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# Investigation of the Effect of $TiO_2$ Nanoparticles on Engine Performance and Emission Characteristics in Diesel Engines

Sefa Koca[1], Oktay Zincirci[1] and Fatih Aktaş[2 *]

[1.] *Graduate School of Natural and Applied Sciences, Gazi University, Ankara 06500, Türkiye*
[2.] *Department of Mechanical Engineering, Faculty of Engineering, Gazi University, Ankara 06570, Türkiye*

**Research Article**

**Abstract**

This study aimed to examine the changes in performance and emission values in a four-stroke and three-cylinder diesel engine by using pure diesel fuel and fuels created by adding $TiO_2$ nanoparticles. Adding $TiO_2$ nanoparticles to the fuel aimed to improve the combustion characteristics of the diesel engine and reduce the harmful effects of exhaust emissions. Pure diesel and $TiO_2$ nanoparticle-added fuel samples in three distinct amounts, 25 ppm, 50 ppm, and 75 ppm, were prepared in magnetic and ultrasonic mixers as D100, D100+25$TiO_2$, D100+50$TiO_2$, and D100+75$TiO_2$. All fuel samples used in the research were tested at a constant speed of 1800 revolutions per minute (rpm) at 25%, 50%, 75%, and 100% full loads. When $TiO_2$-added fuels were compared to pure diesel, there was a 15.12% rise in brake thermal efficiency at %25 load and a 13.36% drop in brake specification fuel consumption at %25 load. EGT values also increased with the increase in load and adding TİO$_2$. The amount of $CO_2$ in exhaust emissions increased by 5% at maximum load in the fuel with the highest $TiO_2$ additive according to neat diesel. There was an average increase of 11.44% in $NO_X$ emissions for all loads with $TiO_2$ addition. The results show that the fuel mixture created by adding $TiO_2$ nanoparticles can be used in certain proportions in diesel engines and that the $TiO_2$ addition positively improves the combustion properties, engine performance, and exhaust gas emissions.

*Keywords*: Combustion; Diesel engine; Emission; Nanoparticle; $TiO_2$

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**Contact**
* Corresponding author
Fatih Aktaş
fatihaktas@gazi.edu.tr
Address: Mechanical Engineering Department, Faculty of Engineering, Gazi University, Ankara, Turkey

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## 1. Introduction

Fossil fuels are going through a period where their importance is increasing worldwide and at the same time, they are much discussed [1]. In these periods when industrialization, urbanization and the number of vehicles using fossil fuels increased rapidly, the world's energy consumption increased significantly [2]. Fossil fuels provide 80% of the energy used in the world [3, 4]. Despite the increase in renewable energy sources, fossil fuels, which cover a significant portion of world energy consumption, make the transition to green energy difficult [5-7]. This addiction in consumption also brings about serious negativities and the addiction of the fossil fuel attracts even more attention, especially as it is one of the main reasons for the deterioration of human health, environmental negativities, and troubles in the country's economies [8].

The International Energy Agency (IEA) states that developing countries' energy consumption will increase by 25% by 2040, which will trigger the formation of more greenhouse gases and the negative effects of climate change [5, 9]. Global programs such as the Sustainable Development Goals (SDGs) also emphasize the urgency of transitioning to sustainable energy sources [10, 11]. In addition to its negative effects, the depletion of fossil fuel resources has increased the search for alternative methods to use these resources more efficiently and reduce their negative effects [12-15]. Studies in this sense have increased, especially in diesel engines used in transportation and industry [16-19].

Studies such as the use of biodiesel fuels, engine modifications, and the addition of fuel additives are examples of studies carried out to reduce the negative effects mentioned above and to use resources more efficiently [20-22]. In case studies using biodiesel fuel and nanoparticles, it has been shown that engine performance can be significantly increased, and harmful emissions can be reduced [23-25].

In the studies have observed that nanoparticles such as $Al_2O_3$, $CeO_2$, ZnO, CuO, $SiO_2$, MgO, $TiO_2$, FeO etc. are used in many experiments to understand engine performance, combustion properties and emission behavior. In these studies, it is known that $TiO_2$ nanoparticles have higher thermal conductivity, improved flammability, and higher surface-to-volume ratio than

ZnO, CuO, MgO, $CeO_2$, FeO nano additives [26]. It has been observed that the $TiO_2$ nanoparticles mentioned here improve the combustion characteristics by having a catalytic effect due to their high thermal conductivity [3, 27]. In addition, $TiO_2$ nanoparticles are characterized by high photocatalytic activity, which contributes to the reduction in NOx, CO and HC emissions from internal combustion engines. Additionally, $TiO_2$ nanoparticles have been found to increase the combustion efficiency of diesel fuels, resulting in improved fuel economy and reduced emissions [5].

