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Carbon nanotube as effective enhancer for performance and emission of diesel engine fueled with waste plastic pyrolytic oil-diesel blend and its combination with titanium oxide nanoparticle

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ABSTRACT

The performance and emissions of diesel engines using titanium oxide (TiO_2) nanoparticles and carbon nanotube (CNT) as fuel-based nanoparticle additives in the plastic pyrolytic oil (PPO)-diesel mixture (B30) were investigated in this work. The fuel mixes were prepared by adding 100 ppm TiO_2, 100 ppm CNT, and their combinations to B30, then mechanically stirring the mixtures at high speed and stabilizing them in an ultrasonic bath. Brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), power, torque, carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), and oxygen (O_2) exhaust gas were all evaluated. The engine was run at full load in the 900 to 2400 rpm range. As CNT was added to B30, BTE increased by 7.01% than that of blank B30. Simultaneously, BSFC of B30 dropped with the addition of CNT, TiO_2 and their combination, with B30-CNT showed the greatest reduction of 16.00% than that of blank B30. CO_2 and HC emissions can be reduced by adding CNT, TiO_2, and their combinations with B30. However, as compared to B30, B30-CNT emits the least CO_2 and HC, with 30.93 and 82.77% reductions, respectively. As a result, using CNT alone to increase performance and reduce emissions is the best option.

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1.0 INTRODUCTION

The energy contained in discarded plastics can be recycled into plastic pyrolytic oil (PPO) and utilized as diesel engine fuel by pyrolysis. As the gap between global plastic production and waste plastic output continues to grow, this method presents a sustainable option for (a) waste plastic management, and (b) partial or complete replacement of fossil crude oil that is being consumed fast (Awang et al., 2021, Damodharan et al., 2019). Kalargaris et al. (2017) used low-density polyethylene derived-fuel (LDPE700) as the fuel to assess the diesel engine's performance, combustion, and emission characteristics. The findings revealed that LDPE700 has a similar brake thermal efficiency (BTE) to diesel, but emits less nitrogen oxide (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and more hydrocarbon (HC) than diesel.

Kumar et al. (2016) investigated the impact of PPO-diesel mixes on performance, combustion, and emissions. The addition of 10% by volume PPO to diesel has caused engine characteristics to be comparable to diesel and is suggested as a replacement, according to this study. Blank PPO also outperformed diesel in terms of performance and decreased CO, HC, and CO_2 emissions, according to the research. The NO_x for PPO was the lowest, followed by the blends, as compared to diesel operation. Churkunti et al. (2016) tested a commercial PPO, which was combined with diesel fuel up to 20%. It was discovered that when the amount of PPO in the mixture increased, the peak pressure fell but the brake-specific fuel consumption (BSFC) remained constant. NO_x emissions dropped as the amount of PPO in the mixture rose, but particulate matter (PM) emissions increased. Because the aromatics content in the oil was lowered, HC and CO emissions were also reduced. Panda et al. (2016) investigated the performance of diesel engines running on PPO produced from waste polypropylene by catalytic pyrolysis. When PPO was added to diesel, the engine was found to produce up to 30% greater comprehension. Aside from that, the operation was shaky owing to vibrations. BSFC is proven to be somewhat less than diesel. NO_x, HC, and CO emissions were found to be greater than in diesel operations.

Because of the benefits of fuel economy while decreasing harmful greenhouse gas emissions, fuel catalysts are now the focused attention among the numerous possible technologies for minimizing hazardous exhaust emissions. Bharathy et al. (2019) investigated the impact of adding 25, 50, 75, and 100 ppm TiO_2 to PPO fuel. Under maximum load, the BTE of the PPO including 50 ppm TiO_2 sample combination rose by 2.1% as compared to pure PPO. CO and HC emissions are considerably decreased when compared to other fuel combinations thanks to the 50 ppm TiO_2 combined with PPO.

Chinnasamy et al. (2019) investigated the performance, emission, and combustion characteristics of single-cylinder diesel engines in diesel and PPO mixes by using aluminium oxide (Al_2O_3) nanoparticles with various average particle sizes (20 and 10 nm) as additives. The addition of 20 and 100 nm Al_2O_3 to the PPO-diesel mixture raises the BTE by 12.2 and 8.9%, respectively, and lowers the BSFC by 11 and 8%. CO, HC, and NO_x emissions can be reduced by adding nanoparticles with sizes of 20 and 100 nm to a PPO-diesel blend. However, as compared to 100 nm particles, 20 nm particles reduce emissions more effectively. PPO was given various doses of magnesium oxide (MgO) nano additives, and the BTE of PPO with 75 ppm MgO nano additives was found to be 2.5% higher. CO and HC emissions have been decreased. NO_x emissions are enhanced by 25 ppm as compared to pure PPO. The trend was not in link with the study by Sundar et al. (2021). They reported the increment of NO_x by adding 200 ppm of TiO_2 in neat PPO. They also reported that the addition of TiO_2 nanoparticles to blank PPO improved BTE over PPO without any additives. Similarly, the findings on emission showed that increasing amount of nano additive will decrease smoke and HC emissions significantly.

Some research have looked into the impact of mixed additives on engine performance and emission parameters. Hussain et al. (2020) investigated the effect of systematic infusion of two nanomaterials on engine emission and performance metrics in a single cylinder CI engine. They looked at the effects of biodiesel blends containing 3% cerium coated zinc oxide (Ce-ZnO) nanoparticles and diesel–soybean biodiesel blends. The BTE increased by 20.66% with 50 ppm Ce-ZnO nanoparticle additive in 25% soybean biodiesel in diesel, SBME25 (SBME25Ce-ZnO50), BSFC increased by 21.8%, and CO, smoke, and HC decreased by 30, 18.7, and 21.5%, respectively, when compared to SBME25 fuel operation. Gavhane et al. (2021) investigated several nano-additives, including silicon dioxide (SiO_2), on the same fuel mixtures. They found a lesser increase in BTE and BSFC than Hussain et al. (2020), which were 3.48–6.39% and 5.81–9.88%, respectively. In comparison to SBME25 fuel blends, CO, HC, and smoke emissions for SiO_2 nano-additive added blends were reduced by 1.9–17.5, 20.56–27.5, and 10.16–23.54%, respectively.

Mujtaba et al. (2020) examined the engine characteristics of B30 (30% biodiesel + 70% diesel) fuel with TiO_2 nanoparticle and oxygenated alcohol (dimethyl carbonate (DMC)) addition. Among all the fuel samples examined, the DMC blended fuel had the best engine performance and emission (HC and CO) characteristics. Furthermore, Razzaq et al. (2021) investigated the effects of combining DMC and graphene oxide nanoplatelets (GNPs) in biodiesel blends on engine performance and emission characteristics. When compared to all other tested blends, the biodiesel blend with combined GNP and DMC had the highest reduction in BSFC of 5.05% and the highest BTE of 22.80%. They came to the conclusion that the combined GNP and DMC had a lot of promise for use in diesel engine operating.

