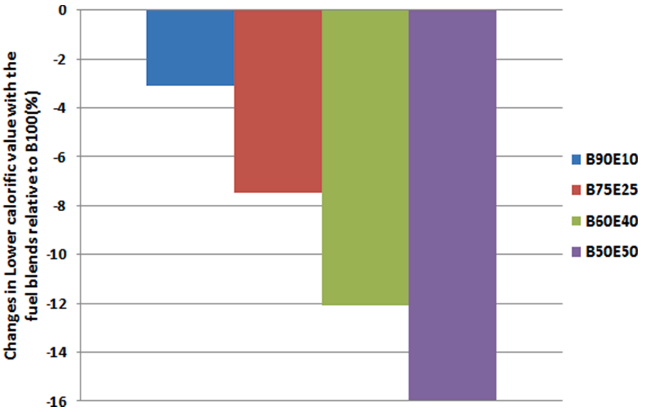

Fig. 5. Changes in lower calorific value with the biodiesel-ethanol blends relative to neat biodiesel.

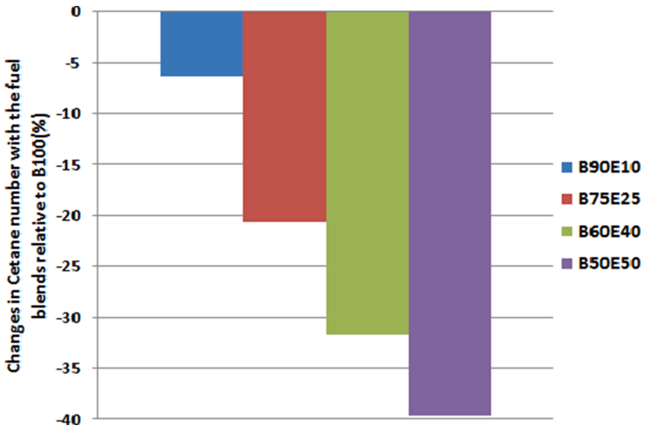

Fig. 6. Changes in cetane number with the biodiesel-ethanol blends relative to neat biodiesel.

properties.

3.2. Engine in-cylinder pressure for various fuel blends

Fig. 7 shows the variation of in-cylinder (combustion) pressure versus crank angle for B90E10, B75E25, B60E40, and B50E50 fuel blends at the engine speed of 1900 RPM and full engine load.

Fig. 7 shows that, in general, the blended fuels including higher biodiesel percentage lead to higher in-cylinder pressure. It could be due to the higher heating value of the biodiesel that causes higher in-cylinder pressure. Another reason is the higher cetane number of biodiesel compared with ethanol that resulted in earlier combustion and more time to occur complete combustion due to its shorter ignition delay [6,45,46]. However, the maximum in-cylinder pressure varies with increasing ethanol concentration because of prolonged the ignition delay which could move the combustion process away from the TDC [47].

On the other hand, the premixed burn portion of ethanol is greater than that of biodiesel. This phenomenon resulted from the superior evaporation rate and longer ignition delay of ethanol which provide enhanced fuel-air mixing during the premixed burn phase that resulted in the highest peak of in-cylinder pressure for B50E50 among all fuel blends [28,48].

3.3. Statistical analysis

The coefficients of regression models, R^2, and p-values for each dependent variable [49] were presented in Table 7. Moreover, the experimental and model data were compared to validate the mathematical models (Fig. 8). The analysis showed that the proposed models were adequate, with no lack of fit and with acceptable values of R^2 for all the independent variables (responses). The mathematical models were also validated with a comparison of the predicted data extracted by the models and experimental data. According to the results, the models' data are in suitable accordance with the experimental data which shows the perfect fit of the models and suitable correlation obtained between the variables.

3.4. Brake power

The predicted values of brake power for various blends and engine speeds are presented in Figs. 9 to 11. As the figures show the brake power increased with increasing the amount of biodiesel in the fuel blend. According to the results, the brake power decreased by 30% with a higher fraction of ethanol in the fuel mixture. The main reason for this behavior could be due to the reduction of the calorific value of the blends containing ethanol. Besides, the higher cetane index of biodiesel which causes shorter ignition delay and longer combustion duration helps to more complete combustion. These results agree well with previous studies [50,51].

The results showed that the brake power enhances at high engine speeds due to the increased atomization and inlet airflow that makes a more homogeneous mixture.

Also, the higher oxygen content of ethanol than that of biodiesel provides more complete combustion conditions especially at high engine loads, and compensates the lower of the heat content of ethanol.

According to the figures, the brake power increased at higher engine loads due to more complete combustion conditions as a result of the high combustion temperature and better mixing of biodiesel and ethanol as the oxygenated fuels with the air molecules that generate more complete combustion and improves the brake power as the other papers have reported [25,28,52]. However, the addition of ethanol in fuel mixture leads to a lower combustion temperature at partial loads due to the lean overall mixture and causes a slight reduction in the engine power.

3.5. Torque

Figs. 12 to 14 indicate the impacts of various biodiesel-ethanol blends and engine speed on the predicted engine torque at different engine loads. According to the figures, the maximum torque belongs to the blends containing more than 70% WCO methyl ester at the engine speed between 1800 and 2000 RPM. Also, the minimum torque occurs at the engine speed higher than 2400 for the blends included<60%

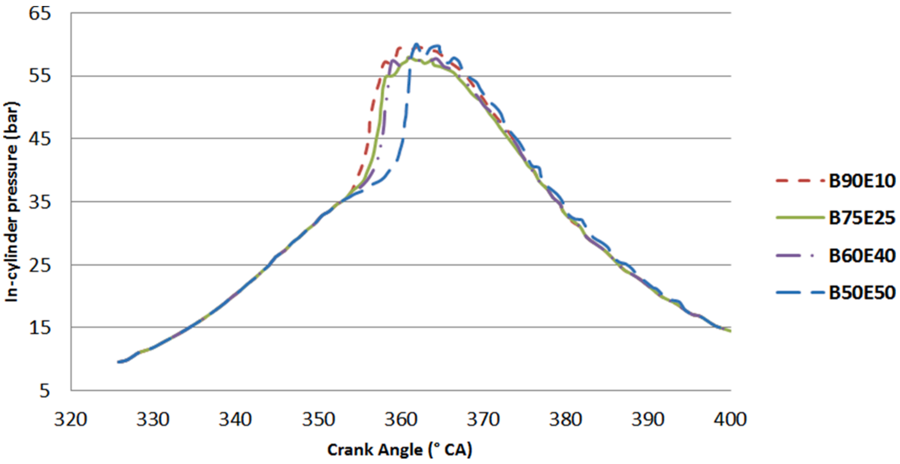

Fig. 7. In-cylinder pressure variations versus crank angle at full engine load.

Table 7

Coefficients, p-values, and R^2 for the emission parameters of the engine.

