



Energy and Exergy Analysis of Graphene–Ferric Oxide Nanoparticle-enhanced Diesel–Waste Plastic Oil–Ethanol Blends: Sustainability and Regulatory Compliance Assessment in a CI Engine

P. Mebin Skaria¹, T. Derifa², D. Balaji¹, K. S. Sreyas¹, M. Chinnasamy³, Samuel James⁴ and V. Hariram^{1*}

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

²Symbiosis Law School, Pune, Symbiosis International (Deemed University), Pune, MH, India

³Department of Civil Engineering, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Chennai, TN, India

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

Received: 06.03.2026 Accepted: 10.04.2026 Published: 30.06.2026

*connect2hariram@gmail.com



ABSTRACT

The present experimental investigation focuses on deriving waste plastic oil (WPO) and its usage as a fuel in a CI engine, along with ethanol and graphene–ferric oxide (Gr–Fe) nanoparticles to control exhaust emissions and improve the engine performance. A batch-type pyrolysis reactor was developed to produce waste plastic oil from heterogeneous waste plastics such as HDPE, PVC, PPE, and LDPE. WPO exhibited a higher density and viscosity, along with a lower flash point. These properties were improved by the addition of ethanol, an oxygenate, at concentrations of up to 10%. Gr–Fe nanofluids were prepared using the ultrasonication technique in the presence of sorbitan monooleate as a surfactant. Diesel was blended with WPO at a 20% blend ratio. Experiments were conducted using D80WPO20, D80WPO20E10, D80WPO20E10Gr–Fe50, D80WPO20E10Gr–Fe75, and D80WPO20E10Gr–Fe100. The test fuel blends were prepared on a volumetric basis and evaluated in a Kirloskar TV1 CI engine to investigate their combustion behavior and emission characteristics. The studies revealed that the addition of Gr–Fe nanoparticles to the diesel–WPO–ethanol up to 50 ppm improved brake thermal efficiency by 5.21% at full load, with a marginal reduction in BSFC at low load. Notable reductions in UBHC and smoke emissions of up to 2.47% and 3.12%, respectively, were observed with the addition of Gr–Fe nanoparticles. Oxides of nitrogen (NO_x) increased by up to 3.21% due to the catalytic activity of Gr–Fe nanoparticles. Enhanced oxidation and a superior premixed combustion phase increased the peak in-cylinder pressure by 1.42% with a noticeable improvement in the rate of heat release. The findings of the present investigation demonstrated that Gr–Fe nanoparticle concentration contributed to achieving cleaner combustion with reduced exhaust emissions. The study also examined the regulatory and standardization requirements necessary for the potential commercialization of waste plastic oil–diesel blends in compression ignition engines.

Keywords: Waste plastic oil; Pyrolysis; Physicochemical properties; Combustion, Emissions; Graphene–ferric oxide nanoparticles.

1. INTRODUCTION

Globally, environmental pollution and energy crisis are the two correlated factors that need immediate attention (Chacko and Jeyaseelan, 2020). Rapid industrialization and higher population growth are the main reasons behind the energy crisis. Additionally, escalated usage of plastic materials and their increased accumulation as waste plastics resulted in significant concerns over human health, flora and fauna, and environmental factors, including water, air, and soil pollution. The levels of toxicity have emerged as a major perturbation for the future human population on Earth. Nowadays, plastic materials have become inseparable from human life due to their longevity, friendliness, light weight, and cost effectiveness (Soudagar *et al.* 2018). It

is estimated that only 19% of single-use plastics are being recycled worldwide. Approximately 69% are disposed of in landfills, while the remaining plastic waste is discharged into the oceans and the environment (Kumar and Muniamuthu, 2024). Recently, the sustainable production of bio-oils from waste plastics has gained considerable attention among researchers due to its high energy content and value-addition potential. One such technique is pyrolysis, in which plastic waste is converted into pyrolysis oil through thermal degradation in the absence of oxygen under an inert atmosphere (Gopinath *et al.* 2021).

