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Original Research Article

Determination of the effect of low concentration titanium dioxide nano fuel additive in biodiesel on performance and emissions

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ABSTRACT

In this study, the effect of nanoparticle addition into rapeseed methyl ester (R0) produced by the transesterification method on engine performance and emissions was experimentally investigated. Titanium dioxide was used as a nano fuel additive and was added to the test fuels at rates of 50 ppm (RTi50) and 75 ppm (RTi75) using an ultrasonic mixer. The effect of titanium dioxide on engine performance and exhaust emissions was experimentally determined by taking advantage of its photocatalysis effect and chemical reaction accelerator properties. Additionally, titanium dioxide additive reduced the viscosity and density of biodiesel fuel, resulting in higher micro explosion. According to the test results carried out at 4 different engine loads, brake specific fuel consumption decreased by 7.51% and 8.62% in RTi50 and RTi75 fuels compared to R0 fuel. Brake thermal efficiency increased by 2.47% and 6.21%, respectively. The improvement in combustion achieved by the nano additive increased the conversion of CO emissions into CO_2, increased NO_X emissions, reduced smoke emissions and caused more complete combustion products to come out of the exhaust.

Keywords: Titanium dioxide, nano additive, engine performance, emissions, micro explosion

1. Introduction

Approximately 40% of energy usage of world based on petroleum products, and the largest share among them is diesel fuel. Environmental problems arising from fuels, instability in fuel prices and other factors have accelerated efforts to increase the efficiency of petroleum-based fuels. These problems have motivated researchers to find alternative and renewable energy sources that are more environmentally friendly. Diesel engines are one of the main sources of many toxic emissions. There are some approaches to decrease diesel emissions. Design changes, improving combustion and exhaust gas treatments are some examples of that approaches. [1]. Biodiesel is an attractive alternative fuel to conventional diesel fuel to minimize import dependence and emissions. It is generally classified as ester-based fuel which can produce from different kind of oil [2]. Biodiesel has a lower content of aromatic compounds and does not contain sulfur. These features contribute to the reduction of exhaust emissions. The biggest disadvantage of biodiesel is its viscosity. Higher biodiesel viscosity may result in decreased atomization quality and increased average droplet diameter [3]. The quality of fuel atomization directly affects the combustion process, which in turn plays an important role on efficiency. Good atomization ensures that the fuel is more homogeneously distributed and burns more efficiently, resulting in energy savings and improved performance [4, 5].

While different fuel additives have been researched for fossil fuel engine applications since the 1970s. Since 2000, fuel additives a good alternative fuel applications [6]. Recent research advances have shown that nanoparticles usage an innovative method to gain better engine efficiency and less emission [7]. Nanoparticle additives can improve fuel quality to advance engine performance [8]. In addition, these fuel additives accelerate combustion by acting as a catalyst, which positively affects performance [7].

Nano fuels can form significant changes in chemical and physical features of the fuel. An example, due to higher cetane number it can provide shorter ignition delay. Consequently, this means that predicting nanofuel effects must deal with many influencing parameters [5]. The most used NMs are titanium dioxide (TiO_2), copper oxide (CuO), iron oxide (γ-Fe_2O_3), aluminum oxide (Al_2O_3), carbon nanotubes (CNTs), cerium dioxide (CeO_2), and zinc oxide (ZnO) nanoparticles (NPs), and functionalized NMs. NMs (nanomaterials) can be classified into (i) energetic and (ii) non-energetic as given in Figure 1 [5].

Nano additives have excess energy of surface atoms, high oxygen adsorption ability, high rapid evaporation, surface area/volume ratio, shorter ignition delay, smoke oxidation feature and high energy transport ability [5,8,9]. It allows for more complete combustion of fuel and more efficient energy release due to its large specific surface area [10]. On the other hand, they improve thermal conductivity, flash point, and viscosity [8]. As a result, NMs can exhibit superparamagnetic behaviors, better catalytic activity, higher reactivity lower melting temperature, and higher theoretical density according to micron or larger sized materials [5].