Regression coefficient	Brake power (kW)	Brake torque (N.m)	BSFC (gr/kW.hr)	Smoke (Soot opacity %)	CO (%)	NOx (ppm)
b_0 *(intercept)*	−62.431	−569.468	405.096	0.013115	+0.1528	322.673
b_1	0.61788	6.04433	−0.50376	0.39570	-1.1601×10^{-03}	−4.6274
b_2	0.048030	0.32961	−0.091181	-4.71779×10^{-03}	-3.19118×10^{-05}	0.17323
b_3	−0.10836	4.29054	−1.15810	−0.097499	-1.01046×10^{-03}	0.8397
b_{12}	2.0899×10^{-04}	1.257×10^{-04}	-3.6141×10^{-04}	-8.32815×10^{-05}	–	-2.04275×10^{-04}
b_{13}	4.5632×10^{-03}	0.014331	6.713×10^{-03}	1.01823×10^{-03}	–	-1.13137×10^{-03}
b_{23}	2.839×10^{-04}	-2.0951×10^{-05}	2.095×10^{-05}	-2.61891×10^{-05}	1.46659×10^{-07}	-1.87514×10^{-03}
b_{11}	-6.766×10^{-03}	−0.0389	-1.417×10^{-03}	-7.86970×10^{-04}	5.02751×10^{-06}	0.045575
b_{22}	-1.6578×10^{-05}	-9.0566×10^{-05}	3.668×10^{-05}	1.92363×10^{-06}	3.87925×10^{-09}	-5.37232×10^{-05}
b_{33}	-1.229×10^{-03}	−0.01803	1.681×10^{-03}	1.17912×10^{-03}	4.36778×10^{-06}	0.055811
R^2	96.5%	98.7%	95.6%	99.3%	95.7%	94.5%
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

biodiesel.

The results also showed that the predicted values for engine torque decreased approximately 27% with the increase of ethanol fraction in the fuel mixture due to the lower heat content of ethanol in comparison with biodiesel. Moreover, high lubricity and shorter ignition delay of biodiesel result in lower friction conditions and better combustion efficiency which enhances the engine torque. The results are in agreement with other studies [53–56].

The figures show the engine torque improves with the increased engine load due to the more complete combustion under the higher engine loads.

3.6. *Brake specific fuel consumption (BSFC)*

Figs. 15 to 17 indicate the impacts of various biodiesel-ethanol blends and engine speed on the predicted BSFC at various engine loads. According to the figures, the maximum BSFC (around 320 g/kW.h) belongs to the blends containing less than 55% biodiesel under engine speed of 2700 to 2800 RPM. Also, the minimum BSFC (<210 g/kW.h) occurred under engine speed of 1500 to 1700 RPM for the blends included<10% biodiesel. Based on the plots, at first, the BSFC values dropped with the increase in engine speed up to 1600 RPM and then increased sharply at the speeds of more than 1800 rpm. The predicted values for the BSFC increased (approximately 16%) with the increasing ethanol proportion in the fuel blend. Given that BSFC is directly related to brake power so the lower calorific value of the ethanol in comparison with biodiesel that causes lower brake power and consequently higher BSFC. As the figures show, the BSFC decreases with an increase in the engine load. It could be due to improving the brake power as compared to fuel consumption in these conditions. Besides, the high-level oxygen of ethanol can participate in the combustion process at higher engine loads and improves combustion behavior to reduce BSFC at this condition. The results were found to agree with other studies [24,52,57].

3.7. *Brake specific energy consumption (BSEC)*

BSEC (Brake Specific Energy Consumption) is the ratio of energy obtained by burning fuel for an hour to the actual energy or brake power. This parameter determines how effective the energy is converted from fuel. It is defined as a product of BSFC and calorific values of fuel. It means how efficiently fuel energy is obtained from given fuel.

Figs. 18 to 20 indicate the impacts of various biodiesel-ethanol blends and engine speed on the predicted BSEC at various engine loads. According to the figures, at high engine speeds the BSEC decreases with increasing biodiesel blending percentage for all load conditions of the engine due to lower brake specific fuel consumption of biodiesel. However, at lower engine speeds there is no significant difference in BSEC between fuel blends which implies that the higher calorific value of biodiesel compared with ethanol compensates the lower BSFC of biodiesel at this engine condition. As the figures show, the BSEC decreases with an increase in the engine load.

3.8. *Smoke level*

The predicted smoke levels (soot opacity percentage) for various blends and engine speeds are indicated in Figs. 21 to 23. The figures show smoke level in the exhaust gas decreased (around 38%) with the increasing ethanol fraction in the fuel mixture. The main reason is the higher oxygen molecules and fewer C- C bonds in the alcohol structure that causes more oxidation and less soot formation and engine running in overall leaner zones. According to the figures, the smoke level decreases with the increasing engine speed as a result of better fuel atomization and more turbulence in the combustion chamber that produces a more homogeneous mixture and reduces smoke level. Similar results can be found in other studies [23,58,59]. As shown in figures, there is an increased soot formation at higher engine loads because of high gas temperatures in the cylinder that leads to a more molecular rate of collisions.

3.9. *CO emissions*

Figs. 24 to 26 indicate the CO emission values for various blends. It can be seen the CO emissions decreased by up to 44% with increasing the biodiesel percentage in the fuel mixture. This decrease may be due to the lower ignition delay of the biodiesel that causes more complete combustion. On the other hand, retarded combustion phasing and lower adiabatic flame temperature of ethanol tend to low combustion temperature especially at lower engine loads and produce more carbon monoxide [60]. The results also showed that the difference between the carbon monoxide values with increasing engine speed at low and medium loads is greater than at high loads. According to the results, the CO emissions decreased for all blends with increasing the engine speed because of better combustion conditions as a result of higher mixing air and fuel and higher combustion temperature. It is in agreement with other studies [51,60,61]. Also, the CO emissions are higher at lower engine loads due to the low combustion temperature of ethanol at lower engine loads that cause higher emission of carbon monoxide. It was pointed out by other researchers [27,62]. Moreover, at low engine loads, bad atomization conditions as a result of the high viscosity of biodiesel lead to an increase in CO emission. But under higher engine loads, the ethanol causes better injection of the blends accompanied by to bring down the viscosity of the biodiesel and separate the hydros of the fuels into smaller elements during combustion. This separation allows the oxygen molecules of ethanol and biodiesel to participate in the combustion; therefore the CO emission decreases in rich zones at higher engine loads.

