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Perspective

Response surface methodology-based parameter optimization of single-cylinder diesel engine fueled with graphene oxide dosed sesame oil/diesel fuel blend

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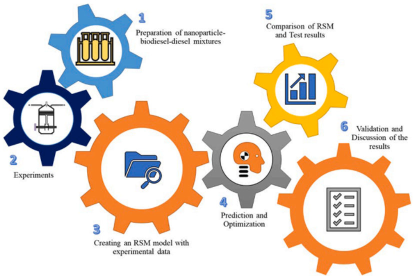
HIGHLIGHTS

- The multi-objective RSM optimization for modified nano fuel is presented.
- Optimum 100 ppm amount of graphene oxide gives the best responses.
- Predictive capabilities of developed model responses are experimentally validated.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, an experimental study was carried out to determine the effects of adding different amounts of graphene oxide (GO) on engine characteristics to a single-cylinder diesel engine operating with 30% sesame oil (SO) + 70% diesel fuel mixture. After that, an optimization was carried out with response surface methodology (RSM) to determine optimum operating conditions at different engine loads. Experimental results showed that GO nanoparticle is a good addition for diesel–biodiesel blends to enhance the performance and reduce emissions. The most appropriate amount of GO is between 75 ppm and 100 ppm for the performance characteristics. The optimal amount of GO for power is 75 ppm, while for brake-specific fuel consumption (BSFC) and exhaust gas temperature (EGT) it is 100 ppm. In addition, the maximum GO amount of 100 ppm is the most suitable for carbon monoxide (CO) and hydrocarbon (HC), and 75 ppm GO amount is the most appropriate for nitrogen oxides (NO_x). On the other hand, optimization results revealed that 100 ppm GO at 1950 W load was optimum conditions for all responses. The responses that emerged under optimum conditions were 1746.77 W, 968.73 g/kWh, 259.8 °C, 0.0603%, 23.13 ppm and 185.61 ppm for power, BSFC, EGT, CO, HC, and NO_x, respectively. According to the validation study, the error between the optimum and experimental results is 4.69% maximum. According to the findings of study, it can be concluded that the RSM model can successfully model a single-cylinder diesel engine and thus save time, and money.

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Nomenclature

BSFC	brake specific fuel consumption
CO	carbon monoxide
EGT	exhaust gas temperature
GO	graphene oxide
HC	hydrocarbon
NO_x	nitrogen oxides
RSM	response surface methodology
SO	sesame oil

1. Introduction

Climate change and the worldwide unbalanced ecosystem that has arisen in connection with climate change have serious adverse effects on human health and agriculture [1]. The large amount of greenhouse gasses resulting from increased in fossil fuel use is one of the leading causes of air pollution and climate change. Air pollution caused by fossil fuel vehicles in factories, power plants and transportation, is estimated to cause 3 million deaths worldwide each year, and this number is expected to increase to 4.5 million by 2040 [2,3]. Renewable energy sources are seen as the most appropriate solution to reduce or eliminate toxic air pollutants caused by burning fossil fuels, which are harmful to the environment and people.

Recently, there have been many developments regarding the use of alternative renewable energy sources, especially solar energy, and wind energy, in homes and offices or in small industrial enterprises. However, using these energy sources in internal combustion engines could not provide very effective solutions. The diesel engine, one of the internal combustion engines, is preferred as the primary engine type in many sectors due to their more remarkable load carrying ability, durability, and better fuel economy than gasoline engines. However, diesel engines significantly contribute to the formation of CO, HC, CO_2, NO_x, and smoke from air pollutants emissions. Therefore, using renewable fuels such as biodiesel as an alternative to diesel fuel in diesel engines can significantly reduce harmful exhaust emissions.

Biodiesel, which has physicochemical properties close to diesel, has a higher flash point than diesel, is nontoxic, does not contain sulfur, is biodegradable and has an oxygenated structure, and is a renewable fuel type that can be produced from vegetable oils, animal oils, kitchen wastes, and algae. However, due to poor cold flow properties and oxidation stability, poor fuel atomization, and relatively higher NO_x emissions, the biodiesel industry still faces problems in commercialization [4,5]. The type of raw material used in the production of biodiesel and the processes in the production play a key role on the properties of the biodiesel. Biodiesels obtained from vegetable oils are seen as more remarkable by researchers. Based on the knowledge that the original diesel engine designed by Rudolph Diesel works with vegetable oil, it can be said that biodiesel obtained from vegetable-based sources is an excellent alternative fuel source for diesel engines. Among the vegetable oils that can be produced from biodiesel, SO is a promising biodiesel raw material that can improve cold flow properties without changing its oxidation stability [4,6]. Studies on the use of SO as an alternative fuel in diesel engines have been carried out by researchers [7–10]. Although vegetable-based biodiesels have many advantages, the main problem when they are used in pure form is high viscosity. With the use of high viscosity fuel in diesel engines, adverse conditions such as poor fuel optimization, clogging of filters and pipes, and even incomplete combustion may occur. These conditions generally lead to a decrease in performance and an increase in exhaust emissions.

In order to reduce harmful exhaust emissions and improve engine performance parameters, many methods such as exhaust gas reduction techniques, use of various biodiesel blends, modification of engine geometry, and modification of fuel formulations have been carried out by researchers [11,12]. Especially in recent years, researchers have turned to fuel formulation methods as the most beneficial way to improve general engine properties. For this purpose, a homogeneous distribution in the fuel can be achieved by using nanoparticles ranging from 1 to 100 nm instead of micron-sized particles that will cause agglomeration and aggregation problems at the bottom of the fuel [11,13]. Nanoparticles act as a secondary energy carrier in liquid fuels and improve combustion properties. Oxides of cerium, copper, iron, aluminum, cobalt, boron, silver, graphene, and platinum have recently been used as additives in biodiesel fuel blends.

In a study [14] on the addition of nanoparticles to biodiesel blends, it was emphasized that BTE could be improved due to the increased combustion rate, superior atomization, and rapid evaporation particles in the fuel, resulting in healthier mixing of the fuel and allowing extra surface area for fuel/oxygen reaction. In the study by Dhana et al. [15], Al_2O_3 nanoparticle additives were used in biodiesel blends, and it was emphasized that Al_2O_3 improved the combustion reaction thanks to its high oxygen content and consequently increased BTE. Elumalai et al. [16] added CuO/ZnO (CZ) nanoparticles to the diesel fuel mixture with pyrolytic oil obtained from waste tires by the pyrolysis process they chose as the primary fuel in their study to investigate the effect on the performance, combustion and emission characteristics of a premixed charged compression ignition engine operated in dual fuel mode. The authors have stated that the BSFC value obtained with a fuel mixture containing 20% pyrolytic oil with 50 ppm CZ added and 80% diesel is low by 3.4%. They also stated that this situation may be the improved combustion reactivity by adding nanoparticles to the mixture.

