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Exergy and Sustainability Analysis of Different Proportions Reduced Graphene Oxide and Graphite Nanoparticles in a CI Engine

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Research Article

Abstract

This study conducted engine tests on utilizing reduced graphene oxide (rGO) and graphite (GT) nanoparticles (NPs) in varying proportions in a diesel engine. The experiments were performed with a four-stroke diesel engine featuring a water-cooled, three-cylinder configuration. Exergy and sustainability analyses are performed using the experimental work's findings. The results of test fuels containing GT and rGO NPs additives were compared with standard diesel fuel. Additionally, rGO and GT NPs are used in diesel fuel at concentrations of 50 ppm and 75 ppm, designated as Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO. The engine tests are made at a constant 1800 rpm and variable torques. The results indicate NPs-added fuels offer better exergy and sustainability performance than diesel. The Diesel+75ppm rGO blend resulted in the sustainability index and highest exergy efficiency with average improvements of 6.2%, and 12.1% respectively, over conventional diesel. Moreover, the highest average reduction in exergy destruction is achieved with Diesel+75ppm rGO at 21.6%, while the lowest average reduction is observed with Diesel+50ppm GT at 15.2%, compared to diesel. With greater amounts of rGO and GT NPs in diesel fuel, the surface-to-volume ratio grows, enabling a broader combustion zone and improved thermal exchange. It was determined that the utilization of nanoparticle additives in diesel fuel, along with an increased concentration, enhances both its exergy efficiency and sustainability.

Keywords: Exergy analysis; Graphite; Reduced graphene oxide; Nanoparticles; Sustainability

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1. Introduction

Energy has become a crucial aspect of our daily existence. The consumption of energy, whether on an individual or societal scale, significantly influences our quality of life [1]. The use of various devices and equipment that require energy, such as transportation, lighting, heating, cooling, and the electrical appliances we use daily, increases our energy dependence. The increasing energy demand has led to substantial growth in the consumption of fossil fuels [2-4]. Most of our energy requirements are fulfilled by fossil fuels, thanks to their high energy efficiency, extensive usage areas, easy storage and transportation, and their natural availability, independent of time and location. These characteristics continue to make fossil-based fuels a significant energy source today [5-6].

Internal combustion engines are machines that convert heat energy into mechanical energy by burning gasoline or diesel fuel in the combustion chamber [7-8]. Internal combustion engines are extensively used in a variety of applications beyond automobiles. Diesel engines are widely preferred for commercial and industrial vehicles, such as trains, trucks, and buses, as well as in the transportation, maritime, agriculture, and various industrial sectors, including industrial machines and power systems like generators [9-10]. The negative effects of using diesel fuel as an energy source can have significant consequences for factors of health and environment [11-12]. Therefore, it is crucial to shift toward alternative energy sources and reduce our reliance on fossil fuels. In this context, various fuel additives can be incorporated into diesel fuel. In addition, when selecting an alternative fuel or fuel additive to replace diesel fuel, it is important that it has a high lower calorific value, minimizes transportation and storage issues, and release low emissions into the atmosphere.

Recent significant research has concentrated on using various metal oxide-based NPs additives to enhance diesel fuel combustion characteristics and reduce emissions from diesel engines [13-21]. Addition of NPs to fuels can improve the thermophysical properties of fuels, such as thermal conductivity, mass dissipation, and high surface area-to-volume ratio, and physical and chemical properties of fuels such as viscosity and density. Fuel properties vary depending on the type of NPs used, particle sizes, and concentration with the base fuel. Reduced graphene and graphite NPs have superior properties such as large surface area, high internal mobility of charge carriers, high thermal conductivity, and good mechanical strength. With these properties, they increase the heat of vaporization of the fuel, thus increasing the density of the fuel-to-air charge. High surface-to-volume ratio provides better oxidation of fuel mixtures. At lower temperature ranges, it behaves as an inert substance when in contact with most materials, which is why it is characterized as a non-toxic substance for human health and the environment [22].

Zhicheng et al. [23] condusted to tests to determine effect of GO NPs impacts on emissions and cold flow properties of diesel fuel. They found that PMA14-GO PPDs significantly improved the CFPP and SP, while also effectively reducing CO and HC. However, NO and CO_2 rised with higher engine loading. In another studt which conducted by Paramashivaiah et al. [24], a fuel mixture was gained by blending graphene with Simarouba methyl ester (SME) blend diesel. Results were obtained for three different graphene NPs mixture ratios. For the test fuel with SME2040 (40 ppm graphene), there was a 9.14% reduction in BTHE, a 15.38% lower HC, 42.855% lower CO, and a 12.71% reducing of NOx.