Haseeb *et al.* (2024) studied the efficacy of using diesel–PPO in a CI engine on its thermodynamics, emissions, and sustainability. High-density polyethylene

grocery bags were used as the feedstock to produce PPO. 15% of PPO was blended with commercial diesel and fueled a single-cylinder multi-speed CI engine to assist its energy and sustainability features. They noted that a lower concentration of PPO up to 5% produced maximum brake thermal efficiency of 51.6% with a superior sustainability index in an unmodified engine. Suresh *et al.* (2024) optimized the pyrolysis reaction by augmenting the process parameters like reaction temperature, reaction time, and heating rate in achieving a larger quantity of waste plastic oil. The derived WPO was characterized using FTIR and ASTM methods. The test engine was fueled with emulsified diesel–WPO blends containing 5%, 10%, and 15% water. The outcome indicated that reaction temperature, reaction time, and heating rate of 403 °C, 96.30 min, and 17.3 °C/min yielded the maximum quantity of WPO. Fueling the engine with WPO–diesel blends significantly reduced the brake thermal efficiency and adversely affected combustion characteristics; however, the incorporation of 10% water into the WPO–diesel blend notably enhanced BTE by 11.75% and significantly reduced CO, HC, and NO_x emissions.

Mohammed *et al.* (2025) explored the possibilities of amalgamating plastic pyrolysis oil, waste cooking oil, and commercial diesel as a fuel in a CI engine. The fuel injection pressure was varied between 170 bar and 230 bar to study the engine behavior in terms of exhaust emissions and performance. Optimal engine performance and better combustion were observed for 10% WPO–20% WCO and 15% WPO–15% WCO fuel blends with diesel at an elevated fuel injection pressure of 230 bar. The interrelation between the influential input factors and the outcomes was modeled using a Python-based statistical analysis, which also confirmed that the fuel injection pressure is one of the most important factors influencing the engine's performance.

Gopinath *et al.* (2025) examined the synergetic effect of amalgamating graphene quantum dots (GQDs) with a diesel 80–WPO 20 fuel blend. The infusion of GQDs was confirmed using ultrasonication testing with homogenization. The addition of 40 ppm GQDs to the diesel–WPO blend resulted in improved combustion characteristics and a 5.17% increase in BTE. Inclusion of GQD nanoparticle additive significantly reduced the NO_x emission by 1.63% across all loading conditions, along with 233% of smoke emission decrement. Enhanced oxidation of the GQD additive showcased notable decrements in UBHC and CO emissions, leading to a cleaner combustion phenomenon. Jayashri *et al.* (2025) collected various heterogeneous plastic materials, including HDPE, LDPE, PE, PS, and others; they used them to derive waste plastic biodiesel through the pyrolysis thermal degradation reaction. The derived WPO was blended with diesel in the presence of 1-butanol in a ternary blend formation along with alumina nanoparticles at low proportions to fuel the compression

ignition engine. Statistical models using a random forest machine learning approach were developed on the aspects of performance and emission outcomes to predict the actual scenario. All the developed models were validated, and their significance was evaluated using analysis of variance (ANOVA) by understanding their interactions. The developed model accurately predicted the reduction in UBHC and CO emissions by 18.6% and 9%, respectively, with the addition of 1-butanol. Further, infusing the fuel blend with 100 ppm of alumina nanoparticles reduced the UBHC and CO emissions by up to 18.5% and 12.5%, respectively.

Faisal *et al.* (2023) conducted a review on CI engines' combustion, performance, and emission characteristics when fueled with waste plastic pyrolytic oil. They have observed that the density and viscosity of PPO were higher with relatively lower cetane index and flash points, leading to elevated ignition delay at premixed combustion duration. Raw PPO oil reduced the BTE by 17.26% and increased the BSFC by 17.88%. Blends of PPO with diesel reduced the NO_x emission by 44.06% with relatively higher CO₂ formation. Bisrul *et al.* (2024) improved the physicochemical properties of rubber seed biodiesel (RSB) with plastic pyrolysis oil (PPO) as an additive. RSB was derived using a jacket reactor with potassium hydroxide as a catalyst. RSB and PPO were blended in volumetric ratios in an incremental factor of 10%. RSB60:PPO40 showcased superior engine performance due to its escalated calorific value. An incremental ratio of PPO by 10% increased the UBHC emission marginally with relatively similar CO emissions. The CO₂ emission was found to have a marginal negative effect with respect to commercial diesel.