Non-metallic GO blended with fuel as a prominent additive to improve engine performance, and emissions have emerged as a promising development [13,17]. Ağbulut et al. [18] synthesized GO nanoparticles and added different amounts (100, 500, and 1000 ppm) to waste cooking oil methyl ester/diesel fuel mixtures containing waste cooking oil methyl ester at different rates (0% and 15%) and investigated the effects on combustion, performance and emission properties in diesel engines. The experiments were carried out at a constant speed of 2400 rpm and different engine loads (3, 6, 9, and 12 Nm). The authors stated that GO nanoparticles increase the oxygen ratio in the cylinder, thus providing more complete combustion. For this reason, they stated that CO emissions decreased by 22.5% and HC emissions by 30.23%. In addition, it was stated that NO_x emission decreased by 15.17% due to the superior surface/volume area ratio and the thermal properties of GO nanoparticles. The authors reported that with the addition of GO nanoparticles, the energy content of the test fuels improved, and therefore BTE increased by 7.90%, while BSFC decreased by 9.72%. As a result, it was revealed by the authors that GO nanoparticles could offer a satisfactory solution to improve the deteriorating properties caused by biodiesel and diesel mixtures in diesel engines. EL-Seesy et al. [19] aimed to investigate the effect of adding GO to pure Jatropha Methyl Ester in a single-cylinder air-cooled direct injection four-stroke diesel engine. Test fuels were obtained with a mixture of Jatropha biodiesel and 25, 50, 75, and 100 mg/l graphene oxide. The results revealed that with the addition of GO, the brake thermal efficiency increased by 17%, and the CO and HC emissions decreased by 60% and 50%, respectively. In addition, the authors stated that 50 mg/L concentration is the optimum level in terms of engine performance and emissions.

Apart from the superior properties of nanoparticles and the improvements they provide to diesel engines, they have the disadvantage that they are expensive [20,21]. Therefore, determining the optimum conditions and nanoparticle concentration in the engine where nanoparticles will be used is crucial for lower fuel cost, better performance, and emissions. Statistical applications, including artificial neural network, Taguchi, fuzzy logic, and RSM methods are used to determine possible engine variations [22–27]. RSM has proven to be an effective tool for determining optimum values of individual parameters [28–30]. Although there are many studies on the use of RSM to determine the optimum operating conditions in a diesel engine, there is no study related to optimizing of the use of GO. Ghanbari et al. [31] used RSM to examine and optimize the effects of adding different amounts of alumina nanoparticles to a six-cylinder, four-stroke diesel engine using diesel/-biodiesel fuel blends. While the authors determined 160 ppm nanoparticle concentration and 1000 rpm engine speed as the best-operating conditions, they added that alumina nanoparticle is a good additive for diesel-biodiesel blends to increase the diesel engine's performance and reduce its emissions. The authors stated that when the nanoparticle concentration in the fuel increases, the CO concentration decreases, and this is due to the increased complete combustion rate. In addition, the authors stated that the HC concentration decreased when the nanoparticle concentration in the fuel increased, and this was because the addition of nanoparticles to the fuel lowered the activation temperature of carbon and improved combustion. In another study, Vali et al. [32] evaluated variables such as compression ratio, biodiesel volume ratio, water percentage, and nanoparticle concentration as working parameters and performed an optimization study with RSM. Zinc oxide was preferred as a nanoparticle. The authors stated that the optimum working conditions are 18.84 compression ratio, 18.98% biodiesel mixing ratio, 5.71% water emulsion, and 90.9 ppm Zinc oxide nanoparticle concentration. Finally, the authors stated that the optimization study was successful with acceptable deviation rates.

Literature studies reveal that although biodiesel as an alternative fuel generally improves engine characteristics, there is deterioration in NO_x emissions in particular. Nanoparticle addition is one of the innovative methods used in this regard. Although there are experimental studies on the addition of GO to diesel and various biodiesels in the literature, no study has been found regarding the addition of SO/diesel fuel mixtures. In addition, there is no study in the literature on the optimization of SO/diesel fuel mixtures with GO added with RSM. The novelty of this study is to examine the effects of adding GO to SO/diesel fuel mixtures and determining the optimum amount of GO with RSM.

Since nanoparticles have the disadvantage of being expensive despite the superior properties and improvements they provide in diesel engines, it is essential to determine the optimum conditions and nanoparticle concentration in the engine to obtain better performance and emissions with lower fuel costs. Accordingly, the main objectives of this study are to improve the performance and emissions by adding different amounts of GO after the best SO/diesel fuel mixture is determined by experiments, and to determine the optimum amount of GO with the minimum number of experiments by optimizing with RSM. Thus, a multipurpose study was carried out to reduce the greenhouse gas effect by using an environmentally friendly fuel, to reduce the adverse effects of biodiesel by adding GO, and to obtain the best results with a minimum number of experiments by optimizing the working conditions with RSM.

2. Materials and methods

Experimental studies with SO/diesel fuel mixtures containing different ratios of SO revealed that the appropriate SO ratio is 30% in terms of performance and emission characteristics, and accordingly, tests were carried out at varying engine loads (500, 1000, 1500, 2000, 2500 and 3000 W) by adding different amounts of GO (25, 50, 75 and 100 ppm) to the fuel mixture containing 30% SO/70% diesel. Different amounts of GO were added to the SO/diesel fuel mixture, and homogeneous fuel mixtures were formed by mixing with a magnetic stirrer for 24 h. The fuel properties of SO and diesel used are shown in Table 1, and the properties of the fuel mixtures formed are shown in Table 2. The physical and chemical properties of fuels and fuel mixtures were determined in the TUBITAK Marmara Research Center Laboratory. In addition, density, kinematic viscosity, and lower calorific value changes of fuel mixtures are graphically shown in Figs. 1–3, respectively.

Table 1
Properties of diesel and SO.

Properties	Diesel	SO	Analysis method
Density at 15 °C (kg/m^3)	830.2	921.9	EN ISO 12,185
Kinematic viscosity @ 40 °C (mm^2/s)	2.861	30.93	ASTM D 445
Lower calorific value (kJ/kg)	43,015	38,075	D240
Cetane number	56.2	52.2	EN ISO 5165
Flash point (°C)	65.5	290	ASTM D 93

A schematic figure of the experimental setup is shown in Fig. 4 with all instruments.

