



Synergistic Effects of CNT-TiO₂ Nanoparticles on Combustion and Performance Characteristics of Waste Plastic Oil–Diesel Blends

N. Isaac Jinu¹, E. Sangeethkumar¹, T. Ahilan¹, V. Ramanathan¹, B. Gajalakshmi², S. Karthikeyan³, V. Hariram^{4*} and Rathod Deepit Nilesh¹

¹Department of Automobile Engineering, Hindustan Institute of Technology and Science, Padur, Chennai, TN, India

²Department of Chemistry, Hindustan Institute of Technology and Science, Padur, Chennai, TN, India

³Centre for Computational Modeling, Department of Mechanical Engg, Chennai Institute of Technology, Chennai, TN, India

⁴Department of Mechanical Engineering, Hindustan Institute of Technology and Science, Padur, Chennai, TN, India

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*connect2hariram@gmail.com



ABSTRACT

The growing demand for energy and the environmental challenges associated with conventional fossil fuels have driven the search for sustainable and efficient alternative fuels for compression-ignition (CI) engines. In this study, waste plastic oil (WPO), derived from the pyrolysis of discarded plastics, was used as a partial substitute for diesel fuel, along with a hybrid nano-additive consisting of carbon nanotubes (CNTs) and titanium dioxide (TiO₂), to enhance fuel properties. A base fuel blend of diesel and plastic oil in the ratio of 85:15 was prepared, and CNT–TiO₂ nanoparticles were added at concentrations of 10 ppm, 25 ppm, and 50 ppm using magnetic stirring and ultrasonication. The blends were tested in a single-cylinder, four-stroke Kirloskar diesel engine under varying load conditions. Key parameters, including brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), heat release rate (HRR), and cylinder pressure (CP), were analyzed. The results showed a 3.53% increase in BTE and a 6.86% reduction in BSFC for the nano-additive blend compared with the corresponding fuel blend without nano-additives. This enhanced performance was primarily attributed to improved fuel atomization and the enhanced catalytic activity of the nanoparticles, leading to more complete combustion.

Keywords: Waste plastic oil; Diesel engine; CNTs; TiO₂ nanoparticles; Nano-additives; Alternative fuels; Brake thermal efficiency; Brake-specific fuel consumption.

1. INTRODUCTION

Diesel fuel has been the backbone of modern society for decades, powering transportation systems, industrial operations, and power generation facilities worldwide. Its widespread use is primarily attributed to its high energy density, superior fuel efficiency, and ability to perform reliably under heavy-duty operating conditions (Venkatesan *et al.* 2019). From trucks and buses to agricultural machinery and construction equipment, diesel engines are everywhere, quietly supporting economic growth and infrastructure development (Shekofteh *et al.* 2020). In countries such as India, diesel serves as a critical energy source that significantly influences agricultural activities, transportation logistics, and the cost of consumer goods. At the same time, this heavy dependence on diesel has created some serious challenges. The burning of diesel releases pollutants, including nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM), which contribute to air pollution and pose adverse environmental impacts (Khan *et al.* 2016; Kumar *et al.* 2020; Hariram *et al.* 2025). With the gradual depletion of fossil fuel reserves and increasing

environmental concerns, researchers have been actively exploring cleaner and more sustainable alternatives that can partially or completely replace conventional diesel fuel. One such promising alternative is waste plastic oil, which is derived from discarded plastic through pyrolysis. Plastics, which are otherwise a major environmental problem, contain high-energy content because they are made of hydrocarbons. Through a process called pyrolysis, these plastics can be converted into useful fuel. In this process, plastic is heated in the absence of oxygen, breaking it down into liquid oil, gas, and solid residue (Hariram *et al.* 2019). The liquid fraction obtained from plastic pyrolysis, known as waste plastic oil (WPO), possesses physicochemical properties similar to those of diesel fuel and can be used in internal combustion engines. The large volume of plastic waste generated worldwide further enhances the relevance of this approach. According to recent reports, India alone generates more than 10,000 metric tons of plastic waste per day, of which only about 40% of it is recycled (Chinnappan *et al.* 2022). The remaining plastic waste often accumulates in landfills or enters terrestrial and aquatic environments, resulting in environmental pollution. Converting this waste into fuel not only helps

mitigate pollution but also creates a valuable energy resource. Studies have shown that plastic oil possesses a calorific value and fuel properties comparable to those of diesel, making it suitable for blending with diesel or for direct use in engines under controlled conditions (Alenezi *et al.* 2021). With the growing use of plastics, managing plastic waste has become a major global concern. Improper disposal leads to environmental pollution, adversely affecting soil, water bodies, and marine ecosystems. Rather than being treated solely as waste, plastic is increasingly being recognized as a valuable resource that can be converted into fuel, thereby addressing two critical challenges simultaneously: waste management and energy demand (Hariram *et al.* 2019).