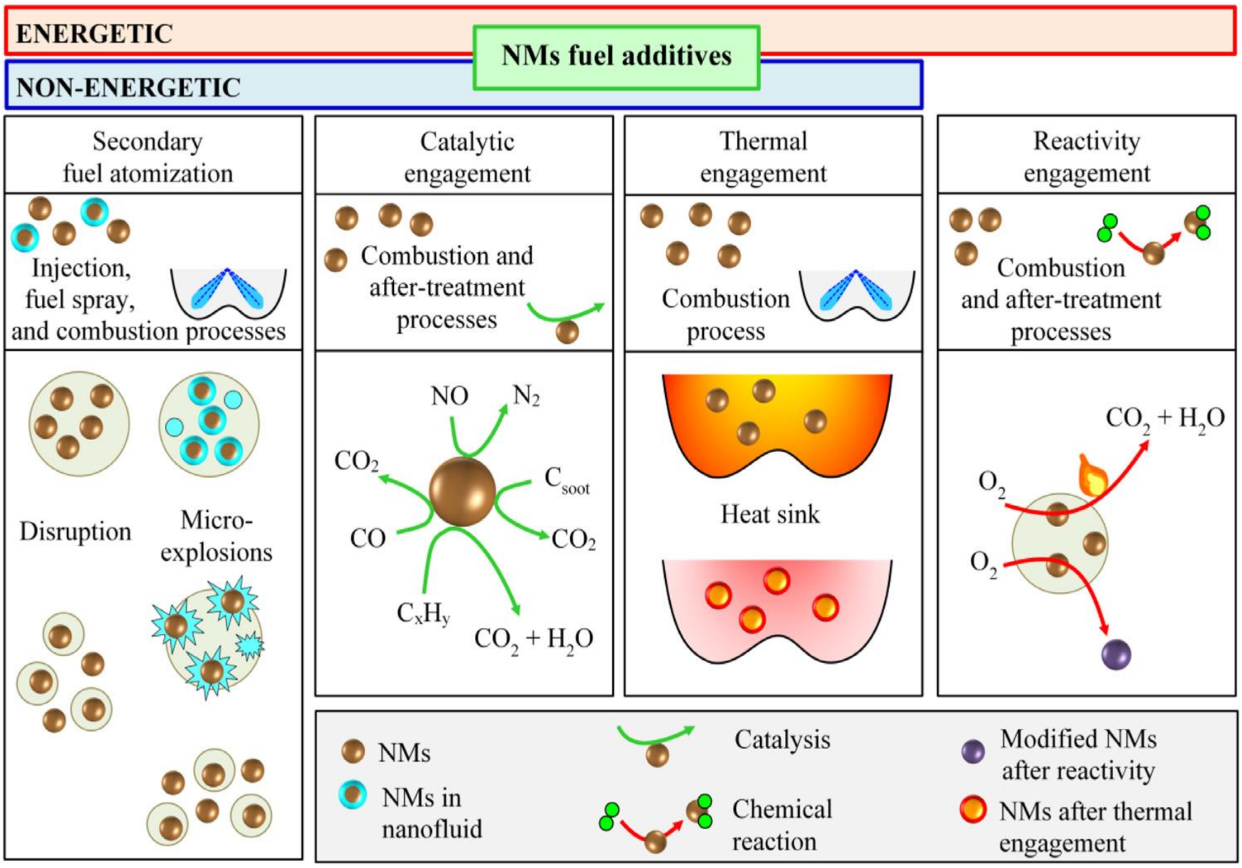

Figure 1. NMs activities in diesel engines [5].

Nanoparticles can add into the fuel two main ways. The first is the powder form. The second is adding it in nanofluids form. As shown in Figure 2 (a), for water-containing nano fuels, the water droplets present in the fuel droplets will preferentially evaporate in cylinder. The water-free nano fuels show micro explosive during combustion, as shown in Figure 2 (b). Since the boiling point of nanoparticles is higher when the nano additive is mixed with biodiesel, the fuel droplets enter a state of overheating and expansion. This event is defined as a microburst. This microburst produces smaller fuel droplets, which accelerates subsequent atomization, called secondary atomization. These two phenomena are very beneficial for optimizing of performance and emissions [11].