To minimize the error that may arise from the measurements during the experiment, the measuring devices were calibrated before the experiments and each experiment was repeated three times. The uncertainties of measured responses have been defined in Table 3 according to the Kline and McClintock method. The uncertainty is ± 3.228 for this study, as shown below.

$$= \sqrt{\left[(U_{Load})^2 + (U_{Power})^2 + (U_{BSFC})^2 + (U_{EGT})^2 + (U_{CO})^2 + (U_{HC})^2 + (U_{NO_x})^2\right]}$$

$$= \sqrt{\left[(0.79)^2 + (1.36)^2 + (1.12)^2 + (0.95)^2 + (1.63)^2 + (1.03)^2 + (1.44)^2\right]}$$
$$= \pm 3.228\%$$

2.1. Construction of RSM

For modeling complex experimental systems with RSM, as in this study, Eq. (1) is used. Here, β denotes the coefficients, x denotes the independent variables, y denotes the model's predicted response, k the model's rank, and finally ε the random error.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \quad (1)$$

This study; determined GO amount and engine load as variables affecting responses to be used for RSM modeling. The different levels of these variables used in the RSM modeling are tabulated in Table 4. Power, BSFC, EGT, CO, HC, CO_2, and NO_x were determined as the responses whose effects were investigated on these variables.

3. Findings

The p-values, R^2 values, and regression equations obtained according to the analysis of variance (ANOVA) performed with RSM modeling are tabulated in Table 5. P-values indicate whether a variable influences the response, while R^2 values indicate the degree of success of the modeling. A p-value less than 0.05 indicates that the variable is significant in modeling applications with a 95% confidence level. On the other hand, the closer the R^2 value is to 100%, the more successful the modeling is. Lastly, regression equations predict the response when variable levels are entered for a response.

3.1. Surface plots of responses

In this section, the combined effect of GO amounts and engine load on engine responses will be illustrated by surface plots.

The effect of GO amount variation on Power and BSFC at different engine loads is shown as surface plots in Figs. 5 and 6. As can be seen from the surface graphs, Power and BSFC, defined as engine performance parameters, were positively affected by the addition of GO. The addition of nanoparticles has led to more efficient combustion and a reduction in BSFC by supporting the carbon oxidation rate in the engine [33,34].

Another advantage of the engine with the addition of GO is the shortening of the combustion time. Reducing the combustion time with the addition of GO allows the fuel droplet to burn near the top dead

Table 2
Properties of test fuels.

Properties	70D30SO25GO	70D30SO50GO	70D30SO75GO	70D30SO100GO	Analysis method
Density at 15 °C (kg/m^3)	855.1	856.7	858.3	859.9	EN ISO 12,185
Kinematic viscosity @ 40 °C (mm^2/s)	5.752	5.765	5.779	5.792	ASTM D 445
Lower calorific value (kJ/kg)	41,465	41,492	41,515	41,541	D240

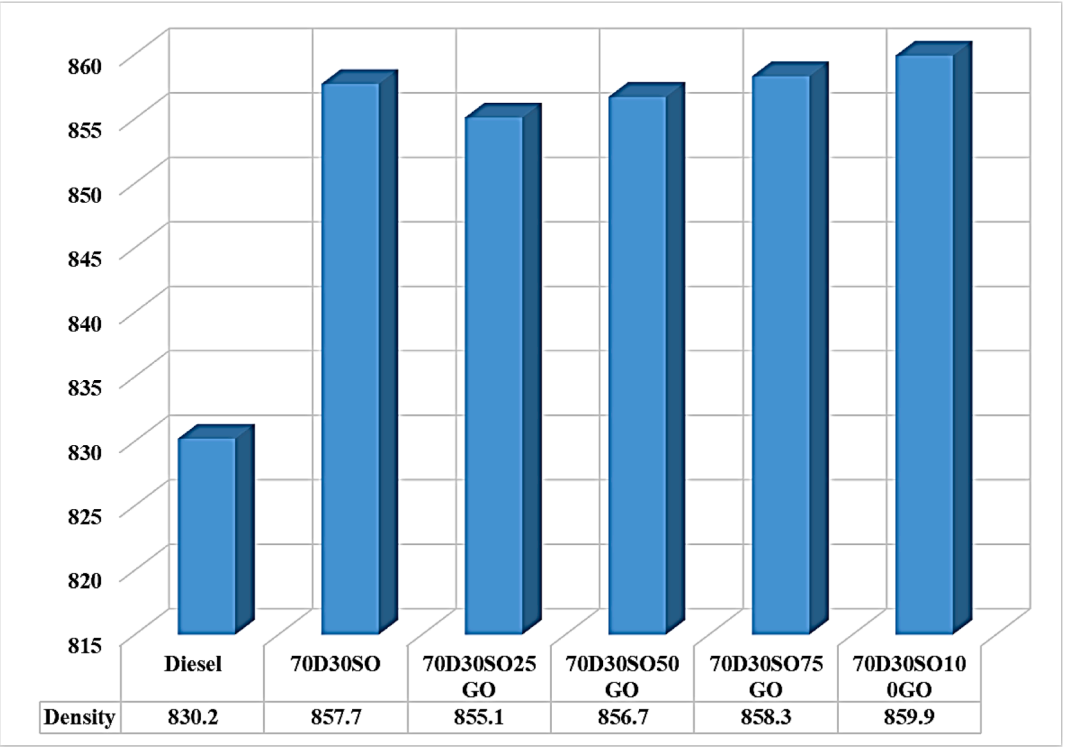


Fig. 1. Comparison of density values of test fuels with diesel.

center, thus leading to higher cylinder pressure and power [35]. Both increased GO amount and engine load had a positive effect on power. On the other hand, the power value started to show a decreasing trend after 75 ppm GO. Compared to the change in GO amount, the effect of engine load on power was more remarkable. The increase in GO amounts from 25 ppm to 75 ppm provided an average increase of approximately 1%, while the increase in engine load from 500 to 3000 increased approximately 5 times. Maximum power was obtained as 2836.89 W at 3000 W load with 75 ppm GO.

GO nanoparticles act as an oxygen promoter to generate high pressure and temperature in the engine cylinder. In addition, better combustion quality and subsequent reduction in fuel consumption are achieved due to the improved fuel reactivity offered by the nanoparticles. In the end, it is seen that the BSFC is also positively affected by the increased engine load. The BSFC decreases as the thermal efficiency is higher at high loads. The lowest BSFC was determined as 897.90 g/kWh with the addition of 100 pm GO at 3000 W load. A reduction of 5.16% was achieved compared to the BSFC (946.75 g/kWh) value obtained by adding 25 ppm GO at the same load.

