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Reducing Soot Nanoparticles and NO_X Emissions in CRDI Diesel Engine by Incorporating TiO_2 Nano-Additives into Biodiesel Blends and Using High Rate of EGR

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Abstract: The developments in the field of nano-additives have increased in the recent years due to the desire to reduce the level of exhaust emissions in diesel engines. The soot characteristics of particulate matter (PM) and nitrogen oxides (NO_X) were experimentally investigated using two concentrations of titanium dioxide (TiO_2) as nano-additives (25 ppm and 40 ppm) blended with C20D (composed of 20% castor oil methyl ester and 80% diesel fuel) and 30% exhaust gas recirculation (EGR). The combustion of C20D + TiO_2 increases brake thermal efficiency (BTE) by 2.8% in comparison with neat C20D, while a significant reduction was obtained in BSFC 6.5% and NO_X emissions were maintained at a level parallel with diesel. The results indicated that the technique involving a high EGR rate and the addition of 25 ppm and 40 ppm of TiO_2 nanoparticles to the C20D exhibits better reductions in NO_X emissions by 17.34% and 21.83%, respectively, compared to the technique comprising the use of C20D + TiO_2 and C20D. The reduction in the total concentration of PM via the addition of TiO_2 nanoparticles to the C20D was 26.74% greater than neat C20D and diesel. In contrast, the incorporation of a high rate of EGR with C20D +TiO_2 increased the PM concentrations by 16.85% compared to the technique without EGR. Furthermore, the high concentrations of TiO_2 nanoparticles (40 ppm) in the C20D produced 19 nm smaller soot nanoparticles compared to the 23 nm larger soot nanoparticles produced from the low concentrations of TiO_2 nanoparticles (25 ppm) added into the C20D. The current investigation reveals that the reduction in NO_X emissions and the production of soot nanoparticles notably improved due to the synergic effect of EGR, the TiO_2 nanoparticles, and biodiesel.

Keywords: castor oil; soot nanoparticles; NO_X emissions; TiO_2 nano-additives; EGR

1. Introduction

Diesel engines are employed as large-scale power sources for various applications, such as marine vessels, motor vehicles, and power plants [1]. Due to changes in the lifestyles of middle-class people and the increase in uneven population growth, rapid energy consumption has increased, which is causing the looming energy crisis. Energy sources are producing high levels of pollutants that effect environmental and human health. The emissions emitted from diesel engines such as nitrogen oxides (NO_X) and particulate matter (PM) constitute the main reason for environmental pollution. Furthermore, the soot nanoparticles of PM have the ability to penetrate cell membranes and accumulate in the lungs, liver, and brain via the blood stream [2,3]. To reduce dependence on fossil fuel resources, protect the environment, and meet the increased energy demand, the scientific community has focused on the use of alternative fuels in internal combustion engines. Therefore, the search for clean fuels and good alternatives to crude oil is imperative for diesel engines. Regarding suitable alternative energy sources, biodiesel is considered a remarkable solution for the rapid depletion of fossil fuel reserves and decreases high levels of diesel exhaust emissions [4,5]. Singh et al. [6] studied the effect of transesterified waste animal fat on the emissions characteristics and engine performance in the CI diesel engine. They observed that the combustion of biodiesel produces less CO and higher NO_X emissions in comparison with mineral diesel. Due to the lower sulphur and aromatic content and higher oxygen content of biodiesel, it has gained rapid momentum recently with respect to its use in compression ignition engines as pure fuel or mixed with diesel fuel. In this context, it is stated that the high oxygen content in biodiesel enhances the reduction in PM and gaseous emissions [7]. According to the studies by Balat et al. [8] and Fayad et al. [9], biodiesel can be produced from more than 350 oil-bearing crops, including soybeans, castor beans, sunflowers, rapeseed, peanuts, and cottonseed, each constituting potential alternatives for fossil fuel. Kumar et al. [10] investigated the effect of waste plastic oil (WPO) blends and variable injection timing on engine performance and emissions in a CRDI diesel engine. They found that the optimal BTE is 6.7% at a 17°bTDC injection interval, and that the emissions of NO_X and CO decreased by 2.15% and 16%, respectively, via the combustion of WPO compared to diesel. Calophyllum Inophyllum Methyl Ester biodiesel slightly decreases thermal efficiency in comparison with diesel [11]. In addition, they found that the hydrocarbon (HC), NO_X, and CO emissions decreased due to the burning of biodiesel blends. Hwang et al. [12] studied the effects of waste cooking oil biodiesel and injection strategies on the emissions and combustion characteristics in a CRDI diesel engine. They found that the fuel consumption increased with biodiesel compared to diesel fuel for all conditions of experiments. In addition, the emissions of HC, CO, and smoke had decreased via biodiesel combustion, while the emissions of NO_X had increased for a different injection strategy. Another work studied the effect of Jatropha and Palm biodiesel blends on the performance of a diesel engine [13]. Due to the higher level of NO_X emissions emitted from diesel engines, several mitigation techniques have been suggested by researchers, such as using hybrid fuels and adding fuel additives that can offer lower exhaust emissions and greater engine performance [14]. The capabilities of nanoparticles have been the subject of attention for recent research developments focused on improving emissions characteristics and engine performance [15,16]. In one study, the effect of the addition of titanium dioxide and zinc oxide nanoparticles to biodiesel was investigated in a diesel engine [17]. They observed that the engine performance improved and exhaust emissions decreased through the addition of titanium dioxide (TiO_2) and zinc oxide nanoparticles to biodiesel in a modern diesel engine. Prabhu et al. [18] found that Jatropha biodiesel blended with nano-additives of cerium oxide (CeO_2) and alumina (Al_2O_3) increases brake thermal efficiency (BTE) and slightly reduces HC, NO_X, CO, and smoke emissions in comparison with regular diesel. The effects of adding nanoparticles of CeO_2 to biodiesel on emission characteristics were studied by Sajith et al. [19]. The addition of the CeO_2 nanoparticles increase the viscosity and flash point of biodiesel compared to the neat biodiesel. They found that adding nanoparticles into biodiesel decreased the HC and NO_X emissions when compared with biodiesel without nano-additives. It was stated that blends of WCO and CeO_2 nanoparticles enhanced the BTE by 36.62% and reduced the hazardous emissions of CO, NO_X, and CO_2 by 0.0192%, 168 ppm, and 1.132%, respectively [20].