The electrical, mechanical, optical, and chemical characteristics of carbon nanotubes (CNTs) are the most appealing, since they pave the way for future applications. CNT is being utilized as an additive to improve the performance characteristics of fuels and minimize hazardous pollutants in the exhaust gas in the current study. Free radicals can be trapped by carbon nanotubes, and carbon fibrils can be utilized as antiknock additives. Carbon fibrils can be utilized as a chelating agent for metal hybrids/impurity ions in engine fuel to minimize the development of insoluble complexes and therefore reduce insoluble impurities. Similarly, adding CNT to diesel fuel increases the cetane number of the mixture and acts as a catalyst to speed up combustion.

Due to the potential features of TiO_2 and CNT, present efforts are aimed at demonstrating the influence on diesel engine performance and emission characteristics when PPO-diesel mixes are utilized, and TiO_2 and CNT are employed as additives. The goal of this research is to (1) determine the variations in fuel properties caused by the addition of TiO_2 and/or CNT, (2) conduct various tests on diesel engines using modified fuel samples and compare to base fuels to determine engine performance enhancement and emission reduction due to the addition of the catalyst, and (3) determine the engine performance enhancement and emission reduction due to the addition of the catalyst.

2.0 EXPERIMENTAL PROCEDURE

Malaysian commercial diesel and PPO are procured from the local market and Kuala Lumpur-based Syngas Sdn Bhd. The present study utilized a mixture of PPO and commercial diesel to make the blend. TiO_2 and CNT, as well as commercially available nanoparticles with a size of 30 to 40 nm, were chosen as fuel additives. The composition of PPO was analysed using gas chromatography-mass spectrometry (GC-MS). In this test, 50 mg of liquid fuel was dissolved in 1 mL of n-hexane, then injected into the chromatographic inlet and processed for 42 minutes.

Helium serves as the carrier gas, with a flow rate of 0.51 mL/min. The separation began at a temperature of 50 to 250 °C with a 5 °C/min heating rate (Juwono et al., 2018).

2.1 Fuel Samples Preparation for Engine Test Rig

To make a B30 fuel combination (10% biodiesel + 20% plastic oil + 70% diesel), the purchased plastic oil was combined with Malaysian commercial diesel (B10). In order to produce a combination of nanoparticles and B30 fuel, an ultrasonic Q500 Sonicator (QSONICA, Newtown, USA) was utilized as shown in Figure 1. B30 fuels with additives as shown in Table 1 were produced on a magnetic stirrer at 700 rpm stirring speed for 30 min, and ultrasonic treatment was used to scatter the nanoparticles at a frequency of 20 Hz for 20 minutes with a 30% amplitude. Table 2 lists the properties that were measured according to ASTM standards.

Table 1: Composition of fuel blend samples.

Fuel sample code	Fuel sample composition
B0	100% PPO
B10	10% biodiesel + 90% diesel
B30	20% PPO + 10% biodiesel + 70% diesel
B30-TiO_2	B30 + 100 ppm TiO_2
B30-CNT	B30 + 100 ppm CNT
B30-TiO_2-CNT	B30 + 100 ppm TiO_2 + 100 ppm CNT

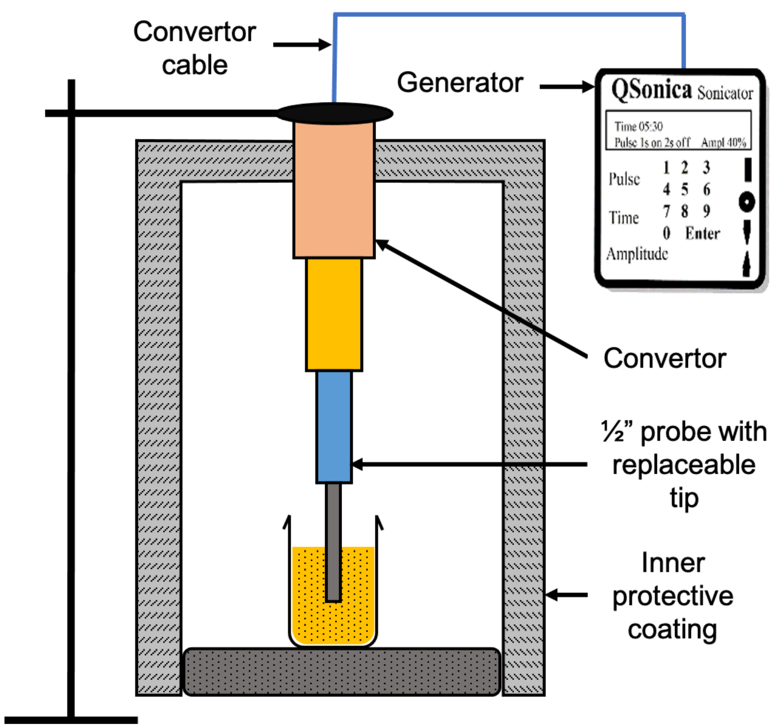

Figure 1: Ultrasound equipment for sonication of B30 fuel with additives.

Table 2: Comparison of properties of fuel blends.

Fuel sample	Density at 15 °C (g/cm^3)	Kinematic viscosity at 40 °C (mm^2/s)	Viscosity index	Calorific value (MJ/kg)
B0	0.7859	1.1771	13.5	42.63
B10	0.8481	3.1794	156.4	42.84
B30	0.8362	2.5759	319.0	40.94
B30-TiO_2	0.8385	2.6238	664.9	42.59
B30-CNT	0.8369	2.5693	420.9	42.60
B30-TiO_2-CNT	0.8392	2.6340	535.4	42.58

2.2 Experimental Set-Up

To examine the influence of fuel mixes on diesel engine performance and emission characteristics, a Yanmar (TF 120M) single-cylinder and radiator cooled diesel engine was used, as illustrated in Figure 2. Maximum power (7.7 kW), compression ratio (17.7), maximum rpm (2400 rpm), injection timing (17º before top dead centre), and injection pressure (200 kg/cm^2) were the diesel engine specifications. The BOSCH BEA 350 gas analyser was used to analyse the engine exhaust gases (HC, CO, CO_2, and oxygen (O2)). Due to a restriction in the gas analyser, NO_x could not be measured. Table 3 displays the measurement accuracies for diesel engine characteristics. These methods were adapted from Mujtaba et al. (2020).