3.10. *No_x emissions*

The predicted NOx emission for various blends and engine speeds are

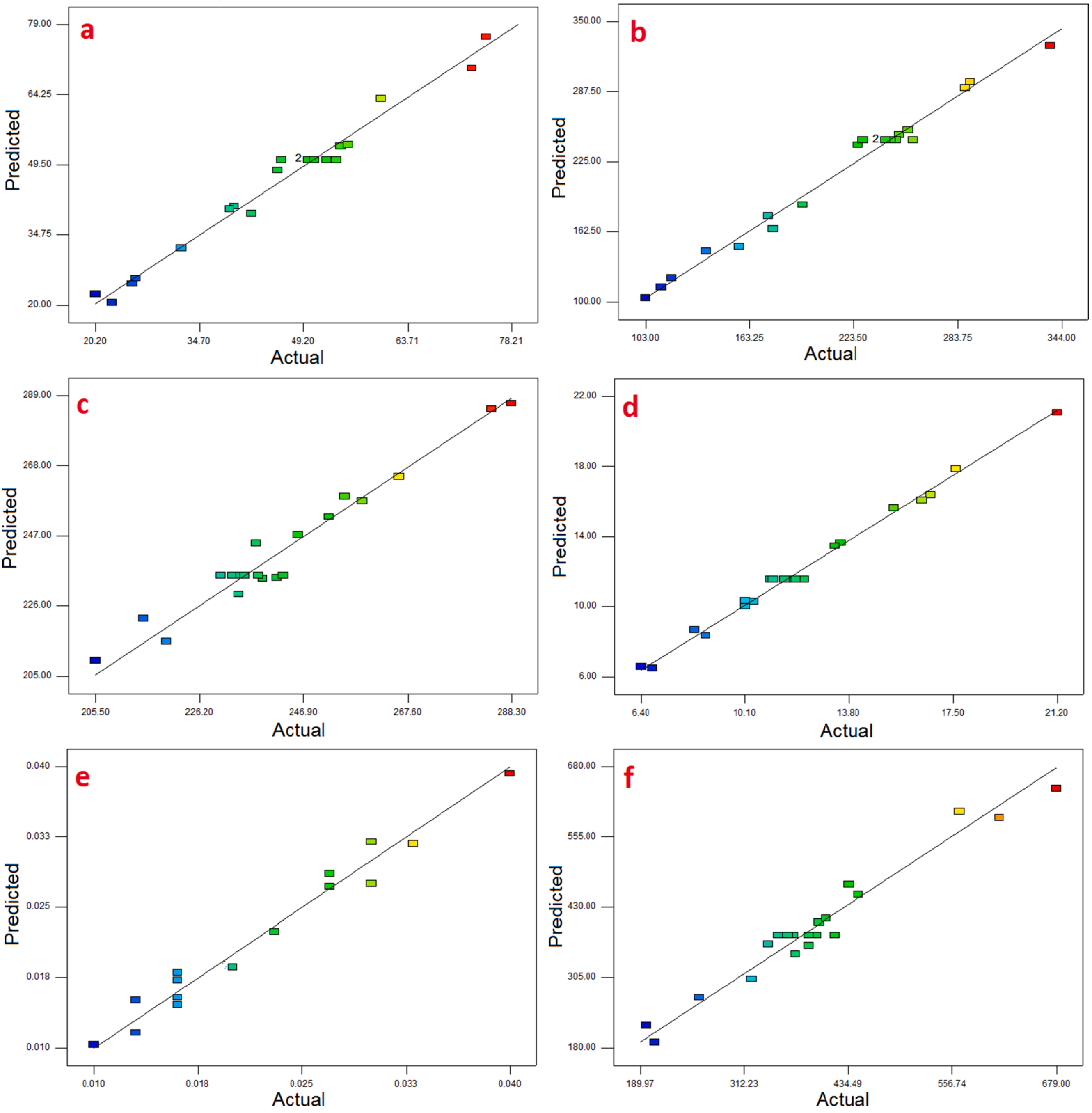

Fig. 8. Predicted values versus actual values of a) brake power b) brake torque c) BSFC d) Smoke level e) CO and f) NOx.

indicated in Figs. 27 to 29. According to the figures, NOx emissions decreased with an increase in engine speed. This is because of less residence time of the peak temperature of the combustion gas as a result of the shorter ignition delay that causes an improvement in NOx emission. However, the difference in NOx values for various biodiesel-ethanol blends at lower engine speeds is greater than that at high engine speeds.

Figures also show that the NOx emissions declined (approximately 17%) with a higher percentage of ethanol in the fuel mixture in agreement with the results of other papers [23,63,64–70]. This behavior could be due to lower temperatures conditions during the combustion of the blends included ethanol as a result of lower cetane number, calorific value, and adiabatic flame temperature of ethanol and its higher latent heat. On the other hand, the higher combustion temperature of biodiesel is the result of its higher heating value and the existence of oxygen molecules in its structure that cause a higher level of NOx emissions. According to figures, the NOx formation increased with the increased engine load for all blends due to an increase in exhaust gas temperature.

3.11. Optimization

In this study, there were three decision parameters namely the biodiesel percentage, engine speed, and load. The following limitations are applied to the decision parameters according to the design of the experiment:

$$\begin{array}{c} 50\leqslant Biodisel\leqslant 100 \\ 1000\leqslant RPM\leqslant 2800 \\ 25\leqslant Load\leqslant 100 \end{array} \quad (3)$$

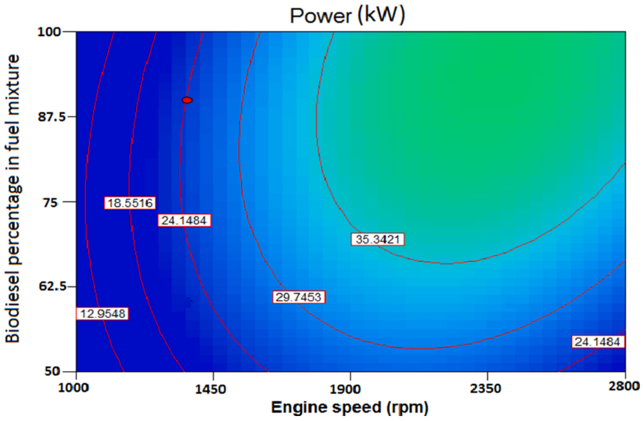

Fig. 9. Brake power versus engine speed at 40% load.

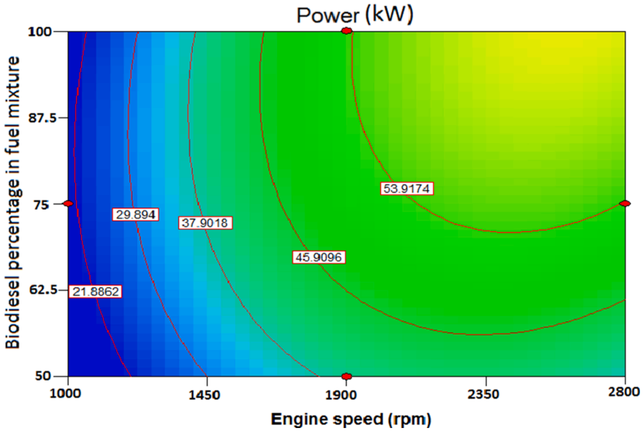

Fig. 10. Brake power versus engine speed at 62.5% load.

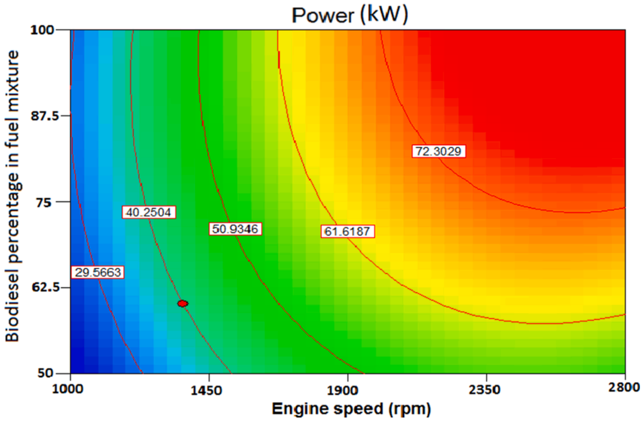

Fig. 11. Brake power versus engine speed at 85% load.

