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# Investigating the Impact of $TiO_2$ Nanoparticles on Waste Plastic Pyrolysis Oil and DEE Diesel Blends for Diesel Engine Performance and Emission Optimisation

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## Abstract

The growing environmental concerns and fossil fuel depletion have spurred interest in alternative fuels, with waste plastic oils emerging as a solution. Waste plastic oils not only help to reduce plastic waste but also contribute to energy production. This study investigates the effects of incorporating $TiO_2$ nanoparticles into waste plastic pyrolysis oil (WPPO) and diethyl ether (DEE) blended with diesel fuel on engine working characteristics. The experimental analysis evaluated four fuel blends: pure diesel, WPD20 (20% WPPO in diesel), WPD20E5 (WPD20 with 5% DEE), WPD20E5T50 (WPD20E5 with 50 ppm $TiO_2$ nanoparticles), and WPD20E5T100 (WPD20E5 with 100 ppm $TiO_2$ nanoparticles) under various load conditions. The results demonstrated that the WPD20E5T100 blend achieved the highest brake thermal efficiency and the lowest brake specific fuel consumption, with improvements of up to 5.26% and 8.31%, respectively, in comparison to neat diesel. The blend also exhibited the most significant reductions in CO and unburnt hydrocarbon emissions, with reductions of up to 6.86% and 11.9%, respectively. Smoke emissions were notably lower with the $TiO_2$ nanoparticle-enhanced blends, achieving an 11.8% improvement over diesel. Although $NO_x$ emissions were slightly higher with DEE, the WPD20E5T100 blend showed the maximum reduction in $NO_x$ emissions, with a reduction of 5.7% at full load. Overall, the WPD20E5T100 blend produced the optimum results at all loads.

**Keywords:** Waste plastic pyrolysis oil; Diethyl ether; $TiO_2$ nanoparticles; Diesel engine; Emissions, Performance

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## 1. Introduction

Growing concerns about the environment and depletion of fossil fuels have driven the exploration of alternative fuel sources, leading to the development of biodiesels [1], waste cooking [2] and waste plastic oils [3] as sustainable fuel options. Biodiesel is produced from vegetable oils and animal fats, and offers a cleaner-burning alternative to petroleum diesel. It is typically produced through transesterification, where triglycerides react with alcohol to form fatty acid methyl esters, the primary component of biodiesel. Biodiesels from non-edible sources, like jatropha, Alexandrian laurel, and karanja, are particularly attractive because they do not compete with food crops. These biodiesels have demonstrated the ability to lower greenhouse gas emissions and improve engine performance with minor modifications [4]. On the other hand, waste plastic oils (WPO) offer a way to convert non-biodegradable plastic waste into fuel through a process known as pyrolysis. WPOs provide dual benefits: reducing plastic pollution and contributing to energy generation. Waste plastic pyrolysis oils (WPPO) are derived through the thermal degradation of plastic waste, producing a liquid fuel suitable for use as fuel in diesel engines [5]. Several

## Nomenclature

**Abbreviations and Acronyms**

$Al_2O_3$– aluminium oxide
BSFC– brake specific fuel consumption
BTE – brake thermal efficiency
$CeO_2$ – cerium oxide
CO – carbon monoxide
$CO_2$ – carbon dioxide
DEE – diethyl ether
HC – hydrocarbon
MgO – magnesium oxide
$NO_x$ – nitrogen oxides
PM – particulate matter
$TiO_2$ – titanium dioxide
UBHC – unburnt hydrocarbon
WPD20– 80% diesel, 20% WPPO
WPD20E5– 80% diesel, 20% WPPO and 5% diethyl ether
WPD20E5T50 – 80% diesel, 20% WPPO, 5% diethyl ether and 50 ppm $TiO_2$ nanoparticles
WPD20E5T100 – 80% diesel, 20% WPPO, 5% diethyl ether and 100 ppm $TiO_2$ nanoparticles
WPPO – waste plastic pyrolysis oil
ZnO – zinc oxide