Although many studies have been researched on fuel additives, there are still problems in this subject. Additionally, there are potential environmental hazard with the use of metal oxides and metal-based nanoparticles. In general, the development of nanotechnology and its different uses cause inevitable interactions between the environment and nanomaterials [12]. Nanoparticle usage will also provide insight into the problems and potential associated with the use of nanoparticles in the management of biodiesel engine emissions and will pave the way for future studies and innovations on this important topic [13]. This study aims to improve the engine parameters without the need for any changes in the engine thanks to the physical and chemical properties of the nanoparticle.

2. Material Methods

Since reactivity, electronic structure, energy level are significantly improved in the same material, titanium (Ti) is not found in a metallic state in nature and has a higher affinity for oxygen. Photocatalytic activity can be increased by adding TiO_2 [14].

The biodiesel (R0) was obtained from rapeseed oil by using transesterification method. Then, TiO_2 additive, weighed on a precision scale, was added into the obtained biodiesel fuel at ratios of 50 ppm and 75 ppm. The mixture was first stirred in a mechanical mixer to ensure a homogeneous distribution. The mixture was then processed in an ultrasonic mixer to achieve a more homogeneous structure and reduce the particles to smaller sizes. The fuel properties of these nano fuels obtained are

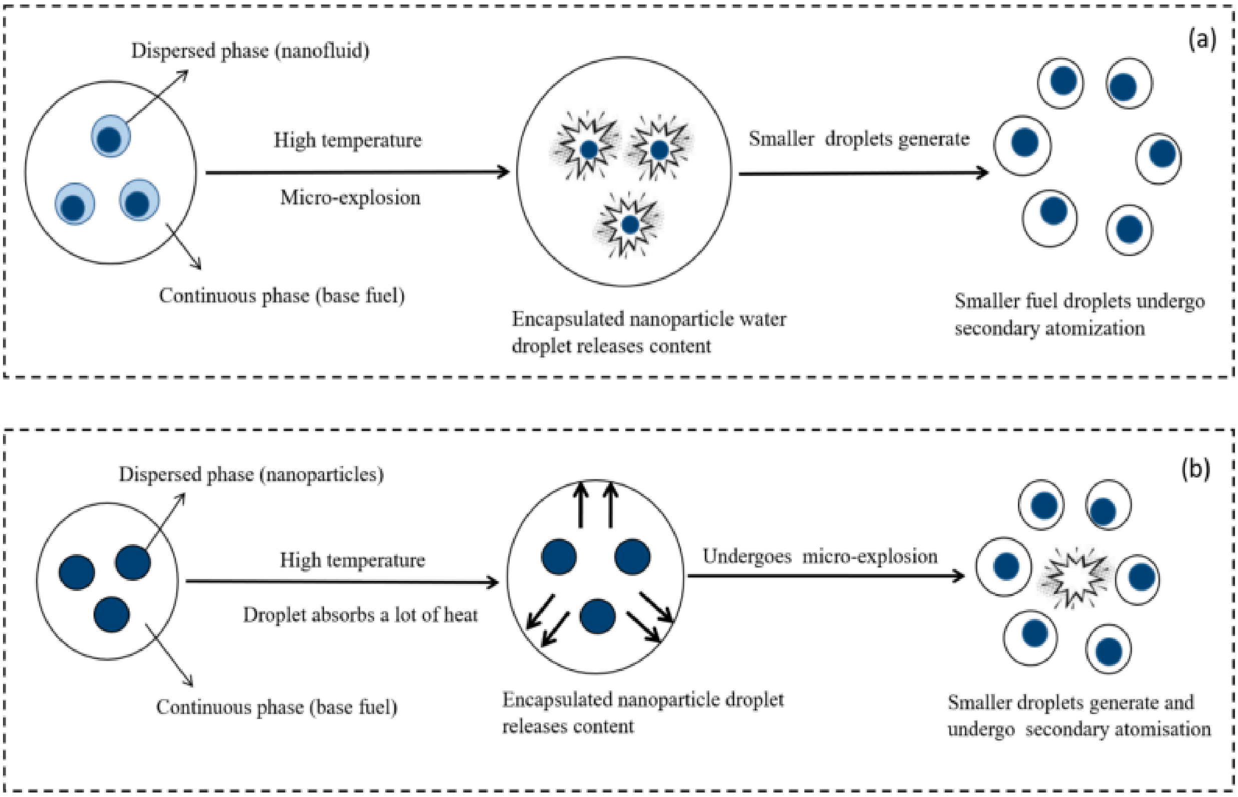

Fig. 2. Secondary atomization- micro explosion behaviors of nano fuels with water (a) without water (b) [11].