Based on the decision parameters, six output parameters including the power, torque, BSFC, CO, NOx, and soot were estimated based on derived mathematical models (Table 7). In order to sum the output parameters, they are normalized into the range of [0, 1] as follows:

$$\begin{aligned} f_1 &= (Power + 0.9213)/97.6413 \\ f_2 &= (Torque + 21.7705)/377.7712 \\ f_3 &= (BSFC - 202.1308)/137.8924 \\ f_4 &= (CO - 0.0074)/0.0530 \\ f_5 &= (NOx - 148.7917)/709.2267 \\ f_6 &= (Soot - 4.9554)/25.2404 \end{aligned} \tag{4}$$

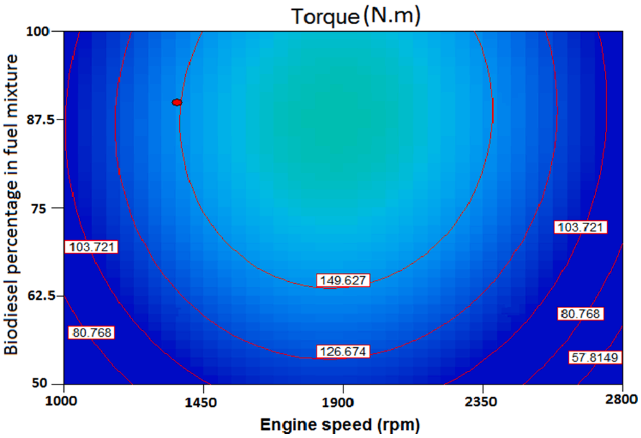

Fig. 12. Torque versus engine speed at 40% load.

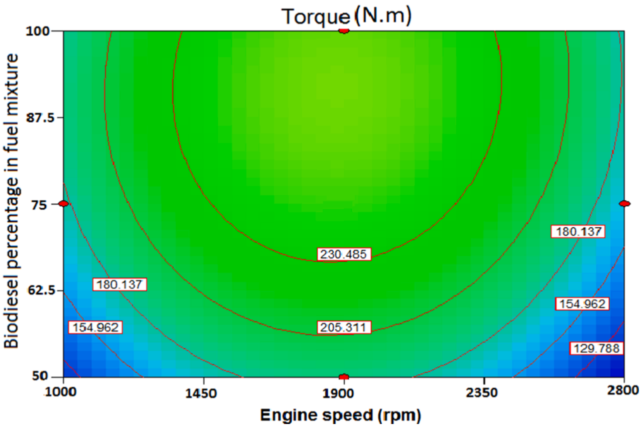

Fig. 13. Torque versus engine speed at 62.5% load.

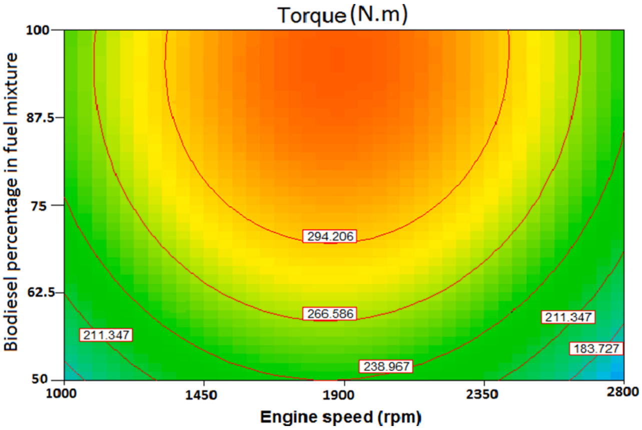

Fig. 14. Torque versus engine speed at 85% load.

Finally, the following fitness function is obtained by a linear combination of the output parameters:

$$f = a_1 f_1 + a_2 f_2 + a_3 f_3 + a_4 f_4 + a_5 f_5 + a_6 f_6 \tag{5}$$

In order to minimize the above fitness function, one should maximize the brake power and torque and minimize the BSFC, CO, NOx, and smoke level, simultaneously. Also, it is desired that CO, NOx, and smoke level are more important than the performance parameters. Therefore, the coefficients of Eq. (5) are selected as follows:

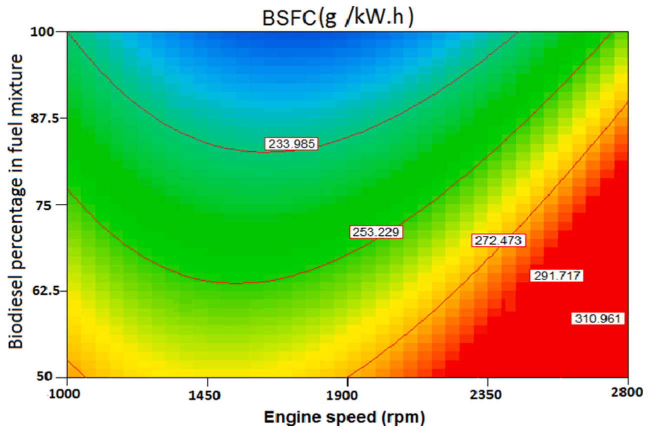

Fig. 15. BSFC versus engine speed at 40% load.

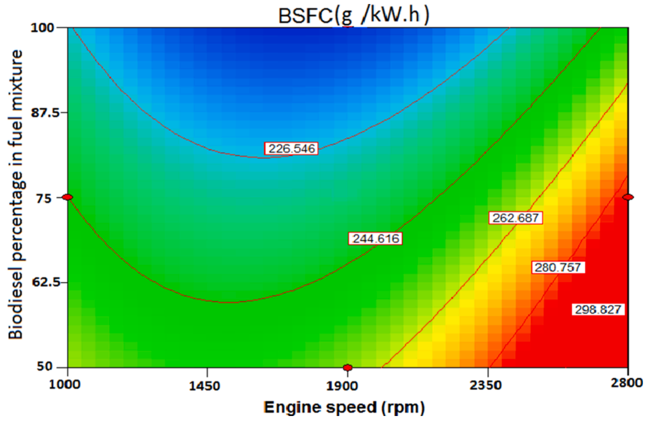

Fig. 16. BSFC versus engine speed at 62.5% load.

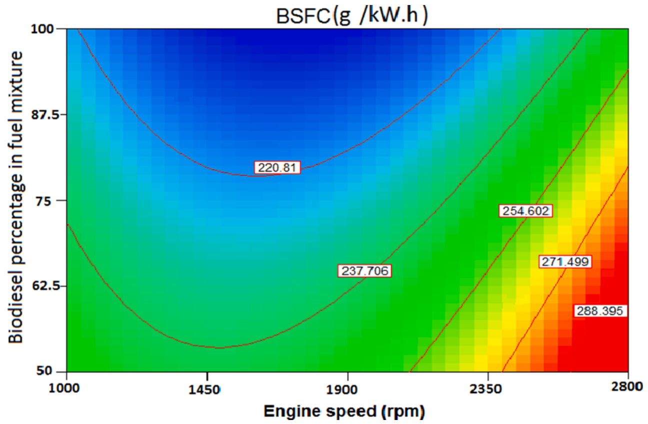

Fig. 17. BSFC versus engine speed at 85% load.

$$
\begin{aligned}
a_1 &= -1\\
a_2 &= -1\\
a_3 &= 1\\
a_4 &= 3\\
a_5 &= 3\\
a_6 &= 3
\end{aligned}
\tag{6}
$$

The GA optimization algorithm is implemented by the MATLAB optimization toolbox. The utilized GA algorithm has the properties presented in Table 8.