Exhaust gas recirculation (EGR) is an effective method for controlling the NO_X emissions of diesel engines. In another study, the emission characteristics brought about by the EGR technique were studied in a diesel engine [21,22]. The NO_X emissions decreased while other emissions of CO and HC increased with the application of the EGR technique in the diesel engine. Ozer Can et al. [23] examined the effect of different rates of EGR (5, 10, and 15%) on combustion and emissions in an experiment conducted using a diesel engine. They concluded that the combined effects of the EGR technique and biodiesel result in maximum in-cylinder pressure and heat release rate with reasonable reduction in emissions. One study reported the influence of an n-octanol-diesel blend and EGR on the performance, combustion, and emission characteristics of a diesel engine [24]. The authors observed that a high EGR rate leads to a significant increase in CO and HC emissions. The effects of EGR rates (10% and 20%) and ternary blends of diesel–palm oil–ethanol on combustion, performance, and emissions characteristics in a CRDI diesel engine were investigated by Qi et al. [25] under a double injection strategy. They found that the BTE was slightly reduced and the BSFC increased in comparison with diesel fuel when applying EGR. For all test fuels, the levels of NO_X emissions were almost identical, which were decreased with a high rate of EGR. They concluded that the ternary blends and 20% application of EGR could be used to decrease the soot and NO_X emissions simultaneously via a double injection strategy in a CRDI diesel engine. The effect of palm biodiesel and EGR on emissions and fuel consumption was studied by Yasin et al. [26] using a diesel engine. The results showed that the NO_X emissions significantly decreased, while there was an increase in the emissions of CO_2, HC, and CO as well as fuel economy when using EGR. The occurrence of EGR together with the use of biodiesel blends slightly decreases NO_X emissions because of biodiesel's lower flame temperature, as mentioned in study of Magno et al. [27]. The combined effects of EGR and nano emulsion on the performance, combustion, and emission characteristics of a CRDI diesel engine were studied in [28]. The emissions of smoke and NO_X decreased by 11.2% and 30.72%, respectively, through the interaction between the EGR and nano blend. In addition, they observed significant reductions of 33.31% and 18.18% for CO and HC emissions, respectively. It has been reported that a drastic reduction by 52.4% in NO_X emissions was achieved with 30% EGR [29]. On the other hand, the application of a 10% EGR rate leads to a reduction in smoke density by 46% at 21°bTDC injection timing. The manipulation of injection timing and EGR rates produced the lowest emissions and high performance. The effect of 5, 10, and 15% EGR on engine emissions at different loads and 2200 rpm in a four-stroke diesel engine fuelled by B20 soybean biodiesel was studied [23]. The authors found that the BSFC and BTE increased by 6% and 3%, respectively, with a 15% EGR rate, while smoke and NO_X emissions were improved by 15% and 55% during high load. Moreover, at low and medium loads, HC emissions decreased via the inclusion of EGR and soybean biodiesel blends. A previous study [9] stated that the drastic reduction in other emissions with high BTE occurred when the nanoparticles of CeO_2 were incorporated into ethanol blends and diesel–castor biodiesel. Further, the authors found a significant increase in the cylinder pressure and BSFC by adding CeO_2 nanoparticles to the fuel. The work by Hasannuddin et al. [30] assessed the effect of adding nano-additives to renewable fuel on the performance characteristics of a CI engine. The authors incorporated copper oxide, magnesium oxide, zinc oxide nano-additives, and aluminium oxide into a 10% water diesel emulsion. They found that the best additive is Al_2O_3, which results in a significant decrease in the emissions and BSFC compared to the other nano-additives used. The good surface energy afforded via the addition of 100 and 200 ppm concentrations of TiO_2 nanoparticles to biodiesel promoted the combustion process and decreased the NO_X emissions [31]. They justified that this was due to the high catalytic activity of nanoparticles. In addition, the evaporation rate improved with the addition of TiO_2 nanoparticles, which resulted in lower levels of smoke emissions. The effects of nanoparticle additives, diesel-biodiesel blends, and EGR on emissions and engine performance in a DI diesel engine were investigated by Venu and et al. [32]. A significant drop in NO_X emissions was found via the combustion of nano-additives + 30% palm biodiesel + 70% diesel fuel + EGR. It was observed that the engine performance, level of soot particulates, and NO_X emissions were optimized when using diesel fuel incorporating nano-additives. A diesel engine's emissions of NO_X can be decreased by applying the EGR technique. Only a few investigations in the literature focused on the interaction between a high rate of EGR and nano-additives when incorporated into renewable fuels to control engine emissions. Therefore, the current study is focused on studying the effects of incorporating a high rate of EGR and the addition of TiO_2 nano-additives into the C20D blend and how they affect NO_X emissions and soot nanoparticle characteristics in a CRDI diesel engine. In addition, the effect of different concentrations (25 ppm and 40 ppm) of TiO_2 on engine emissions is highlighted in this study.