The effects of titanium oxide ($TiO_2$) nanoparticles used with fuel on diesel engine performance and emission characteristics were studied by Silva et al. [23]. When compared to pure fuel, the calorific value of the fuel sample containing $TiO_2$ nanoparticles was 0.59% higher. Furthermore, it has been demonstrated that adding $TiO_2$ nanoparticles to diesel fuel raises the brake thermal efficiency (BTE) at maximum load by 0.9%. $TiO_2$ nanoparticle addition results in a 21.28% reduction in brake-specific fuel consumption at full load. Additionally, at full load, using the $TiO_2$ nanoparticles causes a 32% rise in nitrogen oxide ($NO_X$) emissions. However, using $TiO_2$ nanoparticles resulted in a 25% reduction in carbon monoxide (CO) emissions and an 18.36% reduction in unburned hydrocarbon emissions at full load.

El Seesy et al. [28], investigated the effects of using nanoparticles to diesel-biodiesel-N-butanol mixtures on diesel engine performance. When $TiO_2$ is added to the mixture of 50% Jojoba biodiesel, 40% diesel, and 10% n-butanol (J50D10Bu) by volume, the BTE raised by 17%, and the brake specification fuel consumption (BSFC) decreased by 15% in comparison to the pure J50D10Bu blend. In compared to J50D10Bu, the addition of $TiO_2$ resulted in a significant reduction of 30% and 50%, respectively, in the emissions of CO and unburned hydrocarbons (UHC). However, because the cylinder pressure was increased when $TiO_2$ nanoparticles were used, there was an increase in $NO_X$ emission. Örs et al. [3], experimented on the engine with different ratios of fuel samples prepared with diesel-biodiesel-n-butanol and $TiO_2$ nanoparticles. Maximum brake torque and brake power values for all prepared fuels were recorded at approximately 1400 rpm and 2800 rpm, respectively. When $TiO_2$ nanoparticle was added to the mixture of 20% biodiesel and 80% euro diesel (B20), the engine brake power and torque increased by approximately 10.20% according to the B20 blend. Furthermore, a mixture of 20% biodiesel, 70% euro diesel, 10% butanol (volumetric), and 0.01% $TiO_2$ (mass) (B20But10+ $TiO_2$)'s engine brake power and torque are roughly 9.74% greater than B20But10's. They conclude that engine performance has improved as a result of the $TiO_2$ addition to the fuel sample. Furthermore, the use of $TiO_2$ nanoparticles decreased carbon monoxide, hydrocarbon, and smoke opacity emission levels while increasing carbon dioxide ($CO_2$) and NO emissions as a result of the better combustion process according to fuel mixtures without $TiO_2$ additives. In order to improve a diesel engine's combustion and emission performance, Simhadri et al. [29], caried out an experimental study at various injection pressures on the impact of Mahua biodiesel combined with $TiO_2$ nanoparticles. $TiO_2$ nanoparticles were added at a higher injection pressure, improving performance attributes. At 240 bar fuel injection pressure (FIP), with a mixture of 20% biodiesel, 80% diesel, and 25 ppm $TiO_2$ (B20T25), brake thermal efficiency increased by 3.7% and 1.7% compared to B20 and diesel. Bello et al. [30], stated that adding $TiO_2$ nanoparticles to diesel fuel reduces BSFC, and engine performance will be even higher if an equal amount of fuel is used. Sunil et al. [31] examined the effect of addition of $TiO_2$ in different biodiesel fuel samples. Adding $TiO_2$ into the fuel sample negatively affected the thermal efficiency. Kumar et al. [26] studied the conduct of diesel fuel emissions in single-cylinder, compression-ignition (CI) engines by using $TiO_2$ nanoparticles. It has been observed that CO, hydrocarbon (HC), and NOx emissions are lower than pure diesel at both 50 parts per million (ppm) and 100 ppm $TiO_2$ nanoparticle amounts.

To the best of our knowledge, in the majority of literature studies, it has been observed that $TiO_2$ nanoparticles are added as second additives to biodiesel and its derivatives. In a very few studies, it has been determined that it is added as a direct additive in one or two different amounts or water emulsion together with pure diesel. This study aims to show the effect of $TiO_2$ nanoparticle addition in 3 different concentrations (25 ppm, 50 ppm, 75 ppm) along with pure diesel, which is not available in similar studies, on engine performance and emissions at different loads.

## 2. Materials and methods

### 2.1. Preparing of fuel mixtures with nanoparticles

The $TiO_2$ nanoparticles used in the research with 99.95% purity and average particle size of 5-10 nm were supplied from Nanografi (Product groups: NG Materials, NG Chemicals), and the properties of the nanoparticles are given in Table 1. Utilizing scanning electron microscopy (SEM), the surface and shape of the $TiO_2$ nanoparticles were investigated. The $TiO_2$ nanoparticle SEM results (20 µm and 1 µm) are given respectively in Figure 1. (a) and 1. (b). It is understood from the SEM image that the supplied nanoparticles are at the desired dimensionally. Since the size of the nanoparticles is smaller than the diameter of the fuel injector nozzle, they do not hinder the fuel flow in the nozzle [32]. The nanoparticles supplied are spherical in shape. Small spaces between the particles due to the spherical structure can cause condensation, which can lead to agglomeration [24, 29, 33]. Nanoparticles were measured separately as 25 ppm, 50 ppm, and 75 ppm with the help of Shimadzu AUW320 Analytical Balance device and prepared for mixture in packages. The amount of nanoparticles was limited to 75 ppm by utilizing the literature to minimize precipitation formation [23].