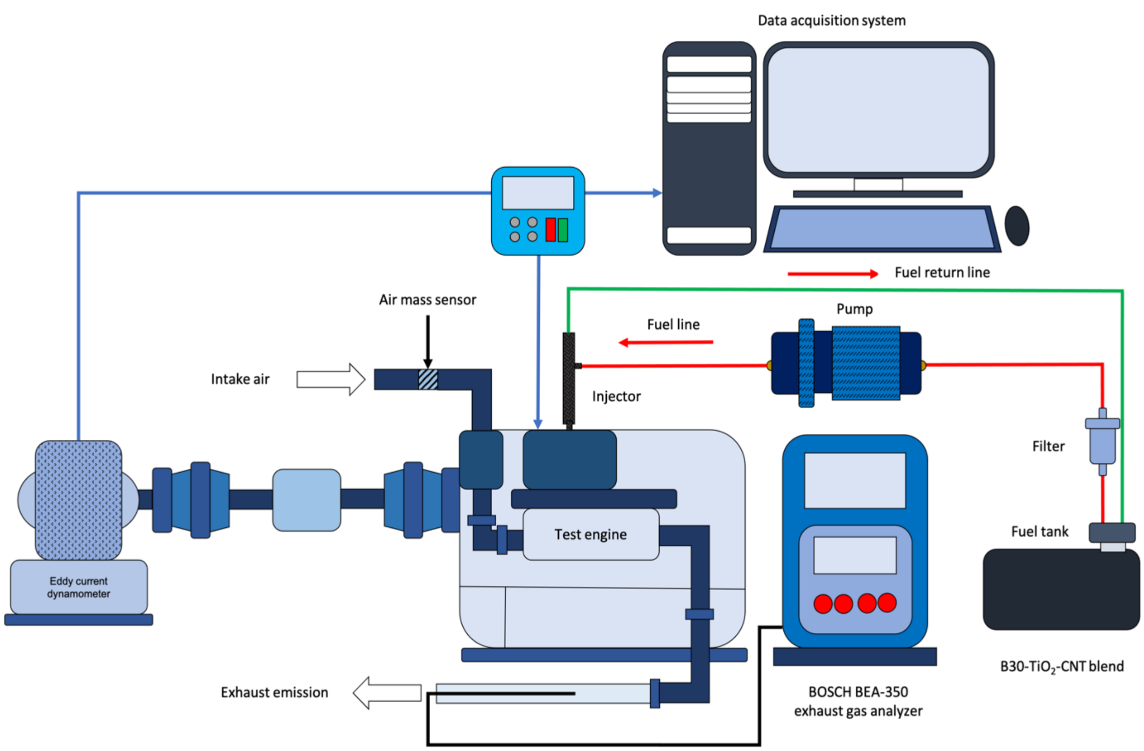

Figure 2: Schematic view of diesel engine set-up.

Table 3: Accuracies of the measurements for diesel engine characteristics.

Measurement	Measurement Range	Accuracy
Speed	60-10,000 rpm	±10 rpm
Load	±120 Nm	±0.1 Nm
Flow	0.5-36 L/h	±0.01 L/h
CO	0-10 vol.%	±0.001 vol.%
CO_2	0-10 vol.%	±0.001 vol.%
HC	0.999 ppm	±1 ppm
O_2	0-10 vol.%	±0.001 vol.%

3.0 RESULTS AND DISCUSSION

3.1 Physicochemical Properties of Fuel Blends

In Figure 3, the effect of adding B0 to B10 and adding additives to the B30 mixture on density, kinematic viscosity and calorific value are explained. Figure 3 shows that the density of the fuel mixture does not change significantly. Due to the higher content of unsaturated HC, the density of B30 is slightly lower than that of B10 (Awang et al., 2020). B30-TiO_2 and B30-CNT showed slightly higher densities by 0.28 and 0.08% than that of B30, respectively. B30-TiO_2-CNT also showed higher density by 0.36% than that of B30. As the density increases, molecules have more energy content, and a small amount of fuel can release more energy (Bharathy et al., 2019). Bharathy et al. (2019) also reported that by adding 100 ppm of TiO_2, the density of PPO increased by 0.82%.

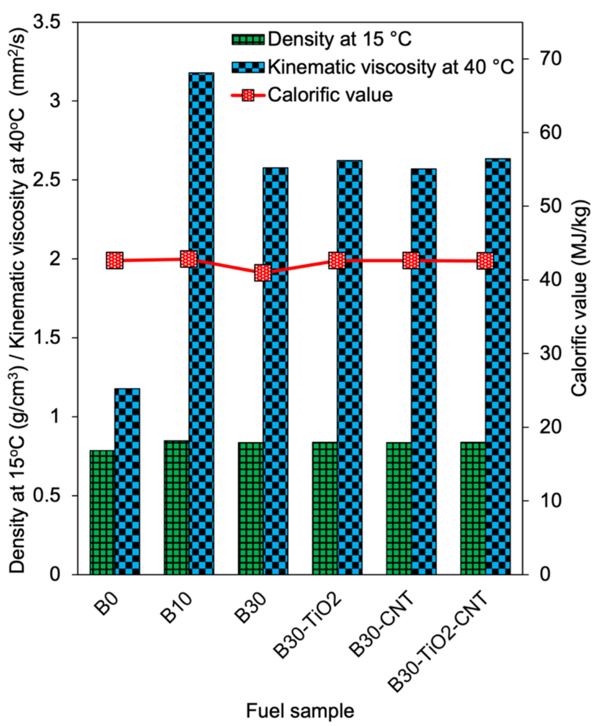

Figure 3: Properties of fuel blends.

The viscosity of B30 is lower than that of B10. The same goes to density; because there are many unsaturated HC in the fuel, the fuel's viscosity is reduced (Awang et al., 2020; Jamshaid et al., 2020). B30-TiO_2 showed higher viscosity by 1.86% while B30-CNT showed lower viscosity by 0.26%, compared to B30. The viscosity of B30-TiO_2-CNT is higher than that of B30-TiO_2. Compared with B30, the viscosity increase value is 2.26%. The rupture of fuel particles is affected by their viscosity. Fuels with higher viscosity tend to form larger droplets when injected, which may cause poor atomization and increase the pollutants (Bharathy et al., 2019). The operation of the fuel injection system and atomization process depend on the viscosity. The lower the viscosity of the fuel atomization process, the better the operation (Chinnasamy et al., 2019). Therefore, the B30-CNT blend provides better fuel atomization than other blends.

Compared with B10, the calorific value of the blend of B0 is slightly lower by 4.43%. Compared to B30-TiO_2 and B30-TiO_2-CNT, B30-CNT showed slightly higher calorific value by 4.04% and provides the highest calorific value. Instead, Chinnasamy et al. (2019) reported that the addition of 10 and 20 ppm of alumina (Al_2O_3) nanoparticles to the PPO-diesel mixture would not cause any significant change in calorific value, and its calorific value is only about 1.53 to 5.10%.

