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ORIGINAL STUDY

Enhancement of the Performance and Emission Attributes for the Diesel Engine Using Diesel-waste Cooking Oil Biodiesel and Graphene Oxide Nanofluid Blends Through Response Surface Methodology

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Abstract

This study examined how diesel fuel and waste-cooked oil (WCO) biodiesel blends added by various concentrations of graphene oxide (GO) nanoparticles can effect the performance and emission characteristics of constant-speed, four-stroke, single-cylinder, water-cooled diesel engines. The GO nanoparticle concentrations are 50 100 and 150 ppm dispersed in different diesel-WCO biodiesel blends are pure diesel fuel (B0), 20% WCO biodiesel and 76% diesel fuel (B20), and 40% WCO biodiesel and 56% diesel fuel (B40). In addition 4% toluene in all blends which used as a surfactant. The diesel engine fueled with these blends and operated at various engine loads are 2, 4, and 6 kW. However, the interactions between the independent variables, such as the percentages of fuel blends, concentrations of GO nanoparticles, and the engine loads studied previously to see how they effect the characteristics of the diesel engine's performance and emissions like the engine brake thermal efficiency, the emissions of oxides of nitrogen (NOx), and the emissions of carbon dioxide. The response surface methodology used specifically to examine and optimize the responses of the diesel engine related to the mentioned independent variables. The performance and emission attributes improved by using various percentages of WCO biodiesel and GO nanoparticles in addition the optimization of response surface methodology. The optimum responses are 18.97% for the brake thermal efficiency, 539 ppm for the oxides of nitrogen emissions, and 2.14 for carbon dioxide emission.

Keywords: Graphene oxide nanoparticles, Internal combustion engine, Oxides of nitrogen emissions, Response surface methodology (RSM), Waste-cooked oil biodiesel

1. Introduction

The demands and the depleted reserves for energy resources are important concerns for the world (Sabapathy et al., 2021; Elkelawy et al., 2018). Diesel fuel is one of the energy resources that nearly may be depleted due to the massive demands and limited supplies (Bakõr et al., 2022; Elkelawy et al., 2008, 2021a, 2022a). Diesel engines are used in many fields such as power generation, transportation, agricultural and construction equipment due to their high efficiency (Nayak et al., 2022a; Elbanna et al., 2023a). In contrast, diesel engines emit enormous emissions that can destroy human being health and the climate (Elkelawy et al., 2021b, 2022b; Elbanna et al., 2023b). Large interests are considered to look for other supplies that can compensate for fossil diesel fuel depletion (Sahu et al., 2022). Alternative fuels have the ability to make up for the depletion due to their availability and can

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reduce pollution less than emissions from the fossil diesel fuel (Lawrence et al., 2011). Alternative fuels have many resources that include alcohol, natural gas, hydrogen, and biodiesel (Basha et al., 2009). Biodiesel is one of the alternative fuels that can be a suitable option for operating diesel engines due to its availability, oxygenated fuel, biodegradable, nontoxic, the engines do not need any modifications, and friendly to the environment (El Shenawy et al., 2019a; Mohammed Elbanna et al., 2022). Biodiesel has many feedstock's for manufacturing like edible resources, nonedible resources, and other resources that include bacteria or algae (Elkelawy et al., 2021b). Waste-cooked oil (WCO) is one of the biodiesel production feedstocks to face the fossil diesel fuel depletion crisis (Hosseinzadeh-Bandbafha et al., 2022). WCO biodiesel can replace completely or blended pure diesel fuel and enhance the diesel engine combustion and emission attributes (Suzihaque et al., 2022). WCO feedstock cost represents 70–95% of the total cost of WCO biodiesel production (Suzihaque et al., 2022; Elkelawy et al., 2021c). WCO biodiesel production techniques may be like dilution, micro-emulsion, and pyrolysis but the transesterification process is the most used technique due to the high specifications. WCO that has high free fatty acids takes more time so the esterification process is required to reduce the free fatty acid before transesterification to avoid soap formation (Adenuga et al., 2021). Two types of catalysts can be used in the transesterification process are acid or alkaline catalysts. Alkaline catalysts like sodium hydroxide or potassium hydroxide are used with the triglyceride oil and alcohol reactions (Adenuga et al., 2021). The alkaline catalysts are better than acid catalysts due to the rapid reaction and less corrosive. The transesterification process is the reaction of oil, alcohol, and the catalyst to produce esters, which is the biodiesel and glycerol. Usually, the ratio of alcohol to oil is 6 : 1 at 65 °C temperature for 1 h. After this step the product is subjected to separation, washing with hot water, and finally, product data analysis to describe the product specifications like density, viscosity, cloud, and pour points, etc (El Shenawy et al., 2019b). Cyclohexane (C) was added at 5, 10, and 15% concentrations of volume to WCO biodiesel, diesel blends at 150 and 250 bar of injection pressure. The three blends are B60 D35C5, B60 D30C10, and B60 D25C15. Compared with using pure diesel (B0) or B60 D40 blend it was observed improvements in all engine performance attributes and reductions in all emissions with increasing cyclohexane concentrations and increasing the injection pressures due to the premixed and rapid combustion (Elkelawy et al., 2021c). WCO biodiesel mixed with pure diesel fuel at blend (B20) in addition to various types of nanoparticles used individually were aluminum oxide, zinc oxide, and graphene in diesel engine combustion. The brake thermal efficiency (BTE) increased by using B20 and graphene nanoparticles. Also, it was observed reduction in all emissions by using B20 mixed with all mentioned nanoparticles individually (Nayak et al., 2022b).

Nomenclature

BSFC	brake specific fuel consumption
BTE	brake thermal efficiency
CCD	central composite design
CO_2	carbon dioxide
EGR	exhaust gas recirculation
FFD	full factorial design
GO	graphene oxide
NO_x	oxides of nitrogen
PPM	parts per millions
RSM	response surface methodology
UHC	unburned hydrocarbon
WCO	waste cooked oil

Nanoparticles represent nanotechnology research in the diesel engine field. Nanoparticles can be classified into four categories according to their size, shape, material, and surface. According to the size, nanoparticles have different sizes ranging from 1 to 100 nm (Ealias and Saravanakumar, 2017). Nanoparticles have different shapes, which can be tubular, flat, cylindrical, and spherical (Machado et al., 2015; Vaghasia et al., 2022). According to the base element for the nanoparticles, there are carbon, organic, inorganic, and composite nanoparticles. Nanoparticles based on carbon have chains of carbon atoms. Organic nanoparticles characterized by are non-toxic, biodegradable, and used in drug manufacturing (Abd and Abouelmagd, 2017). Inorganic nanoparticles include metal nanoparticles and their oxides which are used mainly in compression ignition engines because they enhance the fuel properties like calorific value, viscosity, and conductivity (Shamun et al., 2018). The main reasons for improving the properties of the fuel by adding nanoparticles are increasing in the surface area to volume ratio, high mobility, high mechanical properties, high electrical and thermal conductivity, reduction in the power of pumping, reduction in erosion occurrence, the enhancement in the conductivity and the less particle momentum (Das et al., 2006). Graphene oxide (GO) nanoparticles from the main types of non-metallic nanoparticles that can be used in the combustion of diesel engines due to the high oxygen content, high surface area to volume ratio, and high evaporation rate for the fuel (Dhana et al., 2018). Adding GO nanoparticles to the base fuel at different concentrations using surfactant in the combustion of diesel engines can improve performance attributes like the BTE due to the reduction in brake-specific fuel consumption (BSFC) (El-Din et al., 2010). Also, can reduce emissions like carbon monoxide (CO) due to the existing oxygen atoms that complete the combustion also the oxides of nitrogen (NOx) emissions due to the superior surface area to volume ratio (Ağbulut et al., 2022).