The literature review reported a lack of studies on the use of metal-based nanoparticles in waste plastic oil–diesel blends, which have significant potential to improve combustion and overall performance in the CI engine. This highlights a promising avenue for exploring engine behavior in the present experimental investigation. In the present study, WPO was derived using a batch-type pyrolysis reactor under laboratory conditions. Its physicochemical properties were analyzed to assess its suitability for use in a CI engine. Ternary blends with ethanol and Gr–Fe nanoparticles were prepared at a volumetric ratio for fueling the CI engine. The engine characteristics were evaluated based on performance, combustion, and emission phenomena. Exergy, energy, and sustainability analyses were also conducted in the present investigation.

2. MATERIALS AND METHODS

2.1 Batch Type Pyrolysis Reactor

The batch-type pyrolysis reactor was designed and developed using the SolidWorks tool with an overall

dimension of 400 x 458 x 200 cm, as shown in Fig. 1. The reactor consists of two layers of SS316L stainless steel in cylindrical cross-section, formed by rolling and forging techniques. The inner diameter and the outer diameter of the batch-type reactor were maintained at 66 cm and 76 cm, respectively, with a wall thickness of 5 mm. The intermediate compartment between the cylinders was filled with glass wool to enhance the thermal cycling process, thereby preventing heat loss to the atmosphere. The batch-type reactor was designed with a conical lid with an exhaust chute covering the upper portion of the cylindrical chamber. The batch-type reactor is equipped with three Koyo's induction flexible coils, which are capable of heating the system to 750 °C in incremental values. The system has a temperature controller to prevent overheating problems. The exhaust chute has an arm that directs the pyro-gas into the condensation chamber. During the pyrolytic reaction process, the condensation chamber was filled with 8 L of distilled water. The pyro-gas from the reactor reaches the condensation chamber and amalgamates with the distilled water, forming a pyrolytic liquid in the upper layer of the condensation chamber. An outlet arrangement in the condensation chamber at 45 cm from the ground level separates the pyrolytic liquid from the distilled water.

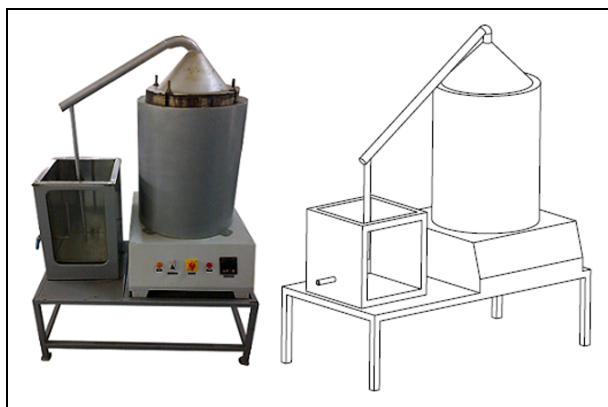


Fig. 1: Batch-type pyrolysis reactor

The batch-type pyrolytic reactor was designed to handle 8–10 kg of preprocessed waste plastic per cycle between the working temperatures of 450–550 °C. The heterogeneous plastics were segregated and thoroughly washed using distilled water. The processed waste plastics were cut into smaller pieces using a shredder machine and dried. In a single batch, 8 kg of preprocessed heterogeneous waste plastics were fed into the batch-type pyrolysis reactor, and the top conical lid was closed to prevent the entry of oxygen. The heating coils were gradually switched on one after the other in an incremental manner to raise the temperature from ambient to 550 °C. During this process, this state of change of plastic materials was witnessed from solid to liquid and gaseous form. Thereafter, when the temperature reaches 400 °C, pyro-gas starts flowing

through the exhaust chute and reacts with the distilled water in the condensation chamber, resulting in the formation of waste plastic pyrolytic oil in the upper layer of the condensation chamber. Further increment in the working temperature up to 550 °C, escalated the yield of pyro-gas, resulting in further accumulation of pyrolytic oil in the condensation chamber. This technique yielded 1.69 L of WPO in a single batch.