Pyrolysis has emerged as one of the most effective methods for plastic-to-fuel conversion. It can process various plastic feedstocks and produce a liquid fuel with properties comparable to those of diesel. However, the direct use of WPO in diesel engines may not always yield optimal performance. Blending WPO with diesel enables its utilization in existing engines without significant modifications, thereby enhancing its practical feasibility for real-world applications (Najafi and Shadidi, 2024). The performance of these blends depends largely on the mixing ratio. When properly optimized, plastic oil–diesel blends can achieve brake thermal efficiency comparable to, or slightly higher than, that of neat diesel. In addition, their use can reduce dependence on conventional fossil fuels. From an economic perspective, waste plastic oil can serve as a viable alternative fuel, provided that its production cost remains significantly lower than that of conventional diesel, ideally below 85% of the diesel's price (Awang *et al.* 2021). For any alternative fuel to be practically viable, its properties and performance characteristics should be comparable to those of conventional fuels in engine applications. Therefore, the physicochemical properties of plastic pyrolysis oil are extensively characterized and compared with established diesel fuel standards, such as ASTM D975 and EN 590. Studies have shown that WPO derived from feedstocks such as high-density polyethylene (HDPE) and polypropylene exhibits properties comparable to those of conventional diesel fuel.

Key parameters such as density, viscosity, and calorific value fall within acceptable limits for engine operation. In addition, the relatively low sulphur content of waste plastic oil is advantageous in terms of emissions. Moreover, the hydrocarbon composition of WPO is comparable to that of diesel fuel, which contributes to combustion stability. Because of this compatibility, plastic oil can be used in diesel engines either in blended form or, in some cases, even directly without requiring major engine modifications.

Despite these advantages, several challenges remain, including long-term storage stability, fuel quality

consistency, and potential effects on engine components. Further research is required to address these issues and to optimize refining and blending techniques, thereby enhancing the viability of waste plastic oil as an alternative fuel. In the pursuit of improved fuel performance and reduced emissions, researchers have increasingly explored the application of nanotechnology in fuel formulations. Diesel–biodiesel blends were initially introduced as a means of reducing emissions; however, they are often associated with drawbacks such as higher viscosity, lower energy content, and, in some cases, increased NO_x emissions (Prabu *et al.* 2024; Zamzamian *et al.* 2025). To overcome these limitations, nanoparticles have emerged as promising fuel additives.

Due to their small particle size and high surface-area-to-volume ratio, nanoparticles enhance fuel–air mixing, improve heat transfer, and promote more complete combustion (Seela *et al.* 2022). As a result, engines running on nano-enhanced fuels often exhibit higher BTE, lower fuel consumption, and reduced emissions such as CO and HC (Kumar *et al.* 2013; Gopinath and Devan, 2020).

Various nanoparticles have been studied, including TiO₂, aluminium oxide (Al₂O₃), and CNTs. Among these, CNTs have gained significant interest due to their excellent thermal conductivity and catalytic properties, which can enhance combustion efficiency and overall engine performance. Similarly, TiO₂ nanoparticles have demonstrated the potential to improve combustion and reduce exhaust emissions when incorporated into diesel fuel blends (Mani *et al.* 2010; Hariram *et al.* 2021). More recently, hybrid nano-additives comprising CNTs and TiO₂ have been investigated in diesel–plastic oil blends. Previous studies have reported improvements in engine performance and reductions in exhaust emissions with the use of such hybrid nano-additives. However, the stability and effectiveness of nano-enhanced fuels depend strongly on the nanoparticle dispersion method, mixing technique, and additive concentration. In addition, challenges such as nanoparticle agglomeration, cost, and potential environmental impacts require further investigation (Seela *et al.* 2022; Yusuf *et al.* 2024).

In the present study, a novel approach was adopted for the preparation and incorporation of CNT and TiO₂ nano-additives in diesel–plastic oil blends. The effects of different nano-additive concentrations on fuel stability and engine performance were systematically evaluated.

2. MATERIALS AND METHODS

2.1 Preparation Process of Waste Plastic Oil

The preparation of plastic pyrolysis oil begins with the collection of waste plastics (in this case, plastic

bottles) from municipal or industrial sources. The collected plastics are segregated to remove impurities such as metals and organic matter, and are subsequently washed and dried. The cleaned plastics are shredded into smaller pieces to ensure uniform heating. These shredded plastic pieces are fed into a closed pyrolysis reactor and heated to 300–400 °C in the absence of oxygen. During pyrolysis, the plastics undergo thermal decomposition, whereby long polymer chains are broken down into smaller hydrocarbon molecules, producing condensable vapors along with small quantities of gases and solid residues.



Fig. 1: Pyrolysis setup



Fig. 2: Distilled plastic oil (DPO)

The generated vapours are passed through a condensation system where they are cooled and converted into liquid plastic oil. Then, the oil is collected, while the non-condensable gases can be reused as fuel for heating the reactor, thereby improving the efficiency of the process. The obtained oil is then further filtered to remove all unwanted impurities, and an additional refining process, such as distillation, is carried out to enhance the fuel quality. Due to its relatively high

viscosity and variable composition, distilled plastic oil (DPO) is typically blended with diesel or biodiesel before being used as a fuel in CI engines. Such blending improves fuel properties, engine performance, and fuel stability (Zamzarian *et al.* 2025; Seela, 2022).