Biodiesel-diesel blend consisting of 30% WCO biodiesel and 70% diesel fuel was mixed with different concentrations of GO nanoparticles and then injected into a single-cylinder diesel engine. RSM was used to determine the optimum operating conditions at various engine loads. The results of the experiments show noticeable improvements in the performance attributes and minimizing in the emissions at specified concentrations of GO nanoparticles (Simsek et al., 2022). GO nanoparticles at different concentrations of 100, 500, and 1000 ppm were used with test fuels to investigate the performance and emission attributes of diesel engines at various engine loads. The test fuels were neat diesel fuel (B0), 15% WCO biodiesel with 85% diesel (B15), B15 + GO at 100 ppm, B15 + GO at 500 ppm, and B15 + GO at 1000 ppm. From the results, it was observed by using B15 only the BTE, CO and UHC reduced and the NOx emissions increased compared with using B0. By using GO nanoparticles at different concentrations it was observed increase in the BTE and reductions in the NOx and CO emissions due to the high surface area to volume ratio and the complete combustion (Ağbulut et al., 2022). The effects of using GO nanoparticles and graphene Nano-platelets (GNP) on the performance and emission attributes of turbocharged diesel engines were investigated. The WCO and karanja biodiesel at a percentage of 20% was blended with 80% diesel fuel (B20). The nano concentrations were 20, 40, and 60 ppm for each type of nanoparticles individually. It was observed reduction in the smoke emissions by 29.2% using 40 ppm of GO nanoparticles and 60 ppm of GNP. The NOx emissions were reduced by 26.4%. From the results, the GO nanoparticles gave lower soot than GNP, but GNP gave lower NOx, CO, and UHC than GO nanoparticles (Chacko and Jeyaseelan, 2020).

Response surface methodology (RSM) is an optimization technique used by designing experiments to optimize the attributes of engine performance and emission (Awad et al., 2017). Previously, the neural networks and the genetic algorithm applications needed a large number of experiments and time but now RSM is an alternative method for predicting and optimizing the responses by a group of experiments (Kumar and Dinesha, 2018). The RSM technique is used in a diesel engine to optimize the performance and emission attributes at a minimum number of experiments and time (Yusri et al., 2018). Firstly, RSM can be applied using approximation equations that indicate the relation between the independent variables and the responses. The function becomes first order if the relationship between the independent variables and the responses is linear as indicated in Eq. (1) (Kiran et al., 2016). The function becomes a quadratic or second order if the relationship is curvature as shown in Eq. (2).

$$\mathbf{y} = \boldsymbol{\beta}_{\circ} + \sum_{i=1}^{k} \boldsymbol{\beta}_i \mathbf{X}_i + \boldsymbol{\varepsilon} \tag{1}$$

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j \geq 1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ij} x_i^2 + \varepsilon \tag{2}$$

where (i) is the linear coefficient, (j) is the second-order coefficient, (β) is the regression coefficient, (k) is parameter numbers, and (ε) is the response error (Ghafari et al., 2009).

The usual RSM procedure used for optimizing the performance and emissions attributes for diesel engine combustion using alternative fuels is shown in Fig. 1. The responses existing generally in investigating the performance attributes using RSM are the brake power (BP), BTE, brake mean effective pressure (BMEP), and exhaust gas temperature in addition to the emission attributes which include carbon dioxide (CO_2), NO_x, CO, and UHC. The independent variables are like the blend percentage, the nanoparticles concentrations if used or the engine load have two levels (±1) or between them is the range that the variable can change. The design of experiments (DOE) is used for selecting the accurate points in which the responses should be calculated. There are many types of designing experiments based on the RSM for investigating the diesel engines. The most recent studies use the central composite design (CCD), full factorial design (FFD) or Box-Behnken design which can be accessed usually by statistical software like MINITAB (MINITAB Inc.), Matlab, and design expert (Stat-ease, Inc.). Full factorial design (FFD) is used for the low-order models in which the responses have accurate results but it has drawbacks with high-order models (Khattree and Rao, 2003). Central composite design (CCD) accurate, do not need 3 level factorial design for making second order model and can give similar

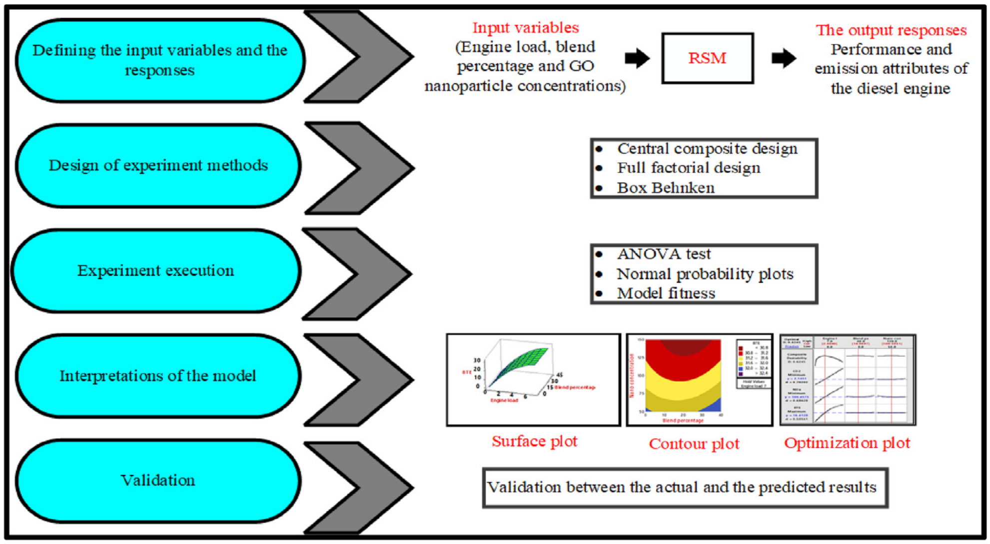


Fig. 1. Response surface methodology applications in diesel engine combustion with alternative fuels.

results to full factorial design with lower number of experiments (Witek-Krowiak et al., 2014). The CCD method has three types are circumscribed, inscribed, and face-centered composite design (Hatami et al., 2015). Box-Behnken method formulated in 1960 by Box and Behnken which based on reducing the number of runs for the experiments in the second-order models (Ferreira et al., 2007).