determined and given in Table 1. TiO_2 added biodiesel fuels were tested at 4 different engine loads (10 - 20 - 30 and 40 Nm) at a constant 1800 rpm engine speed in the experimental setup shown in Figure 3. The technical specifications of the engine used in the experiments are given in Table 2.
Uncertainty analysis of the study results was carried out using the uncertainty and accuracy of the devices used to determine the parameters in the study, and the relevant values are given in Table 3. In this study the uncertainty values of the parameters measured and calculated at the Eq. (1).

$$r = kX_1^a X_2^b X_3^c \ldots \tag{1}$$

The uncertainty function of this form is given at the Eq. (2),

$$u_r = \frac{W_r}{r} = [a^2(u_{x1})^2 + b^2(u_{x2})^2 + c^2(u_{x3})^2 + \cdots]^2 \tag{2}$$

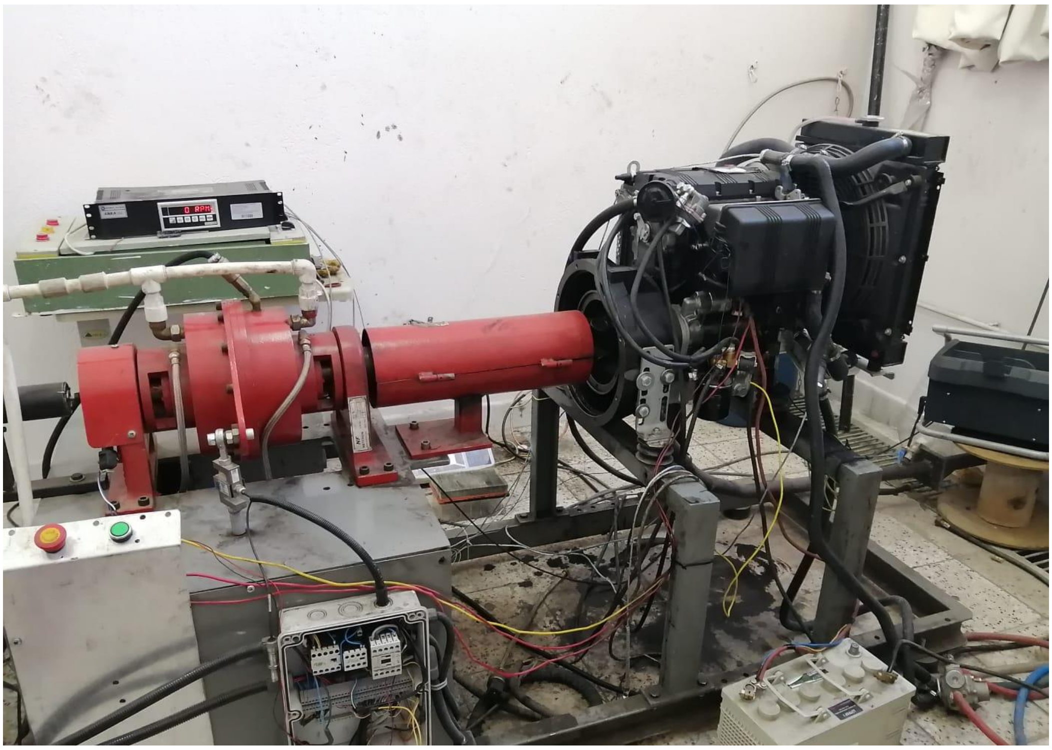

Fig. 3. The experimental setup

Table 1. Physical and chemical properties of nanofuels

	Density (kg/m^3)	Kinematic Viscosity (mm^2/s)	Flash Point (°C)	Lower Heating Value (MJ/kg)
D0 (Diesel)	838	2.5	64	41.13
R0	880	4.5	172	38.98
RTi50	867	4.2	163	39.18
RTi75	850	3.9	156	39.26