studies have evaluated the potential of WPPO as a substitute for diesel [6]. Murugan et al. [7] examined the use of WPPO in a single-cylinder diesel engine and found that the WPPO mixture showed lower combustion efficiency in comparison to neat diesel, which led to an increase in unburnt hydrocarbon (UBHC) and CO emissions. The study attributed these higher emissions to poor atomization and incomplete combustion, which are typical challenges associated with WPPO due to its lower volatility. Yaqoob et al. [8] also evaluated the working characteristics of a diesel engine running on WPPO-diesel blends and revealed that $NO_x$ emissions were reduced due to decreased temperatures in the cylinder, but UBHC and CO emissions notably increased compared to those from conventional diesel fuel. The study suggested that the presence of heavy aromatic hydrocarbons in WPPO contributed to the incomplete combustion, leading to higher levels of CO and UBHCs. Moreover, the increased viscosity of WPPO in comparison to diesel led to inadequate fuel atomization, which contributed to incomplete combustion and elevated emissions of unburnt hydrocarbons. Januszewicz et al. [9] examined the effect of different WPPO-diesel blends on engine performance and emissions. The outcomes have shown that a higher blending ratio of WPPO in the fuel blend led to reduced $NO_x$ emissions but there was a rise in CO and UBHC emissions. This was attributed to the decreased amount of oxygen in WPPO, which hindered complete combustion and resulted in the formation of more unburnt fuel particles. The study also highlighted that WPPO blends up to 20% performed well. Wongkhorsub et al. [10] carried out an experimental investigation to assess the emissions from a diesel engine operating on WPPO-diesel blends. Their findings were consistent with earlier studies, showing that WPPO blends deceased emissions of $NO_x$ while UBHC and CO were raised. The researchers observed that the reduction in $NO_x$ emissions could be linked to the decreased flame temperature during combustion, which hindered the generation of thermal $NO_x$. Comparable results were noted by Mani et al. [11] in their study on the performance of a diesel engine powered by WPPO-diesel blends. They found that WPPO blends resulted in higher levels of emissions of UBHC and CO. This was mainly due to the incomplete oxidation of hydrocarbons during combustion. However, the study also highlighted a reduction in $NO_x$ emissions, which was attributed to the lower combustion temperatures associated with WPPO. The lower peak combustion temperature suppressed the formation of thermal $NO_x$, thus reducing overall $NO_x$ emissions. Despite this benefit, the higher levels of unburnt hydrocarbon (UBHC) and CO emissions pose a significant challenge to the widespread adoption of waste plastic pyrolysis oils (WPPO) as a fuel.

Various strategies, including blending WPPO with oxygenated additives have been explored to mitigate these challenges [12,13]. Various studies have explored the fuel additives and oxygenated compounds to improve combustion efficiency and reduce emissions. Diethyl ether (DEE), an oxygenated additive, has been investigated for its potential to enhance the combustion characteristics of alternative fuels like WPPO [14]. Because of its high oxygen concentration and cetane number, DEE promotes better fuel atomization, faster ignition, and more complete combustion. Kumar et al. [15] reported that adding DEE to WPPO-diesel blends improved engine performance, particularly brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC), while also reducing CO and hydrocarbon (HC) emissions. The presence of DEE led to better combustion, thereby lowering the levels of harmful exhaust emissions. However, the study also noted that $NO_x$ emissions remained relatively high, which may be attributed to the higher combustion temperatures due to DEE. Samraj et al. [16] conducted an experimental analysis on a diesel engine fuelled with DEE-diesel blends and observed a significant reduction in smoke opacity and CO emissions. This reduction was attributed to the oxygenated nature of DEE, which improved the oxidation of fuel during combustion. Kumar et al. [17] found that DEE improves combustion efficiency in biodiesel blends, reducing UBHC and CO emissions. Similarly, Kaimal et al. [18] reported that DEE in WPPO blends improves combustion while reducing UBHC and CO, but slightly increases nitrogen oxide emissions due to increased temperatures in the cylinder. Sezer et al. [19] highlighted DEE's potential in reducing particulate matter (PM) and improving combustion in diesel-biodiesel blends, with similar reductions in CO and UBHC. Rakopoulos et al. [20] studied DEE as an additive in a diesel-WPPO blend and found that DEE lowers the exhaust emissions but there was a reduction in engine performance. Varpe et al. [21] reported similar findings in biodiesel-DEE blends. At higher DEE concentrations, they observed an increase in BSFC. This was due to the reduced energy content of the DEE-biodiesel blend, which necessitated more fuel to achieve the required energy output. Additionally, the lower viscosity of DEE negatively impacted fuel atomization in the combustion chamber, reducing combustion efficiency and leading to incomplete combustion at high loads.