According to Andrew et al. [25], although significant progress has been made, many challenges for the full incorporation of GO and rGO into industrial applications, several challenges still need to be addressed. While current synthetic routes are promising for large-scale production, further investigation is necessary to control and refine particles with uniform properties. Although various methods can improve the properties on average, achieving uniformity is crucial for real-world applications, as industrial products require high reproducibility. Additionally, several unique techniques demonstrate the potential of GO for various applications; however, the key to its exceptional functions lies in non-scalable, expensive, and time-consuming fabrication techniques. Further research is needed to produce nanocomposites via simple, common industrial methods without compromising the exceptional properties of GO. In their studies, GO NPs were added to milk foam oil methyl ester at 20, 40, and 60 ppm using the ultrasonication technique. Engine experiments were conducted at a constant rpm, varying loads. As a result, significant improvements were observed in performance and emission characteristics. BTHE improved by 11.56%, BSFC was reduced by 8.34%, unburned hydrocarbons decreased by 21.68%, smoke by 24.88%, and carbon monoxide by 38.662%. [26].

Yusuf et al. [27] investigated the performance, combustion and emission characteristics of a CI engine running on diesel fuel with different NPs. The experiments were conducted using a single-cylinder, air-cooled, four-stroke CI engine operating at 2000 rpm under various engine loads. Three different NPs with a concentration of 50 mg/l were considered. The Diesel/TiO_2 test fuel blend was reported to provide an average 12% reduction in fuel consumption compared to pure diesel. The addition of nanoparticles into test fuels, especially TiO_2 and GO-TiO_2, demonstrated promising reductions in fuel consumption. Furthermore, their addition modified the combustion process, leading to more reactive smoke emissions.

Heidari-Maleni et al. [28] investigated the impact of graphene quantum dot (GQD) NPs. They determined to its effect on engine performance and emissions for the ethanol-biodiesel blend. The results indicated that adding GQD NPs to the fuel increased power and torque by 28.18% and 12.42%, respectively, while reducing BSFC, CO, and HC by 14.35%, 29.54%, and 31.12%, respectively, compared to D100 fuel.

Yugandharsai et al. [29] explored the effects of GO and injection pressures on emissions and performance values of a diesel engine running on Sapota seed methyl ester. GO NPs at a concentration of 50 ppm were added to test fuels. Engine tests were conducted at injection pressures of 200 and 220 bar. The experiments, carried out at 1500 rpm and different loads. Parameters of BSFC, BTE, CO, HC, CO_2, and NOx were determined after tests. Consequently, NOx emissions were significantly reduced by 39%, and CO and HC emissions were lower in with GO additive when compared to diesel.

Heidari et al. [30] investigated the impacts of adding graphene quantum dots (GQD) and bioethanol (E) to B10 fuel on important engine parameters for a diesel engine. B10 was blended with 90 ppm GQD and various volumes of bioethanol (E2, E4, E6, and E8). The results showed that the addition of GQD and bioethanol to B10 improved engine torque and power, and reduced SFC, CO, HC, and NO_X.

Research was examined the emission impacts on a CI engine operating with diesel, Euglena Sanguinea (ES), and their blends (ES20D80, ES40D60, ES60D40, ES80D20). The average reductions in HC, smoke, and CO for ES20D80 were 2.1%, 2.3%, and 5.7% respectively, compared to diesel fuel. Experiments were performed in HCCI mode with ES20D80 fuel containing varying concentrations of GO (20, 40, 60, and 80 ppm). In this mode, hydrogen gas was introduced from the intake pipe along with air at a constant flow rate of 3 lpm to enrich the air-fuel mixture. The results indicated that the combination of hydrogen-enriched gas and GO-added ES20D80 in HCCI mode provided performance similar to that of a CI engine while significantly reducing NO_X and soot emissions by 75.24% and 53.07%, respectively, compared to diesel fuel [31].

Ağbulut et al. [32] explored the synthesis of GO and their application in a mixture of diesel fuel and waste cooking oil methyl ester (WCO). The study indicated that blending biodiesel with conventional diesel fuel reduced BTHE by 2.67%, CO by 7.5%, HC emissions by 8.53%, BSFC by 5.54%, and NO_X emissions by 3.37% compared to the reference fuel B0. However, the test fuels with added NPs showed significant improvements in all performance and emission characteristics. The addition of GO increased BTHE by 7.90% and decreased BSFC by 9.72%. GO NPs acted as oxygen buffers and catalyzed chemical reactions throughout the combustion process, resulting in more complete combustion and reductions in CO and HC emissions by 22.5% and 30.23%, respectively.

In their study, Bayindirli et al. [22] supplemented cottonseed oil methyl ester with 50 and 75 ppm of rGO and GT NPs additives. The impact of these additives on fuel properties were assessed, along with their effects on engine performance and exhaust emissions. The experimental results demonstrated that the incorporation of homogeneously prepared GT and rGO fuel additives into biodiesel positively influenced engine performance and emissions.