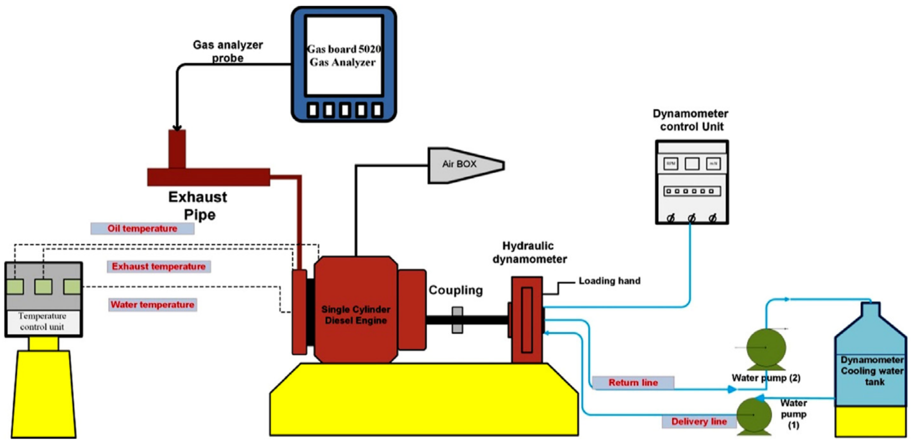
The RSM model was used to optimize marine diesel engine performance and emission attributes. A computational fluid dynamic model and a chemical kinetic mechanism were used to simulate the operation. The marine diesel engine operated at 50, 75, and 100% loading percentages and was fuelled by hydrogen at 5, 10, and 15%, water at the percentage of weight 2, 4, and 6%, and rapeseed methyl ester (RME). From the results, it was observed that using water and hydrogen could enhance the attributes of marine diesel engines attributes. The optimum blend was RME, 15% H_2, 2.5% weight of water, and 74.69% marine engine load percentage. The optimum performance and emission attributes were 208.31 g/kW for the BSFC, 39.22% for the BTE, 941.21 ppm for the NOx emissions, 325.86 ppm for the UHC emissions and 1073.4 ppm for the CO emissions (Tan et al., 2023).

In the combustion of diesel engines, waste soybean cooked oil (WSCO) biodiesel was utilized as an alternative fuel. A mixture of ultra-low sulfur diesel fuel and WSCO biodiesel was used. In various proportions, diesel engines used exhaust gas recirculation (EGR). In order to improve the diesel engine's performance and emission characteristics using RSM. By comparing using pure diesel and without EGR (B0EGR0), it was observed a reduction in smoke emissions by 17.46%, a reduction in NOx emissions by 59.04%, and cost-effectiveness with 35% blend percentage of WSCO biodiesel and diesel (B35) and 15% EGR (B35EGR15) (Dubey et al., 2022). Hemp seed oil was blended at a percentage of 30% with 70% pure diesel fuel and mixed with different concentrations of dioxide of titanium (TiO_2) were 25, 50, 75, and 100 ppm. A single-cylinder diesel engine was used to perform the experiments and investigate the optimum concentration of TiO_2. At 75 ppm concentration of TiO_2 and 2 kW engine load, it was observed the optimum results of the performance and the emission (Uslu et al., 2023).

The objective of the research is to study the performance and emission attributes of single-cylinder diesel engines fuelled with pure diesel and different percentages of WCO biodiesel-diesel blends mixed with different concentrations of GO nanoparticles. The independent variables are optimized by applying a central composite design (CCD) model using the MINITAB software application to obtain accurate and optimized responses in addition to saving time and cost by reducing the number of experiments. The diesel engine loads, the WCO biodiesel-diesel blend percentages, and GO nanoparticle concentrations are the independent variables while the BTE, CO_2 emission percentage, and NO_x emissions concentrations are considered the responses.

2. Experimental setup and methodology

Fig. 2 represents the schematic diagram for the experimental setup, which includes a ZS1115 single-



(a)

(b)

Fig. 2. The schematic diagram with realistic image for the experimental setup with the instruments.

cylinder diesel engine that operates at a constant speed of 1400 rpm. The diesel engine is connected using coupling with ATE-160LC hydraulic dynamometer to maintain the torque and the engine load. The diesel engine is provided with temperature thermocouples for the lubrication oil, exhaust, and water temperature measurements. The dynamometer is conducted with the control unit for engine load maintaining. The diesel engine and the hydraulic dynamometer specifications are shown in Tables 1 and 2 respectively. The diesel engine is supplied with a gas board 5020 gas analyzer for measuring the concentrations of all possible produced emissions like the NO_x emissions in ppm and percentage of CO_2 emission based on pulse infrared source and single source two beams non-dispersion infrared (NDIR) method (Elkelawy et al., 2022c). The

Table 1. The specifications of the ZS1115 diesel engine.

Diesel engine specifications	
Cylinder numbers	Single cylinder
System of cooling	Condenser
Weight	185 kg
Displacement	1.194 L
Cylinder dimensions	(115*115) mm
Lubrication system	Pressure/splash
Starting system	Electrical start

Table 2. ATE-160 LC hydraulic dynamometer specifications.

ATE-160 LC hydraulic dynamometer	
Load cell capacity	0−350 Kg (0−1050 N.m)
Calibration arm	0.7645 m
Connection with diesel engine	Using half coupling
Sense of RPM	Sensor and 60-tooth wheel
Absorption	Hydraulic

Table 3. The specifications of the gas board 5020 gas analyzer.