2.2 Preparation of Diesel–plastic Oil Binary Blend

Diesel and distilled plastic oil were used as base fuels for the experimental study. They were blended in a ratio of 85:15, denoted as D85/DPO15. For each laboratory sample, a fixed total volume of 250 mL was prepared to ensure consistency. Accordingly, 212.5 mL of diesel and 37.5 mL of plastic oil were measured using a calibrated measuring cylinder and mixed thoroughly to obtain a homogeneous base fuel blend.

2.3 Preparation of CNT–TiO₂ Nano-additive Blend

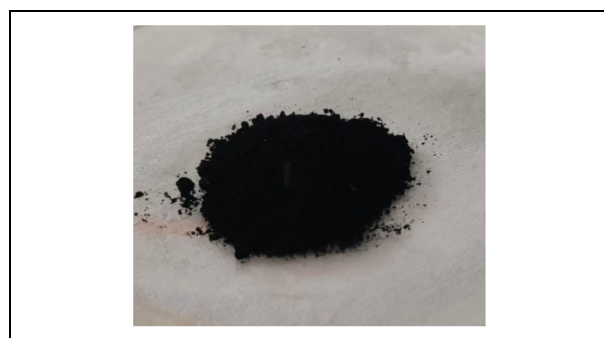


Fig. 3: Carbon nanotubes used in the fuel blend preparation

The fuel samples used for the study are: Diesel (D), Distilled Plastic Oil (DPO), Diesel–Distilled Plastic Oil blend (D85/DPO15), and nano-additive blend (D85/DPO15/CNT–TiO₂).

CNTs and TiO₂ nanoparticles (Figs. 3 and 4) were selected as fuel additives due to their catalytic properties for enhancing combustion. The average particle size of the nanoparticles was 10–30 nm with >99% purity, as provided by the manufacturer. These physicochemical properties ensure effective surface interaction and dispersion within the fuel matrix. The nanoparticles were mixed in equal proportions (1:1 by weight) prior to their addition to the base fuel and were weighed using a high-precision microbalance.

To ensure stable and uniform dispersion of nanoparticles within the fuel, a two-step mixing technique was employed. Initially, the measured nanoparticles were added to the prepared base fuel and subjected to magnetic stirring at 800–1000 rpm for 30 min. This was followed by ultrasonication using a probe-type ultrasonicator operated at a frequency of 20–25 kHz for 45–60 min.

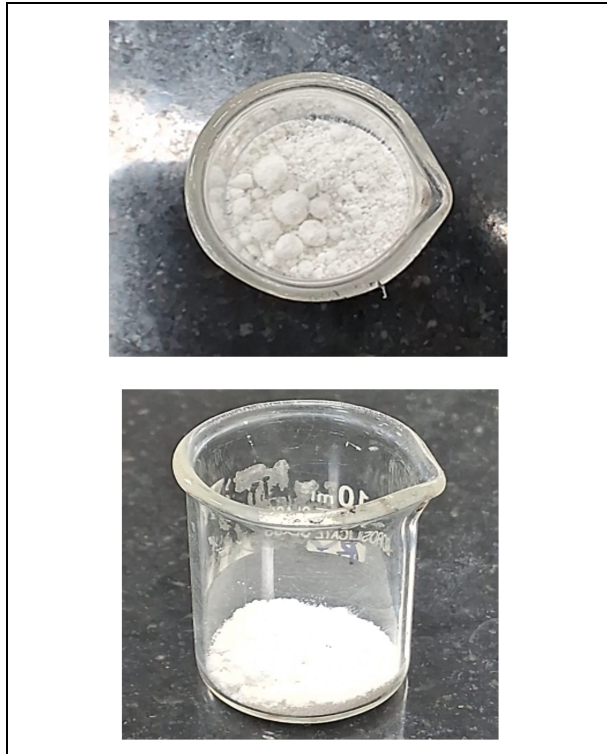


Fig. 4: TiO₂ nanopowder used in the fuel blend preparation

The CNT–TiO₂ nanoparticle blend (Fig. 5) was added to the fuel at concentrations of 10, 25, and 50 ppm (w/w). The required nanoparticle mass was calculated based on the mass of the fuel blend. For a 250 mL fuel blend, the total nanoparticle masses required were 2.1 mg, 5.3 mg, and 10.6 mg for the 10, 25, and 50 ppm concentrations, respectively (Figs. 6a–c and Table 1).



Fig. 5: CNT–TiO₂ nano-additive blend

After the final sonication step, the fuel blends were left undisturbed for 2–3 days to assess sedimentation stability. The 25 ppm CNT–TiO₂ fuel blend exhibited the least sedimentation and was therefore selected for subsequent engine testing.

