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RESEARCH ARTICLE

Evaluation of emissions and performance of a diesel engine running on graphene nanopowder and diesel–biodiesel-ethanol blends

Yaser Noorollahi[1] · Ezzatollah Askari Asli-Ardeh[1] · Ahmad Jahanbakhshi[2] · Ali Khodayari[3] · Shiva Gorjian[4,5]

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Abstract
Today, there are environmental problems all over the world due to the emission of greenhouse gasses caused by the combustion of diesel fuel. The excessive consumption and drastic reduction of fossil fuels have prompted the leaders of various countries, including Iran, to put the use of alternative and clean energy sources on the agenda. In recent years, the use of biofuels and the addition of nanoparticles to diesel fuel have reduced pollutant emissions, improved the environment, and enhanced the physicochemical properties of the fuel. The current research deals with the experimental evaluation of emissions and performance of a diesel engine running on graphene nanopowder together with diesel–biodiesel-ethanol blends. The engine variables studied included the engine speed (in three stages 1800, 2200, and 2600 rpm) and three types of fuel including graphene nanoparticles (with values of 25 and 50 ppm), biodiesel (with volume percentages of 4, 6, and 8), and ethanol (with volume percentages of 2 and 4). The results showed that the power and torque of the D86 + B8 + E6 + G50 fuel increased on average by 20.26% and 28.76% at all engine speeds compared to the D100 fuel. The use of D86 + B8 + E6 + G50 fuel resulted in a significant reduction in CO (38.84%), UHC (21.24%), and NOx (19.92%) emissions compared to D100 fuel. In addition, a significant increase in CO_2 emissions (23.19%) was observed. The results of this study clearly show that the use of biofuels and the addition of nanopowder to D100 fuel are very effective methods to improve combustion, performance, and emission characteristics in diesel engines.

Keywords Compression ignition engine · Emissions · Performance · Biofuel · Nanoparticles

Abbreviations

D or D100	Pure diesel
CI	Compressed ignition
CO	Carbon monoxide (vol. %)
CO2	Carbon dioxide (vol. %)
NOx	Nitrogen oxides (ppm)
O2	Oxygen (vol. %)
UHC	Unburned hydrocarbons
B	Biodiesel
E	Ethanol
G	Graphene nanopowder
ES	Engine speed
FT	Fuel type
LSD	Least significant difference
PM	Particulate matter
SEM	Scanning electron microscope
mg	Milligram
CNT	Carbon nanotube
CQD	Carbon quantum dot
GNP	Graphene nanoparticle
kW	Kilo Watt
L	Liter
Mbar	Millibar
MJ	Mega joules
Nm	Newton meter
ppm	Part per million
rpm	Revolutions per minute

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✉ Ezzatollah Askari Asli-Ardeh
ezzataskari@uma.ac.ir

[1] Department of Biosystems Engineering, University of Mohaghegh Ardabili, Ardabil, Iran

[2] Mechanical Engineering of Biosystems Department, Lorestan University, Khorramabad, Iran

[3] Chemistry Department, Faculty of Science, University of Mohaghegh Ardabili, P.O. Box 179, Ardabil, Iran

[4] Biosystem Engineering Department, Tarbiat Modares University (TMU), Tehran, Iran

[5] Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg Im Breisgau, Germany

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MPa.s	Mega Pascal second
°C	Celsius degree
SFC	Specific fuel consumption
DF	Degrees of freedom
SAS	Statistical analysis system
SOx	Sulfur oxides
XRD	X-ray diffraction
ml	Milliliter
PVP	Polyvinylpyrrolidone
GO	Graphene oxide
rGO	Reduced graphene oxide
NPs	Nanoparticles
D94 + B4 + E2 + G25	94% Diesel + 4% biodiesel + 2% ethanol + 25 ppm graphene nanopowder
D94 + B4 + E2 + G50	94% Diesel + 4% biodiesel + 2% ethanol + 50 ppm graphene nanopowder
D90 + B6 + E4 + G25	90% Diesel + 6% biodiesel + 4% ethanol + 25 ppm graphene nanopowder
D90 + B6 + E4 + G50	90% Diesel + 6% biodiesel + 4% ethanol + 50 ppm graphene nanopowder
D86 + B8 + E6 + G25	86% Diesel + 8% biodiesel + 6% ethanol + 25 ppm graphene nanopowder
D86 + B8 + E6 + G50	86% Diesel + 8% biodiesel + 6% ethanol + 50 ppm graphene nanopowder

Introduction

Today, 88% of global energy consumption is covered by the use of fossil fuels. This high proportion is divided between natural gas, coal, and oil, with respective percentages of 24%, 29%, and 35%. The indiscriminate use of fossil fuels and their limited reserves have encouraged researchers to look for alternative energies such as biofuels (Heidari-Maleni et al. 2023; Awogbemi and Von Kallon 2024; Karami-Boozhani et al. 2024). The economic development of countries mainly depends on the transportation sector. The increasing demand for energy due to the increasing number of vehicles and the growing awareness of environmental issues around the world are the main factors motivating the creation of renewable energy sources as a suitable alternative to diesel fuels. Many researchers have recommended that biodiesel is a promising alternative fuel that can replace diesel fuel as its properties are very similar to diesel fuel. Biodiesel can be derived from both vegetable oil and animal fat (El-Sheekh et al. 2022).

In internal combustion (IC) engines, diesel fuel converts the heat generated during fuel combustion directly into mechanical energy. But diesel fuel causes environmental pollution by releasing undesirable substances into the air. Therefore, there is a need for an alternative fuel that causes less pollution, has better performance, and is more economical. Alternative fuel sources such as biodiesel can meet the current demand. Biodiesel has long been recognized as a renewable biofuel that offers benefits such as environmental friendliness and biological sustainability. More importantly, biodiesel can be blended with fossil fuels in diesel engines without causing any changes (Arya et al. 2022; Yesilyurt et al. 2020).

One of the most important sectors in which fossil fuels are consumed in large quantities is the transportation sector, as almost all vehicles are powered by internal combustion engines that run on fossil fuels. In the transportation sector, diesel engines are preferred due to their high thermal efficiency, greater reliability, better performance, lower cost, and higher compatibility. However, they are one of the main sources of harmful gas emissions (Gad et al. 2023). The amount of oxygen in diesel fuels is zero, but biodiesel fuels contain 10–12% oxygen by weight. The amount of oxygen in biodiesel fuel reduces the emission of harmful gasses. Also, biodiesel has favorable characteristics such as non-toxic nature, biodegradability, high efficiency, and good compatibility with the environment (Caliskan et al. 2024; Noorollahi et al. 2018). But despite these advantages, some features of biodiesel such as high viscosity, low cetane number, deficient atomization, high auto-ignition temperature, poor cold flow, and increased NOx emissions restrict its utilization in diesel engines (Bitire et al. 2023). In order to overcome these limitations, numerous methods have been presented in the literature. Blending optimized percentages of diesel with biodiesel can decrease the viscosity of biodiesel and enhance its usage at low temperatures. Mixing portions of oxygenated lubricants like diethyl ether, some alcohols, and ketones improves the auto-ignition temperature of biodiesel (Imtenan et al. 2015). However, the use of alcohols and ethers as a fuel additive is challenging because of their high auto-ignition temperature, poor heat conductivity, high volatility, weak lubricating properties, and low stability (Mostafa et al. 2023; Mujtaba et al. 2020). According to the results of recent studies, the most effective way to improve the thermophysical properties of biodiesels is by including nano-additives such as metallic or non-metallic nanostructures. These compounds act as catalysts in the combustion zone and upgrade some fuel properties, such as increasing thermal atomization, decreasing ignition delay, improving radiative mass transfer, accelerating chemical reactions, and reducing emissions (Nair et al. 2021; Kumar et al. 2024; Sharifianjazi et al. 2023). CuO, TiO_2, Al_2O_3, CeO_2, Fe_2O_3, and ZnO are the most commonly used metal nanostructures.