Table 2. Technical features of the test engine

Parameters	Feature
Brand	Lombardini LDW 1003
Cylinder number	3
Maximum engine power	19.5 kW @ 3600 rpm
Maximum engine torque	67.0 Nm @ 2000 rpm
Type of fuel injection	Pump/injector unit - direct injection
Cooling system	Water cooled
Swept volume	1028 cm^3
Cylinder bore	75.00 mm
Stroke	77.60 mm
Compression rate	22.8:1

Table 3. Uncertainty analysis of experimental results

Test parameter	Range of measurement	Resolution	Uncertainty (%)
Fuel consumption	0 – 6000 g	1 g	± 0.1%
Speed	0 – 9999 rpm	1 rpm	± 0.2%
Temperature	0 – 1000 ˚C	1 ˚C	± 0.1%
BTE	-	-	± 1.56%
BSFC	-	-	± 0.65%
NO	0 – 5000 ppm	1 ppm	± 1.1%
CO	0 – 10 %	0.001 %	± 0.8%
Smoke	0 – 100 %	0.1 %	± 1.25%

3. Results and Discussion

3.1. Brake specific fuel consumption (BSFC)

To evaluate the engine economy of BSFC is very important parameter [11]. BSFC refers to normalized fuel consumption amounts according to engine power. The main factors affecting BSFC include the fuel's lower calorific value, fuel fraction by mass. viscosity and density. In literature, biodiesel, has higher BSFC than diesel fuel due to higher viscosity and lower calorific values. Using of nanoparticle have a positive effect on BSFC reduction of ICE [11].

Figure 4 presents the BSFC graph of the test fuels. It is seen that there is an increase in BSFC value with decreasing engine load for all tested fuels. This may be due to more heat transfer in the combustion chamber at low engine load [15]. The increase in combustion temperature, which provides higher efficiency in converting heat energy into mechanical work, causes the BSFC to decrease due to the increase in engine load [16].

While BSFC in diesel fuel was 372.05 g/kWh, BSFC in R0 fuel increased by 14.01%. The maximum change in the test fuels with TiO_2 additive was obtained at 10 Nm engine load. Compared to R0 fuel, this decrease in RTi50 and RTi75 fuels was 7.51% and 8.62%, respectively. At 40 Nm engine load, BSFC increased by 17.5%, 14.08% and 9.83% in R0, RTi50 and RTi75 fuels, respectively. Biodiesel, which has higher viscosity and density than diesel fuel, has worse combustion characteristics. However, the TiO_2 additive added to both fuels improves the viscosity and density of the fuel. The lower viscosity forms higher micro explosion [4]. TiO_2 functions as an oxygen enhancer, providing better oxidation and better complete combustion [16]. High surface-volume ratio can release high combustion enthalpy and energy density [17]. This largely oxidizes the fuel to transfer fuel energy to the working fluid as thermal energy [18].

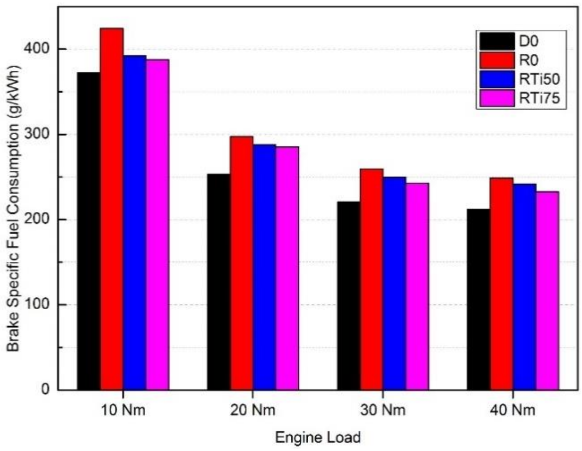

Fig. 4. BSFC graph with load for fuel blends

3.2. Brake thermal efficiency (BTE)

Lower viscosity and density make it easier for the fuel to evaporate in the cylinder [11]. This positively affects the mixing of fuel droplets with the air. Lower viscosity forms smaller fuel droplets and resulting lower surface tension. Good atomization increases the BTE of a engine, providing a complete combustion [19].