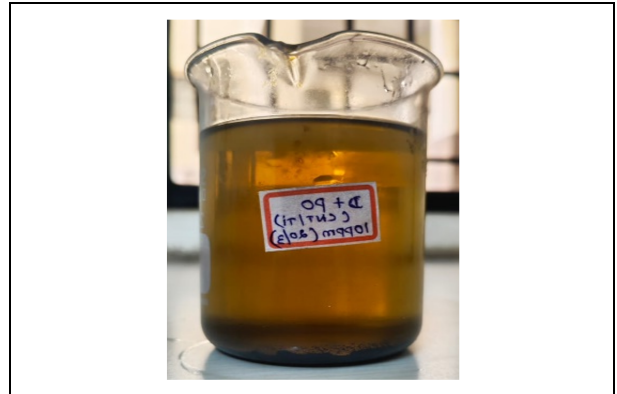


Fig. 6a: 10 ppm CNT–TiO₂ fuel blend

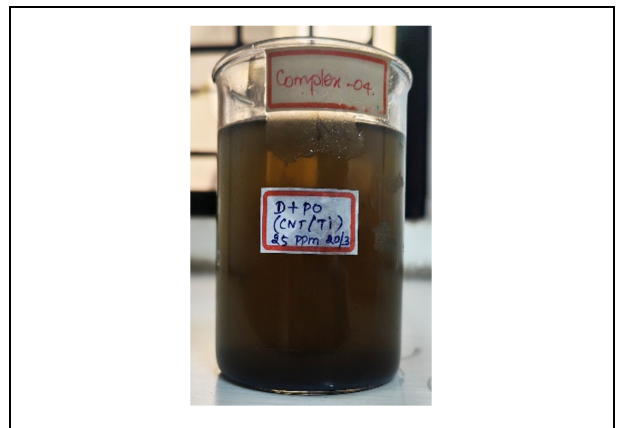


Fig. 6b: 25 ppm CNT–TiO₂ fuel blend



Fig. 6c: 50 ppm CNT–TiO₂ fuel blend

Table 1. Amounts of CNT–TiO₂ nano-additives used for different concentrations

Parts per million	Approximate weight (mg)
10 ppm	2.1 mg
25 ppm	5.3 mg
50 ppm	10.6 mg

2.4 Dispersion Technique

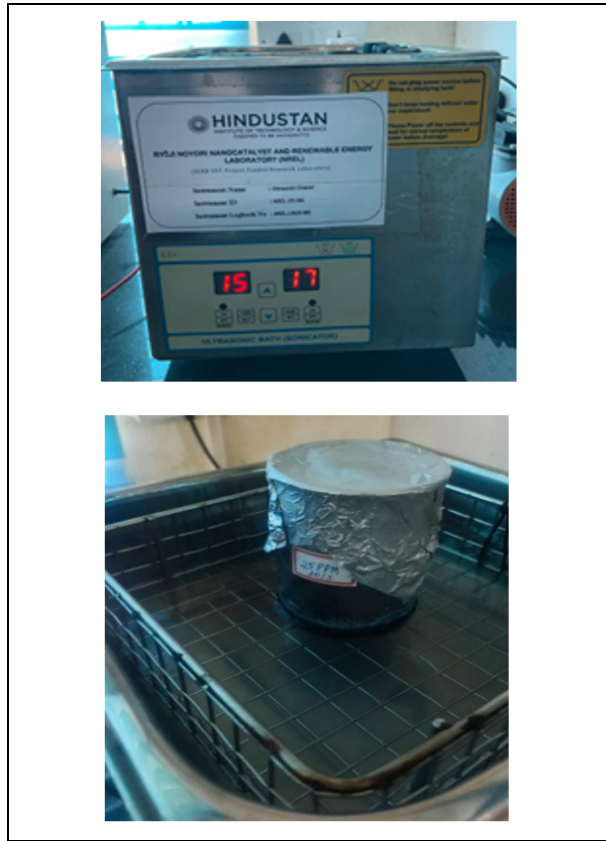


Fig. 7: Sonicator

To achieve uniform nanoparticle dispersion, a two-step dispersion approach was adopted. The weighed CNT and TiO₂ were first dispersed in a small quantity of diesel (20–30 mL) using magnetic stirring for 15–20 min, followed by ultrasonication for 30–45 min (Fig. 7 and 8). Ultrasonication facilitates the breakdown of nanoparticle agglomerates through the generation of high-frequency acoustic waves, which produce cavitation bubbles in the liquid medium. The collapse of these bubbles releases localized energy, promoting the deagglomeration and uniform distribution of nanoparticles throughout the blend, thereby enhancing dispersion stability and reducing sedimentation.

2.5 Stability Analysis

The stability of the prepared nanofuel blends was evaluated using a sedimentation test. The samples were stored in transparent containers and monitored for particle settling over a period of 24–48 h. In addition to visual observation, sedimentation stability was quantitatively assessed by calculating the sedimentation percentage as the ratio of the height of the settled layer to the total fluid height. The results showed that sedimentation remained below 5% during the test period, indicating satisfactory dispersion stability of the nanofuel blends (Dhanapal *et al.* 2024).