The variation of EGT according to GO amount and engine load is presented in Fig. 7. While EGT decreased with increasing GO amount, on the contrary, EGT values increased with growing load. Based on this, the lowest EGT was determined as 164 ℃ at 500 W load with 100 ppm GO. With the increase of GO amount from 25 ppm to 100 ppm at the same load, EGT decreased by approximately 24.54%. It is thought that the ability of GO addition to reducing the rich mixing region in the diffusion mechanism leads to a decrease in EGT. On the other hand, it was mentioned before that the engine load is a parameter that directly affects the in-cylinder temperature. Accordingly, it is natural for the in-cylinder temperature and therefore the EGT to increase as the engine load increases. At the addition of 100 ppm GO, the increase in EGT more than doubled as the engine load increased from 500 W to 3000 W.

The surface graph showing the change of CO emission, which is one of the harmful emissions, which is the product of incomplete combustion, depending on the GO and the load is presented in Fig. 8. Although the change in CO emission resulting from the addition of GO forms an almost horizontal curve, a slight decrease has been achieved. The large surface area of GO that will increase chemical reactivity and shortens the ignition delay and thus improves combustion [36]. As combustion improves, CO emissions are reduced. While the lowest CO emission was obtained at 100 ppm GO amount and 2000 W load, approximately 19.46% reduction was obtained compared to adding 25 ppm GO at the same load.

From another point of view, at 100 ppm, the GO value where the lowest CO emission is obtained, an approximately 76% increase in CO emissions was observed as the engine load increased from 500 W to 3000 W. As can be seen from the figure, there has been a rapid increase in CO emissions after a load of 2000 W. The lack of sufficient time for mixture formation at high loads caused a rapid increase in CO emissions.

The variation of HC emission, which expresses the fuel ejected from combustion in internal combustion engines, depending on the engine load and the amount of GO, is given in Fig. 9. It can be understood from the figure that HC emission decreases rapidly with increasing GO amount, and on the contrary, increases rapidly with increasing engine load. Since the insufficient time for homogeneous mixture formation at high loads will prevent some of the fuel from meeting with oxygen, it is

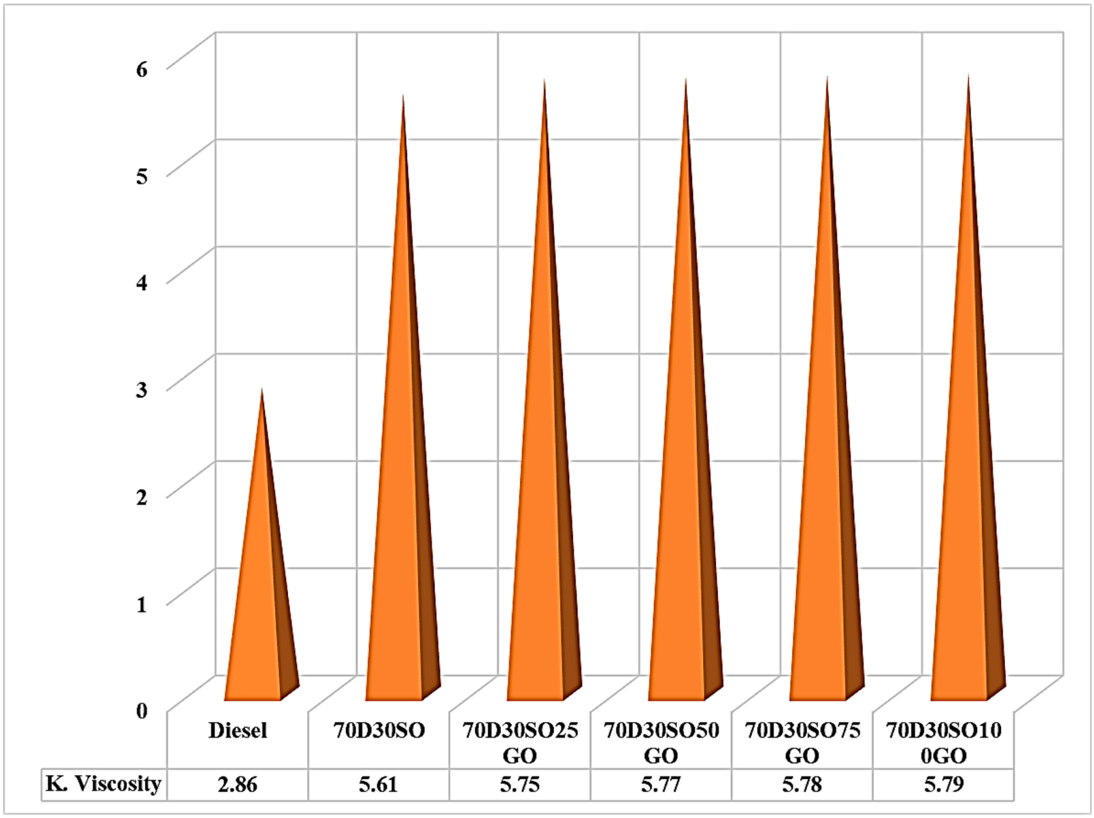


Fig. 2. Comparison of kinematic viscosity values of test fuels with diesel.