But the biosafety issues related to metal-based nanoparticle applications are challenging. Also, metal-based nanoparticles cannot burn with fuel, and consequently, new environmental effects may occur. Due to van der Waals interactions, metal oxides can agglomerate and deposit in the engine component under gravity force (Jin et al. 2023). For these reasons, many researchers are interested in employing nonmetal nanostructures, mainly carbon allotropes (including CNT, CQD, GNP, GO, rGO), to improve biodiesel properties. As a widely used nanostructure, graphene possesses amazing properties, such as enhanced area-to-volume ratio, superior electric and thermal conductivity, unique electron mobility, large surface area, and high flexibility (Yusaf et al. 2022). Unlike metal-based NPs, GNP fuel additives have less magnetic and electrostatic attraction between individual particles and therefore less tendency to aggregate. In addition, the presence of double bonds between some graphene carbons has made it possible to modify its surface by various surfactants. Compact multilayers of 2-D graphene sheets (usually 10–50 layers) are called GNPs (Babaei-Ghaghelestany et al. 2020). This nanostructure acts like an inert substance in contact with other compounds, which makes it non-hazardous for human health and the environment (Pullagura et al. 2024). However, several studies have been conducted to investigate the toxicity of graphene family nanostructures. Most of the results have confirmed that at less than 50 ppm, graphene has no worrying toxicity for living systems (Muzi et al. 2016; Liu et al. 2015; Sasidharan et al. 2011). In recent years, several reports have confirmed that the addition of graphene family nanostructures at concentrations of 25, 50, and 100 ppm to fuel significantly improves engine performance and emissions (Pullagura et al. 2023; Nair et al. 2021; Gad et al. 2021). However, some studies have shown that adding large amounts of carbon-based nanostructures increases CO emissions as the carbon content of the fuel increases (Jin et al. 2023).

Compression ignition engines play an important role in the transportation industry due to their simple design and high reliability. Compared to gasoline engines, compression ignition engines have a higher thermal efficiency as they consume less fuel. On the other hand, compression ignition engines are one of the largest sources of greenhouse gas emissions such as UHC, PM, CO, and NO_x, which are harmful to the human respiratory system and the environment. Greenhouse gas emissions are a major and dangerous threat to humans, animals, and the environment, causing changes to the planet's climate (Narayan et al. 2023; Elkelawy et al. 2022). Compared to fossil fuels, the combustion of biodiesel can lead to a reduction of total UHC by more than 90% and polycyclic aromatic hydrocarbons by 75%. In addition, net emissions of CO, CO_2, and particulate matter are reduced by 78%, 46.7%, and 66.7%, respectively (Palani et al. 2022; Arya et al. 2022). In research, the effect of adding nano-biochar to diesel–biodiesel-ethanol blends in a diesel engine was evaluated. The researchers reported that with the addition of nano-biochar, the specific fuel consumption (SFC) was reduced by 3%, and the engine power increased by 11.7%. Also, NO_x, CO, and UHC emissions decreased by 15%, 3%, and 28%, respectively (Mirbagheri et al. 2020).

In general, additives in fuel play a catalytic role and control the combustion reaction. The production and use of these additives on a nanoscale can increase their efficiency in fuel. The result of using nano-additives in fuel will be a reduction in fuel consumption and emissions from diesel engines. The main objective of this research is to closely examine the effects of incorporating modified graphene nanopowder treated with polyvinylpyrrolidone (PVP) and oleic acid into a diesel–biodiesel-ethanol fuel blend. The aim of this study is to comprehensively evaluate both the exhaust emissions and the performance characteristics of a diesel engine running on this improved fuel blend. The modified graphene nanopowder has an excellent safety profile and outstanding environmental compatibility, which is in line with current sustainability and safety standards. In addition, the desired chemical modification of the nanopowder facilitates optimal interaction with the fuel components, while its excellent miscibility ensures homogeneous distribution in the fuel mixture. Therefore, this research aims to contribute to the advancement of alternative fuel technologies by providing detailed insights into the potential benefits and practical implications of using modified graphene nanopowder in improving diesel engine performance and reducing harmful emissions.

Materials and methods

Diesel fuel

The diesel fuel used in this study was obtained from authorized stations.

Preparation of the biodiesel fuel

For the production of biodiesel in this study, camelina seeds were used because camelina seeds are a rich source of oil (about 40%) and fatty acids (Ghidoli et al. 2023). For this purpose, 3 l of oil was first extracted from the camelina seeds using an oil extraction machine (model OPM 550 and manufactured in Taiwan) (Fig. 1). There are various methods of producing biodiesel from oil, but the most common method is the transesterification method, which is widely used in various countries to produce biodiesel (Noorollahi et al. 2018). In this study, the biodiesel fuel was produced in several steps: preparation of vegetable oil (i.e., camelina seed oil), dissolution of catalyst in alcohol, transesterification

Fig. 1 Oil extraction from camelina seed

reaction, titration, recovery of excess methanol and separation of glycerol from biodiesel, and finally washing and purification of biodiesel. All experiments were conducted in Renewable Energy Institute, Bioenergy Laboratory of Tarbiat Modares University, Iran.

Ethanol preparation

Researchers have reported that ethanol contains 35% oxygen, which can be effective in reducing smoke, particulate matter, nitrogen oxides, and carbon monoxide from diesel engines (Wang et al. 2023; Jahanbakhshi et al. 2021). Therefore, in this study, commercially available ethanol 96% was purchased from reputable chemical companies to blend with diesel–biodiesel fuel.

Graphene nanopowder

Graphene nanopowder type AO-3 (manufactured by Graphene-Supermarket Company, USA) was purchased from a supplier of laboratory materials. Figure 2 shows the XRD pattern of graphene nanopowder in the range of $2\theta = 10–40$ Å. In this pattern, a specific peak can be seen as the main peak at $2\theta = 26.3$ Å with the Miller Index (002), which not only confirms the structure of graphene but also indicates its multilayer nature (Kumar et al. 2017). The absence of additional peaks in the said pattern shows that the graphene used does not contain crystalline impurities.