Once the GA is implemented, the best combination of decision parameters resulting in the smallest fitness function is obtained. The best fitness function value in each generation versus iteration number is presented in Fig. 30. It can be observed that the best and mean fitness function values finally converge to 0.307972. Therefore, it can be concluded that GA is successful in finding the global optimum of the problem.

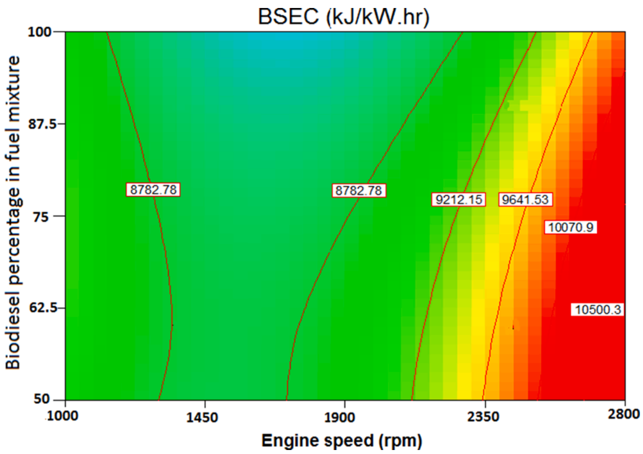

Fig. 18. BSEC versus engine speed at 40% load.

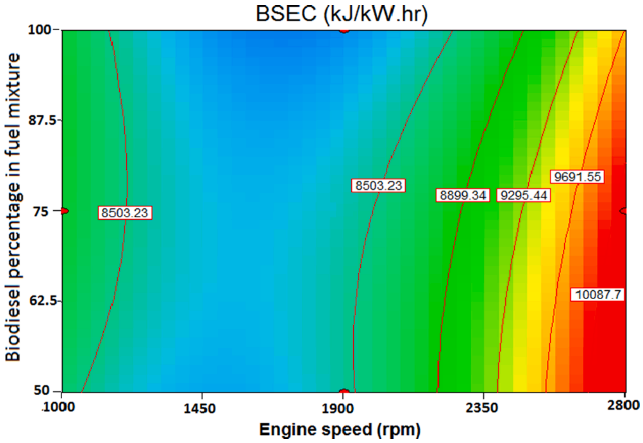

Fig. 19. BSEC versus engine speed at 62.5% load.

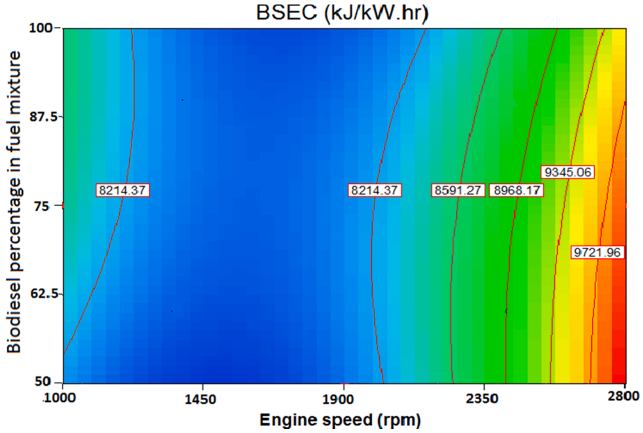

Fig. 20. BSEC versus engine speed at 85% load.

Also, the best individual combinations cause the smallest fitness function values in each generation versus iteration number is illustrated in Fig. 31. It can be seen the biodiesel percentage in the ethanol-

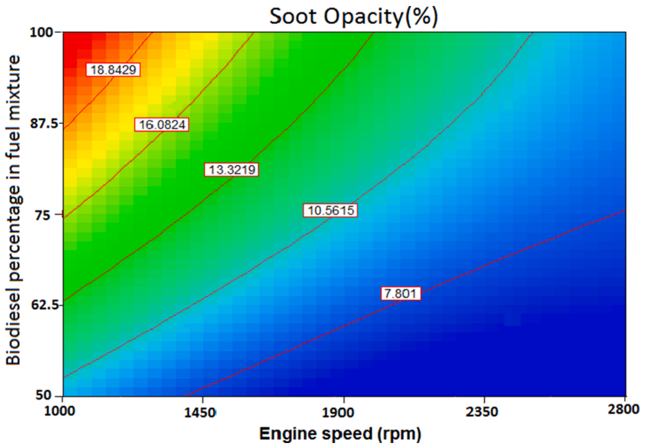

Fig. 21. Smoke level versus engine speed at 40% load.

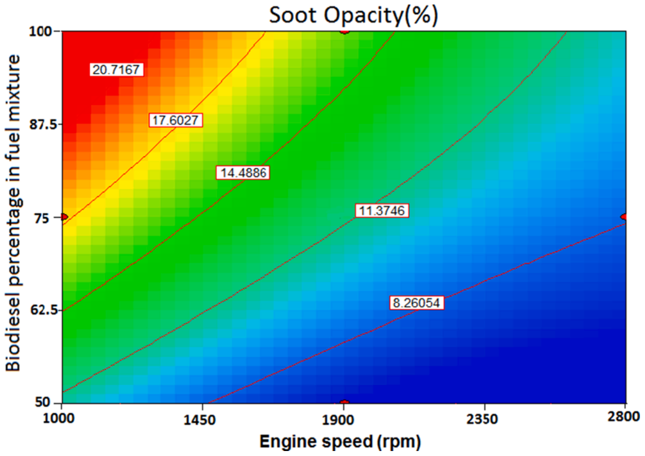

Fig. 22. Smoke level versus engine speed at 62.5% load.

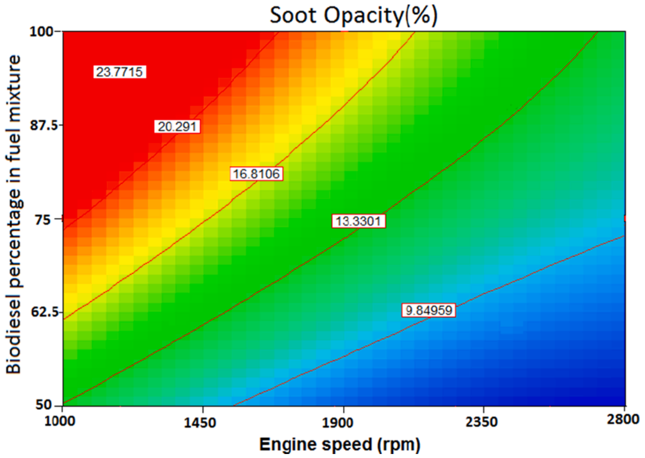

Fig. 23. Smoke level versus engine speed at 85% load.

biodiesel mixture, engine speed, and load was converged to 94.65%, 2800 RPM, and 65.75%, respectively as the optimal conditions.

Also, the resulting output parameters corresponding to the smallest fitness function values in each generation versus iteration number is illustrated in Fig. 32. The results are concluded in Table 9.