2. Materials and Methods

2.1. Preparation of Fuel Blend with TiO_2 Nanoparticles

A local manufacturer provided the castor oil (CO100) as an oxygenated fuel. The 20% castor oil was mixed with 80% diesel fuel to produce the fuel blend (C20D). The properties of neat castor oil, C20D, and diesel fuel are presented in Table 1. The progress in nanotechnology still continues to enrich the literature and fill the gaps in the field of nanoparticles. Further analysis of nanofluids is needed to study the properties of nanoparticles (thermophysical and thermal stability). The study of the addition of nanoparticles to fuel is necessary in the global research framework. For one hour, an ultrasonic mixer was used to mix the blend of TiO_2 nanoparticles into the castor oil to prepare the nano blend (C20D + TiO_2). This process was repeated to ensure no deposition and accumulation would occur in the nano blend. The method of chemical precipitation was used to prepare the TiO_2 in this investigation. Previous study [33] mentioned that the agglomeration of nanoparticles can take place in the base fluid due to the poor dispersion during the fuel mixture. Before starting the test, the nano blend was shaken and stirred for two hours to avoid settling of nanoparticles that can occur in the tube or solution. It is stated in the literature that the addition of surfactants can prevent nanoparticles' agglomeration and accumulation in the nano blend [34]. In another work, it is suggested that the nanoparticles' combustion characteristics can be affected when adding surfactants to the nano blend. Two concentrations of TiO_2 (25 ppm and 40 ppm) were blended with biodiesel in this study. Scanning electron microscopy (SEM) was used to obtain the image of TiO_2 presented in Figure 1. The main specifications of nanoparticles (TiO_2) are listed in Table 2.

Table 1. Specifications of diesel fuel, CO100, and C20D.

Properties	**Diesel**	**CO**	**C20D**
Derived cetane number	51.8	48.4	50.3
Kinematic viscosity at 40 °C (cSt)	2.67	3.224	3.465
Density at 15 °C (kg/m^3)	842.3	881.6	858.4
Latent heat of vaporization (kJ/kg)	241	221	232
Thermal conductivity (W/m K)	0.123	0.123	0.133
Calorific value (MJ/kg)	44.70	39.46	45.74
Flash point (°C)	57	71	66
Total aromatics (wt%)	25.2	0	14.63
Lubricity at 60 °C (μm)	311	206.5	311.5

Table 2. Nanoparticles (TiO_2) properties.

Detail	**Properties**
Name (TiO_2)	Nanoparticles of Titanium dioxide
Appearance	White
Purity of TiO_2	96%
Particle size	30–50 nm
Surface area	>42 m^2/g
Melting point	>233 °C
Formula	$C_{19}H_{42}NBr$

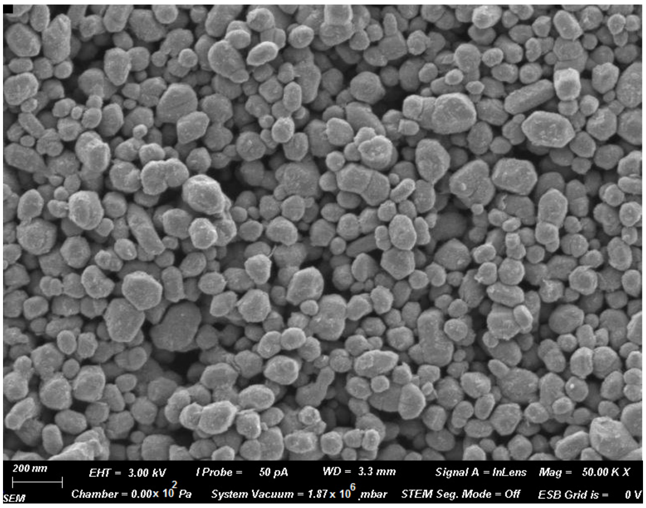

Figure 1. Image (obtained through SEM) of the nanoparticles (TiO_2).