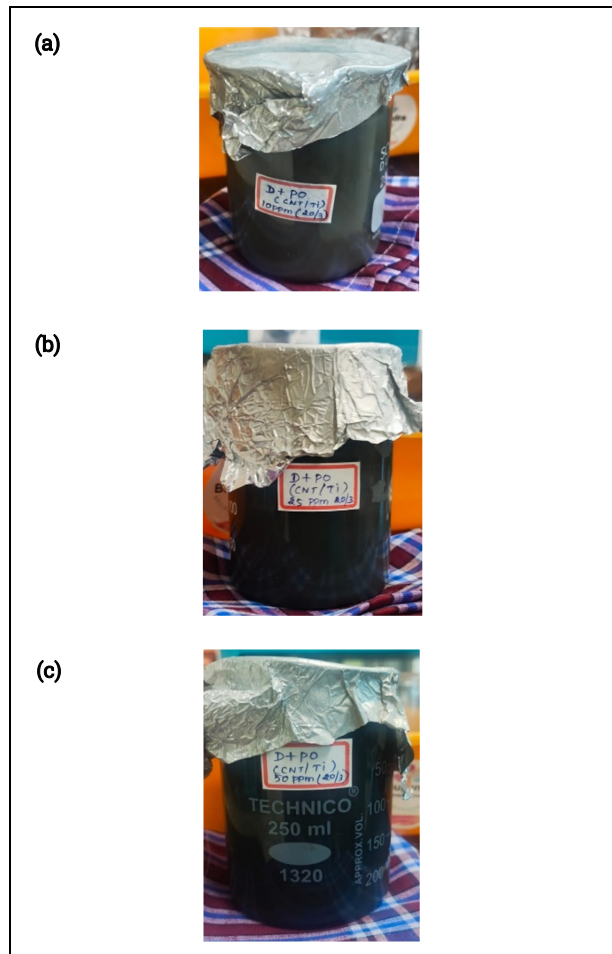


Fig. 8: Nanofuel blend samples after ultrasonication at (a) 10 ppm, (b) 25 ppm and (c) 50 ppm CNT–TiO₂ concentrations

Note: The 25-ppm sample exhibited the highest visual homogeneity and the least sedimentation among the tested samples, suggesting improved dispersion stability compared to the other two blends

2.6 Experimental Procedure for Preliminary Optimization of Nano-additive Concentration

To identify the most suitable nano-additive concentration for subsequent engine testing, a preliminary optimization study was carried out focusing on dispersion stability, visual uniformity, and basic fuel properties. Fuel samples were prepared with nano-additive concentrations of 10 ppm, 25 ppm, and 50 ppm. The required quantity of nanoparticles for each blend was calculated and measured using a digital microbalance. The additives were first dispersed into the base fuel using magnetic stirring, followed by ultrasonication to ensure proper dispersion and to minimize particle agglomeration. The prepared samples were then stored in transparent containers and monitored for 24–48 h to evaluate their stability. Parameters such as sedimentation, agglomeration, and phase separation were closely monitored, along with visual observations for uniform

colour distribution and homogeneity. Basic fuel properties, including density and kinematic viscosity, were assessed to understand the effect of varying concentrations. Based on the overall assessment, the 25-ppm blend exhibited stable dispersion, minimal sedimentation, and acceptable fuel properties and was therefore selected for subsequent investigations. Overall, the optimization process enabled the identification of a nanoparticle concentration that provided satisfactory stability and fuel characteristics.

2.7 Optimization of CNT–TiO₂ Concentration

In the present study, the effect of nano-additive concentration (10, 25, and 50 ppm) on fuel blend performance and emissions was investigated based on literature recommendations and practical considerations of dispersion stability and engine compatibility. At the lowest concentration (10 ppm), the improvement in combustion characteristics was found to be marginal due to the limited availability of active nanoparticles in the fuel. Although the fuel remained stable, the enhancement in performance parameters such as BTE was comparatively low. At the highest concentration (50 ppm), a noticeable improvement in combustion was observed; however, issues related to particle agglomeration and a marginal increase in NO_x emissions were evident. Higher concentrations also tend to affect fuel stability and may lead to injector-related issues during prolonged engine operation.

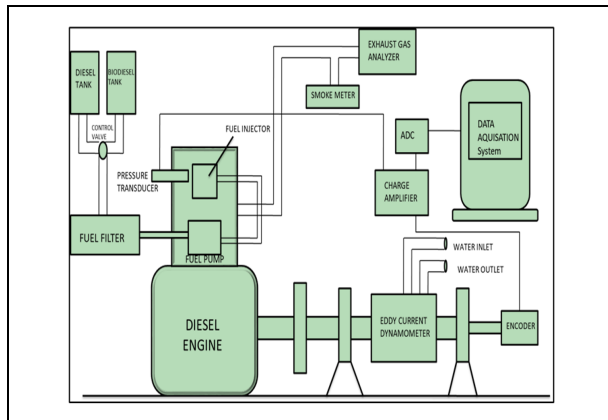


Fig. 9: Layout of the CI engine experimental setup

The medium concentration (25 ppm) exhibited a balanced performance, showing significant improvement in BTE along with considerable reduction in carbon monoxide (CO), unburnt hydrocarbons (HC), and smoke emissions. The dispersion stability of nano-additives at this concentration was found to be satisfactory without significant sedimentation. Based on the comparative analysis, 25 ppm was identified as the optimum concentration, since it provides an effective balance between enhanced combustion, emission reduction, and fuel stability. The fuel properties of the test fuels were presented in Table 2.

2.8 Preparation for Engine Testing

The prepared nanofuel blends were used immediately after preparation to minimize sedimentation effects. Before being supplied to the engine, they were gently shaken to restore uniform nanoparticle dispersion.