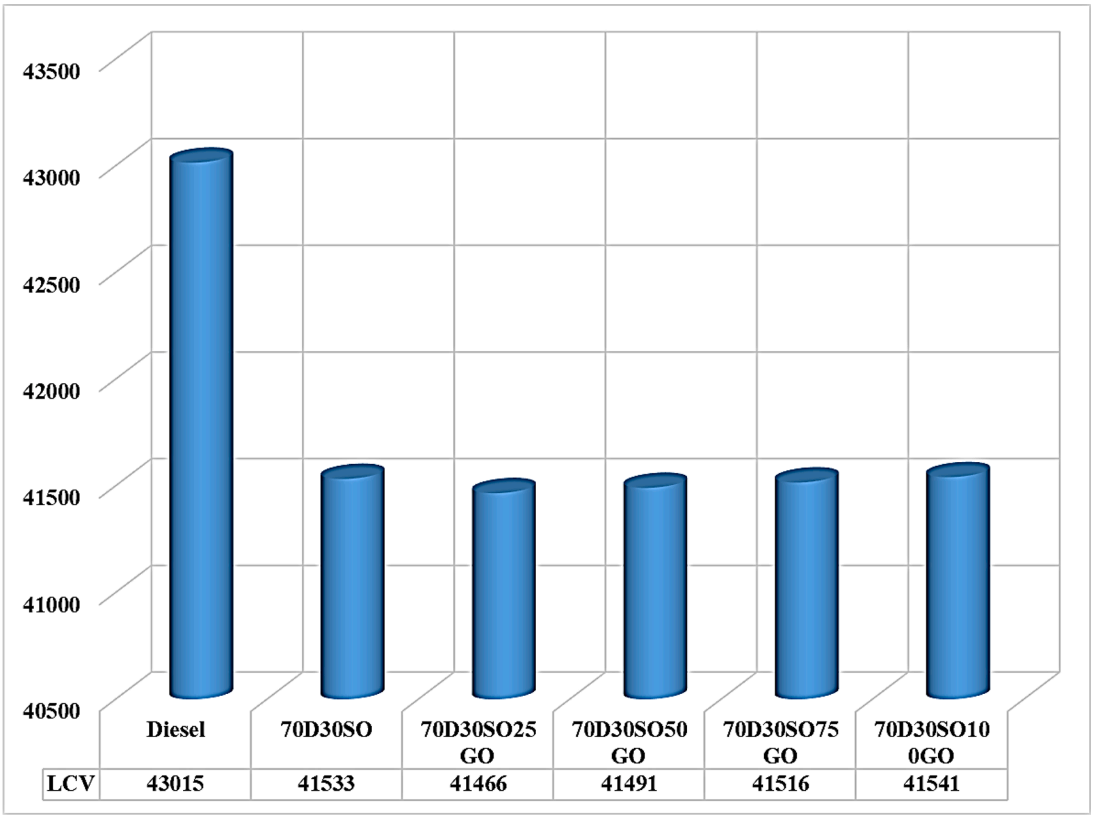
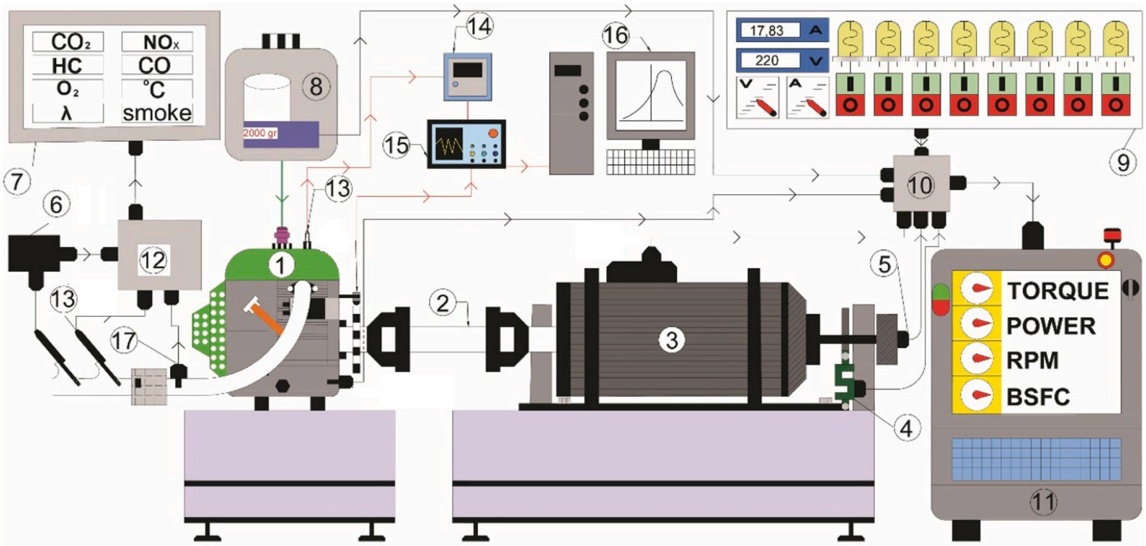


Fig. 3. Comparison of lower calorific values of test fuels with diesel.



1- Single Cylinder Diesel Engine
2- Shaft
3- Dynamometer
4- Torque Load Cell
5- Encoder
6- Exhaust Port 1
7- Exhaust Gas Analyzer
8- Fuel Consumption Measured Unit
9- Load Board
10- Fluke Control Panel
11- Control Unit
12- NDIR NON-Dispersive IR Measuring Module
13- Exhaust Port 2
14- Charge Amplifier
15- Oscilloscope
16- ICP Analysis Unite
17- Exhaust Temperature Sensor

Fig. 4. Schematic figure of a test setup with all instruments.

Table 3
Uncertainties of evaluated responses.

Evaluated responses	Uncertainty
Load	± 0.79
Power	± 1.36
BSFC	± 1.12
EGT	± 0.95
CO	± 1.63
HC	± 1.03
NO_x	± 1.44

Table 4
Factors affecting responses along with their levels.

Factors	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
GO amount (ppm)	25	50	75	100	–	–
Load (W)	500	1000	1500	2000	2500	3000

Table 5
P-values, R^2 values, and regression equations.

Source *p-values*	Power	BSFC	EGT	CO	HC	NO_x
GO	0.287	**0.000**	**0.000**	0.278	**0.000**	**0.000**
L	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
GO^2	0.232	**0.050**	0.157	0.707	**0.035**	0.464
L^2	0.245	**0.005**	**0.000**	**0.000**	**0.004**	**0.008**
GO * L	0.906	0.630	0.318	0.311	**0.047**	**0.009**
R^2 values						
R^2 (%)	98.56	99.15	99.48	97.92	99.35	97.78
Adjusted R^2 (%)	97.66	98.62	99.15	95.84	98.94	96.39
Predicted R^2 (%)	95.58	97.93	96.88	91.29	98.00	87.80
Regression equations						
Power	$-193 + 10.61\,\mathbf{GO} + 0.705\,\mathbf{L} - 0.0725\,\mathbf{GO^2} + 0.000068\,\mathbf{L^2} - 0.00015\,\mathbf{GOL}$					
BSFC	$1117.2 - 1.311\,\mathbf{GO} - 0.01787\,L + 0.00583\,\mathbf{GO^2} - 0.000009\,\mathbf{L^2} - 0.000028\,\mathbf{GOL}$					
EGT	$223.4 - 1.163\,\mathbf{GO} + 0.0147\,L + 0.00465\,\mathbf{GO^2} + 0.000017\,\mathbf{L^2} + 0.000069\,\mathbf{GOL}$					
CO	$0.2301 - 0.00063\,\mathbf{GO} - 0.000274\,L + 0.000008\,\mathbf{GO^2} + 0.000001\,\mathbf{L^2}$ - $0.000001\,\mathbf{GOL}$					
HC	$33.20 - 0.042\,\mathbf{GO} + 0.00676\,\mathbf{L} - 0.002344\,\mathbf{GO^2} + 0.000004\,\mathbf{L^2} - 0.000047\,\mathbf{GOL}$					
NO_x	$21.5 - 0.579\,\mathbf{GO} + 0.1804\,L + 0.00498\,\mathbf{GO^2} - 0.000022\,\mathbf{L^2} - 0.000490\,\mathbf{GOL}$					