2.2. Engine and Equipment

In this study, a 4-cylinder, 4-stroke DI diesel engine was used during experiments. The engine's test specifications are listed in Table 3. The experimental setup and tools used in all tests are shown in the schematic diagram in Figure 2. To keep oil and water temperature constant at 85 °C, the conditioning systems of oil and water were connected to the test setup. Thermocouples (k-type) located in different positions of engine were used to record and measure all the temperatures needed for the tests. An exhaust gas analyser and scanning mobility particle sizer (SMPS) were used to measure NO_X emissions and the concentration of soot nanoparticles, respectively. The volumetric flow measurement system was used to measure fuel consumption. In all tests, the soot nanoparticles were collected from the exhaust pipe on 3.05 mm diameter copper grids attached to a sampling probe. In addition, nitrogen was utilized to clean the lines and samples in order to remove deposited soot particles tools before each test. To analyse the soot nanoparticles' characteristics, transmission electron microscopy (TEM) was used. Furthermore, the morphological parameters of soot nanoparticles (number, size, and diameter of primary particles) were obtained from analysis of the TEM images for all fuels and conditions using MATLAB software (9.3).

Table 3. CRDI diesel engine specifications.

Engine Parameters	Specifications
Type	Common-rail DI Diesel
Number of cylinders and strokes	4 × 4
Cylinder bore × stroke (mm)	104 × 118
Connecting rod length (mm)	160
Compression ratio	17.9:1
Displacement (cc)	3.6 L
Maximum engine speed range (rpm)	3000
Dynamometer	Electrical AC
Fuel pressure range (bar)	500–1000

For each test point, three measurements were repeated and the average has been considered. The total uncertainties were calculated for the results concerning engine performance and emissions characteristics. The characteristics of total uncertainties and accuracies were calculated for the values measured during the study, as shown in Table 4.

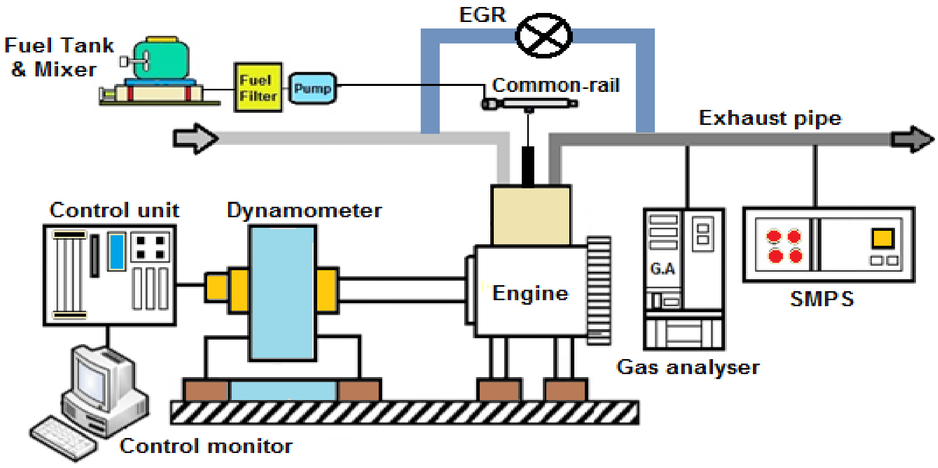

Figure 2. Schematic illustration of the engine setup.

Table 4. Total uncertainties and errors in parameters, exhaust gas analyser, and experimental instruments.

Parameter	Errors (±)
Engine speed	0.1%
Engine load	0.2%
Temperature	0.1%
Time	0.1%
Thermocouples	1.1%
Measurement of fuel	2.0%
BTE	1.7%
BSFC	1.5%
Emissions of NO_X	0.2%
Emissions of PM	0.1%

3. Results and Discussion

3.1. Brake-Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE)

The variation in the BSFC with engine loads from the effect of a high rate of EGR and the addition of TiO_2 to the castor oil blends is shown in Figure 3. The general results from this figure show that the fuel consumption decreased with high engine loads when compared with medium and low loads. For the neat fuels, it is clear that the BSFC increased during C20D combustion in comparison with diesel fuel, and it has also been reported in many previous papers [35,36] that a lower calorific value of castor oil increases fuel consumption. From Figure 3, it is evident that the BSFC decreased by 8.2% and 4.7% with the addition of 25 ppm and 40 ppm concentrations of TiO_2, respectively, to the castor oil blend compared with the neat fuel blend (C20D) and diesel fuel under various engine loads. This is could be due to a reduction in the ignition delay period via the addition of nano-additives [37]. The twofold effect of the high catalytic activity and high surface-to-volume ratio of TiO_2 leads to improved fuel efficiency [38]. Moreover, the consumption of fuel decreased with the addition of TiO_2 to the fuels because of the large diameter of droplets as a result of an increase in the viscosity of the nano blend and improved fuel dispersion inside cylinder [38]. On the other hand, the occurrence of a high rate of EGR with nano blend leads to an increase in the BSFC compared with other fuels (Figure 3). Comparing the two concentrations of nano-additives, the addition of 40 ppm of TiO_2 to the castor oil significantly decreases the BSFC in comparison with 25 ppm of TiO_2 with a high rate of EGR. Interestingly, the addition of a high concentration of TiO_2 to the castor oil with a high rate of EGR maintained a BSFC parallel to that of the nano blend. This can be explained by the lower oxygen content of the intake air which enhances the BSFC [39]. The addition of a high concentration of TiO_2 to the castor oil decreases the negative EGR effect in comparison with a low concentration of TiO_2.