$TiO_2$ nanoparticles of different concentrations, prepared in packages, were placed in one-liter beakers with neat diesel obtained from a local gas station in the amount to be used throughout the experiment. The mixture was first mixed in a magnetic stirrer for thirty minutes. After that, the mixture was blended at 30–40 kHz frequency settings for an hour in an ultrasonicator [3, 29]. The preparation of the fuel and nanoparticle mixture is shown schematically in Figure 2. To prevent settling or sedimentation, the fuel mixture was used immediately after preparation [23]. The properties of diesel and $TiO_2$ nanoparticle-added fuel samples are shown in Table 2 [26].

Table 1. Specifications of $TiO_2$ nanoparticles.

| Product Name | Titanium oxide nanoparticles |
|---|---|
| Chemical formula | $TiO_2$ |
| Purity | 99.95 % |
| Average particles size | 5–10 nm |
| Colour | White |
| Molecular weight | 79.87 g/mol |

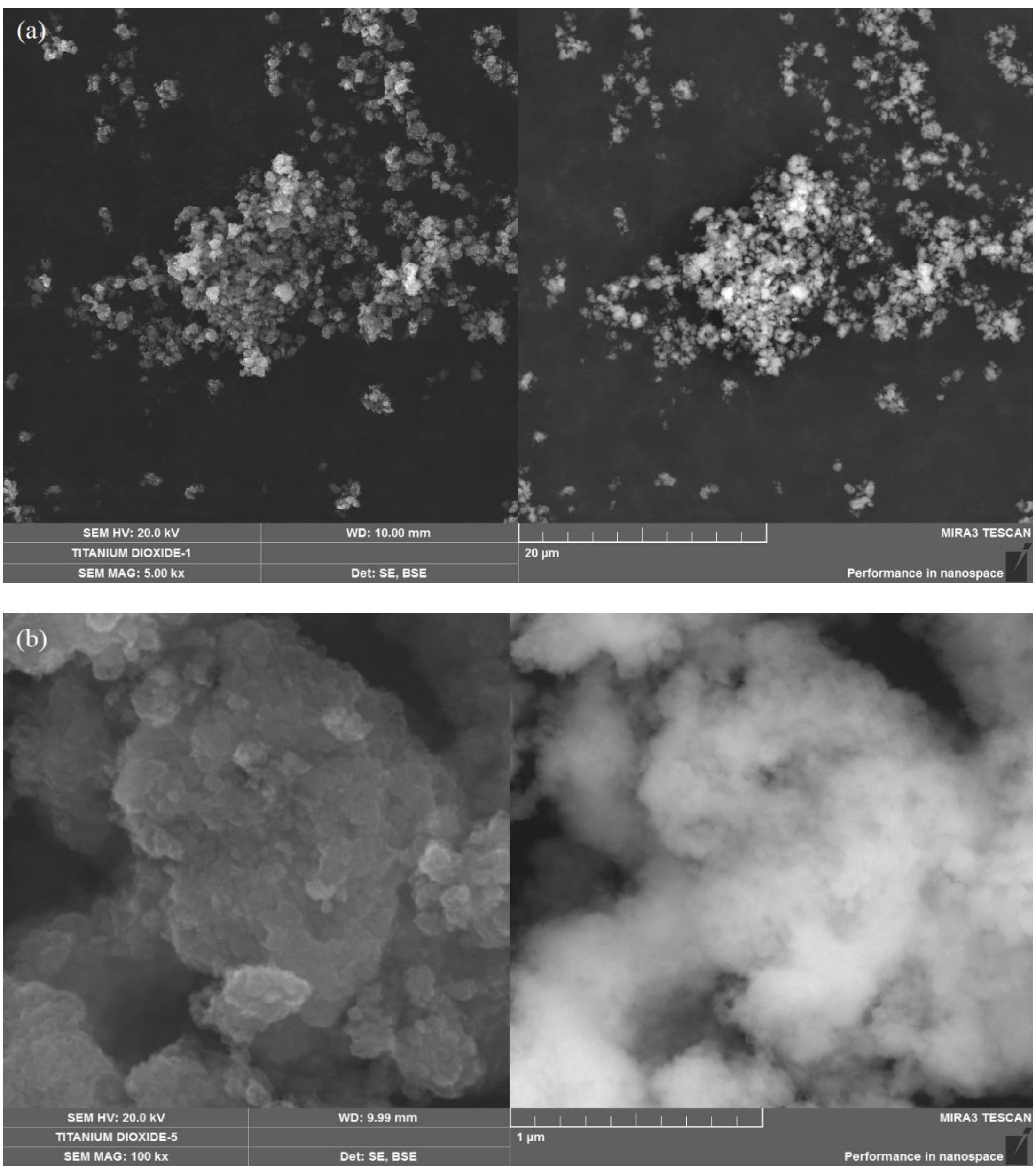


Fig. 1. SEM image of $TiO_2$ nanoparticles.