2.9 Fuel Characteristics

Table 2. Fuel properties

Properties	Diesel	DPO	D85/DP O15	D85/DPO15/ CNT–TiO ₂ (25 ppm)
Kinematic viscosity at 40 °C (cSt)	2.91	2.19	2.37	2.50
Density at 15 °C (g/cm ³)	0.830	0.812	0.8223	0.8453
Gross calorific value (MJ/kg)	45.2	42.3	43.63	43.961
Flash point (°C)	77	43	48	52

2.10 Experimental Engine Setup

A fully instrumented CI engine test rig was employed to investigate the performance, combustion, and emission characteristics of the test fuels. This section describes the CI engine test rig and its associated components, including the combustion measurement unit, dynamometer, fuel measurement system, exhaust gas analyzer, smoke meter, and data acquisition system. A schematic representation of the experimental setup is shown in Fig. 9. It consisted of a single-cylinder, 4-stroke, water-cooled CI engine coupled with an eddy current dynamometer for measuring engine load and torque. Fuel consumption was determined using a fuel measurement system, while combustion parameters were recorded through a data acquisition system. Exhaust smoke emissions were measured using a smoke meter, and gaseous emissions, including HC, CO, and NO_x, were analyzed using an exhaust gas analyzer.

2.11 Specification of the Engine

The engine used in this study is a Kirloskar diesel engine employed to measure the required performance and emission parameters. The engine has a maximum power output of 3.5 kW. A governor is provided to maintain a constant engine speed of 1500 rpm under varying load conditions. The engine is naturally aspirated, with a compression ratio of 17.5:1 and a fuel injection timing of 23°. It is equipped with a hemispherical combustion chamber and an overhead valve mechanism. The cylinder wall and cylinder head are cooled by circulating water through the water jacket from an external source. A single-cylinder, water-cooled, direct-injection, four-stroke compression ignition engine was used in this study (Refer Table 3). The engine was manufactured by Kirloskar Ltd., India. It has a cylinder bore of 87.5 mm, a stroke length of 110 mm, and a

displacement volume of 661 cm³. Fig. 10 shows the photographic view of the CI engine experimental setup.



Fig. 10: CI engine experimental setup

Table 3. Engine specifications

Make	Kirloskar
No. of Cylinders	1
No. of Strokes	4
Fuel	Diesel
Cylinder Diameter (Bore)	87.5
Stroke Length	110 mm
Connecting Rod Length	243 mm
Orifice Diameter	20 mm
Dynamometer Lever Length	185 mm
Rated Power	3.5 kW
Operating Speed	1500 rpm
CR Range	12:1–18:1

2.12 Uncertainty Analysis

In practical experiments, all measurements obtained from the instruments are associated with a certain level of uncertainty. Without considering measurement errors, the recorded values may deviate from the actual values. Therefore, uncertainties associated with the engine setup and measuring instruments must be evaluated to ensure accurate and reliable experimental results.

2.13 Calibration Phase

Each instrument used for data acquisition must be calibrated to account for possible deviations and ensure reliable results. The calibration process provides a documented method for verifying and confirming the

performance characteristics, specifications, and tolerances of measuring and testing equipment.

2.14 Experimental Procedures

The data acquisition system, fuel metering apparatus, and engine were kept in good working condition throughout the experiments. To guarantee the accuracy of the required data, all the instruments have been calibrated and maintained on a regular basis. At various loadings, the engine's load, speed, torque, and fuel volumetric flow rate measurements were made. The engine was allowed to attain thermal stability before recording each measurement. Fuel consumption time was carefully measured and recorded. A variable load was applied to the engine using a dynamometer regulator while maintaining a constant speed of 1500 rpm. The fuel injection timing was maintained at 23° before top dead center (TDC), and the injector opening pressure was set at 200 bar. The compression ratio of the engine was maintained at 18:1 during the experiments. The engine was operated at loads corresponding to 25%, 50%, 75%, and 100% of the maximum power output. In the first phase of the study, experiments were conducted using a ternary fuel blend (D85/DPO15/CNT–TiO₂). The collected experimental data were analyzed and plotted to compare the performance and emission characteristics of different fuel blends.

2.15 Estimation of Uncertainty

The uncertainty estimation of the measured parameters was performed based on the Gaussian distribution method with a confidence limit of $\pm 2\sigma$, indicating that approximately 95% of the measured data lie within two standard deviations from the mean value. The uncertainty of each measured parameter was calculated using the following equation:

The uncertainty of each measured parameter is,

$$(\Delta x_i = \left(\frac{2\sigma_i}{x_i} \right) \times 100 \quad \dots (1)$$

Multiple readings were recorded for each measured parameter under steady-state operating conditions, and the uncertainty was evaluated using statistical analysis. For a calculated parameter R that depends on several independent measured variables ($x_1, x_2, x_3, \dots, x_n$), the overall uncertainty was determined using the error propagation principle.

$$R = f(x_1, x_2, \dots, x_n) \quad \dots (2)$$

The uncertainty in the calculated parameter (Holman, 1973) is expressed as:

$$\Delta R = \left[\left(\frac{\partial R}{\partial x_1} \Delta x_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \Delta x_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} \Delta x_n \right)^2 \right]^{\frac{1}{2}} \dots (3)$$

Using these equations, the uncertainties associated with parameters such as BP, BTE, and fuel flow rate were estimated. The measured parameters included engine speed, load, fuel consumption time, voltage, and current, and their respective uncertainties were calculated based on the Gaussian distribution approach. The estimated uncertainties are presented in Table 4.