The SEM micrograph of graphene nanopowder at × 50,000 magnification is shown in Fig. 3. As can be seen in the image, the graphene nanopowder has a sheet structure that has turned into multilayered structures due to the accumulation caused by the electrostatic interactions of the sheets. The thickness of the multilayers is about 20–30 nm, which is consistent with the manufacturer's specifications. The layer thickness was determined using a point-to-point measurement tool of the "LEO User Interface" software. In this tool, the thickness of the layers is measured from the unfolded edges, based on the scale of the image.

Dispersion of graphene nanopowder in fuel blends

To prepare the mixture of fuel and graphene nanopowder (25 ppm), 25 mg of graphene nanopowder was added to 10 ml of the desired fuel together with 12.5 mg each of PVP and oleic acid as surfactants. The fuel mixture was then placed in an ultrasonic bath for 60 min to mix completely. In the next step, the homogeneous mixture was added to 990 ml of fuel and stirred with a magnetic stirrer at 800 rpm for 10 min. To prepare the mixture of fuel and 50 ppm graphene nanopowder according to the above method, an appropriate amount of the nanostructure was used along with proportional amounts of PVP and oleic acid as surfactants.

In order to verify the duration of suspension (stability) of the nanostructure in the fuel mixture, photographs of the fuel samples were taken at different times. The results showed that the graphene nanostructure modified with PVP and oleic acid remained well suspended in the fuel for at least 12 h and did not settle (see Fig. 4).

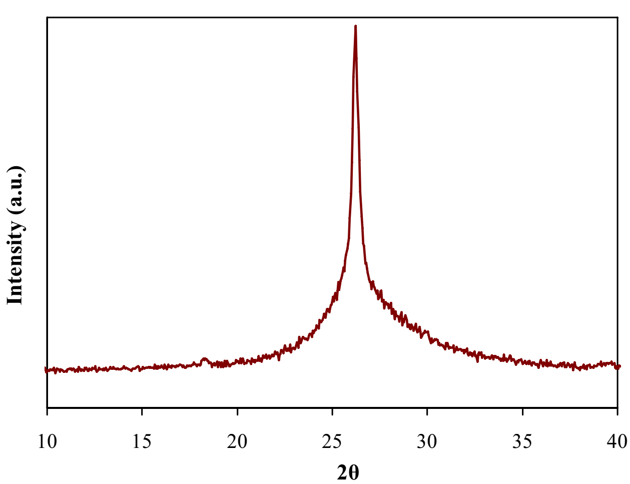


Fig. 2 XRD pattern of graphene nanopowder

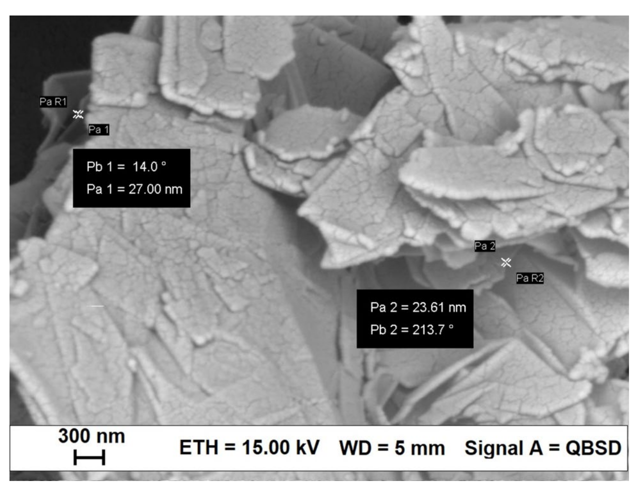


Fig. 3 SEM micrograph of graphene nanopowder

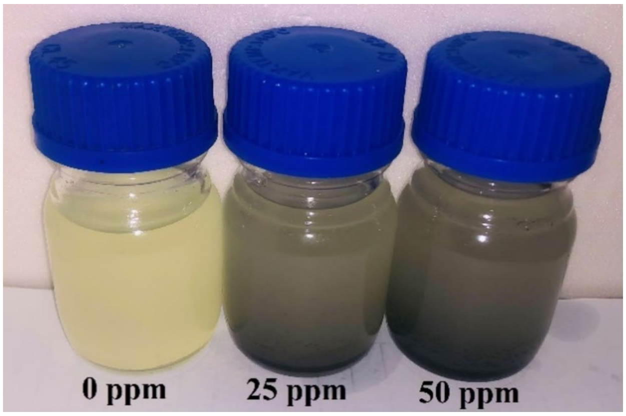


Fig. 4 Investigation of the duration of suspension of graphene nanopowder in different quantities in the fuel mixture

Table 1 Physicochemical properties of the fuels used in this study

Fuels	Dynamic viscosity (cP)	Kinematic viscosity (mm^2/s)	Density (g/cm^3)
D100	2.3864	2.6118	0.9137
B100	4.8404	4.8211	1.0040
D94 + B4 + E2 + G25	3.5626	4.0033	0.8899
D94 + B4 + E2 + G50	3.7229	4.1779	0.8911
D90 + B6 + E4 + G25	2.5484	2.8181	0.9043
D90 + B6 + E4 + G50	2.7391	3.0622	0.8945
D86 + B8 + E6 + G25	2.6258	2.8697	0.9150
D86 + B8 + E6 + G50	2.8761	3.2316	0.8900

Preparation of blends

Biodiesel and ethanol are oxygenated fuels. They have a higher oxygen content than Euro diesel. For the blends, diesel, biodiesel, and ethanol with graphene nanopowder were used in three concentrations of 25 and 50 ppm. To mix the diesel, biodiesel, ethanol, and graphene nanopowder homogeneously, they were first placed in a flask. The flask was then placed in the magnetic stirrer for 1 h. It was then placed in an ultrasonic nanoparticle treatment device for 30 min to ensure uniform distribution of the nanopowder in the mixture, and finally, six mixtures were prepared. The physicochemical properties of the fuels are listed in Table 1. Figure 5 shows an overview of all fuels. The viscosity was measured at the Iranian Institute of Chemistry and Chemical Engineering using the falling ball method and an AMVn viscosity meter (manufactured by Anton Paar in Germany) (Fig. 6).