Table 2. Properties of the tested fuels [26].

| Properties | D100 | D100+25 $TiO_2$ | D100+50 $TiO_2$ | D100+75 $TiO_2$ | Method |
|---|---|---|---|---|---|
| Density (kg/m$^3$) | 750 | 740 | 740 | 740 | ASTM D4052 |
| Kinematic Viscosity @40°C (m m$^2$/s) | 2.7 | 2.6 | 2.5 | 2.4 | ASTM D445 |
| Calorific Value (MJ/kg) | 42.500 | 42.611 | 42.669 | 42.728 | ASTM D240 |
| Flash point (°C) | 45 | 46 | 47 | 48 | ASTM D976 |
| Cetane Number | 49 | 49 | 50 | 50 | ASTMD988 |

## 2.2. Experimental setup

In this experiment, a four-stroke, three-cylinder, water-cooled, and turbocharged DI diesel engine was used. Figure 3 shows a 3D representation of the experimental setup. Table 3 contains technical information about the engine. The diesel engine is assembled to an electric dynamometer, which provides load and speed control, with the help of a cardan shaft. The engine exhaust emissions were measured using the Gas Analyser Capelec Cap 3200, which can detect CO, $CO_2$, HC, $O_2$, and $NO_X$ emissions. Table 4 provides the emission analyzer's technical specs.

Table 3. Diesel engine specification.

| Engine Information | Specification |
|---|---|
| Model | New Holland EngineT 4.55S - S8000 |
| Number of Cylinders | 3 |
| Cylinder volume, cm3 | 2930 |
| Bore / Stroke (mm) | 104 / 115 |
| Connection rod (mm) | 182 |
| Compression ratio | 17.5: 1 |
| Rated engine power ISO TR1439 6 - ECE R120 [kW/hp] | 41 / 55 |
| Rated engine speed (rpm) | 2300 |
| Max. torque ISO TR14396 (Nm @rpm) | 258@1400 |
| Injection system | Direct injection |
| Compressor pressure ratio | 1.40 |
| Cooling type | Water |

In order to warm and stabilize the engine, neat diesel fuel is used throughout the study's initial testing. All tests were started after the cooling water temperature reached 85 °C. Neat diesel and $TiO_2$ mixtures, %100 diesel (D100), %100 diesel + 25 ppm $TiO_2$ (D100+25 $TiO_2$), %100 diesel + 50 ppm $TiO_2$ (D100+50 $TiO_2$), and %100 diesel + 75 ppm $TiO_2$ (D100+75 $TiO_2$) tests were performed at 50Nm (25%), 100Nm (50%), 150Nm (75%), and full load (100%), respectively, by fixing the speed at 1800 revolution per minute (rpm).

Table 4. Specifications of the Capelec Cap 3200 emission analyser.

| Measurements | Measurements range | Accuracy |
|---|---|---|
| HC (ppm) | 0-20 000 | 10 |
| $CO_2$ (% vol.) | 0-20 | 0.3 |
| CO (% vol.) | 0-15 | 0.03 |
| $O_2$ (% vol.) | 0-21.7 | 0.1 |
| NOx (ppm) | 0-5000 | 32 |

## 2.3. Uncertainty analysis

For the reliability of the data, the experiments were repeated three times. The results obtained in the repetitions varied due to variables such as the operating status of the equipment maintenance and calibration, and environmental conditions. Uncertainty values are shown for the parameters considered in Table 5. The uncertainty caused by the variables was calculated as follows:

Overall Uncertainty;

$$= \sqrt{(Load)^2 + (BP)^2 + (BSFC)^2 + (BTE)^2 + (EGT)^2 + (CO_2)^2 + (NOx)^2}$$

$$= \sqrt{(0.4)^2 + (0.5)^2 + (0.7)^2 + (0.6)^2 + (1.1)^2 + (0.4)^2 + (0.5)^2}$$

$$= \pm 1.69\%$$

Table 5. Uncertainty of various parameters

| Measurements | Uncertainty (%) |
|---|---|
| Brake power | 0.5 |
| Brake torque | 0.4 |
| BSFC | 0.7 |
| BTE | 0.6 |
| EGT | 1.1 |
| CO2 | 0.4 |
| NOx | 0.5 |

## 2.4. Calculation of terms and measurements

Parameters such as engine torque, fuel consumption, exhaust gas temperature, and actual engine speed were taken with an electrical dynamometer and the help of instruments on the engine.