Gas board 5020 gas analyzer	
Measurements	CO_2, CO, UHC, NO_x, Lambda display
Technology	CO_2, CO, UHC (NDIR), O_2, NO_x (ECD)
Resolution	$CO_2 = 0.01\%$ $NO_x = 1$ ppm
Relative error	$CO_2 = \pm 4\%$ $NO_x = \pm 5\%$
Absolute error	$CO_2 = 0.4\%$ $NO_x = \pm 25$ ppm
Warm-up time	10 min
Display	LCD display
Power	220 V ± 10% 50HZ ±1HZ
Temperature	0–40 °C
Weight	6 kg

specifications of the gas board 5020 gas analyzer are shown in Table 3. The uncertainty for the responses is analyzed according to the square root method and is indicated in Table 4. The total uncertainty percentage is equal to ±1.523 as indicated in Eq. (3).

$$\text{The uncertainity} = \sqrt{\left[(\text{uncertainity of BTE})^2 + (\text{uncertainity of NOx})^2 + (\text{uncertainity of CO}^2)^2\right]} \quad (3)$$

$$\text{The uncertainity} = \sqrt{\left[(1.35)^2 + (0.5)^2 + (0.5)^2\right]} = \pm 1.523$$

WCO is one of the food wastes that can harm the health of humans and the environment unless it is recycled again with any chemical treatment. Converting WCO to biodiesel is one way of recycling. WCO biodiesel can be used as alternative fuel due to the depletion and the high prices of fossil fuels. WCO biodiesel is characterized by oxygenated, renewable, economical, and friendly to the environment. WCO biodiesel usage in diesel engine combustion has many benefits in decreasing most of the produced emissions like CO, UHC, and NO_x emissions. WCO usage in diesel engine without any chemical treatment is impossible due to the high free fatty acid and the different specifications compared with fossil diesel fuel (El-Sheekh et al., 2022). In this paper, WCO is converted to WCO biodiesel by a transesterification chemical process using alcohol and a catalyst. Transesterification can be divided into three processes reaction, separation, and washing. The reaction process is attempted by mixing the WCO with methanol and NaOH and then heating the mixture for 1 h at 65 °C. The separation process is attempted by leaving the mixture for 24 h until the biodiesel separates from the glycerol (Elkelawy et al., 2022d). The washing occurs by using water at 100 °C and after an hour the produced WCO biodiesel can be used as an alternative fuel. The specifications of the WCO biodiesel in addition to the fossil diesel fuel used in the experiments are indicated in Table 5.

Table 4. The uncertainty percentages for the responses.

The responses	The uncertainty
BTE	±1.35%
NO_x	±0.5%
CO_2	±0.5%

GO nanoparticles are added to the base fuel or the fuel blends at different concentrations using 4% toluene that is used as a surfactant due to the superior characteristics of graphene oxide nanoparticles like the high oxygen content, high thermal, electrical and mechanical properties, high evaporation rate, the high surface area to volume ratio in addition to enhancing the calorific value for the fuel.

GO nanoparticles are prepared by Nanotech Egypt CO. The sample was subjected to a transmittance electron microscope (TEM) test for inspecting the shape and size as shown in Fig. 3 using a JEOL JEM-2100 high-resolution transmission electron microscope at an accelerating voltage of 200 kV. GO nanoparticles were also subjected to crystallographic structures test using radiography Diffraction (XRD) at the Egyptian Nanotechnology Center (EGNC)-Cairo University. The surface properties are inspected using surface-enhanced Raman spectroscopy (SERS) with a Lab RAM HR 800. The specifications of GO nanoparticles are indicated in Table 6.

3. Response surface methodology modeling and analysis of variance

RSM as mentioned previously is a bundle of statistical and mathematical techniques for modeling and optimizing the problems of interest using polynomial regression functions that represent the relationship between the responses and the input variables in addition to (ε) which is the experimental error. CCD is used for designing experiments by using MINITAB software that can give accurate

Table 5. Diesel fuel and waste cooked oil biodiesel specifications.

Specification (unit)		Standard (ASTM)	Diesel fuel	WCO biodiesel
Calorific value	(MJ kg^{-1})	D240	42.10	39.51
Density	(kg m^{-3})	D1298	830	875
Cetane number	–	D976	55	68
Kinematic viscosity	(mm^2 s^{-1})	D445	2.38	3.54
Flashpoint	(°C)	D93	45	158
Auto-ignition	(°C)	D6751	263	273
Cloud point	(°C)	D2500	0	6
Oxygen content	(wt %)	D5291	0	9.414

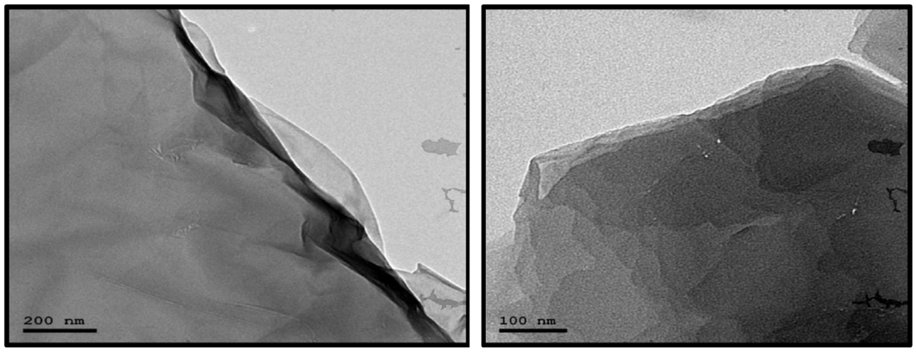


Fig. 3. Transmittance electron microscope inspection for graphene oxide nanoparticles.

Table 6. Graphene oxide nanoparticles specifications.

GO Nanoparticles Specifications	
Color	Brown Black
Form	Powder
Solubility	Have ability to Soluble in Water
Average Sizes	Length in microns and thickness in nanometers
Shape	Sheets

responses by a limited number of experiments are 20 experiments. Table 7 represents each input variable and its levels based on the operation experience of the diesel engine. The input variables in the experiments are the engine load, WCO biodiesel blend percentage, and graphene oxide nanoparticles concentrations, which have great effects on the performance and emissions of the diesel engine. The required responses that want to be optimized from the diesel engine operation are the BTE, CO_2 emission, and NO_x emissions. The 3 s-order polynomial models that represent the correlation between the responses to the independent variables are represented in Eqs. (4)–(6). Table 8 represents the design of the experiments and the responses according to the CCD in addition to the independent variable levels.

$$\mathbf{BTE = 0.662 + 9.354A + 0.0749B - 0.0214C - 0.6923A^2 - 0.001839B^2 + 0.000120C^2 - 0.000359AB - 0.000250AC - 0.000066BC} \tag{4}$$

Table 7. The independent variables and their levels.