Experimental set-up and experimental procedure

A four-stroke diesel engine was used to evaluate the test fuels (Table 2 and Fig. 7). A dynamometer (model MPA-40; manufactured in Iran) was used to measure the performance parameters of the engine. The engine performance and exhaust emissions were measured at different engine speeds of 1800, 2200, and 2600 rpm at full load. Before conducting the experiment, the engine was operated at a fixed speed and full load for 10 min until the exhaust gas temperature stabilized. The engine performance and emission values for each test point were recorded for 15 min. This was repeated three times to ensure consistency. Before each new test, the engine was run for 10 min to ensure that

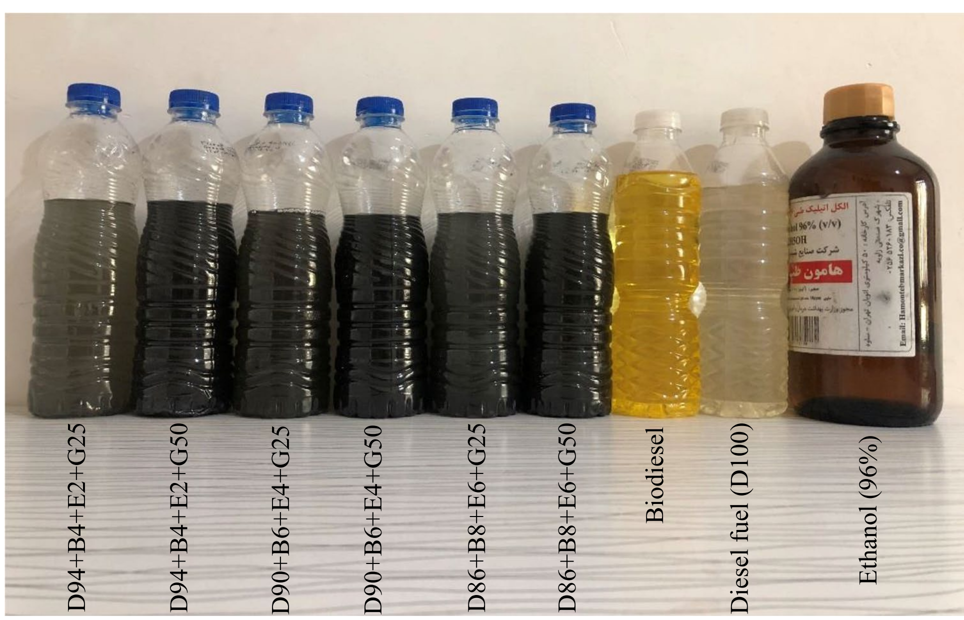


Fig. 5 The fuels used in this study

Fig. 6 Viscosity measurement device

Table 2 Technical specifications of the engine under test

Parameters	Description
Model	3LD 510
Manufacturer	Lombardini, Italy
Number of cylinders	1
Compression ratio	18:1
Cylinder bore	85 mm
Cylinder stroke	90 mm
Cylinder volume	510 cm^3
Maximum power at 3000 rpm	9 kW
Maximum torque at 1800 rpm	32.8 Nm
Combustion system	Direct injection
Cooling system	Air-cooled

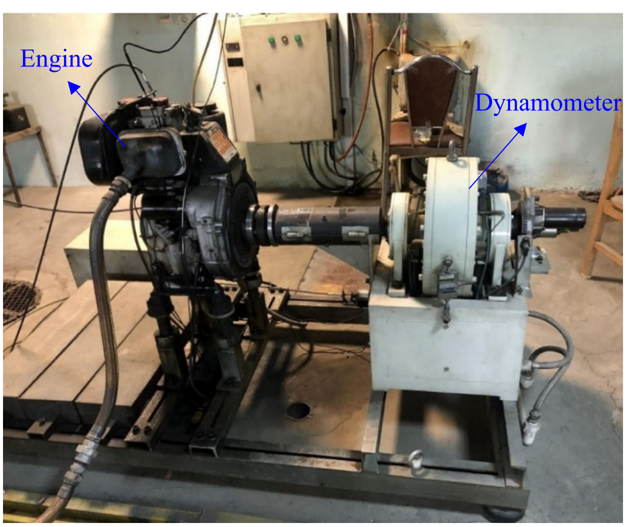


Fig. 7 Diesel engine and test set-ups

Table 3 Technical specifications of the gas analyzer

Measurement factors	Range	Accuracy	Uncertainty
CO	0–10% Vol	±0.01%	±0.3%
CO_2	0–20% Vol	±0.01%	±0.4%
UHC	0–10000 ppm Vol	±1 ppm	±0.6
NO_x	0–500 ppm Vol	±1 ppm	±0.05

the residues of the previous fuel were removed from the fuel line. The gas analyzer was used to measure CO, CO_2, NO_x, and UHC emissions directly from the engine exhaust for 15 min (Table 3). To ensure accuracy, the tests were carefully controlled, and the results were transferred to a computer. The specific fuel consumption (SFC) was calculated using Eq. (1) (Hosseini et al. 2017).

$$\mathrm{SFC} = \left(\frac{\dot{m}}{P}\right) \times 3.6 \times 10^6 \tag{1}$$

where P is the engine power (kW) and $\dot{m}$ is the fuel consumption rate (kg/s).

Uncertainty analysis

During the ongoing engine tests, several errors occurred due to calibration errors, instrument accuracy, environmental conditions, observer error, and other factors. To ensure accurate results, an uncertainty analysis was performed. The uncertainty propagation method, commonly referred to as the root-mean-square approach, was used to quantify the uncertainties in the engine system. This method was used to evaluate the uncertainty associated with the engine performance parameters (Vali et al. 2024; Ooi et al. 2024):

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right) + \left(\frac{\partial R}{\partial x_2} w_2\right) + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \tag{2}$$

The function R depends on the independent variables x_1, x_2, x_3, …, x_n. In addition, w_R denotes the total percentage error, where w_1, w_2, …, w_n represent the errors associated with the independent variables. The error percentages corresponding to the different orders of magnitude are listed in Table 3. Taylor's theorem was used for the error analysis to check the accuracy of the test results. The overall degree of uncertainty is given by

$$\begin{aligned}\text{Overall uncertainty} &= \left[(\mathrm{CO})^2 + (\mathrm{CO_2})^2 + (\mathrm{UHC})^2 + (\mathrm{NO_x})^2\right]^{1/2} \\ &= \left[(0.3)^2 + (0.4)^2 + (0.6)^2 + (0.05)^2\right]^{1/2} \\ &= \pm 0.78\%\end{aligned} \tag{3}$$

Statistical analysis

Using a randomized complete experimental design, factorial experiments were conducted to analyze the effects of three engine speeds and seven fuel types with three replicates (63 treatments in total) (see Fig. 8). Then, the effects of each variable on engine performance and exhaust emissions were analyzed using SAS software (version 9.1). The comparison between the mean values of the treatments was performed using the LSD test ($p < 5\%$) (Heidari-Maleni et al. 2020b).

Results and discussion

Statistical results

The results of the statistical analysis in Table 4 show that the effect of the main factor, i.e., fuel type, on the measured parameters (torque, SFC, CO, CO_2, UHC, and NO_x) is significant with a probability of 1%. For the power parameter, however, the effect is significant at the 5% probability level. Furthermore, the interaction effect of ES × FT is not significant for the measured parameters power, torque, SFC, CO, UHC, and NOx, but it is significant for the parameter CO_2 at the 5% probability level.