Figure 5 shows the BTE graph. BTE values increase as engine load increases and reach the maximum value under higher engine load conditions. While BTE is 23% for D0 fuel at 10 Nm load, it is seen to be 41% at 40 Nm engine load. As the TiO_2 doping ratio increases, the increase in BTE becomes more prominent. The increase in RTi50 and RTi75 fuels compared to R0 fuel was 2.47% and 6.21%, respectively. The increase in BTE is due to better fuel properties, which facilitates the increase of in-cylinder temperature during combustion and reduces ignition delay [20].

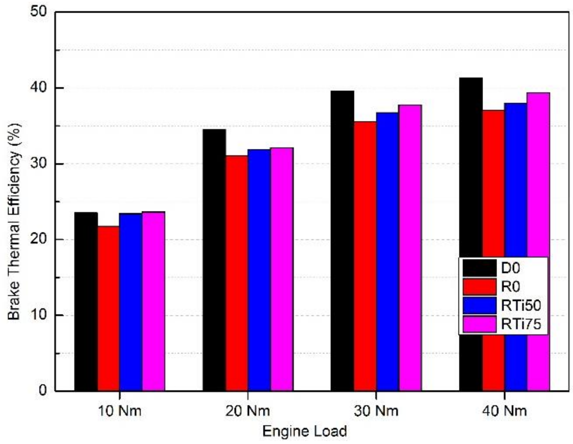

Fig. 5. BTE graph with load for fuel blends

By adding NPs additives to the test fuels, the viscosity of the fuels decreases and the lower heating value increases. The improvement in these properties of the fuels has led to better combustion and BTE, exhibiting improved spraying and atomization properties. Additionally, lower viscosity fuel reduces friction between fuel molecules, resulting in a homogeneous mixture. This reduces the size of the fuel and improves combustion [18]. The use of TiO_2 additive in fuel combustion processes increases combustion efficiency. It leads to increased BTE compared to D0 and B0 fuels that do not contain nanoparticles. This increase promotes rapid and complete combustion, as the nanoparticles exhibit better radiation and heat mass transfer properties through the development of a high surface to volume ratio, which greatly increases the combustion efficiency. This provides higher BTE in diesel engines [11,15].

3.3. CO emissions

Carbon monoxide (CO) emissions indicate insufficient combustion of fuel. The key factors for the generation of CO emissions are a heterogeneous mixture, insufficient O_2 availability and less residence time for combustion [6,21].

Figure 6 shows the CO emissions graph of the test fuels. At 40 Nm load, there was a 9.02% decrease in CO emissions in B0 fuel compared to D0 fuel. The oxygen contained in biodiesel positively affects combustion, causing CO emissions to decrease. The amount of TiO_2 additive added into biodiesel reduced CO emissions. At 40 Nm load, there was an 24.03% in RTi75 fuel compared to R0 fuel. The reduction in viscosity of fuels with added additives causes lower evaporation temperature, helping it to mix and evaporate quickly with oxygen, ultimately resulting in lower CO emissions [18, 22].