Table 4. Uncertainty parameters

Quantities	Uncertainty (%)
Engine speed (rpm)	± 1.3
BTE (%)	± 0.05
Fuel flow rate (g/cc)	± 1.7
Power output (W)	± 1.2
BSFC (g/kWh)	± 0.06

2.16 Error Analysis

In practical experiments, the measurements obtained from instruments are associated with a certain degree of uncertainty due to various sources of error. These errors can be broadly classified into fixed errors and random errors. Fixed (systematic) errors are repeatable in nature and can be minimized through proper calibration and correction methods. In contrast, random errors occur due to unpredictable variations during measurements and are evaluated using statistical analysis. The variations in the measured parameters and their corresponding percentage errors are presented in Table 5.

Table 5. Error Analysis and Variation of Measured Parameters

Parameter	Min. value	Max. value	Error (%)
Engine speed (rpm)	1475.5	1524.5	± 1.4
BTE (%)	30.49	30.79	± 0.04
BP (kW)	3.488	3.571	± 1.3
BSFC (g/kWh)	0.232	0.352	± 0.06

3. RESULTS AND DISCUSSION

The prepared nanofuel blends were evaluated in a Kirloskar single-cylinder, four-stroke, CI engine under varying load conditions of 25%, 50%, 75%, and 100% of the rated power. The performance characteristics analyzed and compared include BTE, BSFC, HRR, and CP.

3.1 Brake Thermal Efficiency (BTE)

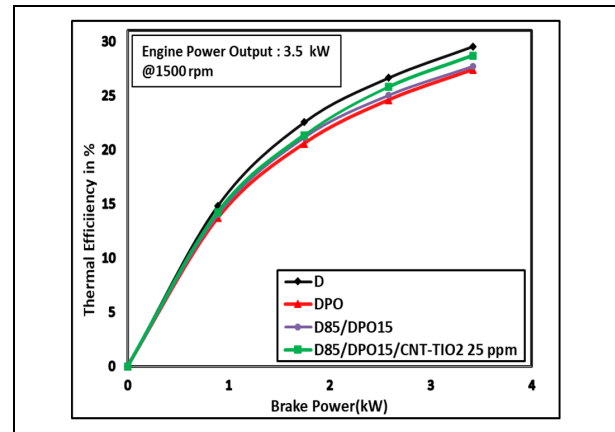


Fig. 11: Variation of BTE with BP for different fuel samples

This trend agrees with the findings reported in earlier studies (Kumar *et al.* 2020; Mani *et al.* 2010; Gopinath and Devan, 2020), which attributed the improved combustion performance to the addition of hybrid nanoparticles. The enhancement can be attributed to the high surface-area-to-volume ratio and catalytic effects of the nanoparticles, which promote better atomization, improved fuel–air interaction, and more complete combustion. This finding agrees with the studies of John *et al.* (2017) and Awang *et al.* (2021), who reported similar improvements in BTE when CNT was used as an additive in waste plastic oil–diesel blends. It also supports the findings of El-Seesy *et al.* (2016), who demonstrated enhanced combustion efficiency with MWCNT addition in biodiesel–diesel blends.

3.2 Brake-specific Fuel Consumption (BSFC)

Fig. 12 shows the variation of BSFC with BP. At maximum load, diesel recorded the lowest BSFC of approximately 0.292 g/kWh due to its higher energy density. The D85/DPO15 blend recorded an intermediate BSFC of approximately 0.335 g/kWh. With the addition of 25 ppm CNT–TiO₂ nanoparticles, BSFC decreased to about 0.312 g/kWh. This corresponds to a reduction of approximately 6.86% compared with the D85/DPO15 blend without nano-additives. This improvement can be attributed to enhanced combustion efficiency, supported by the catalytic activity of TiO₂ and the improved thermal conductivity of CNTs, which facilitate better fuel–air mixing and more complete combustion (Hariram *et al.* 2019; Gopinath and Devan, 2020).

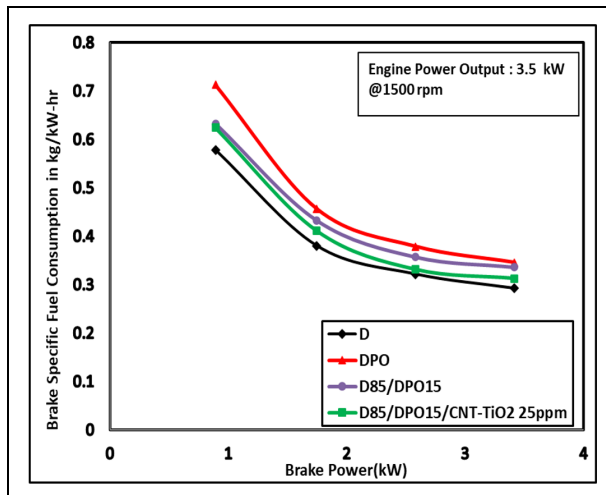


Fig. 12: Variation of BSFC with BP for different fuel samples

3.3 Heat Release Rate (HRR)

Fig. 13 represents the variation of HRR with crank angle at full load conditions. Diesel exhibited the highest peak HRR of approximately $89 \text{ J/}^\circ\text{CA}$, indicating rapid energy release during the premixed combustion phase. The D85/DPO15 blend showed an intermediate peak HRR of approximately $84 \text{ J/}^\circ\text{CA}$. With the addition of 25 ppm CNT-TiO₂ nanoparticles, the peak HRR increased to around $86 \text{ J/}^\circ\text{CA}$, approaching the performance of diesel. This improvement can be attributed to the enhanced heat transfer capability of CNTs and the catalytic activity of TiO₂, which accelerate combustion reactions and promote a more intense premixed phase (Hariram *et al.* 2021; Kumar *et al.* 2020).