	Levels of the independent variables		
	Low-level	Medium-level	High-level
Diesel engine load (A) (kW)	0	3.5	7
WCO biodiesel Blend (B) (%)	0	20	40
GO concentration (C) (ppm)	50	100	150

$$\mathbf{NOx = 268.8 + 128.7A - 5.23B - 0.30C - 2.84A^2 + 0.1218B^2 - 0.00051C^2 + 0.491AB - 0.0321AC + 0.0131BC} \tag{5}$$

$$\mathbf{CO2 = 1.540 + 0.2403A + 0.00621B - 0.00055C + 0.01165A^2 - 0.000119B^2 + 0.000013C^2 + 0.0003268AB + 0.000279AC - 0.000061BC} \tag{6}$$

Tables 9–11 represent the analysis of variance (ANOVA) for the BTE, NO_x, and CO_2, respectively. The degree of freedom (DF) represented by the number of experiments subtracted by 1 (n−1) which is 19. The adjusted mean of squares can be calculated by dividing the sum of squares by the degrees of freedom. The F value can be calculated by dividing the adjusted mean square for the model by the adjusted mean square for the error and this value is a measure of the model significance. The F values for the BTE, NO_x, and CO_2 are 2917.14, 217.63, and 90.56, respectively, which show that the regression models are adequate and with high significance. The *P* values of the regression models are smaller than the (α) value of 0.05, which proves that the three models are statistically significant. The R-squared and R-squared adjusted percentages represent the variations for the response, the higher percentages R-squared the better model fits the data. The R-squared percentages for the BTE, NO_x, and the CO_2 are 99.96, 99.49, and 98.79%, respectively. The adjusted R-squared for the BTE, NO_x, and CO_2 are 99.93%, 99.03%, and 97.70% respectively so the models with high accuracy and with good data fitting. The lack of fit F-values for the BTE, NO_x, and CO_2 are 25.29, 9.60, and 12.24, respectively. Fig. 4 represents the relationship between the residuals and the residual normal probability distribution percentages for the BTE, NO_x, and CO_2,

Table 8. Design of experiments with the experimental and the predicted responses.

Run Order	Process independent variables			Experimental responses			Predicted responses		
	A (kW)	B (%)	C (ppm)	BTE	NO_x	CO_2	BTE	NO_x	CO_2
1	7	0	150	31.35	940	3.21	31.4416	941.166	3.15216
2	3.5	20	100	24.31	643	2.62	24.2702	643.309	2.59309
3	3.5	20	100	24.52	655	2.58	24.2702	643.309	2.59309
4	0	40	150	0	290	1.48	−0.1974	277.266	1.43816
5	3.5	20	50	24.12	675	2.41	24.5527	654.436	2.53636
6	3.5	20	100	24.39	656	2.65	24.2702	643.309	2.59309
7	3.5	20	100	24.28	661	2.68	24.2702	643.309	2.59309
8	7	40	150	30.08	1170	3.74	30.0946	1142.97	3.75716
9	0	20	100	0	210	1.61	0.348727	204.436	1.56836
10	3.5	20	100	24.44	626	2.66	24.2702	643.309	2.59309
11	7	0	50	31.26	995	2.74	31.3626	1003.47	2.75416
12	7	40	50	30.52	1158	3.73	30.2806	1152.77	3.60416
13	3.5	20	100	24.44	635	2.59	24.2702	643.309	2.59309
14	3.5	0	100	24.12	672	2.42	23.8907	638.636	2.41036
15	3.5	20	150	24.64	592	2.73	24.5867	629.636	2.71436
16	0	40	50	0	270	1.45	−0.1864	264.566	1.48016
17	0	0	150	0	212	1.65	0.144568	212.966	1.74816
18	0	0	50	0	230	1.59	−0.1094	252.766	1.54516
19	3.5	40	100	22.57	695	2.56	23.1787	745.436	2.68036
20	7	20	100	31.2	990	3.18	31.2307	1012.64	3.33236

Table 9. ANOVA table for the brake thermal efficiency.

Source (BTE, %)	DF	Adj SS	Adj MS	F value	*P* value
Model	9	2769.67	307.74	2917.14	0.000
Linear	3	2385.52	795.17	7537.60	0.000
A	1	2384.24	2384.24	22600.75	0.000
B	1	1.27	1.27	12.01	0.006
C	1	0.00	0.00	0.03	0.872
Square	3	383.60	127.87	1212.08	0.000
A × A	1	197.77	197.77	1874.75	0.000
B × B	1	1.49	1.49	14.10	0.004
C × C	1	0.25	0.25	2.34	0.157
2-way interaction	3	0.56	0.19	1.76	0.219
A × B	1	0.51	0.51	4.79	0.054
A × C	1	0.02	0.02	0.15	0.711
B × C	1	0.04	0.04	0.33	0.577
Error	10	1.05	0.11		
Lack of fit	5	1.01	0.20	25.29	0.001
Pure error	5	0.04	0.01		
R^2 = 99.96%, R^2 (adj) = 99.93%					

Table 10. ANOVA table for the oxides of nitrogen emissions.

Source (NOx,%)	DF	Adj SS	Adj MS	F value	*P* value
Model	9	1681758	186862	217.63	0.000
Linear	3	1663021	554340	645.62	0.000
A	1	1632968	1632968	1901.86	0.000
B	1	28516	28516	33.21	0.000
C	1	1538	1538	1.79	0.210
Square	3	7653	2251	2.97	0.083
A × A	1	3325	3325	3.87	0.077
B × B	1	6529	6529	7.60	0.020
C × C	1	4	4	0.01	0.944
2-way interaction	3	11084	3695	4.30	0.034
A × B	1	9453	9453	11.01	0.008
A × C	1	253	253	0.29	0.599
B × C	1	1378	1378	1.61	0.234
Error	10	8586	859		
Lack of fit	5	7776	1555	9.60	0.013
Pure error	5	810	162		
R^2 = 99.49%, R^2 (adj) = 99.03%					

Table 11. ANOVA table for the carbon dioxide emissions.

Source (CO_2,%)	DF	Adj SS	Adj MS	F value	*P* value
Model	9	8.63078	0.95898	90.56	0.000
Linear	3	8.04070	2.68023	253.10	0.000
A	1	7.77924	7.77924	734.60	0.000
B	1	0.18225	0.18225	17.21	0.002
C	1	0.07921	0.07921	7.48	0.021
Square	3	0.12245	0.04082	3.85	0.045
A × A	1	0.05602	0.05602	5.29	0.044
B × B	1	0.00626	0.00626	0.59	0.460
C × C	1	0.00286	0.00286	0.27	0.614
2-way interaction	3	0.46764	0.15588	14.72	0.001
A × B	1	0.41861	0.41861	39.53	0.000
A × C	1	0.01901	0.01901	1.80	0.210
B × C	1	0.03001	0.03001	2.83	0.123
Error	10	0.10590	0.01059		
Lack of fit	5	0.09790	0.01958	12.24	0.008
Pure error	5	0.00800	0.00160		
R^2 = 98.79%, R^2 (adj) = 97.70%					

respectively and it is observed the relation is a straight line so the residuals represent a normal distribution. Fig. 5 represents the relations between the predicted values and the actual values for the BTE, NO_x, and CO_2, respectively. It is observed high similarity between the values, which indicates the model, is statistically significant.