In the literature summarized above, the effects of different nanoparticle (NP) additives on diesel fuel performance and emissions have been investigated in detail. However, existing studies have mostly been conducted on specific NP types or under limited engine conditions, limiting a systematic comparison of different concentrations and preparation methods. In addition, research on the direct combination of reduced graphene oxide (rGO) and graphite-derived nanoparticles with diesel fuel is still in its early stages, and the results obtained have often not been tested extensively at different engine loads and injection pressures. In this study, the combination of rGO and GT nanoparticle additives with diesel fuel is targeted. Thus, both the performance of conventional fuels is improved and the effects of nanoparticle additives on engine performance and exhaust emissions are revealed in more detail. Our study aims to fill this gap in the literature and contribute to the development of more environmentally friendly and efficient engine fuel systems in the future.

The original aspect of this study is the systematic investigation of the effects of direct addition of reduced graphene oxide (rGO) and GT nanoparticles into conventional diesel fuel on engine performance and emission characteristics. Although a limited number of studies in the literature have addressed the direct combination of nanoparticle additives with diesel fuel, there is no evaluation supported by comprehensive engine tests performed at different loads and injection pressures. In addition, the performance and emission data obtained during engine tests allow the analysis of the effects of nanoparticle additives on the fuel/engine system from a broader perspective. Thus, this study both reveals the potential benefits of using nanoparticle additive fuel in diesel engines and provides an original contribution to the literature for the development of sustainable and low-emission fuel technologies.

2. Material and Methods

2.1. Experimental set-up and procedure

The experimental studies were conducted using the setup depicted in Figure 1. A Lombardini LDW 1003 diesel engine, featuring a four-stroke, water-cooled, three-cylinder design, was utilized for experiments. The technical specifications of the test engine are outlined in Table 1. The engine was coupled to a Net Brake NF150 hydraulic dynamometer, which measured speeds ranging from 0-6500 rpm and 0-450 Nm engine torque. Experiments were carried out at 1800 rpm, with 10, 20, 30 and 40 Nm engine loads. The engine's performance and emissions under these varying loads were thoroughly evaluated. Torque measurements up to 450 Nm were performed using a load cell. Exhaust emissions were measured with a emission analyzers, which are capable of measuring air excess coefficient (λ), CO, HC, NOx, CO_2, and oxygen (O_2) emissions. The technical details of the emission analyzers were given in Table 2. Additionally, exhaust temperatures were recorded using an Elimko BT01 K-Type Ni-Cr thermocouple, positioned 70 mm before the exhaust outlet. This thermocouple measures temperatures from -40°C to 1200°C with an accuracy of ±1.5°C.

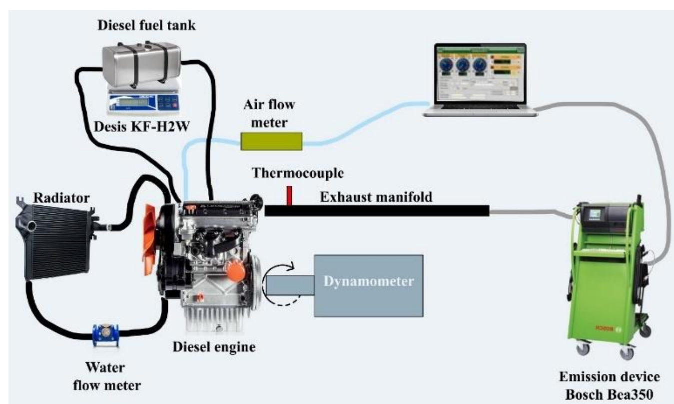

Figure 1. Test engine and measurement setup

Table 1. Test engine’s technical specifications

Parameters	Unit	Specification
Engine Brand/Model	-	Lombardini/LDW 1003
Engine type	-	4 stroke, water cooling and 3-cylindered CI engine
Cylinder bore x stroke	mm	75.00 x 77.60
Swept volume	cm3	1028
Compression ratio	-	22.8:1
Peak engine power (@ speed)	kW	19.5 (3600 rpm)
Peak engine torque (@ speed)	Nm	67.0 (2000 rpm)
Valve system	-	2 valves per cylinder
Intake valve opening/closing	-	16º BTDC/36º ABDC
Exhaust valve opening/closing	-	36º BBDC/16º ATDC
Injection pressure	bar	140-155

2.2. Test fuels and properties

The diesel fuel used in the experiments was mixed with nano additives, specifically graphite (GT) and reduced graphene oxide (rGO) NPs additives, at concentrations of 50 and 75 ppm, weighed using a digital scale and homogenously mixed into biodiesel. The mixture was dissolved using a magnetic stirrer and ultrasonic stirrer to ensure complete dispersion within the fuel over a specified period. The fuel mixtures prepared for the tests were of three different types for each fuel: pure diesel (D100), diesel with 50 ppm additive (Diesel+50ppm GT, Diesel+50ppm rGO), and diesel with 75 ppm additive (Diesel+75ppm GT, Diesel+75ppm rGO). The fuel properties are provided in Table 2.