Studies have demonstrated that blending DEE with WPPO biodiesel-diesel blends effectively reduces the engine emissions. However, reduced performance and increased $NO_x$ emissions remained a challenge, highlighting the need for further enhancements, such as incorporating nano-additives to mitigate this problem [22]. Kaushik et al. [23] investigated aluminium oxide ($Al_2O_3$) nanoparticles in diesel-biodiesel blends. They found improved BTH, reduced BSFC, and lowered CO, UBHC and PM emissions. The improved combustion was attributed to the catalytic effects of $Al_2O_3$. El-Adawy et al. [24] explored the impact of zinc oxide (ZnO) nanoparticles in biodiesel-diesel blends. ZnO improved combustion by increasing the oxygen content, reducing CO and UBHC emissions, but nitrogen oxide emissions were found slightly increased due to higher combustion temperatures. Sathyamurthy et al. [25] examined titanium dioxide ($TiO_2$) nanoparticles in WPPO-diesel blends. The study reported improved BTE, reduced BSFC and lower CO and UBHC emissions due to the improved combustion. Yusuf et al. [26] explored the effect of biodiesel blends in cerium oxide nanoparticles. It was noted that $CeO_2$ incorporated blends improve combustion and reduce CO and UBHC emissions. Rastogi et al. [27] studied copper oxide (CuO) nanoparticles in biodiesel-diesel blends. The outcomes revealed that CuO nanoparticles incorporated blends enhance the atomization, resulting in reduced CO, UBHC and smoke emissions, due to higher combustion temperatures. Alex et al. [28] reported the use of $CeO_2$ in diesel-biodiesel blends, which causes an improvement in BTE and BSFC. The outcomes also showed reduced CO, $NO_x$ and UBHC emissions. Jayaraman et al. [29] investigated the use of magnesium oxide (MgO) nanoparticles in diesel-WPPO blends. MgO improved combustion and emission characteristics, especially in reducing CO and smoke opacity. Gad et al. [30] conducted experiments on a diesel engine fuelled with waste cooking oil with blended graphene nanoparticles and carbon nanotubes (CNTs). The outcomes have shown that the addition of nanoparticles causes an improvement of 19% in BTE and a reduction of 54% in smoke emissions. Kishore et al. [31] studied the role of iron oxide ($Fe_2O_3$) nanoparticles in improving the combustion of biodiesel blends. They found that $Fe_2O_3$ reduced CO and UBHC emissions while enhancing BTE. Gavhane et al. [32] used silica ($SiO_2$) nanoparticles in diesel-biodiesel blends, resulting in reduced CO and PM emissions. $SiO_2$ also improved fuel atomization, enhancing engine performance, though $NO_x$ levels increased slightly due to higher peak temperatures. Dinesha et al. [33] examined the effect of cerium oxide nanoparticles in WPPO blends. They found that $CeO_2$ reduces the exhaust emissions, like smoke and CO. Rajammagari and Wani [34] investigated the impact of ZnO nanoparticles incorporated with a diesel-ethanol blend on diesel engine performance. The addition of nano-additives to the ethanol-diesel blend showed improved engine performance, with a 5.73% increase in BTE and 8.31% reduction in BSFC. Emissions of CO, $NO_x$ and UBHC were decreased by 21.96%, 6.41% and 12.07%, respectively.

The synergistic effects of combining WPPO, DEE, and nano-additives in diesel fuel have been less explored, but the potential for enhanced performance and emission control is significant. To the best of the authors' knowledge, no prior study has examined the combined impact of DEE and nano-additives on diesel engine operation. Therefore, this study focuses on incorporating DEE and nano-additives into diesel-WPPO blends to enhance engine performance and emissions control, representing a novel approach. The studies carried out with four fuel blends representing WPD20, WPD20E5, WPD20E5T50 and WPD20E5T100 are made across four load levels (25% to 100%), and the performance of fuel blends is compared to pure diesel.

## 2. Materials and methods

### 2.1. Experimental test setup

In this study, a water-cooled single-cylinder diesel engine with common rail direct injection was utilised. Figure 1 illustrates the setup of the test rig, while Table 1 provides the engine specifications. The load has been applied to the engine using an eddy current dynamometer.

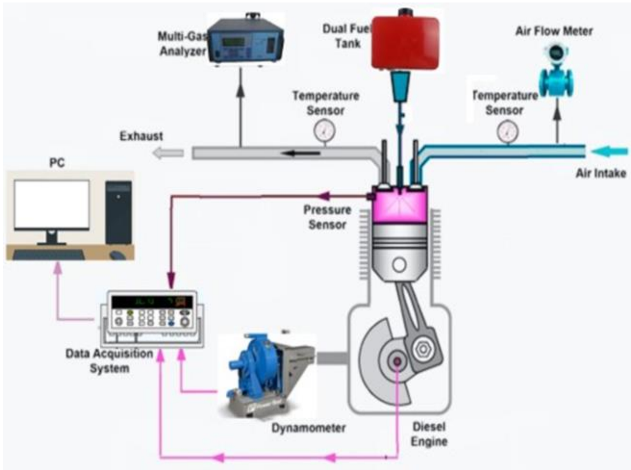


Fig. 1. Layout of the experimental setup.