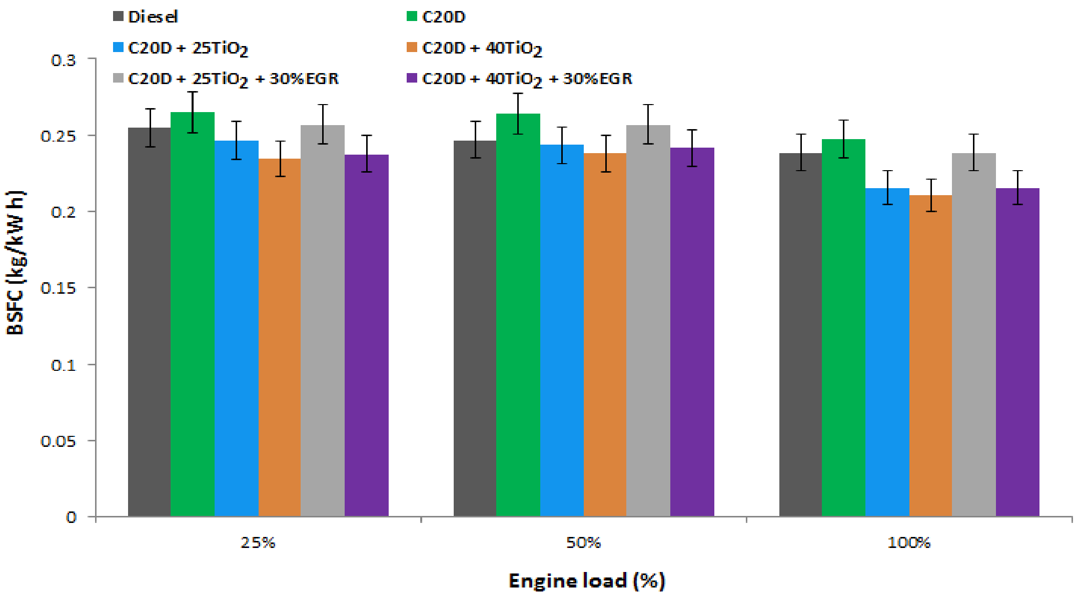

Figure 3. Effect of high EGR rate and two concentrations of TiO_2 nanoparticles on BSFC.

The variation in the BTE with the engine load due to the effect of a high rate of EGR and the addition of TiO_2 concentrations into the castor oil blends is shown in Figure 4. It can be said that the BTE increased with a high load compared with medium and low engine loads for all the fuels studied. It is well known that biodiesel produces a higher BTE compared to diesel fuel due to the oxygen bonds in biodiesel that enhance thermal efficiency [40,41]. Figure 4 illustrates that the BTE increased by 2.8% when adding TiO_2 nanoparticles to the castor oil compared to the neat fuels (without nano-additives). It is suggested that the interaction between the oxygen content and nanoparticles can increase the surface area of the nano blend due to the enhanced fuel properties of the nano blend. It has been stated that the BTE increases due to the high surface area of nanoparticles and the storage of energy in the nanoparticles [42]. The current results are in agreement with Fayad et al. [43] and Patel et al. [44]. It has been reported that the addition of 50 mg per litre (mg/L) of nanoparticles of graphene to ternary fuel biodiesel blends enhances the BTE by 2.03% and reduces the emissions of NO_X, CO, and smoke compared to a neat biodiesel blend [45]. The combined incorporation of a high rate of EGR and a high concentration of TiO_2 into castor oil results in an enhancement of the BTE by 3.2% in comparison with a low concentration of TiO_2, as shown in Figure 4. This could be due to the oxygen content in the nano blend that compensates the reduction in the oxygen concentration inside the combustion chamber via the EGR effect, which enhances the BTE in comparison to fuels that do not incorporate nano-additives or contain low concentrations of nanoparticles. In contrast, a low concentration of TiO_2 in castor oil with EGR produces a lower BTE in comparison with C20D40TiO_2, C20D, and C25D40TiO_2 + EGR with respect to several engine loads.