Engine performance results

Engine power

The amount of work performed per unit of time is called “performance.” In other words, “power” is the speed at which the work is performed. The power of the engine is shown in Fig. 9 as a function of various variables (engine speed and fuel type). The results also show that the engine power tends to increase by increasing the proportion of biodiesel and ethanol in the fuels compared to D100 fuel. In addition, the engine performance is increased by the presence of graphene nanopowder in the fuel compared to D100 fuel. Increasing the amount of nanoparticles from 25 to 50 ppm plays an effective role in improving engine performance. The engine has the highest performance when using D86 + B8 + E6 + G50 fuel and the lowest performance when using D100 fuel. In general, it is observed that engine performance is higher for all diesel–biodiesel-ethanol blends with graphene nanopowder compared to D100 fuel (see Fig. 9). This increase and improvement in engine performance can be attributed to the presence of oxygen in the molecular structure of biodiesel and ethanol fuels compared to diesel fuel (D100) (Veza et al. 2023, 2022; Jahanbakhshi et al. 2021).

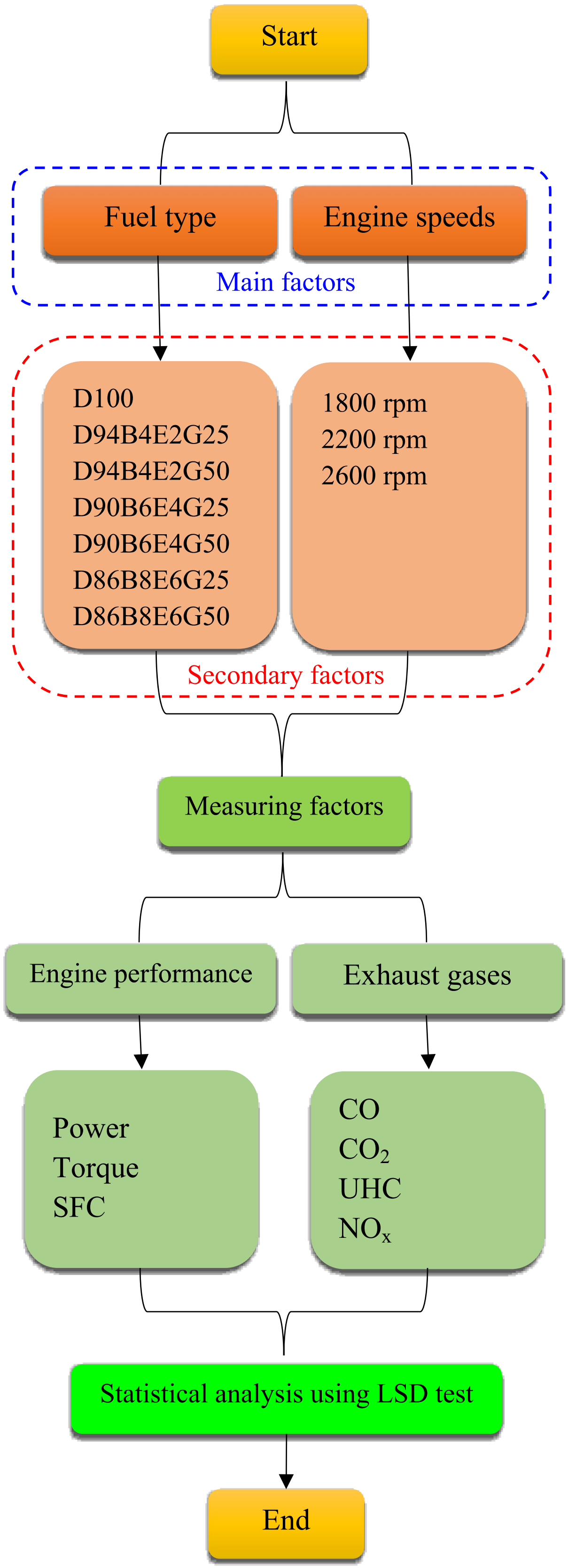


Fig. 8 Chart of statistical analysis

Table 4 Results of variance analysis (ANOVA)

Factors	DF	Mean Square						
		Power	Torque	SFC	CO	CO_2	UHC	NO_x
Engine speeds (ES)	2	0.491$^{n.s}$	46.359**	19,701.372**	0.069$^{n.s}$	0.127**	2630.158$^{n.s}$	1874.619**
Fuel type (FT)	6	0.529*	31.658**	7592.878**	0.351**	0.302**	3205.952**	647.063**
ES × FT	12	0.047$^{n.s}$	0.822$^{n.s}$	454.848$^{n.s}$	0.005$^{n.s}$	0.030*	53.769$^{n.s}$	19.285$^{n.s}$
Error	42	0.208	1.016	1083.326	0.027	0.012	840.873	43.777

** and * indicate significance at the probability level of 1% and 5%, respectively

$^{n.s}$Indicates non-significance

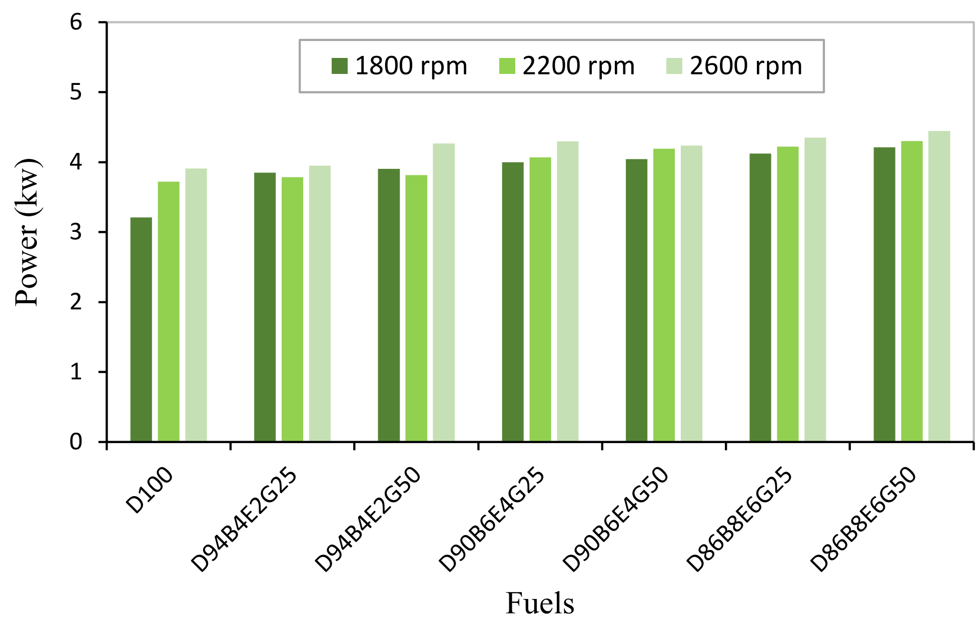


Fig. 9 Changes in power according to the type of fuel and different engine speeds