Significant – ($0.000 < p \leq 0.05$).
(**GO**: Graphene Oxide, **L**: Load, **GO^2**: GO* GO, **L^2**: Load * Load, **GOL**: GO * L).

expected that HC will increase as the load increases. On the other hand, as in CO emission, the primary reason for the reduction in HC emission with the addition of GO is that GO improves combustion by increasing chemical reactivity and shortening the ignition delay. In addition, the oxygen content of GO played an active role in this decrease as it increased the oxygen supply required for fuel combustion. The lowest HC emission concentration was obtained with 100 ppm GO at 500 W load. In other words, the minimum HC emission was obtained with the highest level of the GO amount and the lowest level of the engine load. By increasing the amount of GO from 25 ppm to 100 ppm, approximately 80% reduction was obtained at the same load.

Fig. 10 presents the variation of NO_x emissions. It is seen that the addition of GO affects NO_x emission positively and the engine load negatively. NO_x formation mainly depends on temperature, local oxygen concentration and combustion time [19]. There are two main ways to reduce NO_x emissions: reducing the flame temperature and reducing the combustion time [17,19]. It is thought that NO_x emissions are reduced because the addition of GO causes a shortening combustion time. On the other hand, NO_x emissions increased because the engine load increased the in-cylinder temperature. Minimum NO_x was obtained as 75.33 ppm at 75 ppm GO and 500 W load conditions. An increase of GO from 25 to 75 ppm resulted in a 23.13% reduction in NO_x emissions.

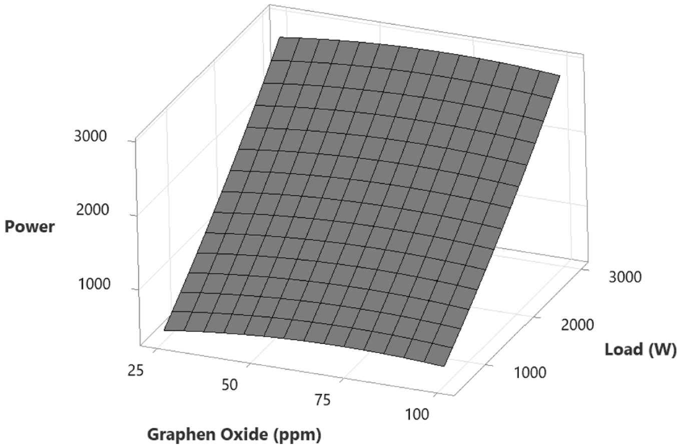


Fig. 5. Variation of power depending on GO and load.

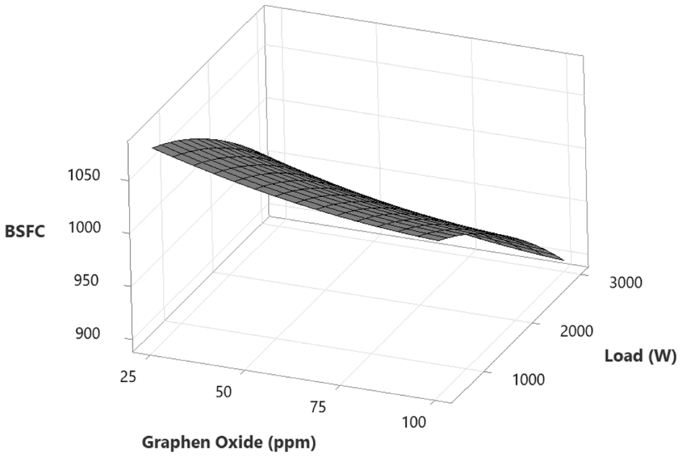


Fig. 6. Variation of BSFC depending on GO and load.

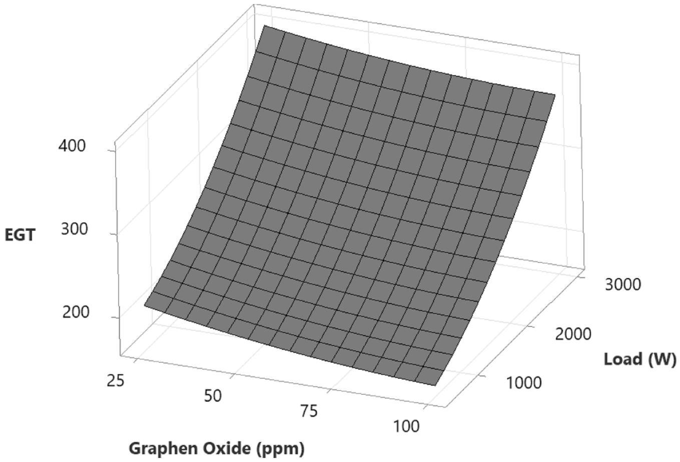


Fig. 7. Variation of EGT depending on GO and load.

3.2. *Evaluation of RSM predicted results and experimental results*

In this section, a comparison was made to determine how well the estimations made using the regression equations and the fourteen experiments used to create the RSM model were compatible. Table 6 presents the comparison of the responses selected as performance criteria, and Table 7 presents the comparison of the emission responses.

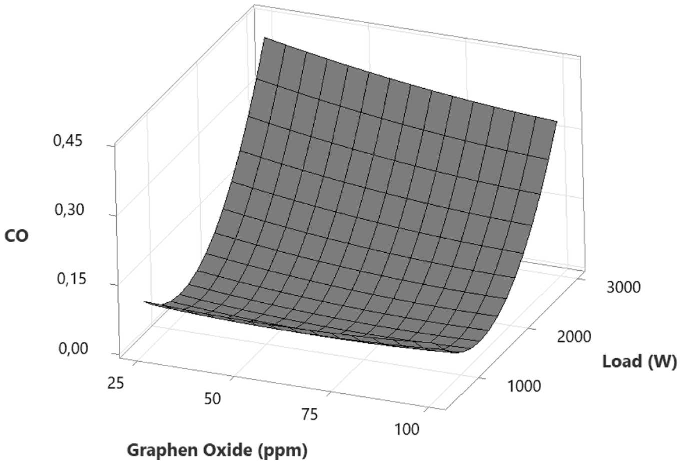


Fig. 8. Variation of CO emission depending on GO and load.