Table 1. Specifications of diesel engine.

| Description | Specifications |
|---|---|
| Make | Kirloskar |
| Type | 4 stroke single cylinder CRDI diesel engine |
| Bore × stroke | 87.5 × 110 mm |
| Swept volume | 661cc |
| Rated speed | 1500 rpm |
| Rated power | 3.5 kW |

Fuel and air flow rates were measured using transmitters, while engine speed was monitored via a proximity sensor. Performance parameters of the engine were recorded and analysed through computerised engine analysis software (Engine Soft). Additionally, exhaust emissions, including $NO_x$, HC and CO, were evaluated using a multi gas emission analyser to monitor and assess the engine emissions. Smoke emissions were monitored by using an AVL smoke meter.

## 2.2. Production and preparation of waste plastic pyrolysis oil blends

High-density polyethylene (HDPE) plastic waste, sourced from the Warangal municipality corporation, was chopped into small pieces ranging between 1–4 cm² for this experiment. The plastic chips were thoroughly washed to remove any contaminants, and a dryer was used to eliminate all moisture content. The chips were then gradually fed into the reaction chamber. The pyrolysis process was carried out in a custom-designed reactor, with dimensions of 50 cm in height and 30 cm in diameter, as depicted in Fig. 2. A temperature controller maintained the reaction temperature between 350–400°C, and the process was sustained for 4 hours under atmospheric pressure. The pyrolysis process resulted in a yield comprising 71% plastic oil, 20% solid coke residue, and 9% gaseous fractions by weight. This distribution highlights the efficiency of converting plastic waste into usable fuel, with the majority being recovered as liquid oil, which can be utilised as a fuel source.

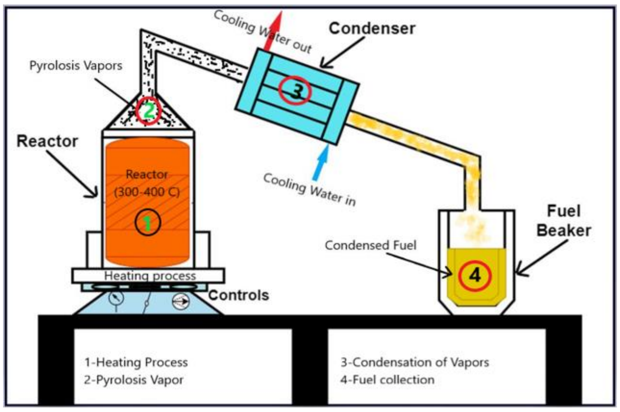

Fig. 2. Production of waste plastic pyrolysis oil.

For fuel blend preparation, WPPO, diesel and DEE were mixed in different proportions. WPPO was mixed with diesel at a ratio of 20% by volume (WPD20), and DEE was added to enhance combustion properties, typically at 5% by volume (WPD20E5). The readily available DEE was purchased from Symax Laboratories located in Hyderabad, Telangana. Nano-additives, such as $TiO_2$, were added in concentrations of 50 and 100 ppm to further improve fuel properties. The $TiO_2$ nanoparticles were purchased from Nano Research Lab Jharkhand, and the specifications of $TiO_2$ nanoparticles are provided in Table 2.

Table 2. Specifications of $TiO_2$ nanoparticles.

| Molecular formula | $TiO_2$ |
|---|---|
| Appearance | White solid |
| Molecular weight, g/mol | 79.87 |
| Density, g/cm³ | 4.23 |
| Purity | 99.9% |
| Morphology | Nearly spherical |
| Titanium content (based on metal) | 99.6% |
| Chemical composition: titanium/oxygen | 59.33%/40.55% |
| Average particle size, nm | 25-40 |
| Thermal conductivity, W/(m K) | 8.6 |

Nanoparticles characterization has been done by SEM and XRD analysis to confirm the morphology and purity of the nanoparticles as illustrated in Fig. 3. The diffraction peaks of $TiO_2$ nanoparticles in Fig. 3 (b) are in line with the previous study conducted by Simhadri et al [35]. To ensure uniform dispersion of nano-additives, the fuel blends were subjected to ultrasonic agitation for 30 minutes, and a surfactant (Span80) was added to stabilise the nano-additives in the fuel. The detailed specifications of the ultrasonicator bath is provided in Table 3.