Table 2. Specifications of test fuels

	Density (kg/m^3) at 15 °C	Viscosity (mm^2/s) at 40°C	Flash Point (°C)	Lower Heating Value (MJ/kg)
Diesel (D100)	838	2.5	64	41.13
Diesel+50 ppm GT	825	2.2	74	43.39
Diesel+75 ppm GT	822	2.1	76	43.57
Diesel+50 ppm rGO	821	2.2	78	43.72
Diesel+75 ppm rGO	815	2.1	81	43.94
Diesel (D100)	Diesel fuel (%100)			
Diesel+50 ppm GT	50 ppm graphite in diesel fuel			
Diesel+75 ppm GT	75 ppm graphite in diesel fuel			
Diesel+50 ppm rGO	50 ppm reduced graphene oxide in diesel fuel			
Diesel+75 ppm rGO	75 ppm reduced graphene oxide in diesel fuel			

2.3. Analyses

Exergy analysis is a method used to evaluate the amount of useful work that can be extracted from a system and to quantify the energy lost due to degradation. In this analysis, the exergy input to the system is represented by the fuel exergy ($\dot{E}xe_{fuel}$), while the exergy outputs include engine power ($\dot{E}xe_{engine}$), exhaust exergy ($\dot{E}xe_{exh}$), heat loss exergy ($\dot{E}xe_{heat}$), and exergy destruction ($\dot{E}xe_{dest}$) (Eq. (1)) [33].

$$\dot{E}xe_{fuel} = \dot{E}xe_{engine} + \dot{E}xe_{exh} + \dot{E}xe_{heat} + \dot{E}xe_{dest} \tag{1}$$

The value of $\dot{E}xe_{fuel}$ can be calculated utilizing Eq. (2). Where, γ_f represents the chemical exergy factor, which can be determined by inserting the compound mass ratios (k = h/c, l = o/c, and m = s/c) of the test fuels into Eq. (3) [34].

$$\dot{E}xe_{fuel} = \dot{m}_{fuel}\ LCV\ \gamma_f \tag{2}$$

$$\gamma_f = 1.0401 + 0.1728\ k + 0.0432\ l + 0.2169\ m(1 - 2.0628k) \tag{3}$$

To determine $\dot{E}xe_{exh}$, the equation provided in Eq. (4) can be applied. In this context, $\varphi_{tm,x}$ and $\varphi_{ch,x}$ denote the specific thermomechanical and chemical exergies at state x, respectively. The value of $\varphi_{tm,x}$ is calculated using the differences in molar enthalpy and molar entropy [35]. Meanwhile, $\varphi_{ch,x}$ is computed using the universal gas constant (kJ/kmolK), the enviroment temperature (K), and the molar ratios of ambient and exhaust gases at state x [36].

$$\dot{E}xe_{exh} = \sum \dot{m}_i[\varphi_{tm,x} + \varphi_{ch,x}] \tag{4}$$

The value of $\dot{E}xe_{heat}$ resulting from heat transfer in the CI engine can be determined using Eq. (5). This calculation takes into account the enviroment temperature (T_{env}), the average cooling water temperature (T_w), and the energy loss from the cooling water (E_w) [37].

$$\dot{E}xe_{heat} = \sum \left(1 - \frac{T_{env}}{T_w}\right) E_w \tag{5}$$

Exergy destruction can be calculated by taking the difference between the input and output exergies of the engine as in Eq. (6) [38].

$$\dot{E}xe_{dest} = \dot{E}xe_{fuel} - (\dot{E}xe_{engine} + \dot{E}xe_{exh} + \dot{E}xe_{heat}) \tag{6}$$

The fraction of $\dot{E}xe_{fuel}$ to $\dot{E}xe_{engine}$ gives the exergy efficiency ($\dot{E}xe_{II}$), as seen in Eq. (7) [39].

$$\dot{E}xe_{II} = \frac{\dot{E}xe_{engine}}{\dot{E}xe_{fuel}} \tag{7}$$

2.4. Sustainability

The sustainability index (SI) can be determined using Eq. (8) to assess the sustainability of diesel and NPs-infused fuels [40].