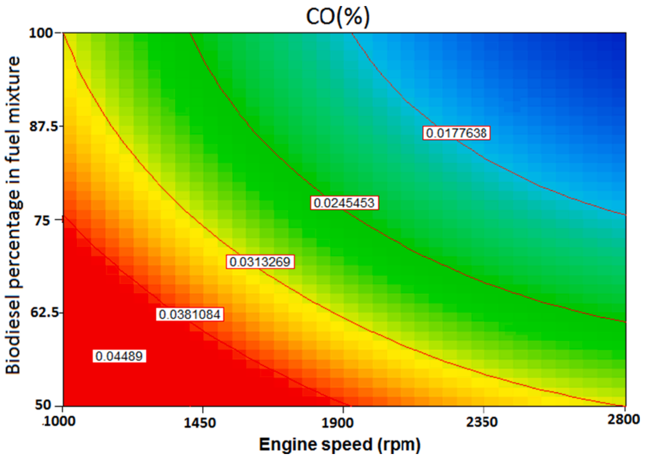

Fig. 24. CO emission versus engine speed at 40% load.

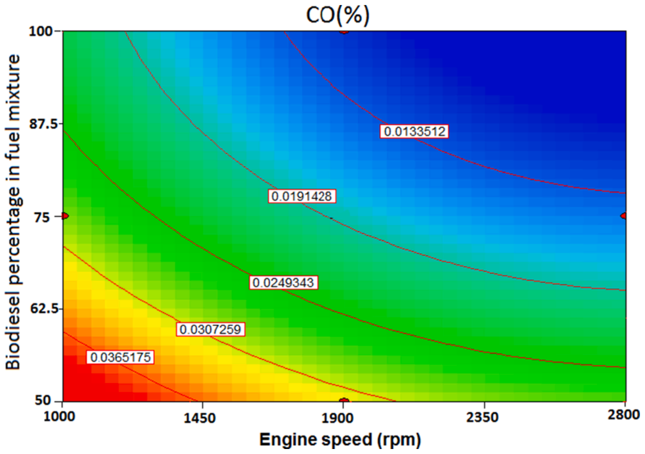

Fig. 25. CO emission versus engine speed at 62.5% load.

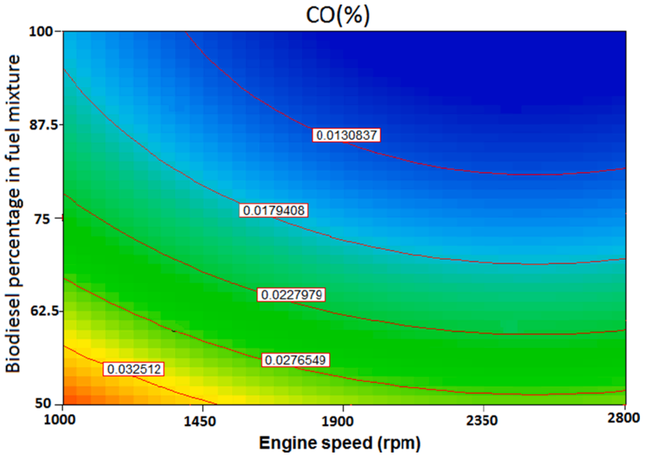

Fig. 26. CO emission versus engine speed at 8% load.

3.12. *Validation of the optimized results*

The experiments were carried at the optimum conditions to validate the optimized results. The average of three measured results was considered as the actual response. The average experimental values, the predicted values, and the percentages of error were presented in Table 10. The validation results demonstrated that the developed

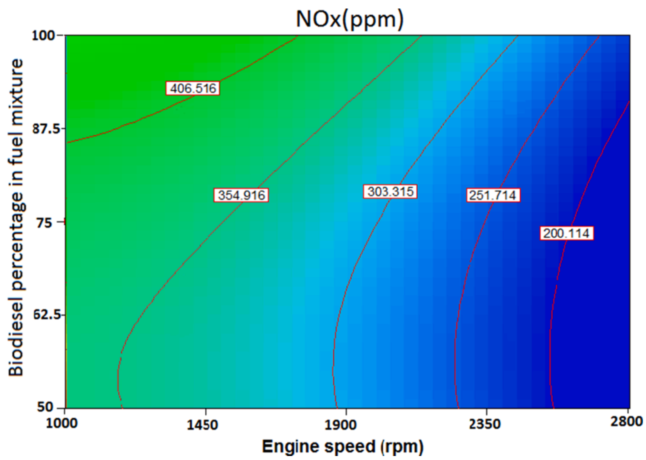

Fig. 27. NOx emission versus engine speed at 40% load.

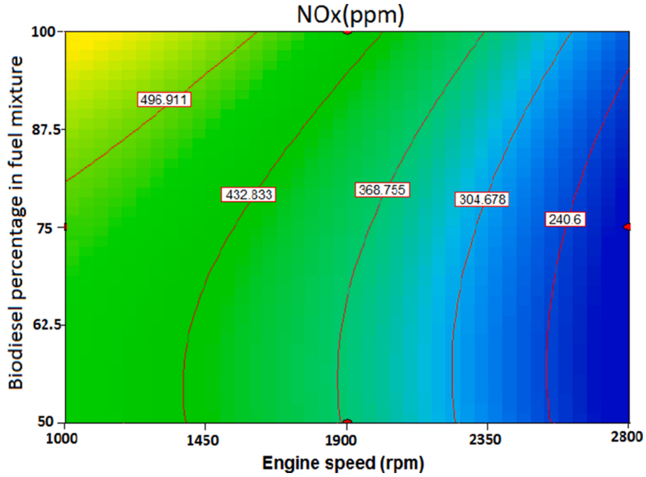

Fig. 28. NOx emission versus engine speed at 62.5% load.

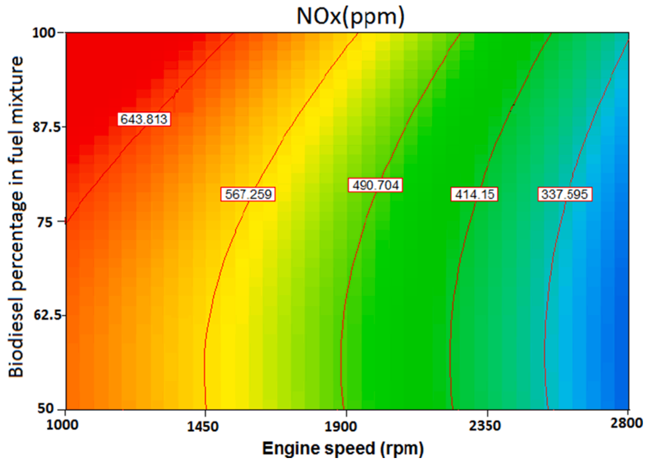

Fig. 29. NOx emission versus engine speed at 85% load.

models gave an accurate description of the experimental data.

3.13. *The comparison of the performance and emission characteristics of the biodiesel-ethanol blend with neat diesel*

Table 8
The properties of the GA algorithm.