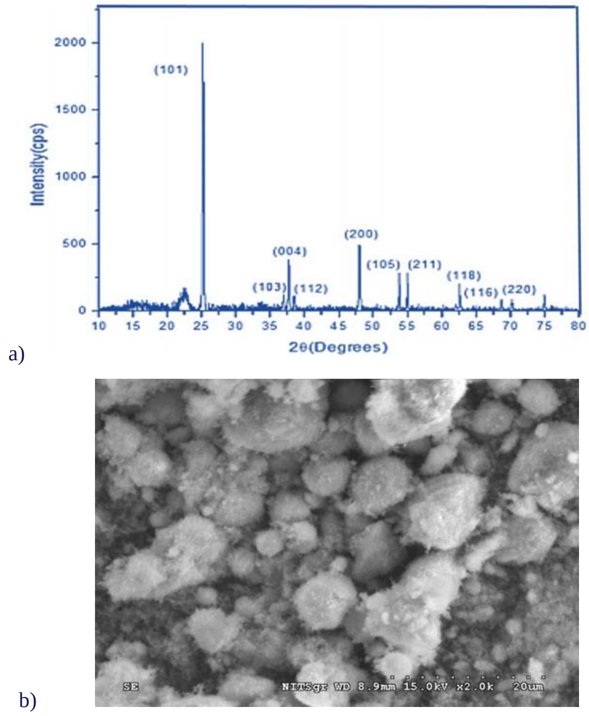

Fig. 3. XRD (a) and SEM (b) of $TiO_2$ nanoparticles.

Table 3. Specifications of ultrasonicator bath.

| Description | Specifications UC-2A |
|---|---|
| Make | LABMAN |
| Tank volume (litres) | 2.5 L |
| Ultrasonic wattage | 50 W |
| Ultrasonic frequency | 40 ± 3 kHz |
| Heating | Ambient to 80°C digitally controlled (dual display) |
| Digital timer | 5 to 60 minutes |
| Power supply | 220 volt, Ac 50 Hz, single phase |

The fuel preparation flow chart is provided in Fig. 4. The prepared blends are WPD20, WPD20E5, WPD20E5T50 and WPD20E5T100. After the preparation of fuel blends, they have been examined for their physicochemical characteristics, including viscosity, density and calorific value, to ensure compliance with standard fuel characteristics before conducting performance and emission tests on the diesel engine. The fuel properties obtained are presented in Table 4, and the results align with previous studies by Mustayen et al. [36], Pal et al. [37], and Vali et al. [38]. Figure 5 illustrates the final fuel blend of WPD20E5T100.

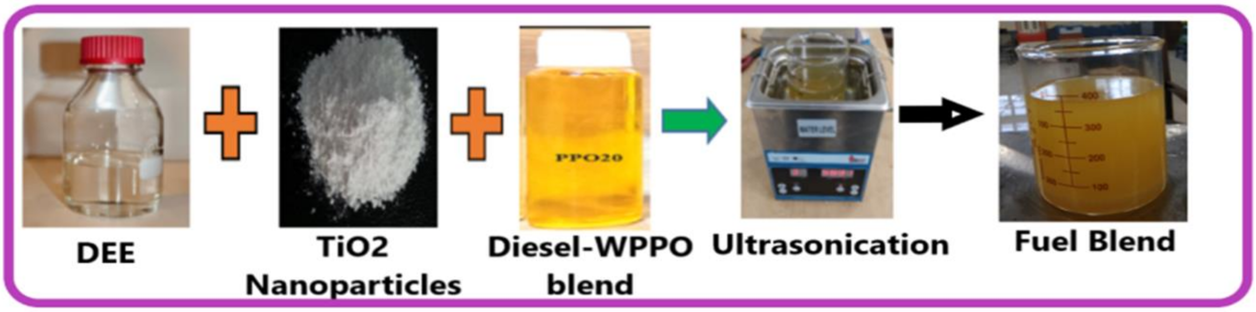


Fig. 4. Fuel preparation flow chart.

Table 4. Properties of fuel blend.

| Property | ASTM standards | Diesel fuel range | D | WPD20 | WPD20E5 | WPD20E5T50 | WPD20E5T100 |
|---|---|---|---|---|---|---|---|
| Density at 15°C , kg/m³ | ASTM D4052 | 820–860 | 825 | 817 | 808 | 808 | 809 |
| Viscosity at 40°C, mm²/s | ASTM D445 | 2.0–4.5 | 3.40 | 3.84 | 3.61 | 3.61 | 3.65 |
| Flash point, K | ASTM D93 | 315–350 | 324 | 320 | 310 | 312 | 315 |
| Calorific value, MJ/kg | ASTM D5865 | 42–45 | 43.2 | 43.8 | 43.4 | 43.6 | 43.9 |

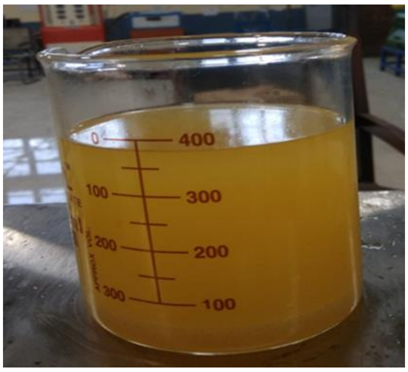

Fig. 5. Final fuel blend (WPD20E5T100).