$$SI = \frac{1}{1 - \dot{E}xe_{II}} \tag{8}$$

3. Results and discussions

3.1. Exergy analysis

Figure 2 presents the change of the fuel exergy of diesel fuel containing rGO and GT nanoadditives in different proportions according to torque. At all torque values, the highest fuel exergy is found with diesel, while the addition of rGO and GT NPs to diesel fuel contributes to a decrease in fuel exergy for each torque. For example, at 10 Nm, the fuel exergy for diesel operation is 8.7 kW, whereas the fuel exergies for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies decrease by 7.2%, 8%, 9.8%, and 10.7%, respectively, compared to diesel operation. Similarly, at 40 Nm, the fuel exergy for diesel operation is 19.9 kW, while the fuel exergies for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies decrease by 8.2%, 8.3%, 9.2%, and 10.1%, respectively, compared to diesel operation. Looking at the overall average between 10 Nm and 40 Nm, the fuel exergies for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies show average decreases of 7.9%, 8.7%, 9.9%, and 10.8%, respectively, compared to diesel operation. According to the fuel exergy results, the lowest fuel exergy is obtained from the study with 75 ppm rGO (Diesel+75ppm rGO), followed by Diesel+50ppm rGO, Diesel+75ppm GT, and Diesel+50ppm GT studies, respectively. The additions of rGO and GT NPs to diesel fuels improve combustion development due to the increased surface/volume ratio. Additionally, the enhancement and acceleration of combustion reactions by the NPs contribute to increased combustion efficiency, leading to reduced fuel consumption and, consequently, a decrease in fuel exergy.

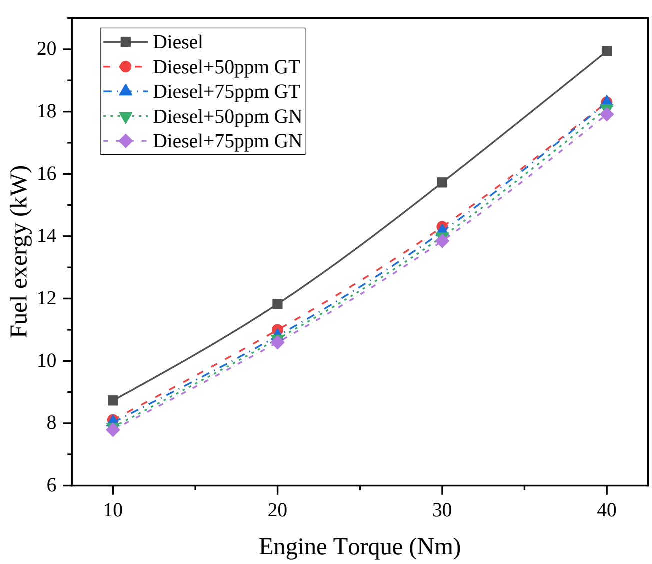

Figure 2. The change of fuel exergy versus engine torque of rGO and GT added diesel fuels.

Figure 3 presents the change of the exhaust exergy of diesel fuel containing rGO and GT nanoadditives in different proportions according to torque. The exhaust exergy values for Diesel, Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO are quite closer to each other at all torque values. For example, at 10 Nm, the exhaust exergy for diesel operation is 0.88 kW, whereas the exhaust exergies for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies are 0.86 kW, 0.88 kW, 0.88 kW, and 0.89 kW, respectively. Similarly, at 40 Nm, the exhaust exergy for diesel operation is 1.88 kW, while the exhaust exergies for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies are 1.89 kW, 1.91 kW, 1.93 kW, and 1.94 kW, respectively. The similarity in exhaust gas temperatures and exhaust mass flow rates of the test fuels leads to parallel and close results in exhaust exergy.

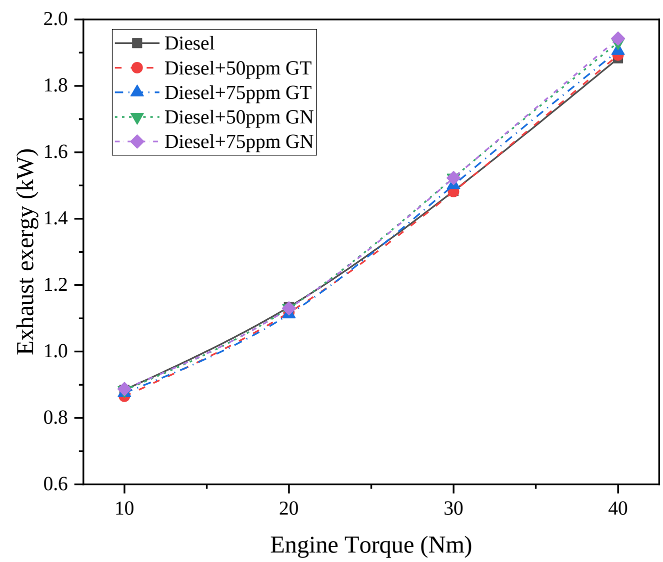

Figure 3. The change of exhaust exergy versus engine torque of rGO and GT added diesel fuels.