3.2 GC-MS Analysis

Figure 4a shows the GC-MS data, which is arranged in the carbon number range of the alkanes and olefin compounds present in B0. Most of the alkanes of B0 are in the range of C_{11}-C_{20}, while the composition of C_{21}-C_{30} and C_{31}-C_{40} is less. This can be why the viscosity of B0 is lower than that of B10, so it is suitable for injection with diesel in diesel engines. The presence of low-carbon number compounds in pyrolysis oil leads to lower CO and CO_2 emissions than B0. B0 also has olefins in the low carbon range (C_1-C_{10} and C_{11}-C_{20}). Figure 4b shows the composition of aromatic compounds present in B0. The content of aromatic compounds in B0 is low, so it can only be used as a mixed fuel with B10.

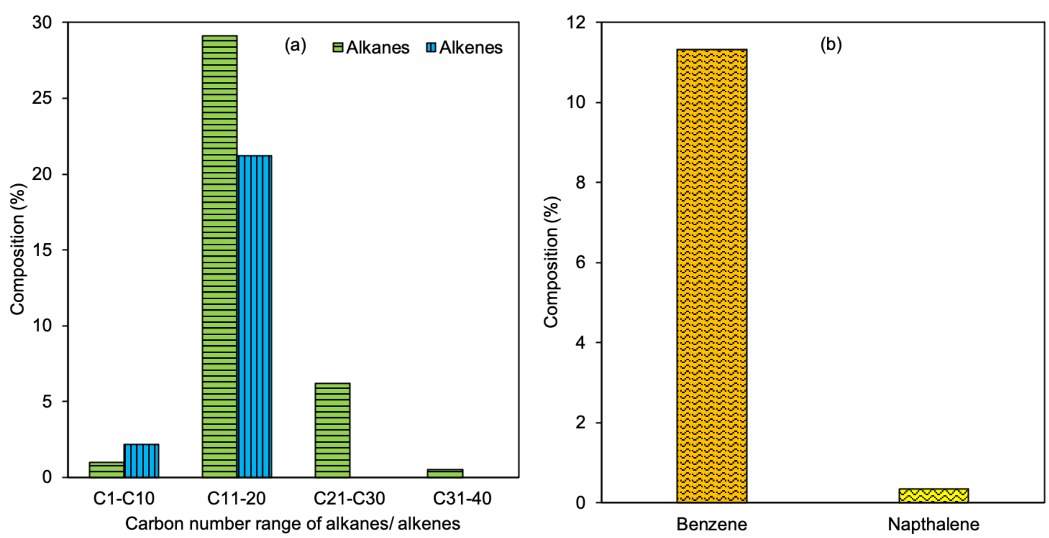

Figure 4: Composition of (a) carbon number range of alkane and alkenes and (b) aromatic products of B0.

3.3 Performance Characteristics of Fuel Blends

Figure 5 illustrates the variation of BSFC, BTE, brake power and brake torque with engine speed for all samples. Figure 5a shows that the BSFC decreases as the speed increases and then increases as the speed increases, up to 2100 rpm. Compared with B10, the B30 blend increases the average BSFC of the entire speed by 5.4%. This is due to the low calorific value of B30. In this way, more fuel is used for the same power generation Heydari-Maleney et al. (2017) . Experimental results show that due to the lower calorific value, the BSFC of the PPO mixture is higher than that of diesel (Ani & Lu, 2020; Hazrat et al., 2016; Kaewbuddee et al., 2020; Hariram et al., 2017). Chinnasamy et al. (2019) also reached the same agreement, in which the PPO-diesel blend provides about 11% higher BSFC than diesel due to its higher viscosity. However, in the present study, the viscosity of B30 was lower than that of B10. Therefore, the higher B0 molecular weight can offset its lower viscosity, which requires more energy and time to degrade the fuel, resulting in longer ignition delay and higher BSFC (El-Seesy et al., 2016).

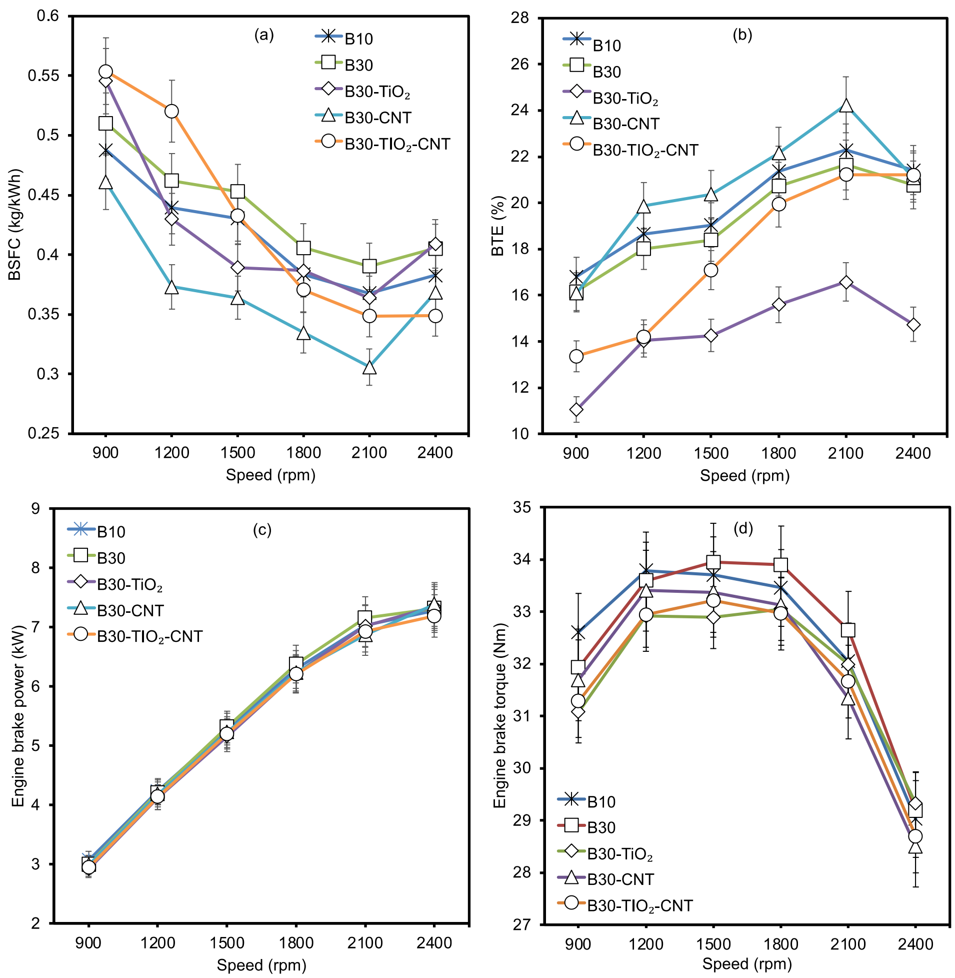

Figure 5: Variation of (a) BSFC, (b) BTE, (c) brake power and (d) brake torque with engine speed.