4. Results and discussion

4.1. Effects of the independent variables on the brake thermal efficiency (BTE)

Fig. 6 indicates the influences of the engine load and WCO blend percentages on the BTE with holding the GO nanoparticles concentration at 150 ppm. From the figure, it is observed increase in the BTE with increasing the engine load and WCO blend percentage due to the high calorific value for the fuel mixed with GO nanoparticles at 150 ppm holding values, the high oxygen content for the mixture in addition to the high surface area to volume ratio. Fig. 7 indicates the influence of the WCO blend percentages and GO nanoparticles concentrations on the BTE with holding the engine load at 7 kW. It is observed increasing in the percentage of the BTE nearly at 15% of WCO biodiesel blend percentage then the percentage of the BTE decreases gradually whereby increasing the WCO biodiesel blend percentage. This is due to the fuel viscosity will be higher than the pure diesel viscosity so the fuel atomization process will face some problems and consequently increasing in the ignition delay period so the BTE will be decreased by increasing the WCO blend percentages.

4.2. Effects of the independent variables on the oxides of nitrogen (NOx)

Generally, the NO_x emissions concentrations increase according to two reasons the increase in the combustion time by increasing the ignition delay period and so increasing the temperatures of the combustion. Fig. 8 indicates the influences of the engine load and WCO biodiesel blend percentages on the NO_x emissions with holding the GO nanoparticles concentration at 150 ppm. From the figure,

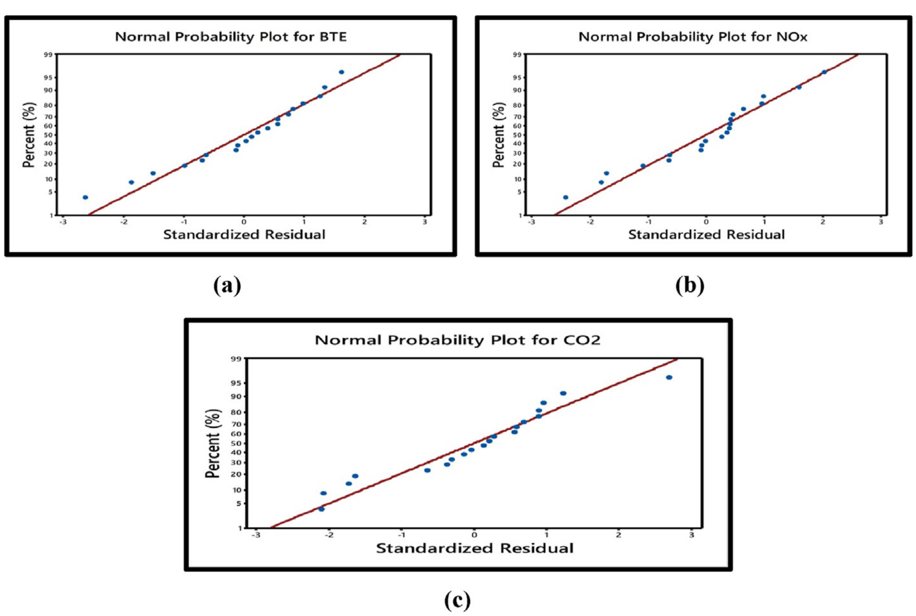


Fig. 4. The normal probability plots for the responses.

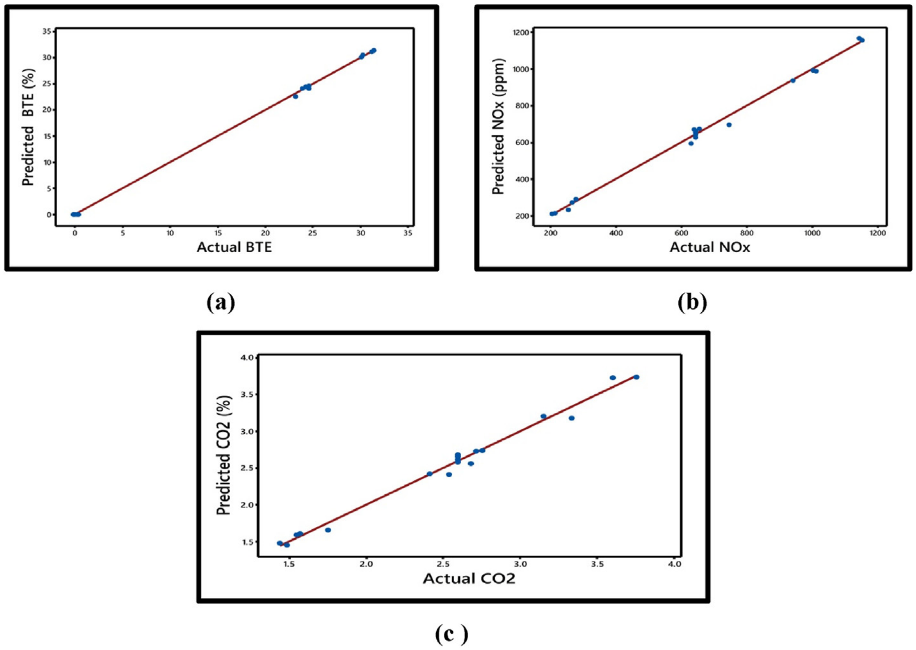


Fig. 5. The relationships for the responses actual and the predicted values.

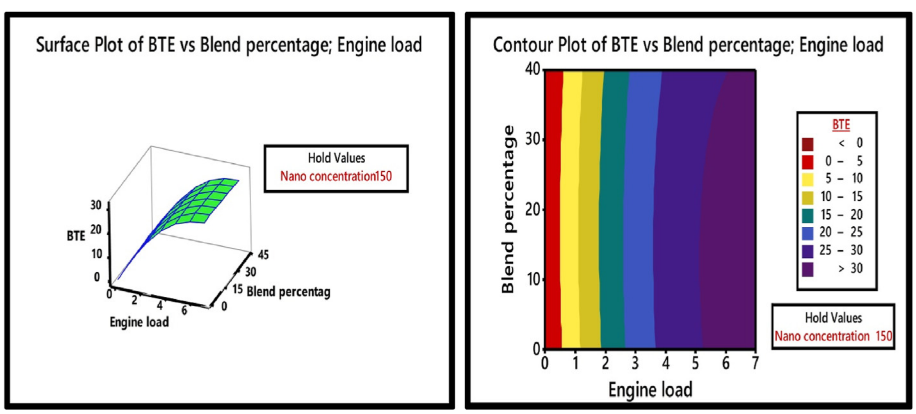


Fig. 6. The effect of the engine load and waste cooked oil biodiesel blend percentage on the brake thermal efficiency with holding graphene oxide nanoparticles concentrations at 150 ppm.