Figure 4 presents the change of the heat loss exergy of diesel fuel containing rGO and GT nanoadditives in different proportions according to torque. As the torque increases from 10 Nm to 40 Nm, all test fuels show a tendency for heat loss exergy to increase. This is due to the increased filling associated with the rise in engine torque, which provides more fuel energy and subsequently leads to higher combustion temperatures, resulting in greater heat transfer. The lowest heat loss exergy is obtained with diesel fuel at 10 Nm, while the use of NPs results in an increase in heat loss exergy. For example, at 10 Nm, the heat loss exergy for diesel operation is 0.47 kW, whereas the fuel exergies for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies increase by 17.1%, 21.8%, 22.9%, and 26.4%, respectively, compared to diesel operation. Conversely, at 40 Nm, the heat loss exergy for diesel operation is 1.06 kW, while the fuel exergies for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies decrease by 11%, 7.9%, 6.9%, and 6.8%, respectively, compared to diesel operation. The significantly higher other loss energy of diesel at full load compared to the other test fuels leads to a considerable increase in heat loss exergy, resulting in higher values compared to the others. Looking at the overall average between 10 Nm and 40 Nm, the heat loss exergies for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm GN, and Diesel+75ppm rGO studies show average increases of 5.3%, 7.9%, 9%, and 10.7%, respectively, compared to diesel operation. The catalytic effect of nanoparticle addition accelerates combustion reactions. Furthermore, the addition of nanoparticles increases the surface-to-volume ratio, contributing to the development of the flame front. This leads to higher combustion temperatures and consequently increases heat transfer to the coolant. Similarly, Jafarmadar and Niaki (2022) reported in their study that the use of nanoparticles in diesel fuel enhances the surface-to-volume ratio, resulting in greater heat transfer to the coolant and significant heat losses [41]. Additionally, other studies in the literature are consistent with the results of the present study [42-43].

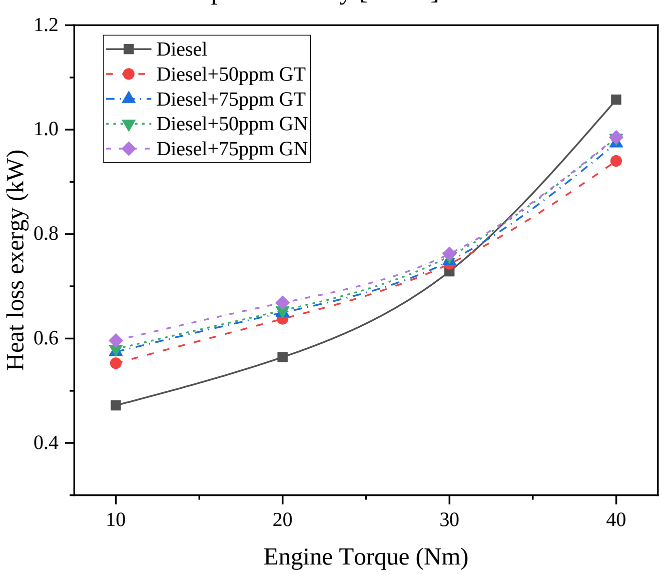

Figure 4. The change of heat loss exergy versus engine torque of rGO and GT added diesel fuels.

Figure 5 presents the change of the exergy destruction of diesel fuel containing rGO and GT NPs in different proportions according to torque. As seen in the figure, 50 ppm and 75ppm rGO and GT NPs additions into diesel significantly affect exergy destruction. At all torque values, the highest exergy destruction is found with diesel, while the addition of rGO and GT NPs to diesel fuel contributes to a decrease in exergy destruction for each torque. For example, at 10 Nm, the exergy destruction for diesel operation is 5.5 kW, whereas the exergy destruction for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies decreases by 12.5%, 14.5%, 17.5%, and 19.4%, respectively, compared to diesel operation. Similarly, at 40 Nm, the exergy destruction for diesel operation is 19.9 kW, while the exergy destruction for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies decreases by 16.2%, 16.8%, 19.2%, and 21.3%, respectively, compared to diesel operation. Looking at the overall average between 10 Nm and 40 Nm, the exergy destruction for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies shows average decreases of 15.2%, 17.2%, 19.7%, and 21.6%, respectively, compared to diesel operation. The use of rGO and GT NPs in diesel supports combustion development, enhancing combustion stability and efficiency. This results in lower fuel consumption and reduced loss of exergy. Additionally, the increase in the surface/volume ratio of the NPs contributes to higher combustion temperatures and improved combustion efficiency. These two factors can be considered the main reasons for the reduction in exergy destruction.

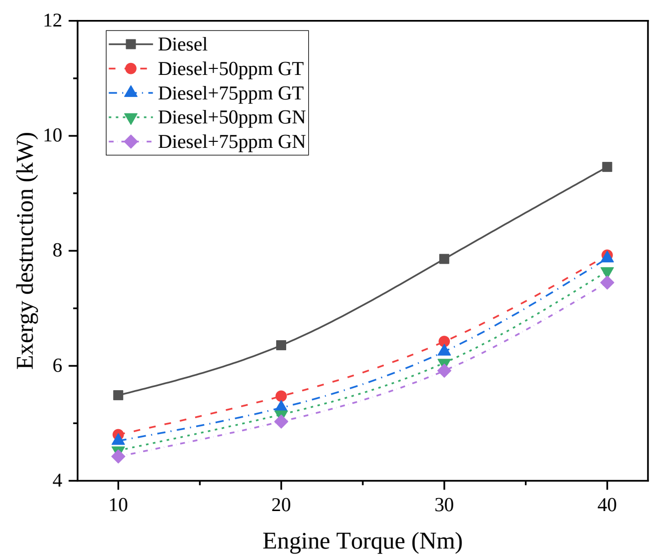

Figure 5. The change of exergy destruction versus engine torque of rGO and GT added diesel fuels.