Parameter	Value
Population Size	50
Crossover Fraction	0.8
Elite Fraction	0.05
Migration Fraction	0.2
Penalty factor	100
Stall Generation Limit	50
Function Tolerance	1e−6
Constraint Tolerance	1e−6
Fitness Scaling	Rank
Selection Function	Stochastic Uniform

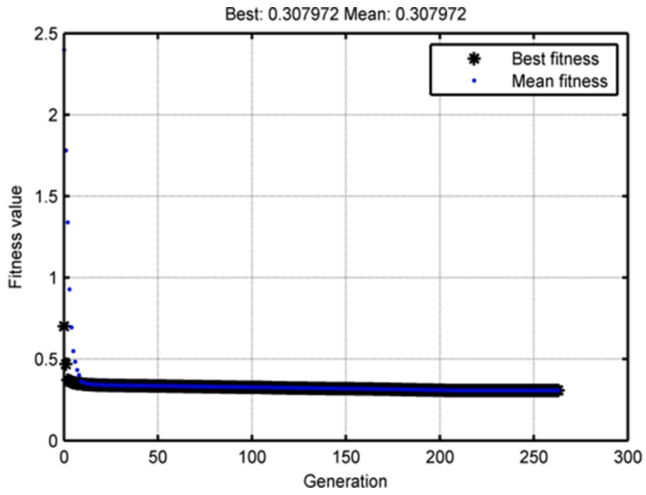

Fig. 30. The best fitness function value in each generation versus iteration number.

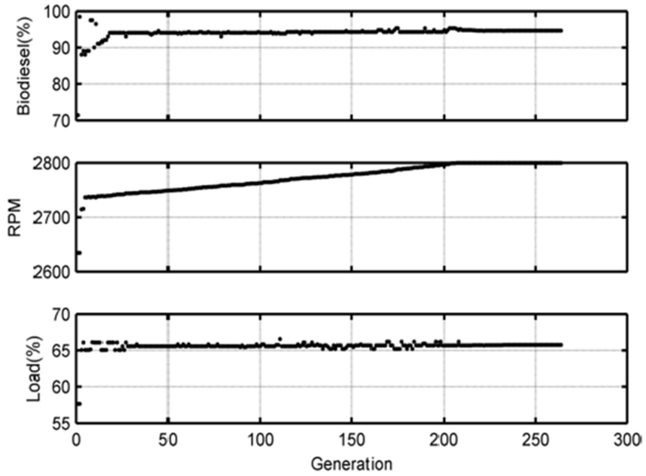

Fig. 31. The best individual combinations in each generation versus iteration number.

The comparison of the performance and emission characteristics for B75E25 blend with neat diesel at the engine speed of 1900 rpm and various engine loads are depicted in Figs. 33 to 38.

According to the results, the brake power and torque values are lower for B75E25 in comparison with diesel fuel because of the lower energy content of biodiesel and ethanol compared with diesel fuel No.2. Also, the biodiesel-ethanol fuel blend has higher BSFC values compared with neat diesel. The results also showed that the NOx emissions boosted up slightly with the use of biodiesel-ethanol fuel blend in comparison with D100 due to less compressibility, high isentropic bulk modulus, and

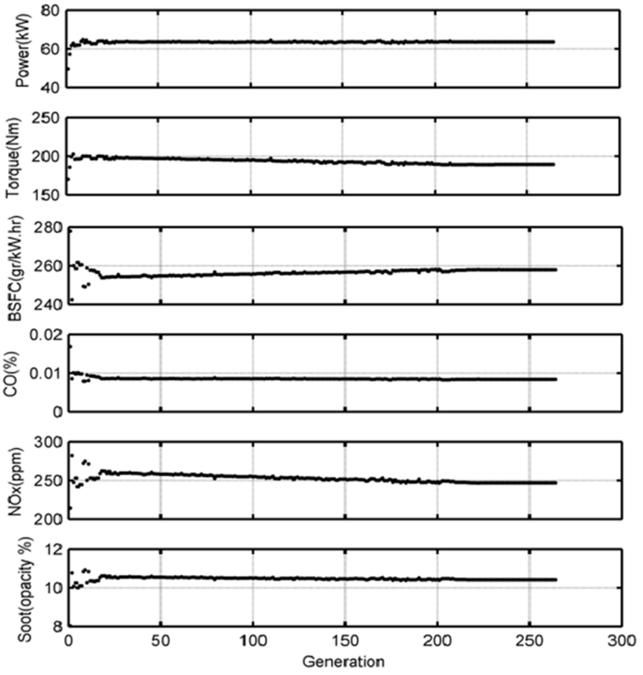

Fig. 32. The resulting output parameters corresponding to the smallest fitness function values in each generation versus iteration number.

Table 9
The results of the GA optimization problem.

Decision parameters		Output parameters		Fitness function	
parameter	value	parameter	value	parameter	value
Biodiesel	94.65%	Brake power (kW)	63.5621	Mean	0.307972
		Brake torque (N.m)	189.1575		
Engine speed (rpm)	2800	BSFC(g/kW.h)	257.9915		
		CO (%)	0.0084	Best	0.307972
Load	65.75%	NOx(ppm)	246.9442		
		Smoke level (Soot opacity %)	10.4186		

cetane number of biodiesel. Although, using ethanol causes retarded combustion that reduces combustion temperature and prevents from increasing the NOx emissions. The results also indicated that the CO emission and smoke reduced with using B75E25 in comparison with diesel fuel because of oxygen contents in the molecular structure of ethanol and biodiesel. According to the results, the difference between the brake power, torque, and BSFC values of the B75E25 fuel blend and neat diesel decrease at 85% engine load. This can be due to the presence of oxygen molecules in biodiesel and ethanol structure that leads to higher combustion efficiency and compensates for the loss of heating value of biodiesel and ethanol. However, this trend has been reversed for emission parameters, and the difference is greater at high engine load due to the effective role of oxygen molecules in reducing hydrocarbons and carbon monoxide and increasing NOx.

4. Conclusions

In this research, the mathematical models were developed based on the experimental test to determine the emission and performance parameters of a diesel engine fuelled with biodiesel-ethanol blends. The genetic algorithm was employed for the optimizations of the parameters. The results showed that the fitted models can properly predict the parameters of the engine. Also, the results showed that the brake power, torque, smoke level, and NOx emissions were decreased by 23%, 17%, 19%, and 7% respectively with increasing the amount of ethanol in the fuel mixture. However, the BSFC increased around 11% with a higher amount of ethanol. Based on the results, the engine power, torque, BSFC, and CO emission improves with the increased engine load. The results also showed that at higher engine speeds the BSEC decreases with increasing biodiesel blending percentage for all load conditions of the

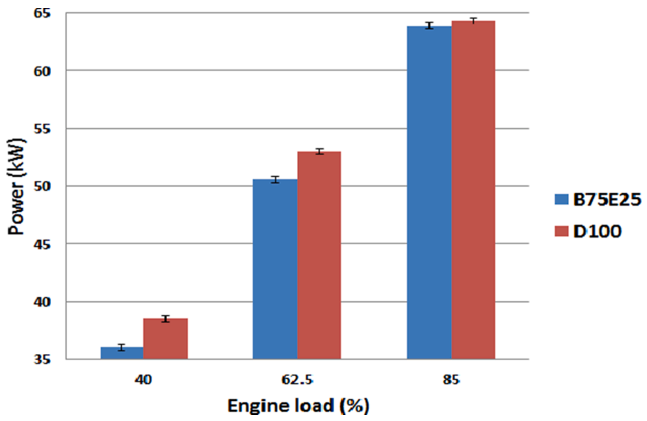

Fig. 33. The comparison of the brake power values for B75E25 blend with neat diesel.