## 3. Results and discussion

### 3.1. Brake thermal efficiency

In Fig. 6, the variation of BTE with different test fuels and various loads is presented. As the engine load increases from partial load to full load, there is a noticeable improvement in BTE across all fuel blends. This increase can be attributed to the fact that higher loads generally lead to increased combustion temperatures and better energy utilisation in the engine. In the case of the WPD20 blend, which combines WPPO with diesel, there is a modest improvement in BTE compared to pure diesel. This suggests that WPPO contributes positively to the combustion process by providing additional fuel energy. However, when 5% DEE is introduced into the blend (WPD20E5), a slight decrease in BTE is observed in contrast to WPD20. This reduction can be attributed to DEE's lower calorific value, which reduces the overall energy content of the blend, resulting in a slight decrease in BTE. Despite this, the addition of $TiO_2$ nanoparticles to the WPD20E5 blend significantly improves BTE at all loads and shown higher BTE compared with other fuel blends. A similar trend is also observed in previous research conducted by Vali et al. [38] and Chellaih et al. [39]. The nanoparticles enhance the fuel-air mixing and promote better atomization, leading to more complete combustion and shorter ignition delay. At full load, the WPD20E5T100 blend, with 100 ppm of $TiO_2$ nanoparticles, achieves a 5.26% and 2.24% improvement in BTE in contrast to neat diesel and WPD20 blend. This highlights the role of $TiO_2$ nanoparticles in optimizing combustion efficiency and improving overall engine performance, particularly under high-load conditions.

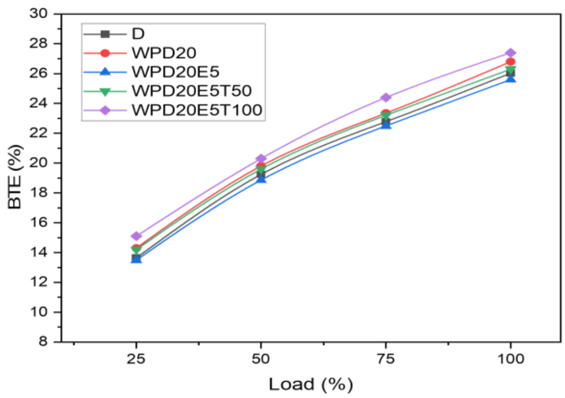


Fig. 6. BTE of various fuel blends under different load conditions.

### 3.2. Brake specific fuel consumption

Figure 7 illustrates the changes in BSFC for the various test fuels at different engine load levels. The trend in BSFC reveals a consistent pattern of improved fuel efficiency with increasing engine load. As the load moves from partial to full, BSFC decreases across all fuel blends, which indicates that the engine becomes more efficient in fuel utilisation under higher loads.

Specifically, the WPD20 blend shows a modest reduction in BSFC compared to pure diesel. This suggests that incorporating WPPO helps enhance fuel energy content. On the other hand, the introduction of 5% diethyl ether to the WPD20 blend results in a slight increase in BSFC due to DEE's lower energy content, leading to increased consumption of fuel to achieve the same power output. Nevertheless, the presence of $TiO_2$ nanoparticles in the blends showed a notable reduction in BSFC, which was found minimum compared with other fuel blends at all loads. Similar outcomes are reported by Srinivasarao et al. [40] in their study conducted on a diesel engine using calophyllum biodiesel with ZnO nanoparticles. At the full load, the WPD20E5T100 blend demonstrates the lowest BSFC at 0.287 kg/kWh, marking an 8.31% and 4.65% decrease over neat diesel and WPD20 blend. This significant reduction in BSFC is attributed to the enhanced fuel atomization and combustion efficiency provided by the $TiO_2$ nanoparticles, which facilitate more complete combustion and optimisation of fuel economy, especially under high-load conditions.

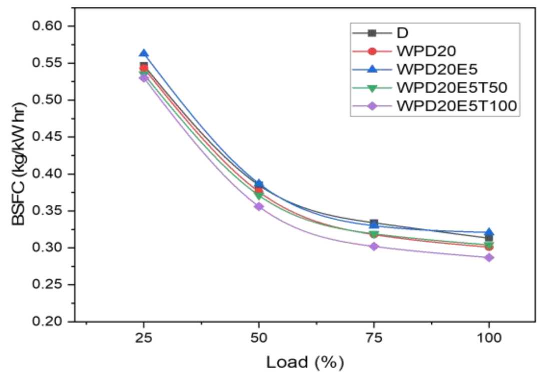


Fig. 7. BSFC of various fuel blends under different load conditions.