Figure 6 presents the change of the exergy efficiency of diesel fuel containing rGO and GT NPs in different proportions according to torque. As seen in the figure, 50ppm and 75ppm rGO and GT NPs additions into diesel significantly affect exergy efficiency for all torques. At all torque values, the highest exergy efficiency is found with Diesel+75ppm GT, while Diesel fuel exhibits the lowest exergy efficiency. For example, at 10 Nm, the exergy efficiency for diesel is 21.6%, whereas the exergy efficiency for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies increases by 7.7%, 8.7%, 10.8%, and 12%, respectively, compared to diesel operation. Similarly, at 40 Nm, the exergy efficiency for diesel is 37.8%, while the exergy efficiency for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies increases by 9%, 9%, 10.2%, and 11.3%, respectively, compared to diesel operation. The higher exergy efficiency of NPs-infused fuels compared to diesel is due to the NPs improving important fuel properties such as viscosity and lower heating value, which in turn enhances combustion performance. In other studies, involving NPs additives, it is noted that the engine performance improvements result from the enhancement of fuel properties and combustion due to the nano-additives [44,45 and 48]. Looking at the overall average between 10 Nm and 40 Nm, the exergy efficiency for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies show average increases of 8.6%, 9.6%, 11%, and 12.1%, respectively, compared to diesel operation. The increase in exergy efficiency with the rise in nanoparticle additive content is due to the homogeneous distribution of nanoparticles within the fuel, which enhances combustion temperatures and expands the combustion surface area, leading to faster flame front propagation. Additionally, the literature indicates that nanoparticle additives in fuel accelerate ionization between fuel molecules by enlarging the combustion surface area and volume [46,49,50].

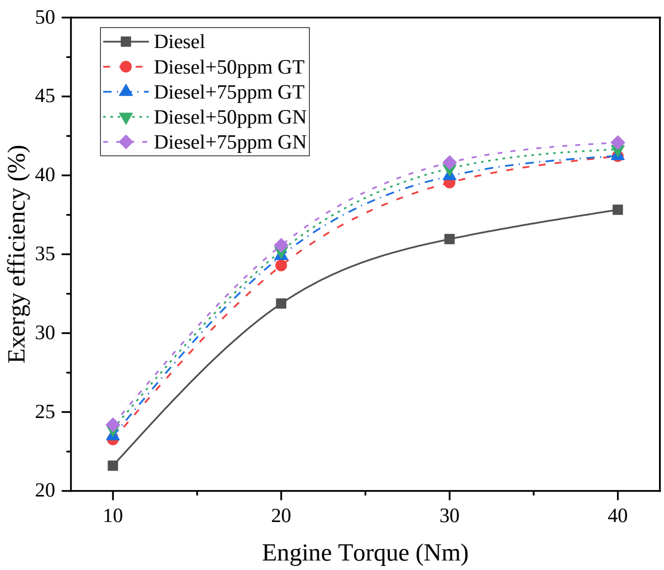

Figure 6 The change of exergy efficiency versus engine torque of rGO and GT added diesel fuels.

3.2. Sustainability analysis

Figure 7 presents the change of the sustainability index (SI) of diesel fuel containing rGO and GT NPs in different proportions according to torque. The fuel that enhances sustainability the most in diesel engines is the Diesel+75ppm rGO blend containing 75 ppm of rGO, while diesel fuel shows a lower SI compared to other NPs-added fuels. The highest SI at all torques is obtained with Diesel+75ppm rGO, followed by Diesel+50ppm rGO, Diesel+75ppm GT, Diesel+50ppm GT, and Diesel fuels, respectively. For example, at 10 Nm, the SI for diesel is 1.28, whereas the SI for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies increases by 2.2%, 2.5%, 3.1%, and 3.4%, respectively, compared to diesel operation. Similarly, at 40 Nm, the SI for diesel is 1.61, while the SI for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies increases by 5.8%, 5.8%, 6.6%, and 7.4%, respectively, compared to diesel operation. Thanks to the high thermal conductivity of rGO and GT NPs, it increases combustion efficiency by providing better heat transfer in the combustion zone, which allows the current load to be met with less energy. Thus, the SI of the fuel also increases. Looking at the overall average between 10 Nm and 40 Nm, the SI for Diesel+50ppm GT, Diesel+75ppm GT, Diesel+50ppm rGO, and Diesel+75ppm rGO studies show average increases of 4.4%, 4.9%, 5.6%, and 6.2%, respectively, compared to diesel operation. Aghbashlo and et. al (2017) reported that the use of cerium oxide nanoparticle additives in fuel increased combustion efficiency due to the catalytic properties of the nanoparticles, and consequently, the SI increased [47].