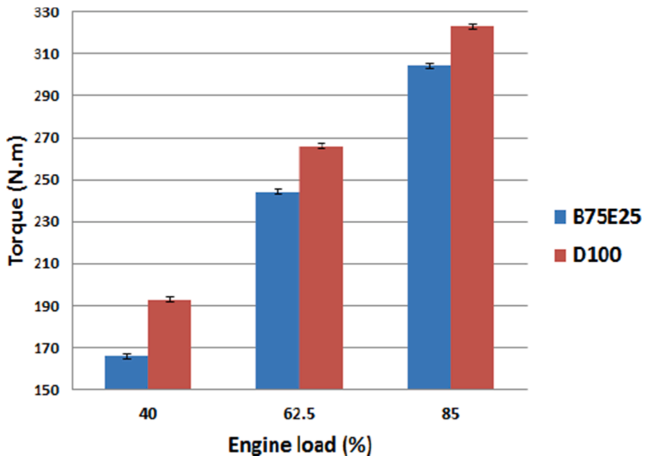

Fig. 34. The comparison of the brake torque values for B75E25 blend with neat diesel.

Table 10
Validation of the GA results.

Biodiesel percentage in fuel mixture (%)	Engine speed (RPM)	Engine load (%)		Brake power (kW)	Brake torque (N.m)	BSFC (gr/kW.hr)	CO (%)	NOx (ppm)	Smoke level (%)
94.65%	2800	65.75%	Predicted	63.56	189.16	257.99	0.0084	246.94	10.418
			Actual	60	204	268	0.008	238	10.2
			% Error	4.7	7.8	3.9	4.8	3.6	2.1

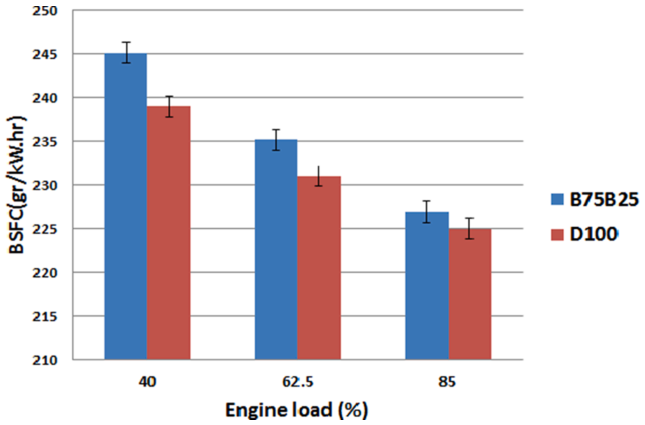

Fig. 35. The comparison of the BSFC values for B75E25 blend with neat diesel.

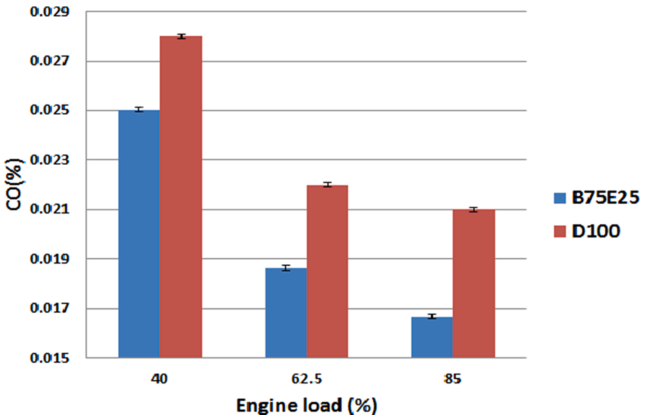

Fig. 36. The comparison of the CO values for B75E25 blend with neat diesel.

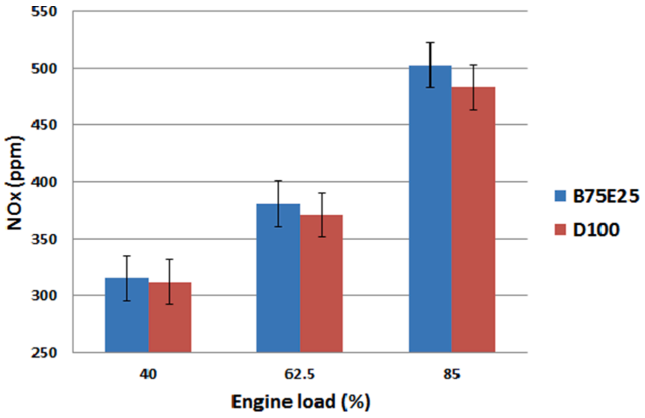

Fig. 37. The comparison of the NOx values for B75E25 blend with neat diesel.

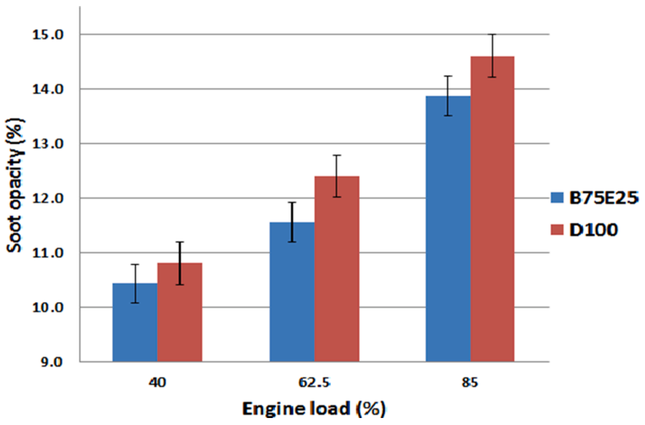

Fig. 38. The comparison of the smoke level values for B75E25 blend with neat diesel.

engine due to lower brake specific fuel consumption of biodiesel. However, at lower engine speeds there is no significant difference in BSEC between fuel blends. On the other hand, the CO emissions decreased up to 36% with increasing the biodiesel percentage in the fuel mixture due to the lower ignition delay of the biodiesel that causes more complete combustion. The results also showed that the addition of ethanol has more influence on kinematic viscosity and cetane number in comparison with the other two properties. Moreover, the blended fuels including higher biodiesel percentage lead to higher in-cylinder pressure, while the highest peak of in-cylinder pressure was for B50E50 among all fuel blends. According to the optimization process, the optimum conditions are 94.65% biodiesel fraction in the mixture, 2800 rpm engine speed, and 65.75% engine load to obtain 63.5(kW), 189 (N.m), 258 (gr/kW.hr), 0.0084 (%), 247 (ppm) and 10.42 (%) of brake power, torque, BSFC, CO, NOx, and smoke emissions respectively. The brake power and torque, CO, and smoke values are lower for B75E25 in comparison with diesel fuel. However, the results showed that the BSFC and NOx values boosted up slightly with the use of the biodiesel-ethanol fuel blend in comparison with D100. It is concluded that the use of ethanol in fuel mixture is more effective to improve the emission parameters than that of engine performance. Besides, the real applications and meaning of this study could be that the presence of ethanol up to 25% in the biodiesel-ethanol mixture can be used in engines designed for pure diesel with a minimal negative impact on engine performance and emission parameters and no, modification requirement.

CRediT authorship contribution statement

Alireza Shirneshan: Conceptualization, Writing - original draft, Supervision. **Seyed Amin Bagherzadeh:** Writing - original draft, Formal analysis, Investigation. **Gholamhassan Najafi:** Investigation, Validation, Writing - review & editing. **Rizalman Mamat:** Writing - review & editing, Investigation. **Mohamed Mazlan:** Writing - review & editing, Conceptualization.

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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