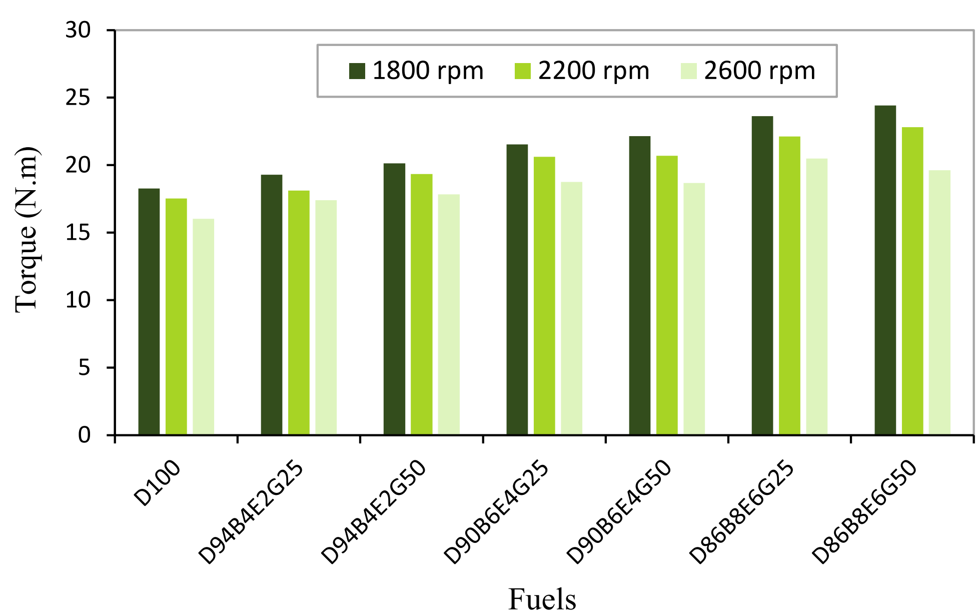


Fig. 10 Changes in torque according to the type of fuel and different engine speeds

Engine torque

Figure 10 shows the changes in engine torque as a function of various variables (engine speeds and fuel type). The results show that diesel–biodiesel-ethanol blends with graphene nanopowder increase engine torque compared to D100 fuel. The more torque the engine has, the more power the engine can generate. The addition of graphene nanopowder to diesel–biodiesel-ethanol blends increases the power and torque of the engine (see Figs. 9 and 10). As the energy generated in the cylinder is higher, combustion in the engine is improved. As a result, the power and torque of the engine increase due to the increase in the surface-to-volume ratio of the nanopowder and the presence of oxygen in biodiesel and ethanol (Ooi et al. 2023; Gundoshmian et al. 2021). For all fuel types, the maximum engine torque was observed at a speed of 1800 rpm. As the inertia of the moving parts increases and there is not enough time for air consumption in the cylinder, the pressure increases. Therefore, the ignition pressure and engine torque decrease (Heidari-Maleni et al. 2020a; Örs et al. 2018).

The maximum torque (24,430 Nm) was achieved at an engine speed of 1800 rpm with fuel D86 + B8 + E6 + G50. The minimum engine torque (16.02 Nm) was observed with D100 fuel at 2600 rpm.

Specific fuel consumption (SFC)

The effects of the different variables (engine speed and fuel type) on the SFC of diesel engines are shown in Fig. 11. The results show that increasing the engine speed from 1800 to 2600 rpm also increases the SFC value. The increase in engine speed causes the gas valve to open and more air to enter the combustion chamber. Therefore, the engine control unit must respond by injecting more fuel to maintain the correct fuel-to-air ratio in the combustion chamber. The results presented in Fig. 11 show that the addition of graphene nanopowder to diesel–biodiesel-ethanol blends reduces the SFC. The addition of nanopowder and the presence of oxygen in the structure of biodiesel and ethanol improve combustion, increase engine performance, and reduce SFC.

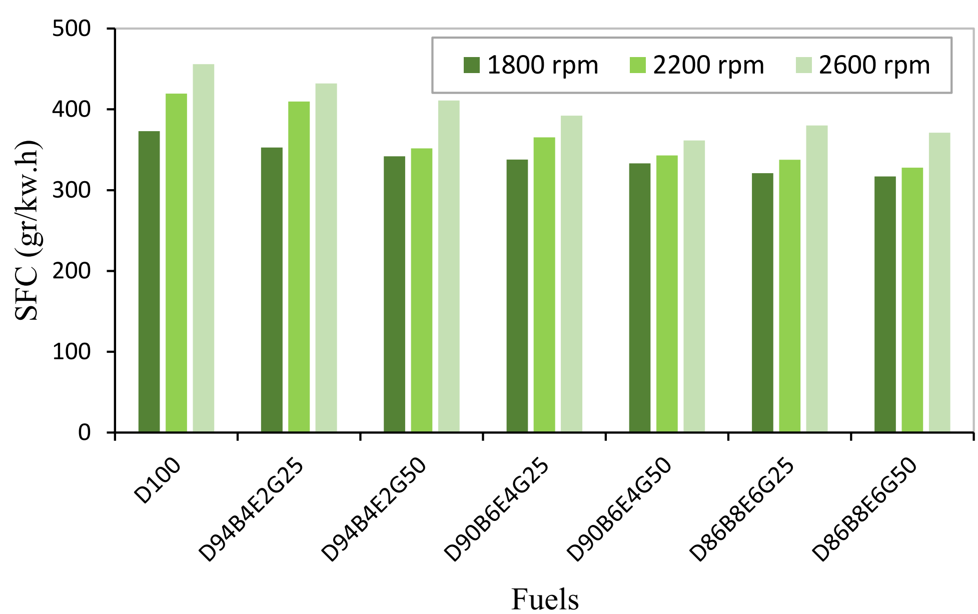
In similar studies, researchers have reported that the addition of nanopowder and the presence of oxygen in the structure of biodiesel and ethanol are the main reasons for the decrease in SFC. They attribute this SFC reduction to faster and more complete combustion, higher heat release, and lower viscosity (Heidari-Maleni et al. 2020a; Hosseini et al. 2022), which leads to an increase in engine performance. At all engine speeds, the lowest SFC value corresponds to fuel D86 + B8 + E6 + G50, and the highest SFC value corresponds to fuel D100 (see Fig. 11).