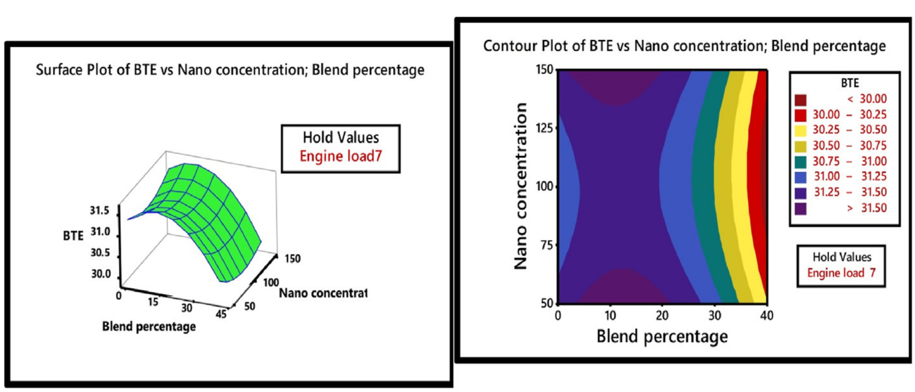


Fig. 7. The effect of the waste cooked oil biodiesel blend percentage and graphene oxide nanoparticles concentrations on the BTE with holding the engine load at 7 kW.

it is observed increasing in the NO_x emissions by increasing the engine loads due to the combustion completion and the increase in the temperatures of the combustion. The NO_x emissions also increase by increasing the WCO biodiesel blend percentages due to the high oxygen content for the mixture that complete the combustion and generate increasing in the combustion temperatures. The influence of using WCO biodiesel blend percentages and GO nanoparticles concentrations on the NO_x emissions are indicated in Fig. 9 at the 7 kW holding value for the engine load. By increasing the WCO biodiesel blend percentages, the NO_x emissions increase due to the high oxygen content for the mixture that produce high combustion temperature. It is observed also an increase in the NO_x emissions with increasing GO nanoparticles concentrations due to the high surface area to volume ratio, high oxygen content, and the high evaporation rate for the mixture and consequently increasing the temperatures of the combustion.

4.3. Effects of the independent variables on the carbon dioxide (CO_2)

Fig. 10 indicates the influences of the engine load and WCO blend percentages on the CO_2 emission while holding GO nanoparticles concentration at 150 ppm. Generally, the CO_2 emission increases due to the complete combustion and conversation the CO emission to CO_2. From the figure, it is observed increase in the values of the CO_2 emission with an increase in the engine load due to the improvement and completion of the combustion and consequently converting CO to CO_2. In addition, it is observed rising in CO_2 emissions with increasing percentages of the WCO biodiesel blends due to the high oxygen content in the WCO

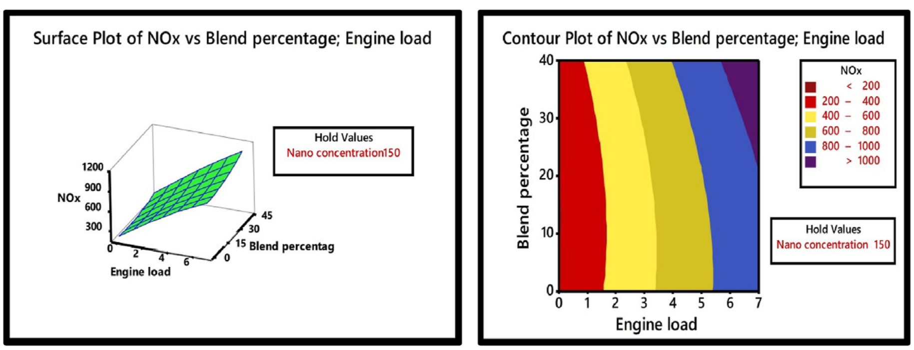


Fig. 8. The effect of the engine load and waste cooked oil blend percentage on the oxides of nitrogen emissions with holding graphene oxide nanoparticles concentration at 150 ppm.

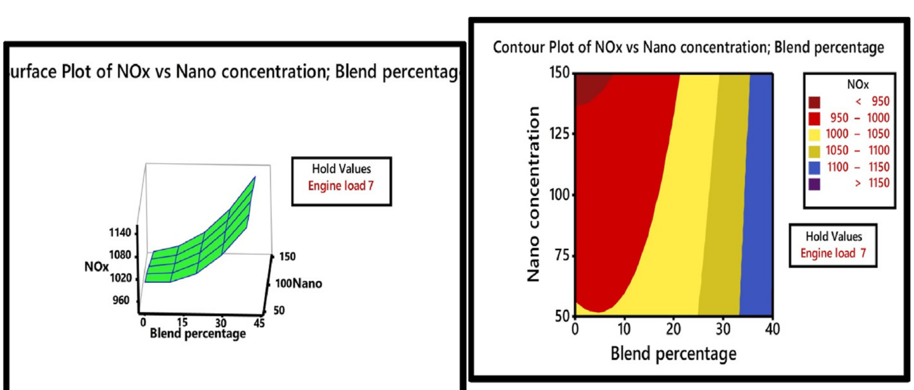


Fig. 9. The effect of the waste cooked oil blend percentage and graphene oxide nanoparticles concentration on the oxides of nitrogen with holding the engine load at 7 kW.

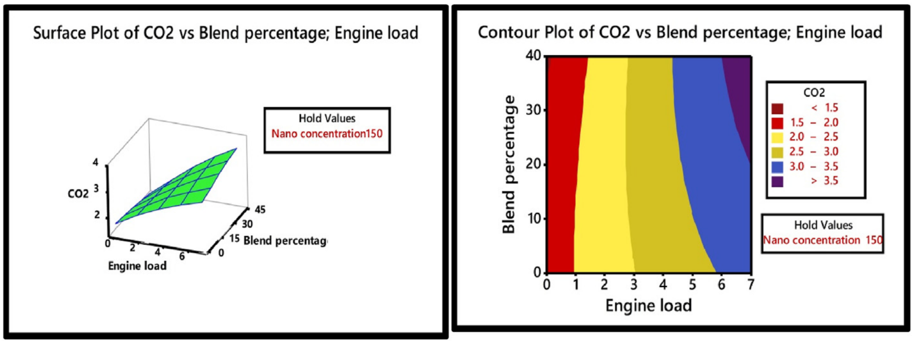


Fig. 10. The effect of the engine load and waste cooked oil blend percentage on the carbon dioxide emission with holding graphene oxide nanoparticles concentration at 150 ppm.

biodiesel blends and consequently complete combustion and converting CO to CO_2. The influence of using WCO blend percentages and GO nanoparticles concentrations on the CO_2 emissions is indicated in Fig. 11 with the 7 kW holding value of the engine load. As indicated by increasing the WCO biodiesel blend percentages the CO_2 emissions increase due to the high oxygen content for the mixture and consequently complete the conversion for CO to CO_2. It is observed also increase in CO_2 emissions with increasing GO nanoparticles concentrations due to the high surface area to volume ratio that increase the chemical reactivity, increases the evaporation rate, and so completes the combustion.