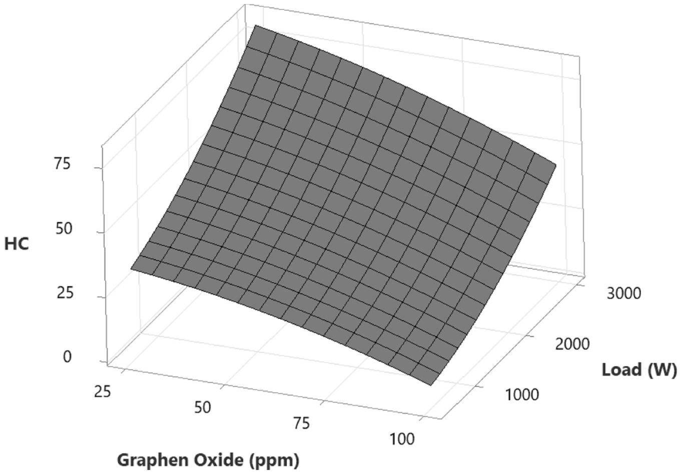


Fig. 9. Variation of HC emission depending on GO and load.

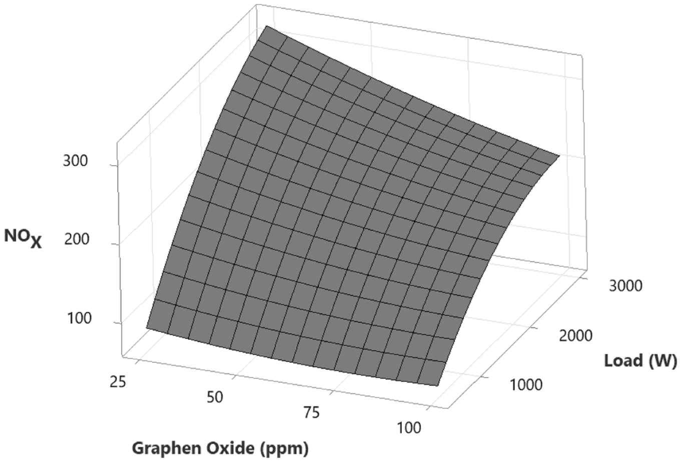


Fig. 10. Variation of NO_x emission depending on GO and load.

According to the comparison results, the highest deviation was found in the HC emission response with 6.13%, and the lowest was obtained in the BSFC response with 0.40%. Additionally, a graphical comparison of the results is made in Fig. 11. In the graph, blue balloons show test results, while orange balloons show prediction results. According to the graph, it can be said that the test and prediction results are in good

Table 6
Comparison of experimental and RSM results for power, BSFC, and EGT.

TrialNo.	Term		Responses								
			Power (W)			BSFC (g/kWh)			EGT (°C)		
	GO (ppm)	Load (W)	Test	RSM	Deviation(%)	Test	RSM	Deviation(%)	Test	RSM	Deviation(%)
1	25	500	428.85	394.56	8.00	1077.58	1076.53	0.10	217.33	209.69	3.52
2	25	1500	1210.50	1231.81	1.76	1036.51	1039.96	0.33	248.00	260.12	4.89
3	25	2000	1767.64	1701.44	3.75	1011.21	1014.93	0.37	299.33	298.08	0.42
4	25	3000	2791.88	2742.69	1.76	946.75	951.36	0.49	399.33	399.51	0.04
5	50	1000	1005.80	921.75	8.36	1043.31	1037.96	0.51	208.00	212.03	1.94
6	50	1500	1486.80	1355.50	8.83	1020.89	1017.07	0.37	244.67	242.35	0.95
7	50	2500	2251.44	2325.00	3.27	967.29	961.80	0.57	331.00	328.50	0.76
8	75	500	491.20	558.81	13.76	1034.42	1039.43	0.48	173.00	176.52	2.03
9	75	1000	994.05	956.69	3.76	1015.84	1022.70	0.68	200.00	199.21	0.40
10	75	2000	1781.80	1854.44	4.08	968.54	975.73	0.74	269.67	270.08	0.15
11	100	500	501.20	505.00	0.76	1035.17	1031.82	0.32	164.00	168.65	2.84
12	100	1000	1010.08	901.00	10.80	1016.80	1014.73	0.20	199.67	192.20	3.74
13	100	2000	1784.16	1795.00	0.61	966.70	967.06	0.04	265.67	264.80	0.33
14	100	3000	2827.28	2825.00	0.08	897.90	901.39	0.39	366.33	371.40	1.38
Error (%)					**4.97**			**0.40**			**1.67**

Table 7
Comparison of experimental and RSM results for CO, HC, and NO_x.

TrialNo.	Term		Responses								
			CO (%)			HC (ppm)			NO_x (ppm)		
	GO (ppm)	Load (W)	Test	RSM	Deviation(%)	Test	RSM	Deviation(%)	Test	RSM	Deviation(%)
1	25	500	0.088	0.082	6.46	35.33	34.48	2.42	98.00	88.71	9.48
2	25	1500	0.066	0.063	4.52	47.33	48.06	1.54	208.33	212.86	2.17
3	25	2000	0.074	0.077	4.07	55.33	57.86	4.56	257.33	258.44	0.43
4	25	3000	0.455	0.450	1.10	80.67	83.44	3.44	313.33	316.59	1.04
5	50	1000	0.073	0.077	5.50	32.33	33.65	4.07	128.33	138.90	8.23
6	50	1500	0.063	0.062	1.59	38.33	40.86	6.58	189.00	189.35	0.19
7	50	2500	0.121	0.127	4.97	56.67	61.27	8.11	266.67	257.25	3.53
8	75	500	0.086	0.083	3.47	18.00	19.48	8.24	75.33	72.41	3.88
9	75	1000	0.071	0.073	2.80	25.67	24.10	6.10	122.00	127.74	4.70
10	75	2000	0.063	0.065	3.17	41.33	39.34	4.83	213.33	205.39	3.72
11	100	500	0.082	0.087	6.12	7.00	7.59	8.43	85.67	73.60	14.09
12	100	1000	0.063	0.065	3.16	12.00	11.62	3.17	111.33	122.80	10.30
13	100	2000	0.059	0.053	10.11	22.33	25.68	14.99	206.33	188.20	8.79
14	100	3000	0.340	0.343	0.88	43.67	47.74	9.33	197.67	209.60	6.04
Error (%)					**4.14**			**6.13**			**5.47**

agreement.

4. Optimization and confirmation of responses

An optimization study was carried out to determine the best conditions to examine the effects of adding different amounts of GO at different loads on the performance characteristics and emissions to the diesel engine, in which 30% diesel + 70% SO mixtures are used as fuel. The optimization aims to bring the emissions closer to the minimum values of BSFC and EGT, and to bring the Power closer to the maximum. The RSM optimization results with deviations are shown in Table 8 for all responses. Based on the values and deviation rates shown in the table, it can be clearly said that the RSM optimization and experimental results are very close. While the minimum deviation was 0.05% in the BSFC response, the maximum deviation was 4.69% in the HC emission response.