### 3.3. Carbon monoxide emissions

In Fig. 8, the change in CO emissions with different loads for various test fuels is illustrated. The CO emissions data reveal a consistent pattern across different engine loads. As the load increases from partial to full, CO emissions are raised for all fuel blends. The WPD20 blend, exhibits slightly higher CO emissions than pure diesel, reflecting the influence of WPPO's composition on combustion efficiency. The WPD20E5 blend shows a marginal decrease in CO emissions compared to WPD20, at all loads. This decrease is due to DEE's oxygen content, which may lead to improved combustion. Furthermore, the inclusion of $TiO_2$ nanoparticles in the WPD20E5T50 and WPD20E5T100 blends significantly reduces CO emissions at all loads compared with other blends. At full load, the WPD20E5T100 blend shows a 9.2% and 6.86% reduction in comparison to WPD20 and pure diesel. This decrease signifies an improved combustion efficiency due to the $TiO_2$ nanoparticles, which boost fuel atomisation as well as fuel and air mixing, resulting in enhanced combustion and reduced CO emissions. The results demonstrate that $TiO_2$ nanoparticles are effective in mitigating CO emissions.

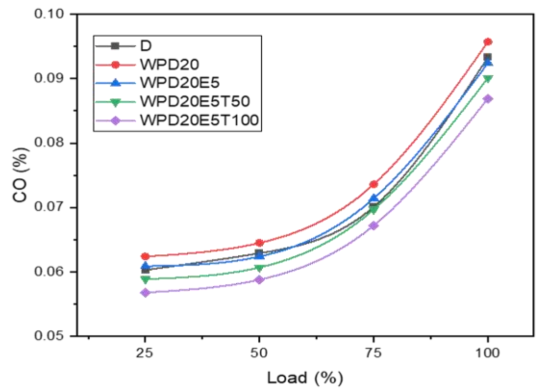


Fig. 8. CO emissions of various fuel blends under different load conditions.

### 3.4. Smoke emissions

Figure 9 illustrates the changes in emissions of smoke for all test fuels at varying load levels.

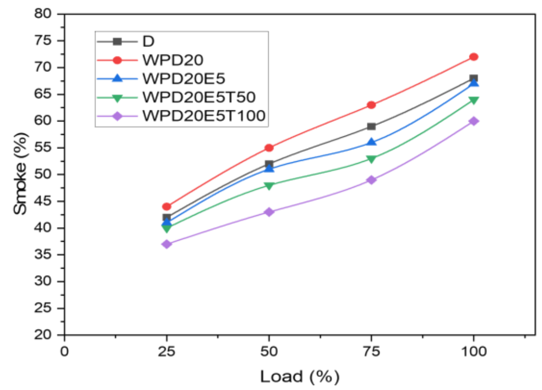


Fig. 9. Smoke emissions of various fuel blends under different load conditions.

The analysis of smoke emissions across varying engine loads shows a distinct pattern. As the load rises, smoke emissions also rise for all fuel blends. The WPD20 blend results in increased smoke emissions in contrast to diesel due to the less efficient combustion characteristics of WPPO. The introduction of 5% diethyl ether in the WPD20E5 blend slightly reduces smoke emissions compared to the WPD20 blend, indicating some improvement in combustion efficiency. However, the decrease in smoke emissions is noted with the addition of $TiO_2$ nanoparticles to the WPD20E5 blend. It has been observed that the smoke emission is reduced with respect to the concentration of nanoparticles in the WPD20E5 blend. The reduction at full load for the WPD20E5T100 blend records the lowest smoke emissions with an 11.8% and 16.67% reduction over pure diesel and WPD20 blend. It is attributed to better fuel-air mixing, accelerated combustion facilitated by their catalytic properties, and a shorter ignition delay, all contributing to more efficient combustion and lower smoke emissions. Overall, $TiO_2$ nanoparticles effectively reduce smoke emissions, especially under higher engine loads.

### 3.5. Unburned hydrocarbon emissions

Figure 10 depicts the changes in UBHC emissions for various fuel blends across different engine load conditions.

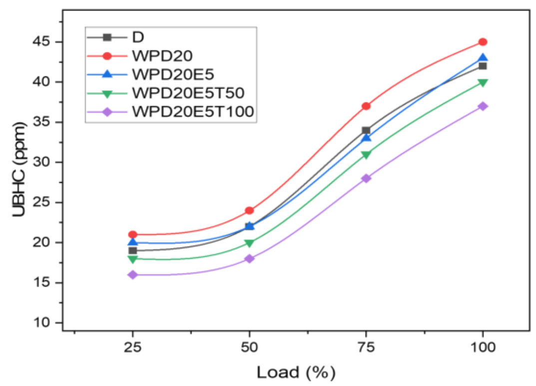


Fig. 10. UBHC emissions of various fuel blends under different load conditions.