4.4. The optimized responses

The individual desirability and composite desirability indicate how a group of independent variables can achieve the goals for the responses. The individual desirability (d) indicates the optimum settings for a single response but composite desirability (D) indicates the settings to optimize all responses and has values from zero to one which refers to the ideal setting while zero refers to there are unaccepted responses. The individual desirability is calculated using MINITAB software by utility transfer function but the composite desirability calculated by the weighted geometric mean of the individual desirability for the responses. Fig. 12 indicates the best independent variables for the optimum responses using the response optimizer tool at the MINITAB software application. The aim of this study is to optimize the performance and emission attributes for the mentioned diesel engine at the following conditions 2.47 kW engine load, 3.6364% WCO biodiesel blend percentage, 50 ppm GO nanoparticles concentration, and composite desirability 65.22%. The optimum responses are found as follows, the maximum BTE is 18.973%, the minimum NO_x emissions is 539.33 ppm and the minimum CO_2 emission is 2.1423%.

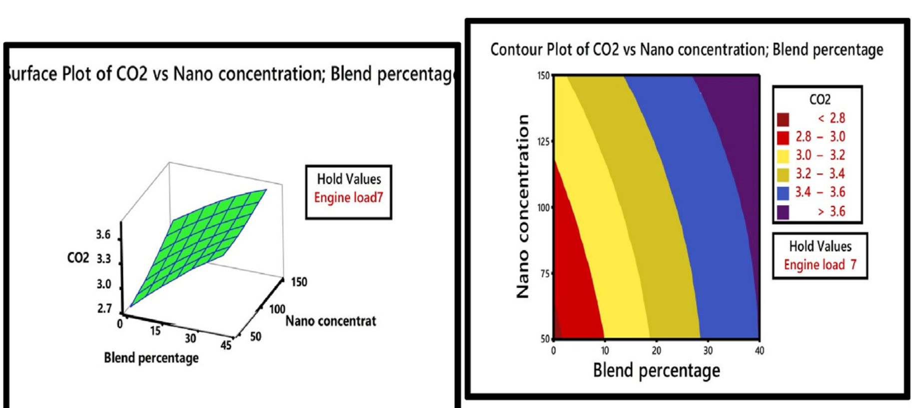


Fig. 11. The effect of the waste cooked oil blend percentage and graphene oxide nano concentration on the carbon dioxide emission with holding the engine load at 7 kW.

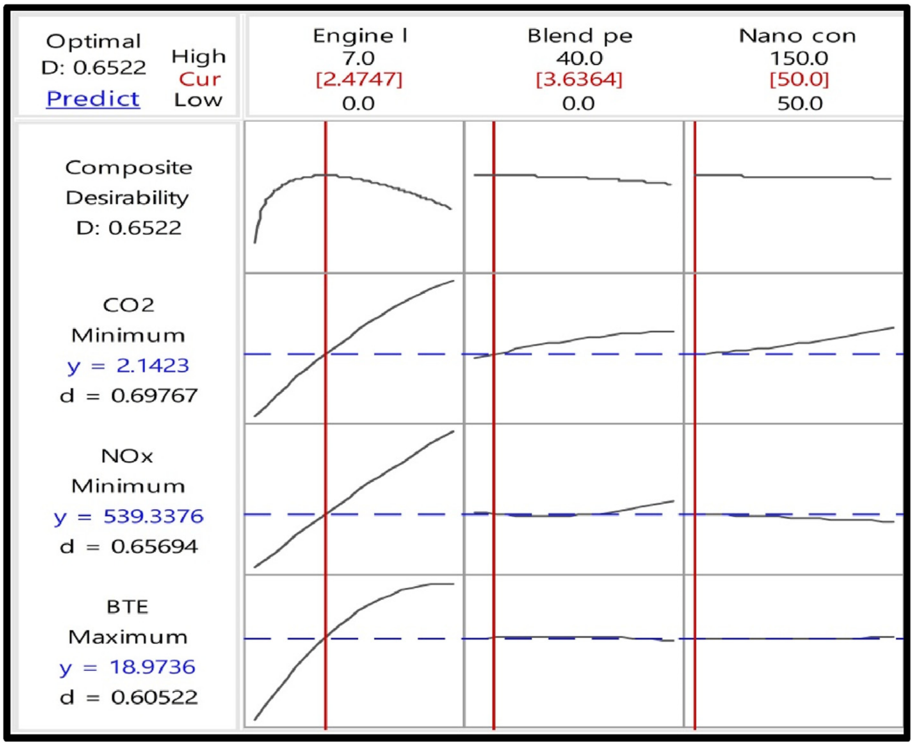


Fig. 12. The best independent variables values to optimize the performance and emission engine attributes.

5. Conclusion and future recommendations

In this research, the influences of using GO nanoparticles at different concentrations with pure diesel or diesel blended with WCO biodiesel at different percentages on the performance and emission attributes of four-stroke, single cylinder, and constant speed diesel engine are studied. GO nanoparticles concentrations are 50 100 and 150 ppm and are mixed with various diesel-WCO biodiesel blends (B0, B20, and B40) using 4% toluene as a surfactant. The tested engine was supplied with different blends and operated at various engine loads of 0, 3.5, and 7 kW. The interactions between the independent variables such as fuel blend percentage, GO nanoparticles concentrations, and the engine loads on the attributes of the performance and emissions for the diesel engine like the BTE, the NO_x emissions, and the CO_2 emission are analyzed and optimized by the DOE. To determine the minimum experiment number must be performed according to the CCD of the RSM using MINITAB software application. The results found are summarized below:

(a) It is observed enhancements in the BTE, NOx emissions and CO_2 emissions by increasing the percentages of WCO biodiesel blends due to the increasing in the oxygen content for the mixture. It is observed enhancements in all diesel engine attributes by using GO nanoparticles due to the high surface area to volume ratio that increase the chemical reactivity, increase the evaporation rate, and so complete the combustion.
(b) The predicted results by using the RSM software application are validated by the required experiments and it is observed that the models are statistically significant.
(c) The coefficient of determination (R squared) that represents the model's accuracy has 99.96% for the BTE, 99.49% for the NO_x emissions, and 98.79% for the CO_2 emission.
(d) The RSM optimizer tool is used to optimize the independent variables that produce the optimized responses. The optimum responses are 18.97% for the BTE, 539.33 ppm for the NOx emissions, and 2.14% for the CO_2 emission at 2.47 kW engine load, 50 ppm GO nano concentration, and 3.63% WCO biodiesel blend percentage.

For future recommendations study the influence of a combination of different resources biodiesel fuel at varied percentages, and different nanoparticles at different concentrations on the diesel engine performance and emission attributes in addition to optimization of the responses by different RSM techniques. It can also use numerical modeling approaches like computational fluid dynamics for reducing the experiment numbers with accurate responses.

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Authors contributions

All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by Medhat Elkelawy, Hagar Bastawiss, E. A. El Shenawy, and Mahmoud M. Shams. The first draft of the manuscript was written by All authors read and approved the final manuscript.

Conflict of interest

There are no conflicts of interest.

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