In addition, due to the improved atomization, enhanced heat transfer and combustion characteristics with CNT, B30-CNT showed lower average BSFC of the entire speed by 11.4% as compared to B10 (Gad & Jayaraj, 2020). Correspondingly, it is certain that the catalytic reactivity, heat transfer rate, and fuel-air mixing are improved under the nanoparticles' action. Compared with B30 (0.39 kg/kWh), for the fuel mixture B30-CNT, the lowest BSFC was determined to be 0.31 kg/kWh, followed by the fuel mixture, B30-TiO_2-CNT (0.35 kg/kWh) and B30-TiO_2 (0.36 kg/kWh) at 2100 rpm. The same agreement was reached by Heydari-Maleney et al. (2017), in which the addition of CNT can improve combustion and reduce BSFC. In addition, compared with the B30-CNT blend, B30-TiO_2-CNT showed higher average BSFC of the entire speed by 16.7%. Therefore, the use of B30-TiO_2-CNT becomes undesirable.

As shown in Figure 5b, the average BTE of the entire speed of B10 is 19.93%, while the average BTE of B30 (19.29%) is slightly lower. As shown in Figure 4b, the slight decrease in BTE is because of the content of aromatic compounds is low and thereby, less energy is required to break the bond (Chinnasamy et al., 2019). However, B30-CNT showed higher average BTE to 20.64%. Due to better combustion, better atomization, more excellent surface area/volume ratio, and enhanced heat transfer, the BTE of B30 blend with CNT is improved. The reaction surface of CNT acts as a potential catalyst to reduce the evaporation time (Gad & Jayaraj, 2020). Gad and Jayaraj (2020) also reported the same trend as the present study. The BTE of the corn biodiesel-diesel mixture containing 100 ppm of CNT increased by about 13.78% compared with the blank corn biodiesel-diesel mixture. On the contrary, compared with B30, B30-TiO_2 and B30-CNT showed lower average BTE by 25.44 and 7.48%, respectively. Therefore, it is desirable to use B30-CNT.

Figure 5c shows the variation of braking power with speed. It can be seen that the braking power increases as the speed increases. Hosseini et al. (2017) also observed a similar trend that studied the effect of CNT in biodiesel-diesel mixtures on performance and emission characteristics. Compared with B10, B30-TiO_2, B30-CNT and B30-TiO_2-CNT reduce braking power by 1.2, 0.9, and 1.7%, respectively. Compared with B30-TiO_2 and B30-TiO_2-CNT, B30-CNT has the most negligible reduction in power value, which means that fuel combustion efficiency is higher. Figure 5d shows the change of the braking torque of the mixed fuel with speed. The same goes for the braking power; it was observed that the braking torque of B30 increased slightly by 0.29%, while the braking torque of B30-TiO_2, B30-CNT and B30-TiO_2-CNT decreased slightly by 1.74, 1.64, and 1.96 %, respectively, when compared to B10. If CNT is added to the mixed fuel, the result is inconsistent with Hosseini et al. (2017). They reported that using CNT with mixed fuel can significantly improve engine torque as compared to pure diesel.

3.4 Emission Characteristics of Fuel Blends

The change in CO emissions concerning speed is shown in Figure 6a. As the speed increases, the percentage of CO emissions decreases. In most cases, the amount of CO is minimal at 2400 rpm. This shows that if the engine runs at a speed close to maximum power, CO emissions will be minimal. In addition, at higher speeds, CO emissions are decreased due to reduced fuel consumption and poor air-fuel mixture at higher speeds. Due to the higher cetane number, the B30 blend can reduce CO emissions by 6.64% compared with B10. Another reason may be the low carbon number of compounds in B0, as shown in Figure 4a. Chinnasamy et al. (2019) did reach the same agreement with this study. They reported that due to the lower cetane number, the PPO-diesel mixture's CO emissions are slightly higher than that of diesel by 13.85%.

Compared with B30, B30-CNT showed lower CO emissions by 39.47%, while B30-TiO_2 showed lower CO emissions by 30.93%. The CO emissions of B30 containing nano blends are significantly reduced. Gad and Jayaraj (2020) also reported that compared with the blank biodiesel-diesel mixture, adding 100 ppm of CNT to the biodiesel-diesel mix can reduce CO emissions by approximately 16.24%. CNT has more significant surface contact, catalytic activity, and shortened ignition delay. The enrichment of CNT improves fuel and air mixing and improves ignition and complete combustion (Gad & Jayaraj, 2020). Simultaneously, the addition of TiO_2 can provide enough O_2 and improve the cetane number to minimize CO emissions. TiO_2 accelerates the combustion due to the higher carbon combustion activation and shortened ignition delay, thereby increasing the air-fuel mixing degree and promoting almost complete combustion (Aalam et al., 2015). Compared with B30, B30-TiO_2-CNT showed lower CO emissions by 21.84%. In the case of the B30-TiO_2-CNT mixture, fuel molecules are more difficult to rupture due to their higher viscosity (Figure 3), which leads to the formation of an inappropriate air-fuel mixture, which ultimately leads to more CO emissions. Therefore, it is more desirable to use B30-CNT and B30-TiO_2 than B30-TiO_2-CNT.

Figure 6b shows the change in CO_2 emissions relative to mixed fuel speed. The percentage of average CO_2 emissions increases as the engine speed increases. By comparing the amounts of CO and CO_2, it can be found that their molecular composition and balance have opposite behaviors for a given fuel. For example, B30-TiO_2, B30-CNT, and B30-TiO_2-CNT fuels have the highest CO_2 content at 2400 rpm, while these three fuels have the lowest CO content. This means that the carbon present in the exhaust gas may become CO or CO_2.

To conclude, we should refer to the amount of O_2 in the exhaust gas (Figure 6d). The least O_2 was observed in the fuels of B10 and B30-TiO_2-CNT. This shows that half of the O_2 moles are combined with CO to produce one mole of CO_2. The remaining half of O_2 moles are related to the production of NO.

Literature reported that due to insufficient O_2, all carbon could not be converted into CO_2. Some fuels were not burned, and some carbon eventually existed in the form of CO (using cerium oxide nanoparticles and CNT as additives to the diester mixture) (Selvan et al., 2014). The lowest O_2 content belongs to the B30-CNT variety. This shows that most of the O_2 is consumed in the mix during the fuel combustion process, and the combustion is more complete. The maximum power generation is related to this fuel mixture, which minimizes fuel consumption. Also, the minimum content of CO and HC is associated with this fuel.