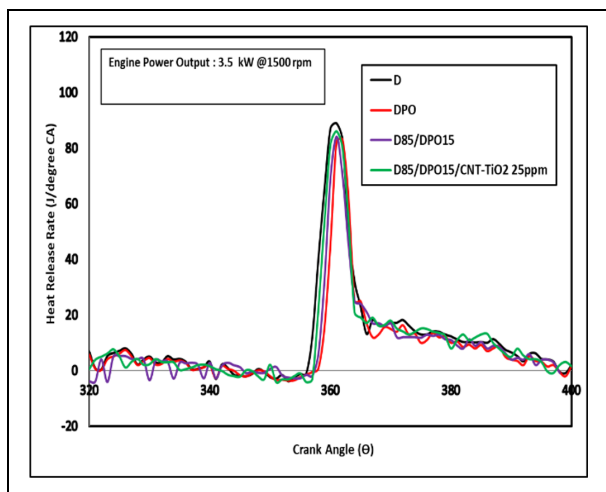


Fig. 13: Variation of HRR with crank angle for different fuel samples

3.4 Cylinder Pressure

Fig. 14 illustrates the variation of in-cylinder pressure with crank angle at full load conditions. Neat diesel exhibited the highest peak pressure of

approximately 66.96 bar, indicating the most intense combustion among all the tested fuels. The D85/DPO15 base blend showed a slight improvement, reaching a peak pressure of approximately 64.28 bar. Notably, the addition of 25 ppm CNT-TiO₂ nanoparticles further enhanced the combustion process, increasing the peak pressure to around 65.40 bar. This trend aligns with the observed heat release characteristics, suggesting that the nanoparticles improve in-cylinder combustion through better atomization, enhanced heat transfer, and accelerated reaction kinetics, as reported in earlier studies (Mani *et al.* 2010; Devaraj *et al.* 2015).

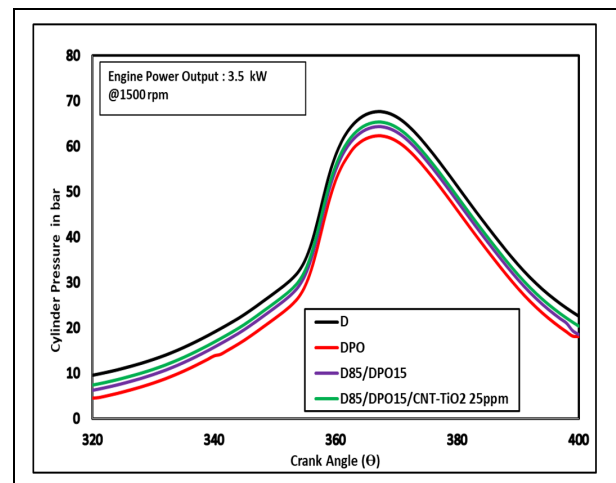


Fig. 14: Variation of cylinder pressure with crank angle for different fuel samples

4. CONCLUSION

This study examines the combined influence of CNT-TiO₂ hybrid nano-additives on the performance and combustion behaviour of waste plastic oil-diesel blends in a single-cylinder, four-stroke compression ignition engine. A nanoparticle concentration of 25 ppm was selected as the optimum additive level among the tested samples due to its better particle dispersion and enhanced catalytic activity. The results indicate that blending 15% waste plastic oil with diesel, along with the addition of 25 ppm CNT-TiO₂ nano-additives, significantly improves engine performance, achieving a brake thermal efficiency only 2.80% lower than diesel and a BSFC of 0.312 g/kWh at full load conditions. These results correspond to a 3.53% improvement in brake thermal efficiency and a 9.56% reduction in brake-specific fuel consumption compared with the baseline D85/DPO15 blend. The findings suggest that hybrid nano-additives can effectively overcome the limitations associated with plastic oil utilization while reducing dependence on conventional diesel fuel.

The 25 ppm CNT-TiO₂ blend consistently delivered superior performance, achieving a peak heat release rate of approximately $86 \text{ J/}^\circ\text{CA}$ and a maximum cylinder pressure of 65.40 bar.

Overall, the use of waste plastic oil blended with hybrid CNT–TiO₂ nano-additives demonstrates promising potential for cleaner and more efficient diesel engine operation. However, further investigations are required to establish its practical viability, particularly regarding long-term engine durability under continuous nanofuel operation, detailed emission characterization including NO_x and particulate matter, fuel production scalability, and a comprehensive economic assessment comparing the cost of waste plastic oil with conventional diesel.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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