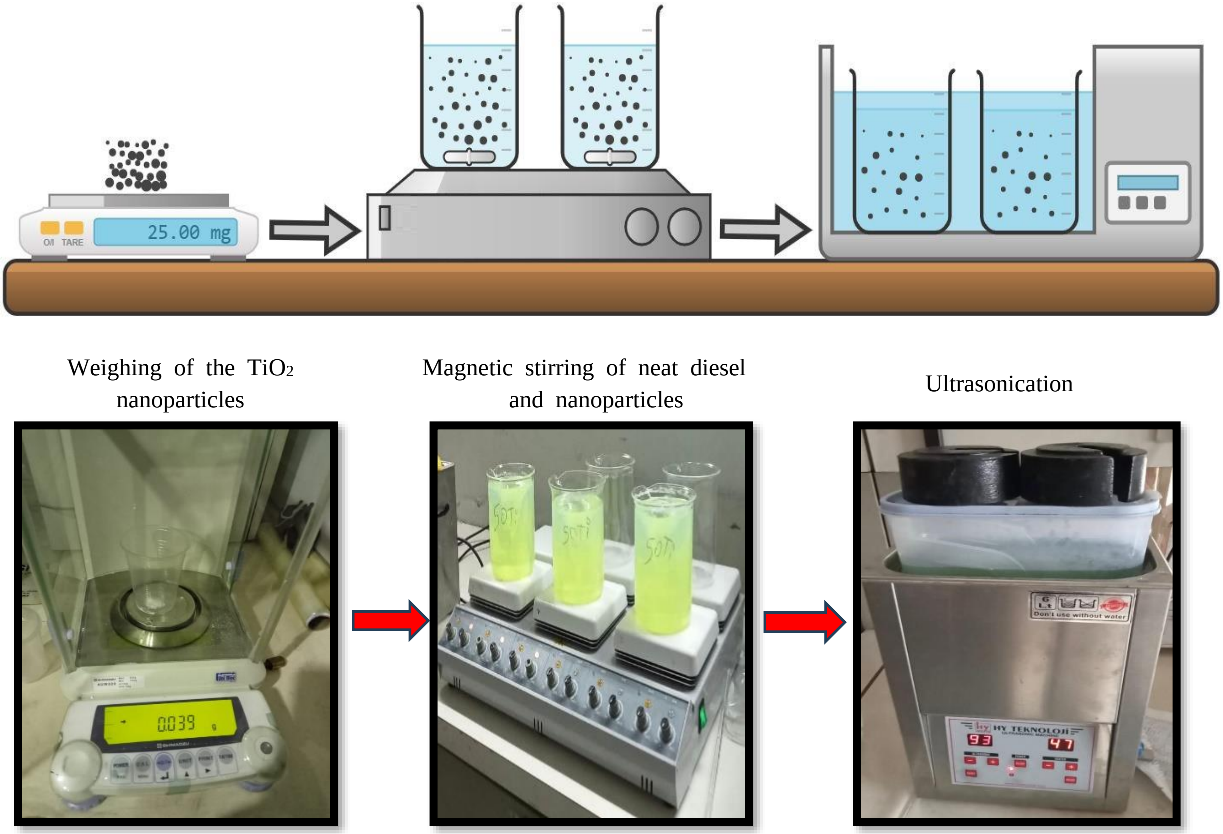


Fig. 2. The preparation of the fuel and nanoparticle mixture

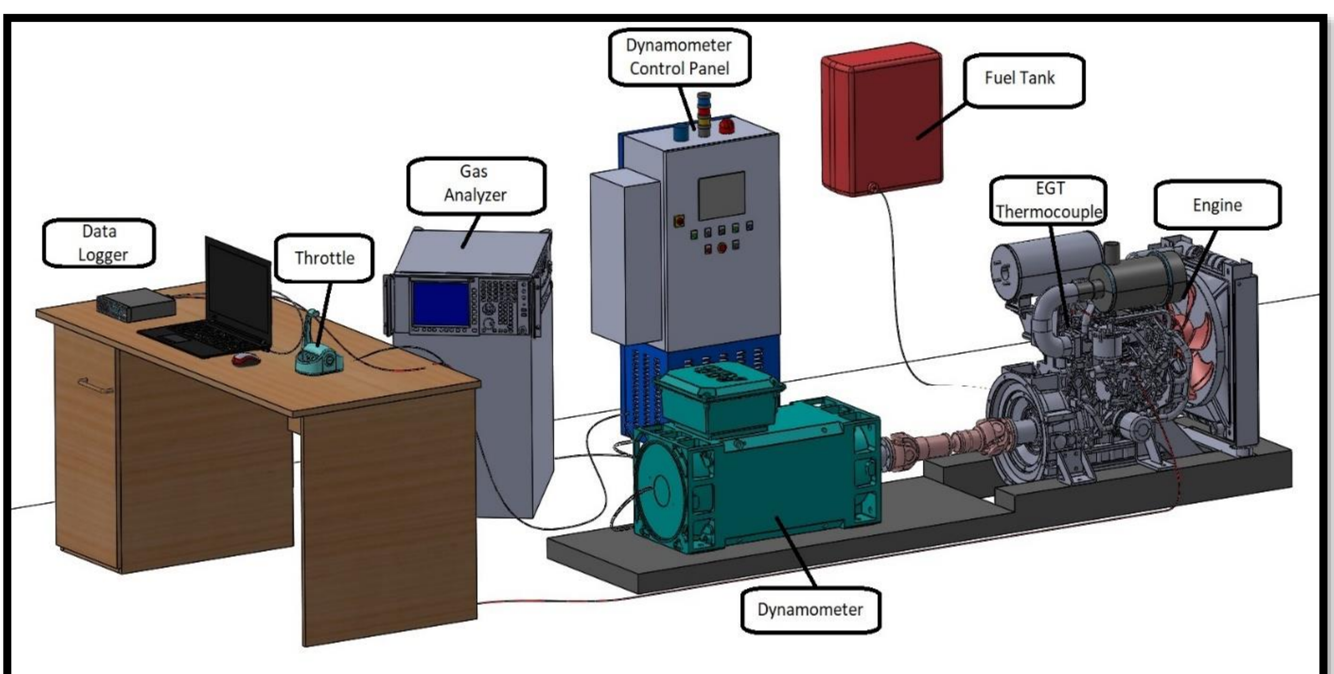


Fig. 3. Schema of Engine setup

Brake power, brake thermal efficiency, and brake specification fuel consumption data were obtained with the following formulations.

Brake power;

$$BP = \frac{2\pi NT}{60000}(kW) \quad (1)$$

where, BP represents brake power (kW), T represents engine torque (Nm) and N represents engine speed (rpm).

Brake thermal efficiency;

$$\eta_{bte} = \frac{BP}{m_f \times CV} \times 100\% \quad (2)$$

where, $\eta_{bte}$ represents brake thermal efficiency (%), BP represents brake power (kW), $m_f$ represents mass of fuel supplied (kg/s) and CV lower calorific value of fuel (kj/kg).

Brake specification fuel consumption;

$$BSFC = \frac{m_f}{BP}(g / kWh) \quad (3)$$

where, BSFC represents brake specific fuel consumption (g/kWh), mf represents fuel consumption (g/s) and BP represents engine brake power (kW).

## 3. Results and discussion

This part, the effect of $TiO_2$ nanoparticle addition (with different percentages) at 1800 rpm constant speed with different load conditions on engine performance in examined in line with BTE, BSFC, exhaust gas temperature, $CO_2$ and NOx emissions. Each experimental data obtained was compared with similar studies in the literature.