On the other hand, the most significant CO_2 emissions belong to this fuel. Compared with B10, the average CO_2 emission of the B30 mixture is lower. It was also observed that B30-TiO_2 and B30-CNT showed greater average CO_2 emissions by 20.25 and 24.21%, respectively, compared with the B30 mixture. Besides, compared with B30, B30-TiO_2-CNT showed higher average CO_2 emissions by 6.17%.

Figure 6c shows the variation of HC emissions from the mixed fuels with speed. The fuel consumption is lower at high speed, and the HC emission produced at high speed is lower (Gad & Jayaraj, 2020). Compared with B10, B30 blends increase the average HC emissions by 32.76%, because the aromatic content in B0 is low. Compared with B30, the average HC emission in the blend of B30 reduced by 61.54 and 82.77% B30-TiO_2 and B30-CNT, respectively. In the case of B30-TiO_2 blending, due to the almost complete combustion, the TiO_2 nanoparticles minimizes HC emissions due to the catalytic activity and the nanoparticles provide sufficient O_2 to oxidize HC (Prabu & Anand, 2016).

In addition, TiO_2 also plays the role of biodiesel, in which the presence of O_2 bound in biodiesel increases the combustion speed and shortens the ignition delay of biodiesel. Nanoparticles act as catalysts, leading to enhanced oxidation of HC, catalytic surface activity and complete combustion

(Gad & Jayaraj, 2020). However, B30-TiO_2-CNT showed lower HC emissions by 40.17% than that of B30. Due to the high viscosity of the B30-TiO_2-CNT blend, the nanoparticles' catalytic activity is disturbed to a certain extent, which leads to incorrect air-fuel mixing and insufficient O_2 supply; and complete combustion cannot be achieved (Chinnasamy et al., 2019). In addition, B30-TiO_2 showed lower HC emission, because the addition of TiO_2 nanoparticles can enhance combustion and reduce the emission of HC (Selvan et al., 2014).

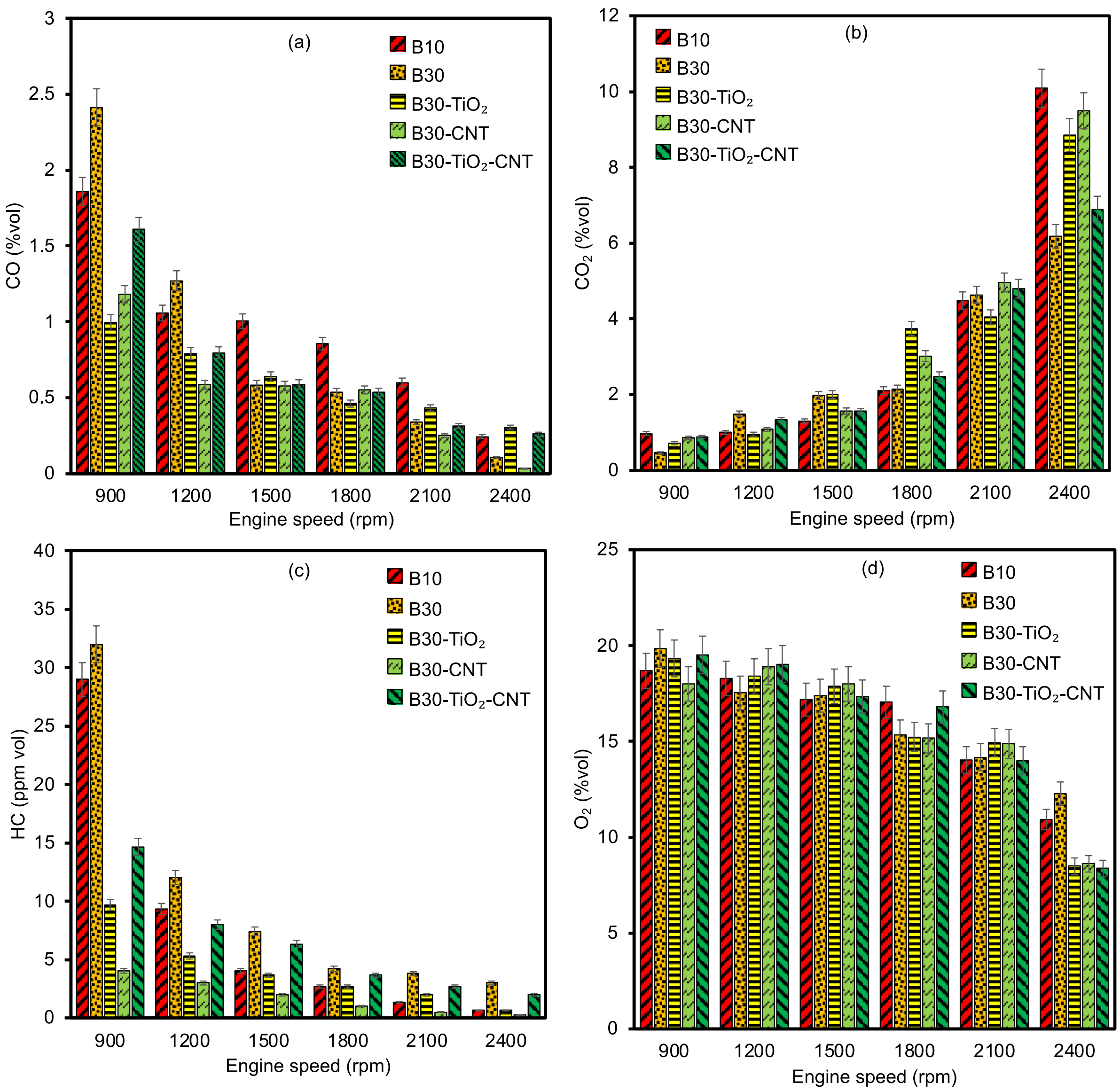

Figure 6: Variation of (a) CO, (b) CO_2, (c) HC and (d) O_2 emission with engine speed.

3.5 Emissions Comparison for B30 With Nano-Additives

As shown in Figure 7, under full engine load, diesel engines' exhaust emissions with PPO-commercial diesel blended with nano additives were compared. Compared with B10, B30, B30-TiO_2, B30-CNT and B30-TiO_2-CNT are 6.64, 35.52, 43.50, and 27.03%, respectively for the reduction of CO emission. Compared with B10, the CO_2 emissions of B30 and B30-TiO_2-CNT decreased by 15.39 and 10.17%, respectively, while the CO_2 emissions of B30-TiO_2 and B30-TiO_2-CNT increased by 1.73 and 5.10%, respectively. The HC emission reduction of B30 with nano-additives (B30-TiO_2, B30-CNT and B30-TiO_2-CNT) were 48.94, 77.13, and 20.57%, respectively, while the HC emission increase of B30 without nano-additives was by 32.76% when compared with B10. Compared with the B30 blend, the maximum reduction of CO and HC of B30-CNT are 42.50 and 77.13%, respectively, and the maximum increase of CO_2 of B30-CNT was 5.10%.

