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Abstract



Research Article

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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	History
fuel samples in three distinct amounts, 25 ppm, 50 ppm, and 75 ppm, were prepared in magnetic and	Received 05.05.2024 Revised 28.05.2024
ultrasonic mixers as D100, D100+25TiO ₂ , D100+50TiO ₂ , and D100+75TiO ₂ . All fuel samples used in	Accepted 07.06.2024
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 TIO2. The amount of CO2 in	
exhaust emissions increased by 5% at maximum load in the fuel with the highest TiO ₂ additive according	Contact
to neat diesel. There was an average increase of 11.44% in NO _X emissions for all loads with TiO ₂ addi-	* Corresponding author
tion. The results show that the fuel mixture created by adding TiO ₂ nanoparticles can be used in certain	Fatih Aktaş
proportions in diesel engines and that the TiO ₂ addition positively improves the combustion properties,	fatihaktas@gazi.edu.tr
engine performance, and exhaust gas emissions.	neering Department, Faculty

Keywords: Combustion; Diesel engine; Emission; Nanoparticle; TiO2

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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 Al₂O₃, CeO₂, ZnO, CuO, SiO₂, MgO, TiO₂, FeO etc. are used in many experiments to understand engine performance, combustion properties and emission behavior. In these studies, it is known that TiO₂ nanoparticles have higher thermal conductivity, improved flammability, and higher surface-to-volume ratio than



ZnO, CuO, MgO, CeO₂, FeO nano additives [26]. It has been observed that the TiO₂ nanoparticles mentioned here improve the combustion characteristics by having a catalytic effect due to their high thermal conductivity [3, 27]. In addition, TiO₂ nanoparticles are characterized by high photocatalytic activity, which contributes to the reduction in NOx, CO and HC emissions from internal combustion engines. Additionally, TiO₂ 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 (TiO₂) 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 TiO₂ nanoparticles was 0.59% higher. Furthermore, it has been demonstrated that adding TiO₂ nanoparticles to diesel fuel raises the brake thermal efficiency (BTE) at maximum load by 0.9%. TiO₂ nanoparticle addition results in a 21.28% reduction in brake-specific fuel consumption at full load. Additionally, at full load, using the TiO₂ nanoparticles causes a 32% rise in nitrogen oxide (NO_X) emissions. However, using TiO₂ 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 TiO₂ 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 TiO₂ 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-biodieseln-butanol and TiO₂ nanoparticles. Maximum brake torque and brake power values for all prepared fuels were recorded at approximately 1400 rpm and 2800 rpm, respectively. When TiO₂ 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% TiO₂ (mass) (B20But10+ TiO₂)'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 TiO₂ addition to the fuel sample. Furthermore, the use of TiO2 nanoparticles decreased carbon monoxide, hydrocarbon, and smoke opacity emission levels while increasing carbon dioxide (CO₂) and NO emissions as a result of the better combustion process according to fuel mixtures without TiO₂ 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 TiO₂ nanoparticles. TiO₂ 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 TiO₂ (B20T25), brake thermal efficiency increased by 3.7% and 1.7% compared to B20 and diesel. Bello et al. [30], stated that adding TiO₂ 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 TiO₂ in different biodiesel fuel samples. Adding TiO₂ 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 TiO₂ 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 TiO₂ 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 TiO₂ 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 TiO₂ nanoparticles were investigated. The TiO₂ 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].



TiO₂ 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 TiO₂ nanoparticle-added fuel samples are shown in Table 2 [26].

Table 1. Specifications of TiO2 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 TiO₂ nanoparticles.

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Table 2. Properties of the tested fuels [26].					
Properties	D100	D100+25 TiO2	D100+50 TiO2	D100+75 TiO2	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, watercooled, 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, CO₂, HC, O₂, 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 TiO₂ mixtures, %100 diesel (D100), %100 diesel + 25 ppm TiO₂ (D100+25 TiO₂), %100 diesel + 50 ppm TiO₂ (D100+50 TiO₂), and %100 diesel + 75 ppm TiO₂ (D100+75 TiO₂) 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:

overall Uncertainty;		
$1(T + 1)^2 + (DD)^2$		

=	$\sqrt{(Load)^2 + (BP)^2 + (BSFC)^2 + (BTE)^2 + (EGT)^2}$
	$+ (CO_2)^2 + (NOx)^2$
=	$\sqrt{(0.4)^2 + (0.5)^2 + (0.7)^2 + (0.6)^2 + (1.1)^2 + (0.4)^2}$
	$+ (0.5)^2$
=	$\pm 1.69\%$

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.



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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;

$$BP = \frac{2\pi NT}{60000} \left(kW \right) \tag{1}$$

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

Brake thermal efficiency;

$$\eta_{bte} = \frac{BP}{m_f \times CV} \times 100\% \tag{2}$$

where, η_{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;

$$BSFC = \frac{m_f}{BP} \left(g / kWh \right) \tag{3}$$

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 TiO₂ 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+25TiO₂, 207.7 Nm for D100+50TiO₂, and 208.9 Nm for D100+75TiO2. 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 TiO₂ 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 TiO₂ 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 TiO₂ 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 TiO2, BSFC was always lower than diesel fuel. This revealed that the high surface area of TiO₂ 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 TiO₂ mixtures. This may be because air and fuel mix better in a low-concentration TiO₂ 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 TiO2 in each load increases. BSFC decreased as the load increased, opposite to BTE, and increased from low TiO₂ 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 - TiO₂ 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 CO₂ formation increases. Therefore, TiO₂ additive both increases CO₂ emissions and reduces CO emissions compared to neat diesel [3]. In TiO₂ added fuel samples, the CO₂ level was lower than diesel at low loads, but with the increase in TiO₂ towards full load, it was higher than diesel. In the 75 ppm TiO₂ fuel mixture and at maximum load, the CO₂ value was measured to be 5% higher than diesel. This can be attributed to the increased catalytic activity of TiO₂ 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 CO₂ 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 TiO₂ 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 TiO₂, 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 TiO₂ 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 nanoparti-

cles 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 TiO₂ was %15.12 compared to pure diesel.
- In contrast to BTE, BSFC increased from low TiO₂ concentration to high concentration at each load and declined as the load increased.
- The maximum decrease in BSFC was observed when 25 ppm TiO₂ was added at low load. Compared to diesel, a 13.36% reduction in fuel consumption was observed.
- At low loads, when TiO₂ was added to fuel samples, the CO₂ level was lower than diesel; but, as the TiO₂ level increased towards full load, it exceeded diesel CO₂ level. At full load and with a 75 ppm TiO₂ fuel mixture, the CO₂ level was found to be 5% greater than that of diesel.
- It is clear that when TiO₂ 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 TiO₂ 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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