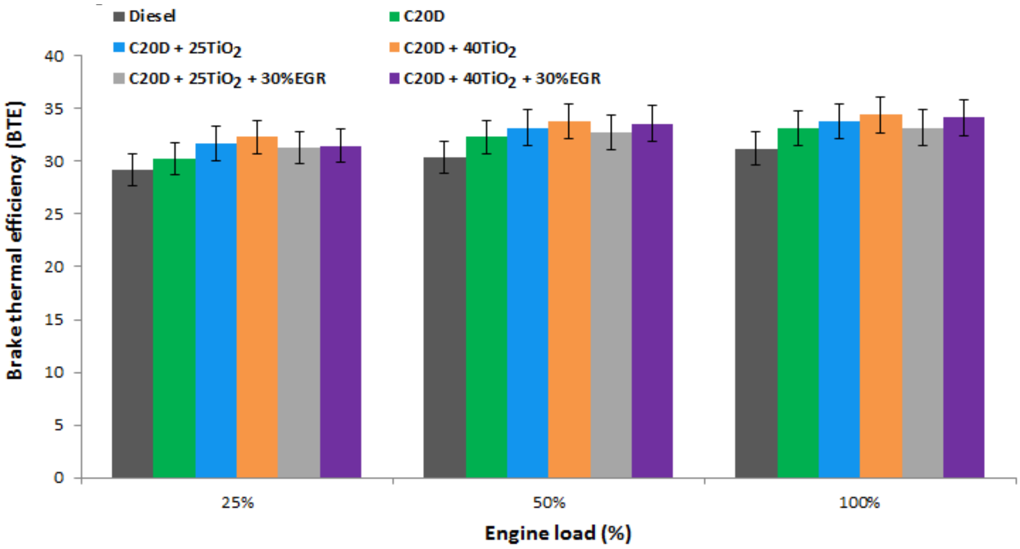

Figure 4. Effect of high EGR rate and two concentrations of TiO_2 nanoparticles on BTE.

3.2. NO_X Emissions

The NO_X emissions levels versus engine loads obtained via EGR and the addition of TiO_2 concentrations into the castor oil blends are shown in Figure 5. The general trend of all fuels indicates that the NO_X emissions increased with a high engine load compared with medium and lower engine loads due to an increase in the combustion temperature inside the combustion chamber. The NO_X emissions are a slightly higher with the combustion of the castor oil blend compared to the other tested fuels during low load (Figure 5). In contrast, a remarkable reduction in NO_X of 13.42% was achieved when adding TiO_2 nanoparticles compared with the absence of nanoparticles in the fuel. This is due to the lower level of active radicals, which results in an increased potential for the inhibition of NO_X formation. Venu et al. [46] revealed that the addition of nano-additives leads to a decrease in the rate NO_X emissions generation. The high rate of EGR and high concentration of TiO_2 in the nano blend offer better reductions—by 17.34% and 21.83%—of NO_X emissions compared with C20D + TiO_2 and C20D. It has been stated that a lower concentration of oxygen and flame temperature inside the combustion chamber [39] due to a high rate of EGR result in a decrease in the formation of NO_X [43].

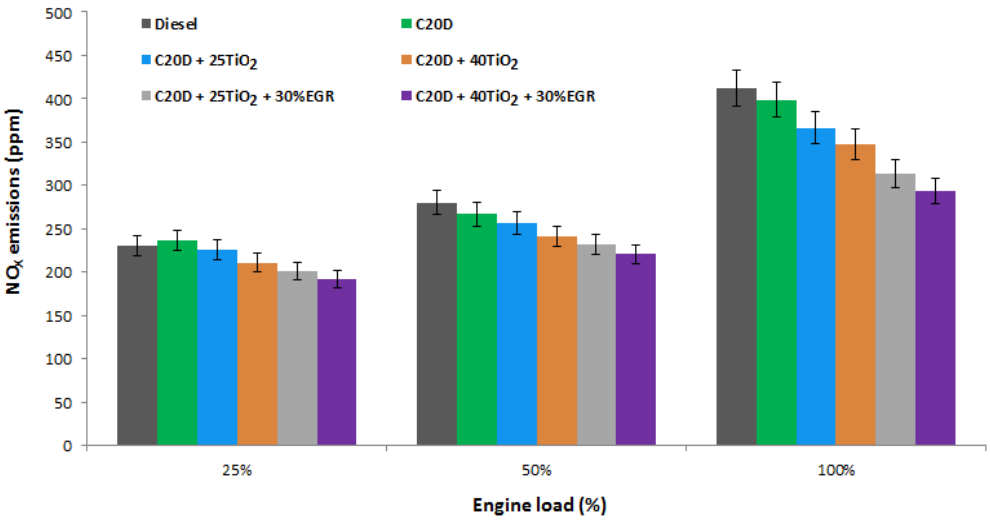

Figure 5. Effect of high EGR rate and two concentrations of TiO_2 nanoparticles on NO_X emissions.