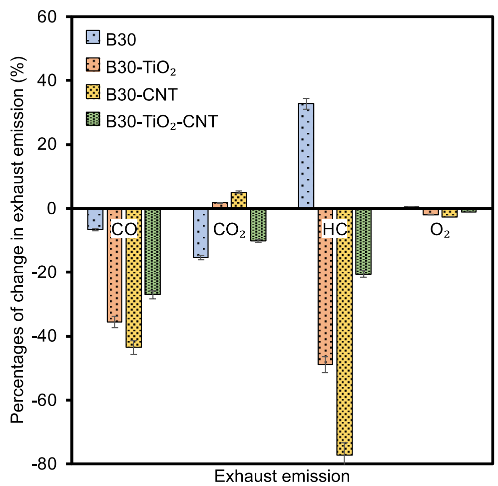

Figure 7: Change percentages in emissions related to B10 at entire speed.

3.6 Optimal and Economic Fuel Mode

Figure 8 reveals the average values of BSFC, BTE, torque and power for different fuel mixtures at the entire speed from 900 to 2400 rpm. In all cases, by adding nanoparticles to the B30 fuel mixture, BSFC will be reduced. The largest BSFC belongs to B30-CNT. Regardless of the nanoparticles, the BSFC of the B30 fuel mixture is higher than that of the B10. B30-CNT has the highest BTE. Adding nanoparticles to the B30 fuel mixture does not cause any trivial changes, the difference is only about 2%. Likewise, the torque trend follows the power curve and does not change significantly.

In Figure 9, the average value of emissions is shown. The minimum and maximum CO emissions are exhibited by B30-CNT and B10 fuel mixtures, respectively. The minimum and maximum CO_2 emissions as shown by B30 and B30-CNT mixture. The lowest and highest values of HC emissions are related to the B30-CNT and B30 mixtures, respectively. Finally, the minimum and maximum values of O_2 are respectively associated with the B30-CNT and B30 fuel mixtures.

Figure 10 is a summary of the average parameter changes of B30-CNT fuel compared with B10 fuel. Compared with B10 fuel, BTE and CO_2 emissions increased by 3.56and 5.10% on average, respectively. Compared with B10 diesel, BSFC, CO, HC and O_2 emissions are reduced by 11.4, 43.50, 77.13, and 2.66%, respectively.

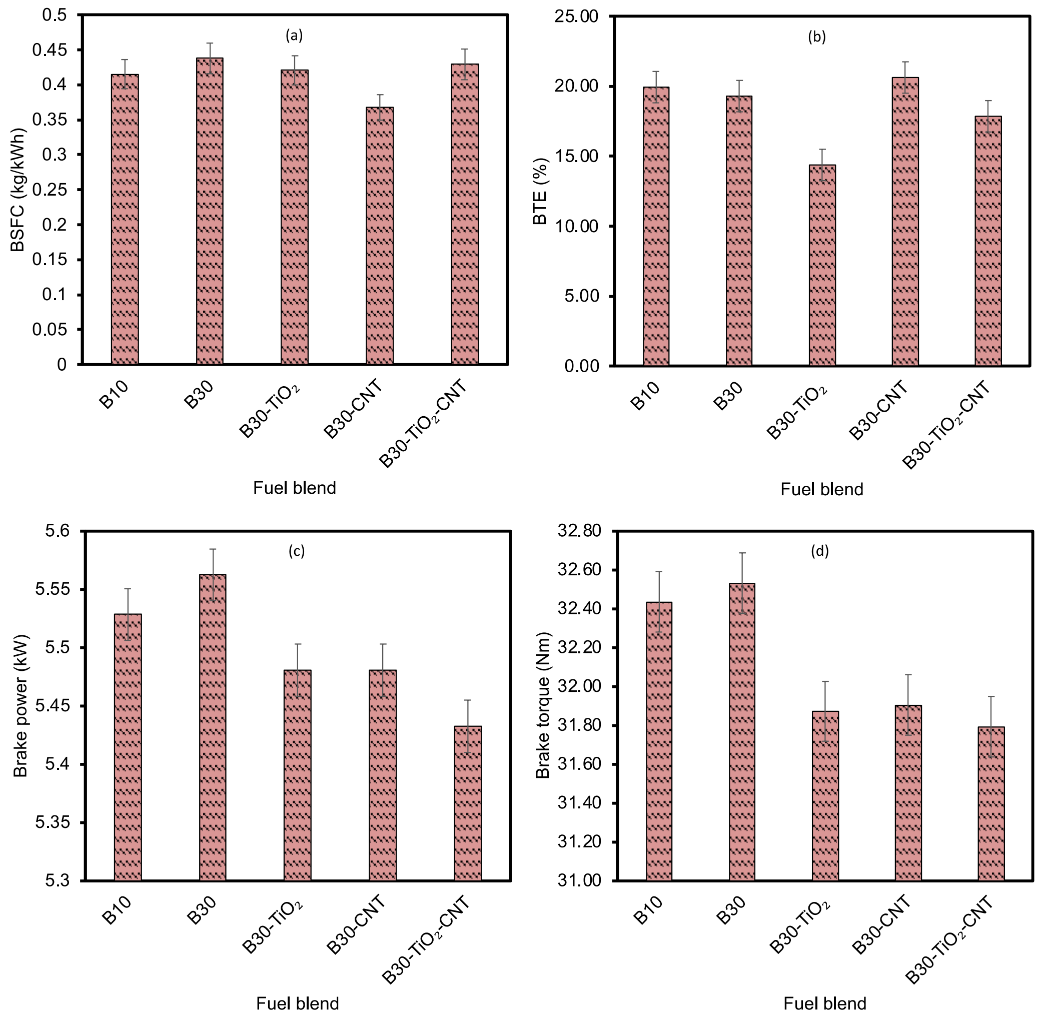

Figure 8: Average of (a) BSFC, (b) BTE, (c) brake power and (d) brake torque in entire speeds of 900 rpm to 2400 rpm for different fuel blends.