5. Conclusion

In this study, which aims to improve performance and emissions by adding different amounts of GO (25, 50, 75, and 100 ppm) after determining the best SO/diesel fuel mixture (30% SO + 70% diesel) with experiments, is also aimed to determine the optimum amount of GO with the minimum number of experiments by optimizing with RSM. The findings are summarized below.

- ü According to the evaluation made along with the performance characteristics, it is understood that the most appropriate amount of GO is between 75 ppm and 100 ppm. The optimal amount of GO for power is 75 ppm, while for BSFC and EGT it is 100 ppm. It is clearly understood that the addition of GO improves diesel engine performance.
- ü It has been determined as a result of the findings that GO also has a positive effect on emissions, the maximum GO amount of 100 ppm is the most suitable for CO and HC, and 75 ppm GO amount is the most appropriate for NOx.
- ü The effect of engine load increase on power, BSFC and CO were positive, but negative on EGT, HC, and NOx.
- ü The maximum error between the estimation results made using the regression equations of the experiments used to create the RSM model and the experimental results were determined as 6.13%. It can be said that statistically significant and acceptable results were obtained.
- ü Optimization results revealed that 100 ppm GO at 1950 W load was optimum conditions.
- ü The responses that emerged under optimum conditions were 1746.77 W, 968.73 g/kWh, 259.8 °C, 0.0603%, 23.13 ppm, and 185.61 ppm for Power, BSFC, EGT, CO, HC, and NO_x, respectively.

Based on the findings obtained from the study, it can be clearly understood that the RSM model can successfully model a single-cylinder diesel engine and thus save time, labor, and money.

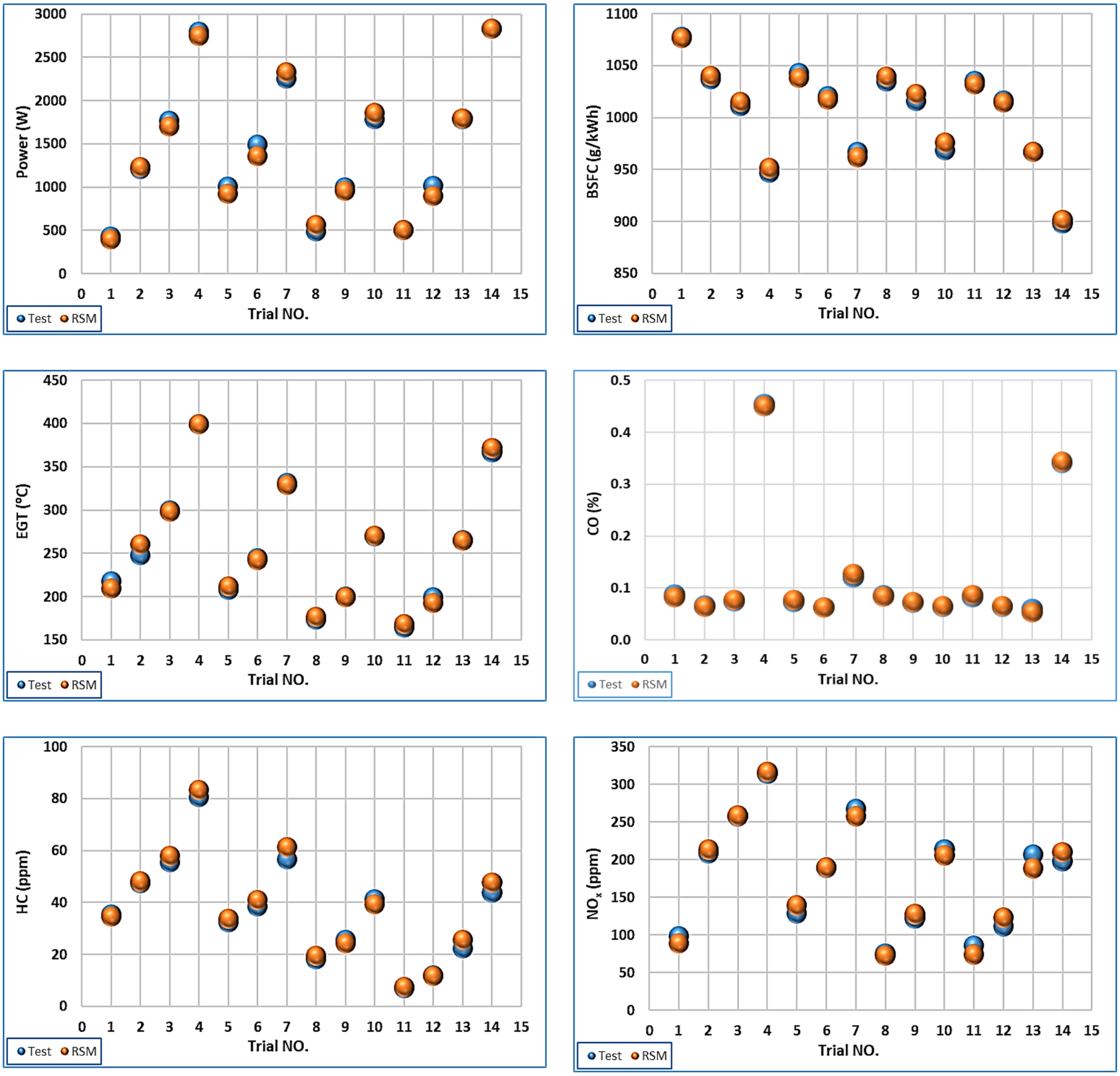


Fig. 11. Demonstration of the agreement of test and prediction results for all responses.

Table 8
RSM optimization outcomes.

Solution	GO(ppm)	Load(W)	Power (W)	BSFC(g/kWh)	EGT(°C)	CO(%)	HC(ppm)	NO_x(ppm)
Optimization	100	1950	1746.77	968.73	259.8	0.0603	23.133	185.61
Test			1745.46	969.20	262.4	0.0595	22.10	191.58
Deviation			0.08	0.05	0.98	1.29	4.69	3.12

Authors' contributions

Suleyman Simsek and Hatice Simsek designed the entire experiment. Samet Uslu established the model, analyzed the results, and wrote the manuscript.

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Declaration of Competing Interest

The authors declare that they have no conflict of interest. The authors acknowledge that no financial interest or benefit has been raised from the direct applications of their research.

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