### 3.1. Brake thermal efficiency (BTE)

Figure 4 shows the BTE results of diesel fuel and $TiO_2$ added fuel at 1800 rpm and different loads. In the all figures, the values on the load axis are stated as percentages. The values stated as a percentage correspond to 50 Nm for 25%, 100 Nm for 50%, 150 Nm for 75%, and full load for 100%. Full load values for each fuel sample were 199.2 Nm for D100, 201.5 Nm for D100+25$TiO_2$, 207.7 Nm for D100+50$TiO_2$, and 208.9 Nm for D100+75$TiO_2$. These values will be taken as basis for the BTE figure and future figures. Brake thermal efficiency and brake power are directly related to the rise in engine load because the combustion chamber's peak temperature rises as engine load increases [3, 24]. With the use of $TiO_2$ nanoparticles in the fuel, BTE increased according to pure diesel fuel at all loads. The reason of this increase can be shown as the increasing micro explosion tendency of nanoparticles [23, 34, 35]. Although, BTE is higher in nanoparticle added fuels than diesel, as the load rises, the increment rate of brake thermal efficiency of the fuel of the same concentration decreases. In other words, the brake power of the fuel with 25 ppm nanoparticle added increased compared to pure diesel with each load increase, but the increment rate decreased towards the full load. Also, it was determined that BTE decreased as the amount of nanoparticles raised from 25 ppm to 75 ppm at each load. Decreases in BTE as the amount of nanoparticles in the fuel increases may be due to the increase in radiative heat losses caused by nanoparticles [31]. The peak increment rates of BTE were realized at a 25 ppm concentration and the lowest load. The maximum brake thermal efficiency increment was %15.12 for D100+25 $TiO_2$ compared with pure diesel at a load of %25.