Exhaust emissions

CO emission

CO is an odorless, colorless, and highly toxic gas in the atmosphere that is produced by the incomplete combustion of fuel in an engine. CO is highly reactive. The tendency of CO to react with the hemoglobin of the blood is about 200 times higher than that of oxygen. The CO content in human blood is around 5%, and if this level reaches 20%, it leads to death (Algayyim et al. 2024; Hamzah et al. 2024). Figure 12 shows the amount of CO emissions under the influence of different variables (engine speed and fuel type). From the results shown in Fig. 12, it can be seen that of all the fuels

Fig. 11 Changes in SFC as a function of fuel type and different engine speeds



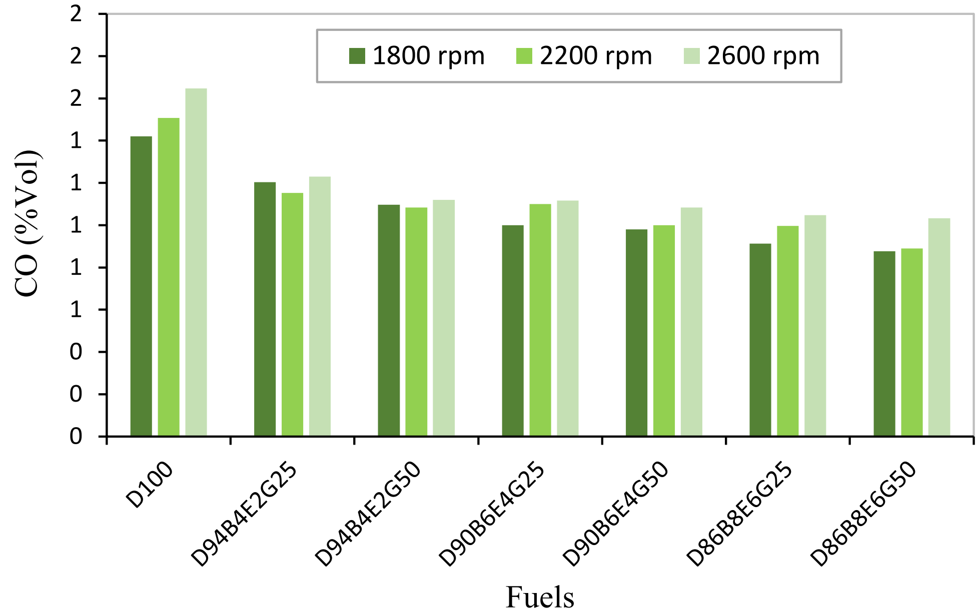


Fig. 12 CO emissions under the influence of fuel type and engine speed variables

tested, D86 + B8 + E6 + G50 has the lowest CO emission. This may be due to the addition of nanopowder as well as the presence of oxygen in biodiesel and ethanol, which resulted in better and complete combustion of the fuel in the engine. When there is not enough oxygen for the combustion cycle in the engine and the mixture of fuel and air for combustion in the engine is rich, CO emissions increase. In this study, the highest CO emissions were found when using D100 fuel. In similar studies, researchers have mentioned the addition of nanopowder and the use of biodiesel and ethanol in D100 fuel as the main factors in reducing CO emissions (Çalhan and Kaskun Ergani 2023; Noorollahi et al. 2018; Ghanbari et al. 2021).

CO_2 emission

The results in terms of CO_2 emissions under the influence of different variables (engine speed and fuel type) are shown in Fig. 13. For all fuels tested, CO_2 emissions were highest when D86 + B8 + E6 + G50 was used (see Fig. 13), while CO emissions were lowest when D86 + B8 + E6 + G50 was used (see Fig. 12). These results show that the amount of carbon in the engine exhaust was converted to CO_2. In addition, the addition of nanopowder and the use of biodiesel and ethanol in D100 fuel led to an oxygenation of the fuel and thus to a more complete combustion, which in turn resulted in a decrease in CO and an increase in CO_2 emissions.

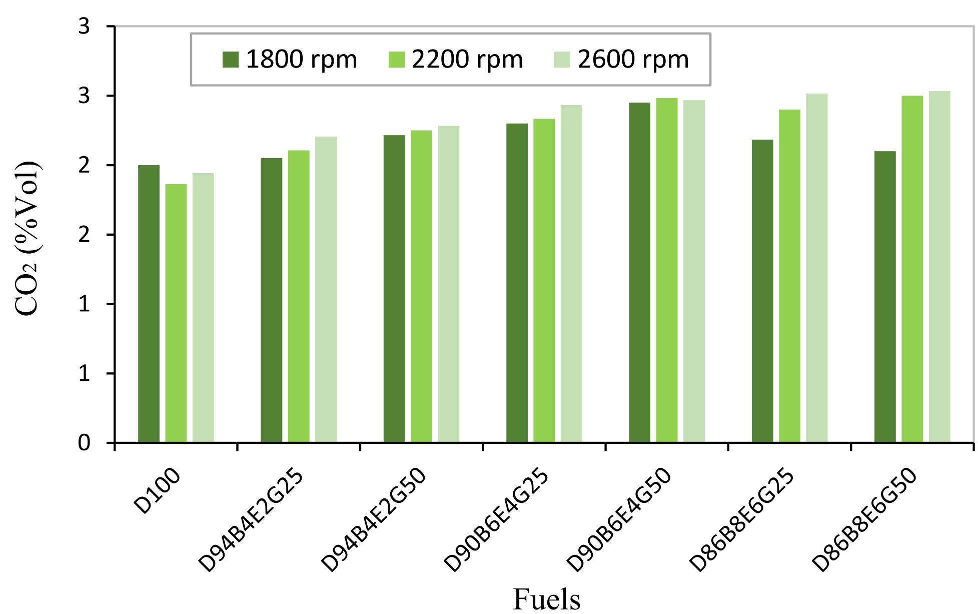


Fig. 13 CO_2 emissions under the influence of fuel type and engine speed variables

UHC emission

Figure 14 shows the results of UHC emissions under the influence of different variables (engine speed and fuel type). If there is not enough oxygen for the complete combustion of the fuel, incomplete combustion occurs, which is one of the main causes of UHC in internal combustion engines. The results in Fig. 14 show that the fuel D86 + B8 + E6 + G50 has the lowest amount of UHC emissions at all engine speeds. The presence of oxygen in the molecular structure of biodiesel and ethanol and the high catalytic activity of nanopowder improve the chemical process and increase the energy generated in the cylinder, resulting in more complete combustion of the fuel and a reduction in UHC emissions (Noorollahi et al. 2018; Heidari-Maleni et al. 2021).

Both fuel-rich and fuel-lean mixtures can contribute to UHC emissions. Incomplete combustion, nonstoichiometric air–fuel ratio, a temperature drop, and deposits on the walls of the combustion chamber in the expansion phase are also important factors for UHC emissions. The use of graphene nanopowder in the fuel also improves fuel injection. This is because the lower viscosity, the improvement in the heat transfer rate, and the increase in the surface-to-volume ratio of the nanopowder lead to better atomization of the fuel (Hosseini et al. 2017).

NO_x emission

The effects of injection timing, combustion timing, maximum temperature, and maximum heat release rate are the main causes of NO_x emissions (Hosseini et al. 2017; Ghanbari et al. 2021; Hoseini et al. 2018). Figure 15 shows the results of NO_x emissions under the influence of different variables (engine speeds and fuel type). The results show that the highest amount of NO_x emissions at all engine speeds and fuels tested occurred when using D86 + B8 + E6 + G50 fuel. This fuel increased NO_x emissions on average by 19.92% compared to D100 fuel. The addition of graphene nanopowder to diesel–biodiesel-ethanol blends increases the gas pressure and temperature in the cylinder, which increases NO_x emissions.