3.3. Soot Nanoparticle Emissions

The variations in the soot nanoparticle concentration with engine load due to the effects of a high rate of EGR and the addition of TiO_2 concentrations into the castor oil blends are shown in Figure 6. For neat fuels, the concentration of soot nanoparticles decreased during C20D combustion compared to diesel fuel due to the high rate of oxidation and the oxygen bonds in the C20D fuel which enhance the inhibition of soot formation. This same trend of oxygenated fuels has already been reported in previous works [47,48]. It was found that the addition of TiO_2 nanoparticles to the C20D fuel decreases its total soot emissions concentration by 26.74% compared to those emitted from neat C20D and diesel fuels. Figure 6 shows that the soot emissions decreased by 32.68% and 24.74% when 25 ppm and 40 ppm of TiO_2 nanoparticles were added to the castor oil, respectively, in comparison with the neat castor oil. This could be due to the lower sulphur content and number of aromatic compounds in the castor oil fuel, as well as the oxygen and high surface area of the nanoparticles, which enhance soot oxidation and decrease soot formation inside the combustion chamber [49]. According to the TEM image, it is evident that the concentration of soot particles is lower for the nano blend (C20D40TiO_2) compared to the soot emissions from C20D and diesel, as depicted in Figure 7. The soot emissions inside the cylinder are inhibited due to the high activation energy of the TiO_2 nanoparticles [50,51]. Furthermore, the high potential for direct reactions between the soot emissions and metal oxide could be the main reason behind the decrease in the soot particles engendered by the addition of nano-additives [52]. The presence of a high EGR rate tends to increase soot emissions when combined with nano blends (Figure 6). In contrast, the addition of the 40 ppm concentration of TiO_2 nanoparticles into the nano blend with 30% EGR improves the reduction in soot emissions by 16.64% in comparison with the 25 ppm concentration of TiO_2, as presented in Figure 6.

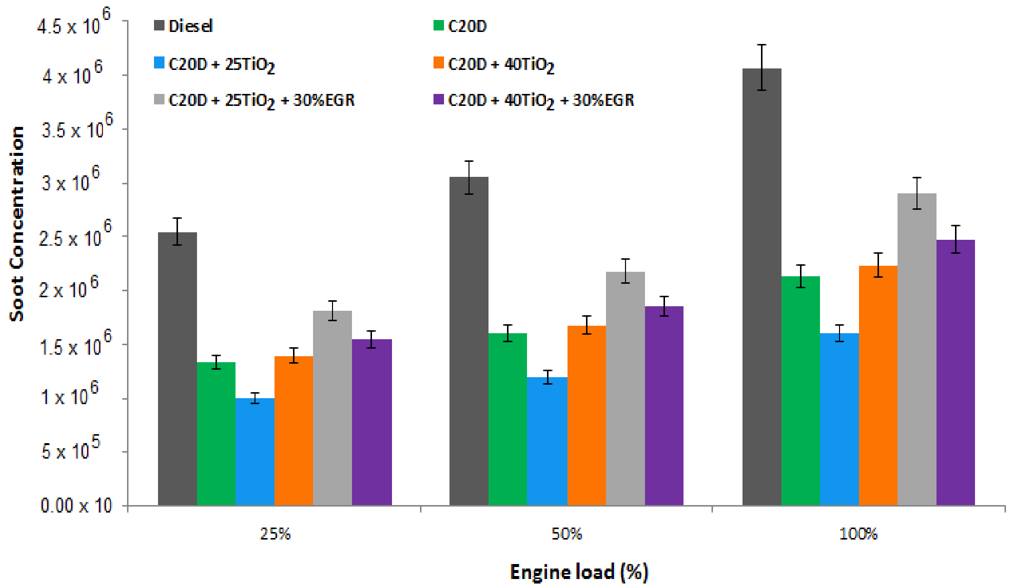

Figure 6. Effect of high EGR rate and two concentrations of TiO_2 nanoparticles on PM concentrations.

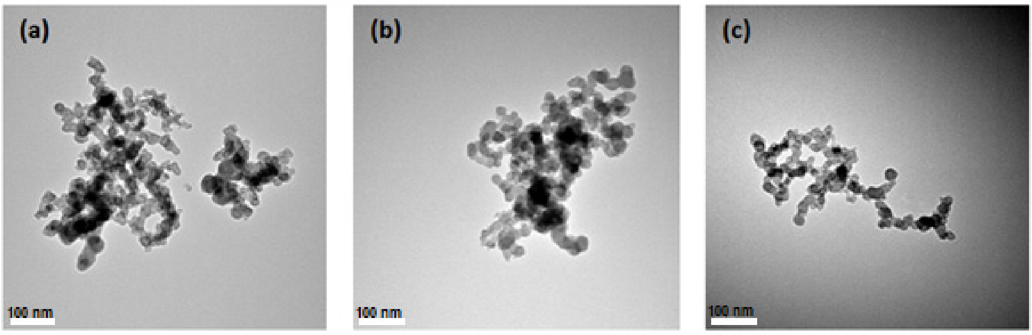

Figure 7. Samples of TEM images for (**a**) diesel, (**b**) C20D, and (**c**) C20DTiO_2.

Figure 8 shows the effects of two concentrations of nano-additives and a high EGR rate on the number of soot particles (n_{po}) for different loads. The results indicate that the number of soot particles is reduced by 19 nm and 23 nm when adding 40 ppm and 25 ppm, respectively, of the TiO_2 nanoparticles to the C20D in comparison with the number of soot particles produced from the neat biodiesel and diesel fuel. Moreover, adding 40 ppm of TiO_2 to the C20D contributes to a great reduction in the total number of soot particles compared to the addition of 25 ppm of TiO_2 to the C20D, as depicted in Figure 8. Less aggregation of the soot particles occurred with high concentrations of nano-additives both inside the combustion chamber and within the exhaust pipes [53]. In addition, the degree of soot oxidation increased with the addition of the nano-additives due to the oxygen content in the TiO_2 nanoparticles and the C20D blend, which resulted in an improved the combustion process. Figure 8 shows that the number of soot particles increased with the occurrence of a high rate of EGR and the addition of nano-additives compared to the technique that did not involve EGR. This could be due to the low collision rate between nanoparticles and soot emissions during combustion, which results in increased soot particle formation. For the high EGR rate, the total number of soot particles decreased with the addition of the 40 ppm concentration of TiO_2 in comparison to the 25 ppm of TiO_2 (Figure 8). As an explanation, the increase in potential oxidation between soot emissions and TiO_2 nanoparticles could result in a slight decrease in the number of soot particles.