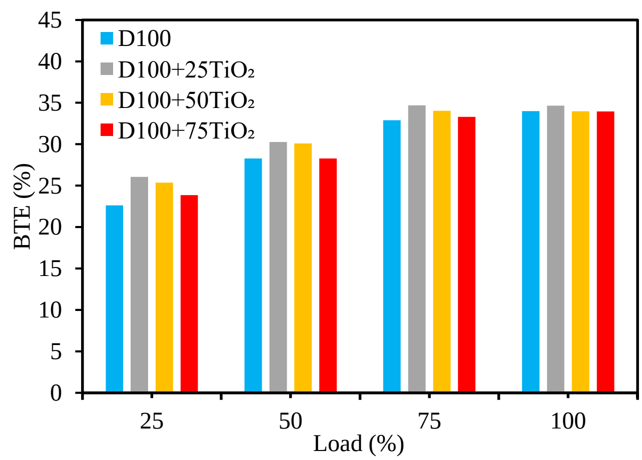


Fig. 4. Variation of BTE at various load for different nanoparticles percentage

### 3.2. Brake specific fuel consumption (BSFC)

Figure 5 shows the results of diesel fuel and $TiO_2$ additive on the BSFC at 1800 rpm and different loads. It is observed that BSFC value is reduced with a rising in load for all the fuel samples. In all concentrations of $TiO_2$, BSFC was always lower than diesel fuel. This revealed that the high surface area of $TiO_2$ particles leads to better combustion quality due to improving the reaction surface area [3]. The lowest BSFC values are seen in high-load and low $TiO_2$ mixtures. This may be because air and fuel mix better in a low-concentration $TiO_2$ mixture, providing better combustion [23, 28]. Additionally, as we move towards full loads, the BSFC value in all fuel samples approaches each other and decrease [31]. As the load increases, BSFC becomes lower as higher thermal efficiency is achieved [30]. This also shows that it is compatible with the BTE figure. Figure 4 shows that the performance increases as the load increases, and the performance decreases as the amount of $TiO_2$ in each load increases. BSFC decreased as the load increased, opposite to BTE, and increased from low $TiO_2$ concentration to high concentration at each load. Compared to diesel, shown that the lowest BSFC value, 13.36%, is in the fuel sample with low load and 25 ppm $TiO_2$.

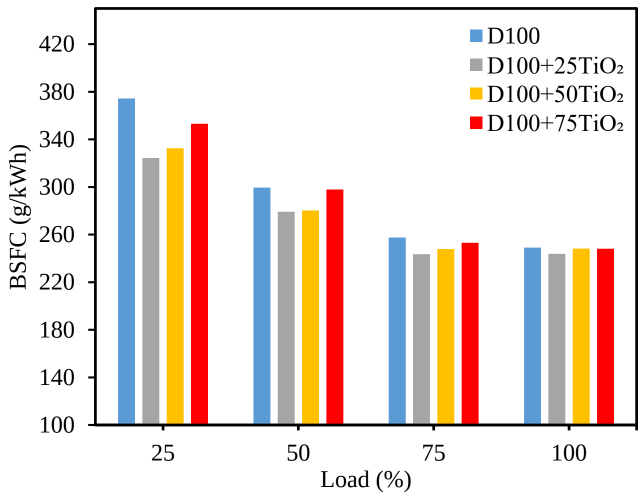


Fig. 5. Variation of BSFC at various load for different nanoparticles percentage

### 3.3. Exhaust gas temperature (EGT)

Figure 6 shows the effect of diesel fuel and $TiO_2$ additive on the exhaust gas temperature at 1800 rpm and different loads. EGT is an indicator of the energy released during combustion [31, 36]. The results show that for all fuel samples, EGTs increase as load increases. When BTE, BSFC, and EGT were evaluated together, Figure 6 shows that the fuel with $TiO_2$ added may have a higher combustion quality than pure diesel, especially when the related EGTs are considered. It can be argued that combustion quality is better in nanoparticle-added fuels than in pure diesel, especially when considering the relevant exhaust gas temperatures (EGTs) and shorter ignition delays. Considering that higher temperatures cause nanoparticles to be more reactive, better combustion can be achieved and higher temperatures can enable significant amounts of fuel to be burned [30].

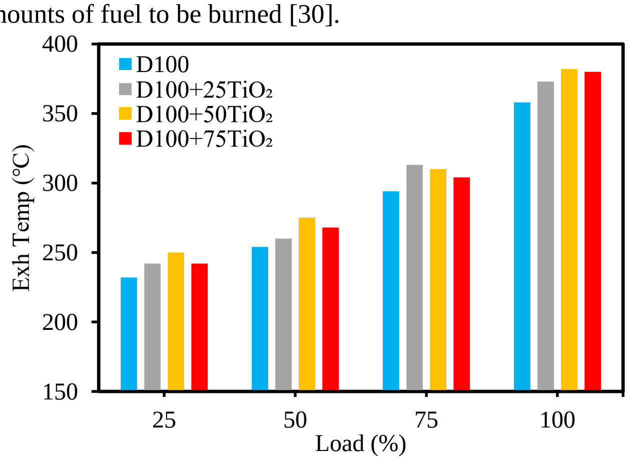


Fig. 6. Variation of EGT with various load for different nanoparticles percentage

### 3.4. Carbon dioxide emissions

Figure 7 shows the variations of carbon dioxide with various loads at a constant speed of 1800 rpm for diesel and a mixture of diesel - $TiO_2$ nanoparticles. The result shows that load increases $CO_2$ increases. This increase in $CO_2$ may be due to the increase in temperature in the cylinder with the increase in load and better combustion [23]. This may also explain that there is a balance between nanoparticles improving the combustion process so that CO emissions decrease and $CO_2$ formation increases. Therefore, $TiO_2$ additive both increases $CO_2$ emissions and reduces CO emissions compared to neat diesel [3]. In $TiO_2$ added fuel samples, the $CO_2$ level was lower than diesel at low loads, but with the increase in $TiO_2$ towards full load, it was higher than diesel. In the 75 ppm $TiO_2$ fuel mixture and at maximum load, the $CO_2$ value was measured to be 5% higher than diesel. This can be attributed to the increased catalytic activity of $TiO_2$ nanoparticles. Due to this effect, the air-fuel mixture in the combustion chamber is improved, and complete combustion is achieved [23, 29, 37].