The examination of unburned hydrocarbon emissions shows a clear trend as engine load increases. UBHC emissions rise across all fuel blends from partial to full load. The WPD20 blend exhibits increased UBHC emissions when compared to diesel fuel, likely due to the less efficient combustion of WPPO. The addition of DEE in the WPD20E5 blend displays a slight reduction in UBHC emissions relative to WPD20 blend, due to DEE's role in enhancing combustion. The incorporation of $TiO_2$ nanoparticles in the WPD20E5 blend significantly lowers UBHC emissions at all loads in comparison with all fuel blends. The WPD20E5T100 blend, in particular, attains the lower UBHC emissions in comparison to the other fuel blends. At full load, WPD20E5T100 blend results in 17.78 and 11.9% lower UBHC emissions in comparison with WPD20 blend and pure diesel. This can be attributed to the enhanced catalytic activity of the nanoparticles and their high surface-to-volume ratio, which improves fuel atomization and combustion efficiency, resulting in reduced hydrocarbon emissions.

### 3.6. Nitrogen oxide emissions

The evaluation of $NO_x$ emissions across various engine loads shown in Fig. 11 reveals the distinct patterns of different fuel blends. It was noted that $NO_x$ emissions rise with an increase in engine load. The WPD20 blend shows a slight reduction in emissions of $NO_x$ in contrast to diesel, but the emissions remain relatively high. The WPD20E5 blend results in a small rise in $NO_x$ emissions compared to the WPD20 blend. It is attributable to a DEE tendency to raise temperatures during combustion and also to the existence of oxygen in DEE molecular structure, which increases the oxygen availability during combustion, further contributing to higher $NO_x$ formation. It was noticed that the addition of $TiO_2$ nanoparticles to the WPD20E5 blend lowers $NO_x$ emissions at all loads compared with other fuel blends. The level of reduction in $NO_x$ emissions is inversely proportional to the amount of $TiO_2$ nanoparticles in the fuel blend.

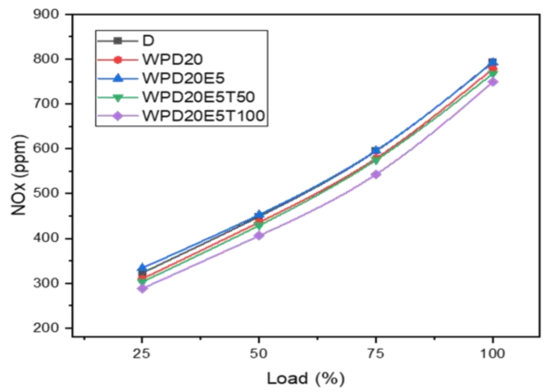


Fig. 11. $NO_x$ emissions of various fuel blends under different load conditions.

In particular, the WPD20E5T100 blend records the lowest $NO_x$ emissions marking a 5.7% and 3.85% reduction over pure diesel and WPD20 blend. The reduction in nitrogen oxide emissions with $TiO_2$ nanoparticles is due to the enhanced combustion efficiency and improved air-fuel mixing, which help lower the peak combustion temperatures and shorten ignition delay, which typically results in lower $NO_x$ formation.

## 4. Conclusions

The experimental results highlight the impact of various fuel blends on engine performance and emissions at different loads. Incorporating WPPO into diesel blends demonstrated improvements in performance whereas an increase in emissions was observed. The addition of DEE and $TiO_2$ to diesel-WPPO blends showed an improved performance as well as a reduction in emissions, with the highest efficiency achieved using $TiO_2$ nanoparticles in the WPD20E5T100 blend. The experimental results revealed the following key findings:

- BTE of the engine was improved by the addition of nanoadditives to fuel blends, and the maximum BTE was found for the WPD20E5T100 blend in comparison with diesel fuel. The percentage of improvement is 5.26% at full load.
- This blend also showed significant reductions in BSFC and smoke emissions, with the notable reduction of up to 8.31% and 11.8%, respectively, compared to pure diesel.
- In terms of CO emissions, the WPD20E5T100 blend showed the most substantial reduction, achieving a 6.86% reduction over neat diesel. Similarly, UBHC emissions were notably lower with the $TiO_2$ nanoparticle-enhanced blends, with WPD20E5T100 showing a reduction of up to 11.9% compared to diesel.
- However, $NO_x$ emissions were higher with DEE addition and varied across different blends. The WPD20E5T100 blend achieved the lowest $NO_x$ emissions, showing up to a 5.7% reduction compared with diesel fuel at full load.

Overall, the use of $TiO_2$ nanoparticles in WPPO-DEE-diesel blends enhanced engine performance, reduced CO, UBHC, $NO_x$ and smoke emissions, and demonstrated significant improvements in BSFC. Overall, the findings suggests that the

WPD20E5T100 blend achieved the optimised results at all loads in comparison with other fuel blends.

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