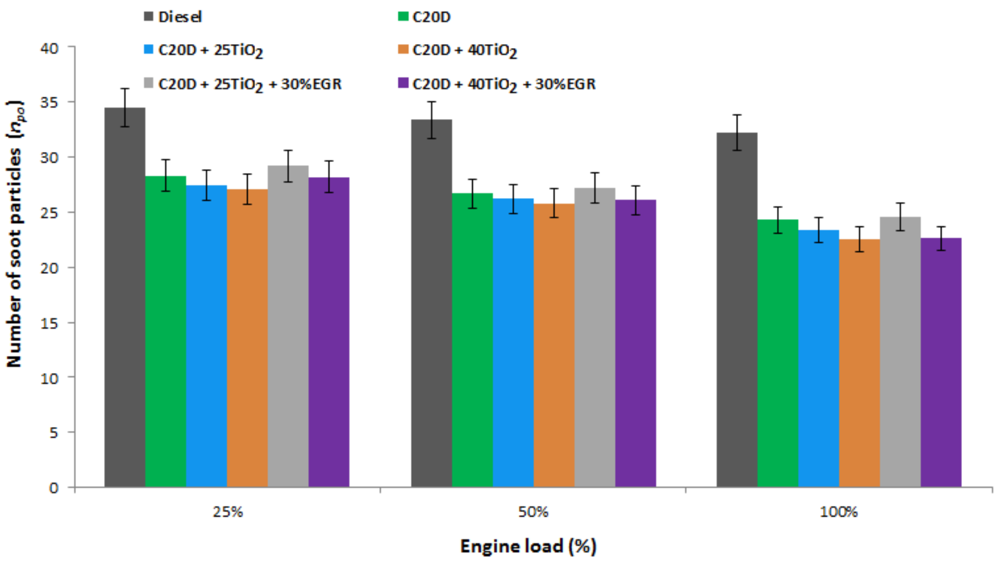

Figure 8. Effect of high EGR rate and two concentrations of TiO_2 nanoparticles on number of soot nanoparticles.

4. Conclusions

The influence of a high rate of EGR and two concentrations of TiO_2 nano-additives incorporated into a castor oil blend on the performance and emissions (NO_X and soot nanoparticles) of a diesel engine were analysed in this experimental study. The conclusions obtained in the current study are listed as follows:

- It was found that the BSFC decreased with the addition of 25 ppm and 40 ppm of TiO_2 to the nano blend compared to the fuel without nano-additives. The reduction in BSFC was clearly due to the addition of 40 ppm of TiO_2 nanoparticles as opposed to the addition of 25 ppm of TiO_2 to the nano blend.
- It was concluded that the BTE improved by 6.4% with the addition of TiO_2 into the castor oil blend compared to the neat biodiesel blend and diesel fuel.
- The engine performance was decreased with the application of a high rate of EGR and low concentration of nanoparticles into the nano blend, while the engine performance slightly improved with the increase in the nanoparticle concentration of TiO_2 in the C20D fuel and applying a high EGR rate.
- The NO_X emissions were reduced by 13.42% when the nano blend was combusted in comparison with the C20D fuel. Moreover, there was a significant decrease in NO_X emissions with the application of a high EGR rate and a nano blend.
- The soot emission concentration and number of soot particles were evidently decreased with the addition of 25 ppm and 40 ppm of TiO_2 to the C20D fuel in comparison with absence of TiO_2 in the C20D and diesel fuels, while these parameters increased with the occurrence of a high rate of EGR.
- It was observed that the integration of a high concentration of TiO_2 nanoparticles and a high rate of EGR produces beneficial effects on engine performance as well as a slight reduction in NO_X emissions and soot emissions (concentration and number).
- We suggest that future research should attempt to determine the effects of fuel injection strategies, the EGR rate, and the use of a nano blend (TiO_2 with biodiesel blend) on NO_X emissions and PM characteristics, as this will be an engaging topic.

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Nomenclature

BSFC	brake-specific fuel consumption
BTE	brake thermal efficiency
CO100	castor oil
C20D	20% castor oil methyl ester and 80% diesel fuel
CO	carbon monoxide
CRDI	common-rail direct injection
CO_2	carbon dioxide
DI	direct injection
EGR	exhaust gas recirculation
EGT	exhaust gas temperature
SEM	scanning electron microscope
SMPS	scanning mobility particle-sizer
TEM	transmission electron microscopy

TiO_2	titanium dioxide
HC	hydrocarbon
THC	total hydrocarbon
NO_X	nitrogen oxides
PM	particulate matter

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