In similar studies, researchers have reported that the increase in NO_x emissions may be due to the relatively high oxygen content in biodiesel and ethanol. This is because oxygen in biodiesel and ethanol leads to complete combustion and a higher combustion temperature and increases NO_x emissions (Riyadi et al. 2023; Hosseini et al. 2017; Ghanbari et al. 2021; Abdollahi et al. 2020; Hoseini et al. 2018).

Conclusions

The experimental studies were conducted with the aim of evaluating the effect of adding graphene nanopowder with different concentrations in diesel–biodiesel-ethanol blends and comparing their performance with base fuel (D100). It was found that the addition of graphene nanopowder to diesel–biodiesel-ethanol blends can have a significant impact on the emission characteristics and performance of diesel engines. The experimental results obtained in this study lead to the following conclusions:

- Maximum power was achieved at all engine speeds (1800, 2200, and 2600 rpm) using D86 + B8 + E6 + G50 fuel at 4.213, 4.303, and 4.447 kW. Compared to D100,

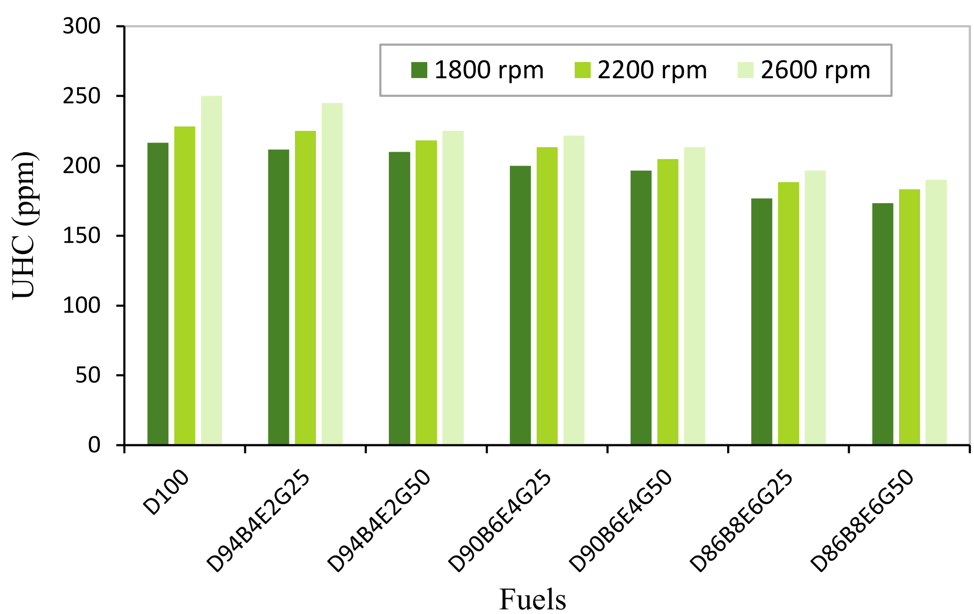


Fig. 14 UHC emissions under the influence of fuel type and engine speed variables

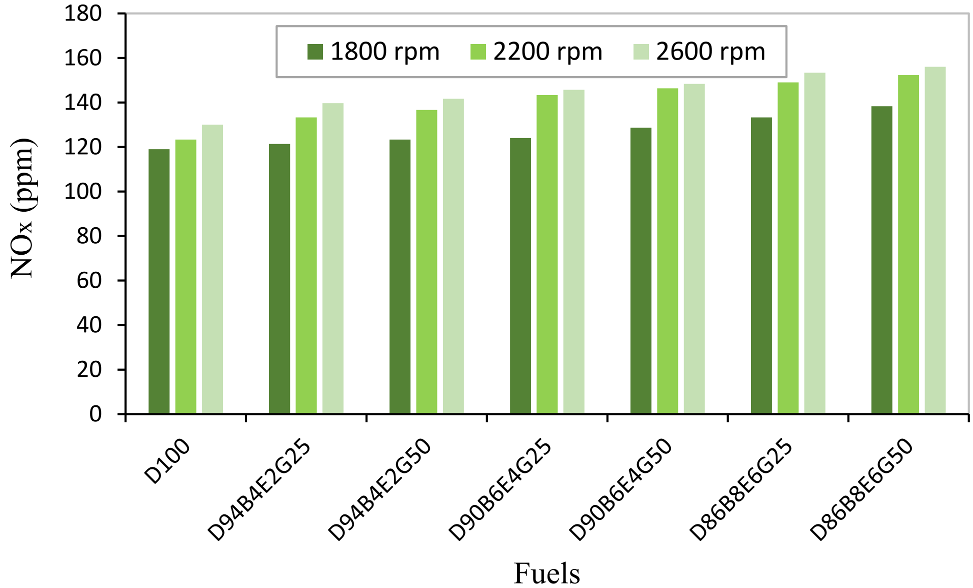


Fig. 15 NO_x emissions under the influence of fuel type and engine speed variables

this fuel improved performance by 31.37%, 15.67%, and 13.73%, respectively.

- D86 + B8 + E6 + G50 fuel increased engine torque by an average of 28.76% at all engine speeds compared to D100 fuel.
- D86 + B8 + E6 + G50 fuel reduced specific fuel consumption by an average of 18.50% at all engine speeds compared to D100 fuel.
- On average, the fuel D86 + B8 + E6 + G50 reduced CO emissions by 38.84% compared to the fuel D100.
- CO_2 emissions from the use of D86 + B8 + E6 + G50 fuel have increased by an average of 23.19% compared to D100 fuel.
- UHC and NO_x emissions decreased by 21.24% and increased by 19.92% when using D86 + B8 + E6 + G50 fuel compared to D100 fuel.
- Biodiesel can be considered as an oxygenated fuel. Oxygen atoms, along with the higher cetane number of biodiesel fuel compared to diesel fuel, lead to more complete combustion and, as a result, higher thermal efficiency in the engine.
- Combining oxygenated fuel (biodiesel) and graphene nanopowder with diesel fuel can be a promising solution to improve thermal efficiency and thus reduce fuel consumption in diesel engines.

Author contribution Yaser Noorollahi: project administration, methodology, data curation, investigation, software, and writing—original draft. Ezzatollah Askari Asli-Ardeh: supervision, project administration, methodology, investigation, conceptualization, validation, and writing—review and editing. Ahmad Jahanbakhshi: formal analysis, conceptualization, methodology, investigation, validation, and writing—original draft. Ali Khodayari: methodology, investigation, validation, and writing—review and editing. Shiva Gorjian: validation and writing—review and editing.

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Declarations

Ethical approval This study does not involve any human or animal testing and thus, no ethical approval was required.

Consent to participate Not applicable.

Consent for publication All authors were informed and consented to publish the article.

Competing interests The authors declare no competing interests.

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