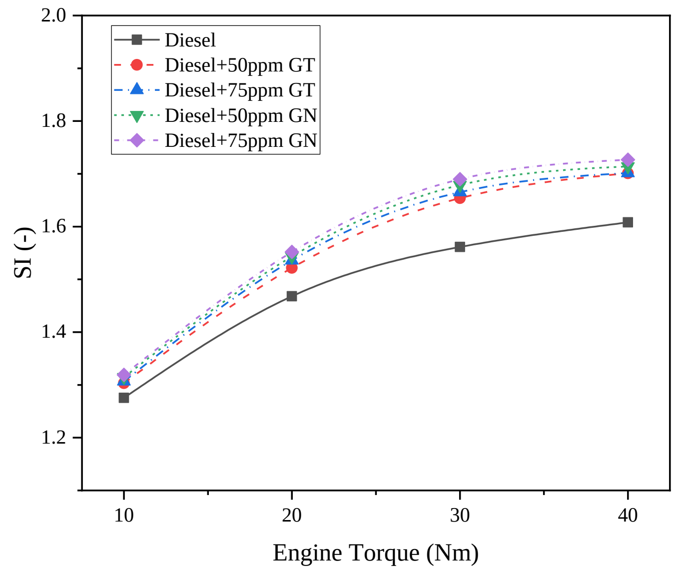

Figure 7 The change of SI versus engine torque of rGO and GT added diesel fuels.

4. Conclusions

In this study, experiments are conducted by adding rGO and GT NPs into diesel fuel in proportions of 50 ppm and 75 ppm, respectively, under engine torques of 10, 20, 30, and 40 Nm at an engine speed of 1800 rpm. Exergy and sustainability analyses are examined using the outputs obtained from the experimental work. A summary of the exergy and sustainability analysis results for the rGO and GT NPs used as additives in diesel fuel is presented below:

* The addition of NPs to diesel allows the required power to be met with lower fuel exergy. Compared to diesel combustion, the highest average reduction in fuel exergy is achieved with Diesel+75ppm rGO fuel at a rate of 11%, while the lowest average reduction in fuel exergy is obtained with Diesel+50ppm GT

fuel at 8%. The addition of NPs supports the improvement of combustion, enabling the use of smaller amounts of fuel.

* As the proportions of rGO and GT NPs in diesel fuel increase, the surface-to-volume ratio also increases. This expands the combustion zone and allows for higher heat transfer. As a result, in-cylinder combustion temperatures rise. Compared to diesel combustion, the largest average increase in heat loss exergy is observed with Diesel+75ppm rGO fuel at a rate of 10.7%, while the lowest average reduction in fuel exergy is seen with Diesel+50ppm GT fuel at 5.3%.

* rGO and GT significantly reduce exergy destruction, which is also an indicator of combustion irreversibilities. The improvement of fuel properties by NPs leads to lower fuel consumption and fewer combustion irreversibilities. The addition of 75 ppm rGO to diesel fuel results in a maximum reduction of 13% in exergy destruction. Overall, other NPs-containing fuels exhibit lower exergy destruction compared to conventional diesel fuel.

* The highest exergy efficiency is achieved with Diesel+75ppm rGO at 40 Nm, with a rate of 42.1%. The significant reduction in fuel consumption and the lower energy losses compared to other fuels, thanks to the rGO NPs, contribute to the substantial increase in exergy efficiency.

* rGO and GT NPs positively impact sustainability. The highest SI is achieved with Diesel+75ppm rGO at 40 Nm, with a value of 1.73. Overall, the average SI output for Diesel+75ppm GN is 1.57. The ranking of fuels from the most sustainable to the least sustainable in this study is as follows: Diesel+75ppm rGO > Diesel+50ppm rGO > Diesel+75ppm GT > Diesel+50ppm GT > Diesel.

As a result, the use of nanoparticle additives in diesel fuel and the increase in nanoparticle concentration enhance the exergy efficiency and sustainability of the fuel. In future studies, diesel fuels containing rGO75 and rGO50, which demonstrated high exergy performance and sustainability, could be examined in terms of environmental impact, enviroeconomic effects, and environmental hazard costs.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

Credit Author Statement

Cihan Bayindirli: Investigation, Experiments, Writing-original draft, Editing, Conceptualization, Supervision
Derviş Erol: Writing-original draft, Investigation, Validation, Data curation, Formal analysis
Mehmet Çelik: Methodology, Investigation, Validation, Data curation, Formal analysis
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