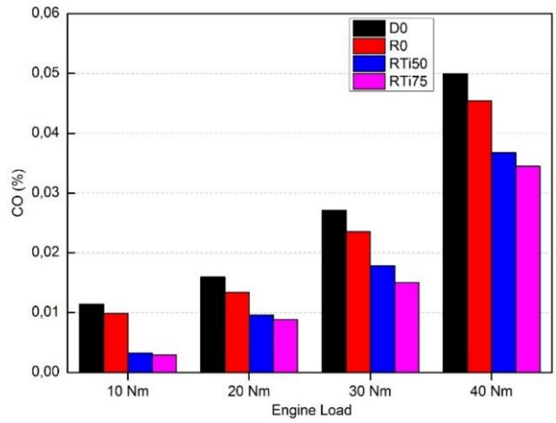

Fig. 6. CO emission graph with load for fuel blends

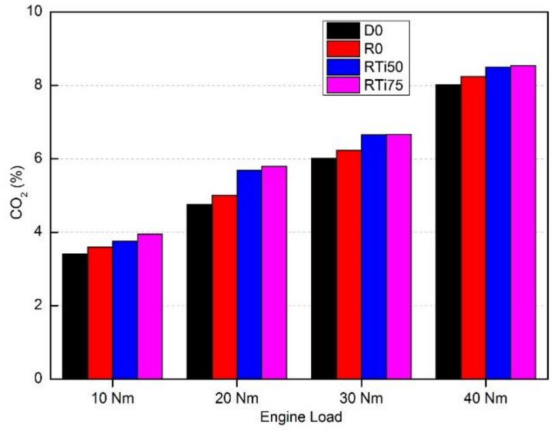

Fig. 7. CO_2 emission graph with load for fuel blends

3.4. CO_2 emissions

Figure 7 shows the CO_2 emissions graph. With the increase in load, CO_2 emissions also increase. At 40 Nm load, there was a 2.78% increase in CO_2 emissions in R0 fuel compared to D0 fuel. In the test fuels to which TiO_2 is added, as the amount of additive increases, CO_2 emissions also increase due to the effect of complete combustion. Compared to D0 fuel, the increase in CO_2 emissions RTi75 fuels was 6.52%, respectively. This is because the added nanoparticle increases the presence of oxygen in the fuel, resulting in sufficient oxygen for combustion and more CO_2 emissions. In addition, the use of nanoparticles results in a higher surface area to volume ratio, higher oxygen value and therefore increased CO oxidation, leading to a higher temperature in the combustion chamber as well as a better combustion efficiency [16].

3.5. NO_x emissions

Nitric oxide (NO) is a major environmental problem due to their negative effects on air quality and human health. The biodiesel has higher NO_x emissions compared to diesel [22]. Figure 8 shows the nitrogen oxide emissions of the test fuels. NO_x emissions increase as engine load increases and there is a direct relationship with engine load. NO_x emissions of fuels with TiO_2 additives increase. While this increase is greater at low loads, the increasing trend decreases at high loads. The increase in NO_x emissions of R0 fuel compared to D0 fuel was 15.96% at 10 Nm load and 8.79% at 40 Nm load. It has been shown that the combustion of biodiesel has an earlier ignition time and, as a result, a longer residence time at high temperatures [11]. At 40 Nm load, the increase in NOx emissions was 25.13% and 26.15%, in RTi50 and RTi75 fuels with TiO_2 added compared to D0 fuel. Mixing nanoparticles with diesel increases the flame temperature, causes more N_2 to oxidize to NOx [23].

3.6. Smoke emissions

Smoke emissions of biodiesel and fuels mixtures were measured at different engine loads. Figure 9 shows the smoke emissions graph of biodiesel, diesel and mixtures of fuels with added additives. Smoke emissions tend to increase with increasing engine load of the tested fuels. At 40 Nm load, smoke emission was 1.31 min^{-1} in D0 fuel, while it was 1.23 min^{-1} in B0 fuel, with a decrease of 6.18%. This is due to the oxygen content of biodiesel.

In test fuels with TiO_2 added, the maximum reduction in smoke emissions occurred at low loads. At low loads, where the burning rate is slower, the nanoparticle additive plays a faster and complementary role in burning thanks to its micro explosion. This explains the rate of smoke emission reduction at low loads. At the same time, the additive increases the amount of oxygen in the fuel, resulting in rich atomization, resulting in homogeneous combustion and lower smoke emissions. However, the low density of the test fuels, thanks to the additive, led to a decrease in the heat of vaporization and rapid evaporation, resulting in a decrease in smoke emissions [18].