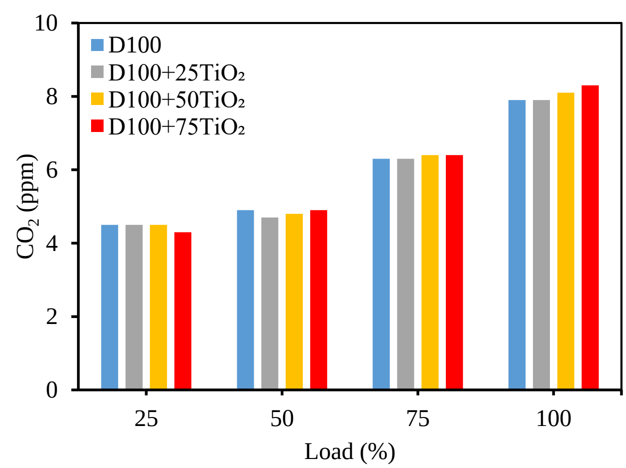


Fig. 7. Variation of $CO_2$ with various load for different nanoparticles percentage

### 3.5. Nitrogen Oxide ($NO_X$) emissions

Figure 8 shows the variation of $NO_X$ with various loads at a constant speed of 1800 rpm for diesel and a mixture of $TiO_2$ nanoparticles fuel samples. It is noted that NOx rises with load. With an increasing load, the temperature level increases, and the oxygen concentration creates a suitable environment for NOx formations to occur [23, 31]. Owing to the high reactivity and higher surface area of $TiO_2$, it contributes to the improvement of combustion properties in terms of in-cylinder pressure and temperature, leading to high $NO_X$ levels [30]. Moreover, with the increase of $TiO_2$ addition, NOx emission rises due to the amount of additional oxygen, catalytic activity of the nano-particle fuel [23, 24, 38].

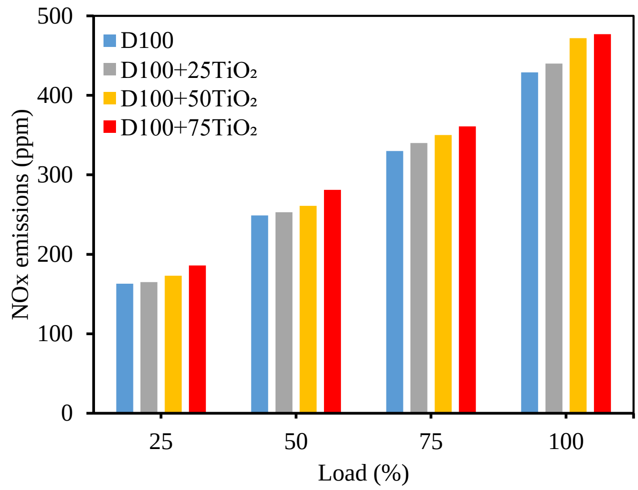


Fig. 8. Variation of NOx with various load for different nanoparticles percentage

## 4. Conclusion

Using neat diesel and their mixture with 25, 50, and 75 ppm concentrations of $TiO_2$ nanoparticles, the engine's performance and emission properties were studied. The experimental investigation yielded the following conclusions:

- At the lowest load and fuel sample concentration of 25 ppm, the BTE peak increment rate was achieved.
- At a minimum load of 50 Nm, the maximum brake thermal efficiency increment for D100+25 $TiO_2$ was %15.12 compared to pure diesel.
- In contrast to BTE, BSFC increased from low $TiO_2$ concentration to high concentration at each load and declined as the load increased.
- The maximum decrease in BSFC was observed when 25 ppm $TiO_2$ was added at low load. Compared to diesel, a 13.36% reduction in fuel consumption was observed.
- At low loads, when $TiO_2$ was added to fuel samples, the $CO_2$ level was lower than diesel; but, as the $TiO_2$ level increased towards full load, it exceeded diesel $CO_2$ level. At full load and with a 75 ppm $TiO_2$ fuel mixture, the $CO_2$ level was found to be 5% greater than that of diesel.
- It is clear that when $TiO_2$ is added, NOx emissions increase due to increased oxygen content, catalytic activity of the fuel, and better oxidation.
- NOx emissions were 11.44% higher on average at all loads, especially with 75 ppm $TiO_2$ fuel, compared to pure diesel.

## Conflict of Interest Statement

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

## CRediT Author Statement

**Sefa Koca**: Conceptualization, Writing - original draft, Analysis, Validation,
**Oktay Zincirci**: Data curation, Formal analysis, Validation
**Fatih Aktaş**: Conceptualization, Writing - review & editing, Supervision

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