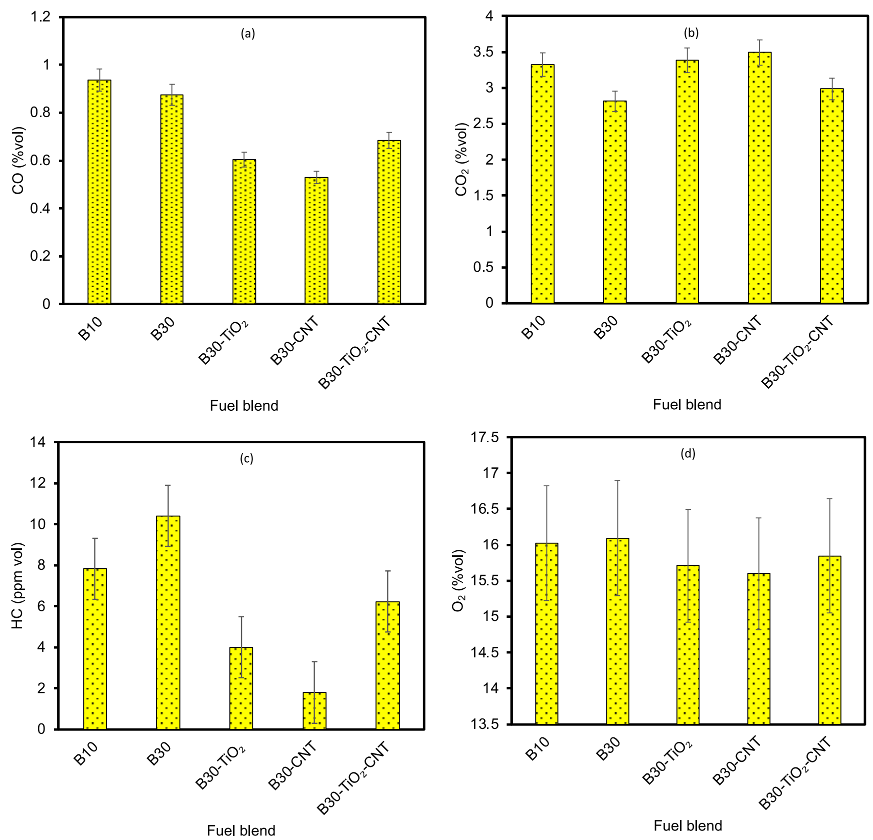

Figure 9: The average emissions of (a) CO (b) CO_2, (c) HC and (d) O_2 in entire speeds of 900 to 2400 rpm for different fuel blends.

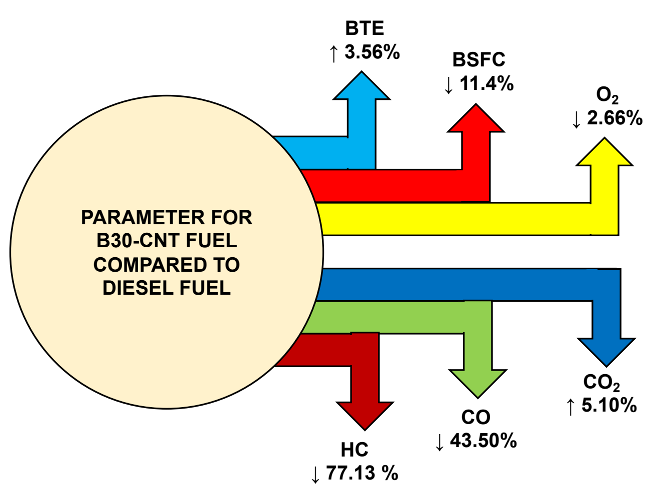

Figure 10: Average percent change in the parameters measured for B330-CNT fuel compared with diesel fuel.

To confirm and better explain the experimental results, similar studies were reviewed. Table 4 briefly lists the performance and emission characteristics derived from this research and other research results. For all performance characteristics such as BSFC and BTE, similar trends have been obtained. Similarly, the emission characteristics of CO, CO_2, and HC display the same trend. Most likely, the addition of CNT to the PPO-diesel mixed fuel will significantly affect the injector's prayer to the fuel mixture, pulverization and vaporization, thereby improving engine performance and reducing emissions (Hosseini et al., 2017).

Table 4: A brief comparison of performance and emission characteristics resulted from the present study with other research works.

Type of fuel with additives	**Performance**		**Emission**			**Reference**
	BSFC	**BTE**	**CO**	**CO_2**	**HC**	
B30-CNT	11.40% ↓	3.56% ↑	43.50% ↓	5.10% ↑	77.13% ↓	Present study
Al_2O_3 in diesel	0.50% ↓	-	11.00% ↓	-	13.00% ↓	Gumus et al. (2016)
TiO_2 in PPO	12.50% ↓	8.90% ↑	66.67% ↓	-	4.90% ↓	Sachuthananthan et al. (2018)
Al_2O_3 in waste plastic oil-diesel blend	13.02% ↓	12.43% ↑	13.08% ↓	-	3.18% ↓	Chinnasamy et al. (2019)
CNT in biodiesel-diesel blend	10.83% ↓	13.78% ↑	16.24% ↓	-	21.00% ↓	Gad and Jayaraj (2020)

Although the knowledge about the effects of CNT on human health is not sufficient and has only been recently used, it has a negative effect on the human body. So, it is necessary to adopt effective methods to remove the material's residues through filtration. The hazardous effects of CNT to the human body should be studied. The maximum allowable residual concentration and the solution to effectively remove the residual should be determined. The concentration of nanoparticles in the fuel is very low (100 ppm). Compared with reducing emissions, carbon nanotubes are the least harmful.

On the other hand, these particles are deformed into CO, CO_2 and HC in the combustion chamber. According to the material safety data sheet (MSDS) of CNT, the best disposal method of CNT is to dissolve or mix the material with a combustible solvent and then burn it in a chemical incinerator equipped with an afterburner and scrubber. Therefore, its use in internal combustion engines can be explained. The adverse effects of nanoparticles on engine parts have not been carefully studied.

CONCLUSION

The diesel engine performance and emission characteristics of B30-TiO_2, B30-CNT and B30-TiO_2-CNT were studied to understand the roles of TiO_2, CNT and their combination as fuel additives in PPO-diesel (B30) fuel. Compared with the B30 fuel mixture, BTE increased by 7.01% for B30-CNT. Simultaneously, the BSFC of B30-CNT, B30-TiO_2 and B30-TiO_2-CNT decreased by 16.00, 3.90 and 1.95% compared to B30 fuel, respectively. Among these blends, B30-CNT showed the highest decrease in BSFC. Therefore, in terms of performance, the use of B30-TiO_2-CNT in diesel engine becomes undesirable. B30-CNT, B30-TiO_2 and B30-TiO_2-CNT showed reduction in CO and HC emissions by 39.47, 30.93 and 21.84%, and 82.77, 61.54 and 40.17%, respectively. Among these blends, B30-CNT has the least CO and HC emissions, which are 0.53 %vol and 1.79 ppm vol, respectively. In terms of emission, it is the best to use CNT alone in diesel blend to minimize emissions.

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