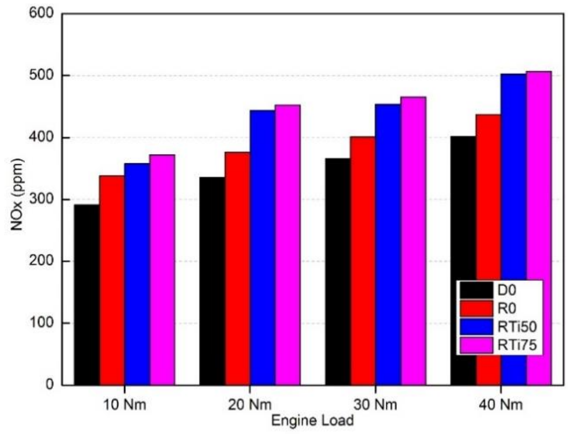

Fig. 8. NO_x emission graph with load for fuel blends

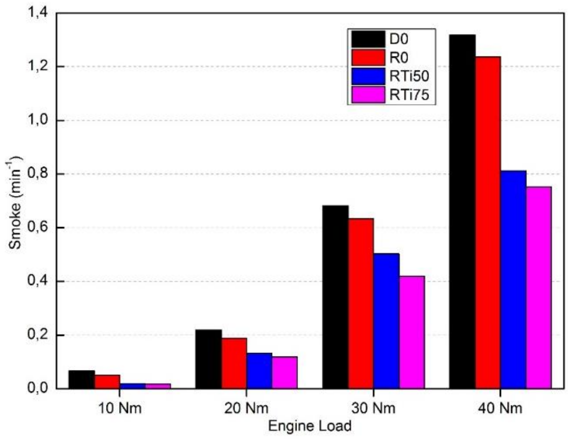

Fig. 9. Smoke emission graph with load for fuel blends

4. Conclusion

In this study, the effects of TiO_2 nanoparticle additives added to biodiesel were investigated on diesel engine's performance and emissions. The findings show that the tested fuels have significant effects on engine performance parameters and emissions:

- It has been observed that biodiesel fuel has higher BSFC values compared to diesel fuel. This is due to the higher viscosity and lower calorific value of biodiesel. However, a decrease in the BSFC values of fuels with TiO_2 additive added was observed. RTi75 fuel showed an increase of 8.62% compared to R0 fuel. This decrease is related to the fact that the nanoparticle additive reduces the viscosity of the fuel and increases the combustion efficiency.
- An increase in BTE values of fuels to which TiO_2 additives were added was observed. An increase of 6.21% was observed in RTi75 fuel compared to R0 fuel. This increase can be explained by the fact that nanoparticles provide better atomization and oxidation, thus increasing combustion efficiency.
- A decrease in CO emissions has been observed in fuels to which additives have been added. B0 fuel showed a decrease of 9.02% compared to D0 fuel. RTi75 fuel with TiO_2 added reduced CO emissions by 24.03% compared to R0 fuel. This is due to the improving effect of the oxygen and nanoparticles contained in biodiesel on the combustion process.
- CO_2 emissions increased as engine load increased. As the amount of additive increased in the test fuels with TiO_2 added, CO_2 emissions also increased. An increase of 6.52% was observed in RTi75 fuel compared to D0 fuel. This increase is due to the increase in CO_2 emissions resulting from complete combustion.
- Compared to D0 fuel, a 26.15% increase was observed in RTi75 fuel with TiO_2 added. This increase is due to the higher combustion temperatures of biodiesel and the flame temperature-increasing effect of nanoparticles.
- A decrease in smoke emissions has been observed in fuels containing biodiesel and additives. There was a 6.18% decrease in R0 fuel compared to D0 fuel. A more significant decrease in smoke emissions was observed at low engine loads in fuels with TiO_2 added. This decrease is due to the improving effect of nanoparticles on the combustion process and the low viscosity of the fuel.

In conclusion, blends of biodiesel and TiO_2 nanoparticles have the potential to provide performance improvements and emission reductions in diesel engines. This study shows that the use of diesel, biodiesel and nanoparticle additive fuels can reduce environmental impacts while increasing engine performance. In the future, investigating the effects of different nanoparticle types and concentrations on fuel performance and emissions may contribute to obtaining more comprehensive results.

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