2.2 Preparation of Nanofluid

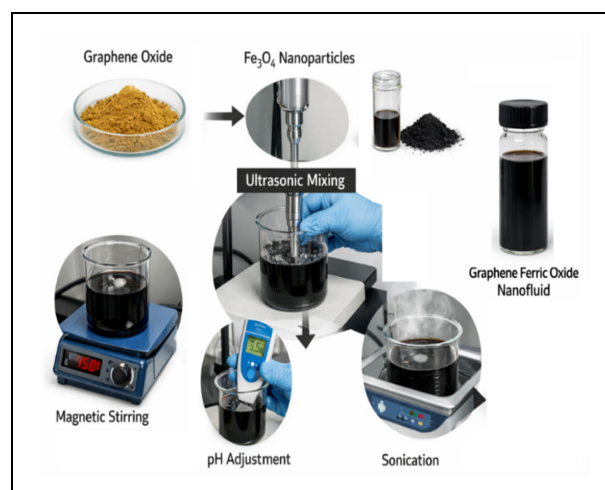


Fig. 2: Preparation of Gr-Fe nanofluid

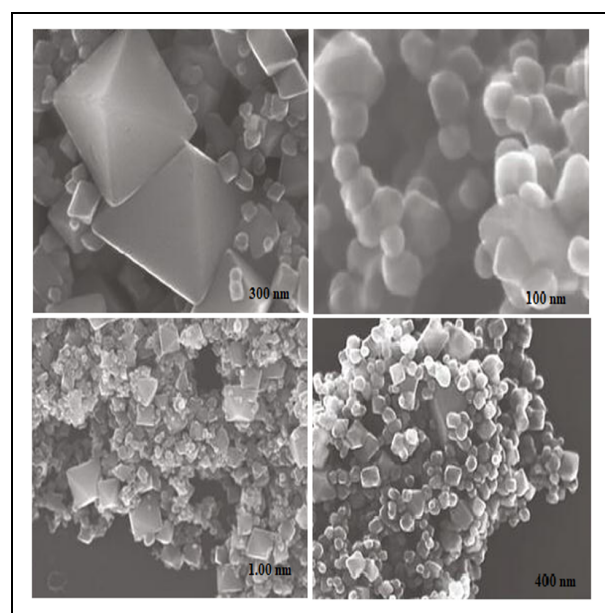


Fig. 3: SEM image of Gr-Fe nanoparticles

The nanofluid composed of Gr-Fe nanoparticles was prepared using ethanol as a solvent. Gr-Fe nanofluid preparation is depicted in Fig. 1 and the SEM image of Gr-Fe nanoparticles is shown in Fig. 2. Initially, for Gr-Fe 100 ppm fuel preparation, 0.01 mg of graphene oxide and ferric oxide, respectively, were mixed thoroughly with 75 mL of laboratory-grade

ethanol in a sterile conical flask. The mixture was continuously agitated at 200 rpm in the ambient temperature to prevent sedimentation and agglomeration for 15 min. Further 5 mL of sorbitan monooleate, a surfactant, was mixed to prevent clustering of the nanoparticles and to ensure regimentation with a higher surface area and energy. 500 mL of waste plastic pyrolytic liquid was added to the mixture, which was then ultrasonicated at 75 Hz and 500 rpm for 30 min. The pH value was maintained between 5.2 and 6.1 throughout the processing. The presence of sorbitan monooleate surfactant prevented agglomeration and sedimentation for a longer period of time. Likewise, 75 ppm and 50 ppm of Gr-Fe nanoadditive-based test fuel were prepared.

2.3 Test Fuel Preparation

In the present investigation, experimental runs were conducted with straight diesel as the base. Based on the literature reviews, waste plastic pyrolytic oil replaced diesel up to 20%, and its effect on the engine performance was also verified. To improve the engine's efficacy, ethanol up to 10% was blended with diesel-WPO (as a ternary fuel blend). Further, Gr-Fe nanoparticles were infused with a ternary fuel blend at multiple ratios between 50 ppm and 100 ppm using the ultrasonication technique to ensure homogeneity in the test fuel. Utmost care was ensured during the preparation of test fuel blends, as it would reflect in the performance,

combustion, and emission characteristics throughout the experimentation (Faisal *et al.* 2023). The composition of test fuel blends is presented in Table 1, and the fuel samples are shown in Fig. 4.

Table 1. Composition of test fuel blends (volumetric ratio)

S. No.	Test Fuel	Volumetric Blend Ratio			Gr-Fe Nanoparticles (ppm)
		Diesel	WPO	Ethanol	
1	D100 – Straight diesel	100	-	-	-
2	D80 WPO20	80	20	-	-
3	D80 WPO20 E10	72.73	18.18	9.09	-
4	D80 WPO20 E10 Gr-Fe50	72.73	18.18	9.09	50
5	D80 WPO20 E10 Gr-Fe75	72.73	18.18	9.09	75
6	D80 WPO20 E10 Gr-Fe100	72.73	18.18	9.09	100

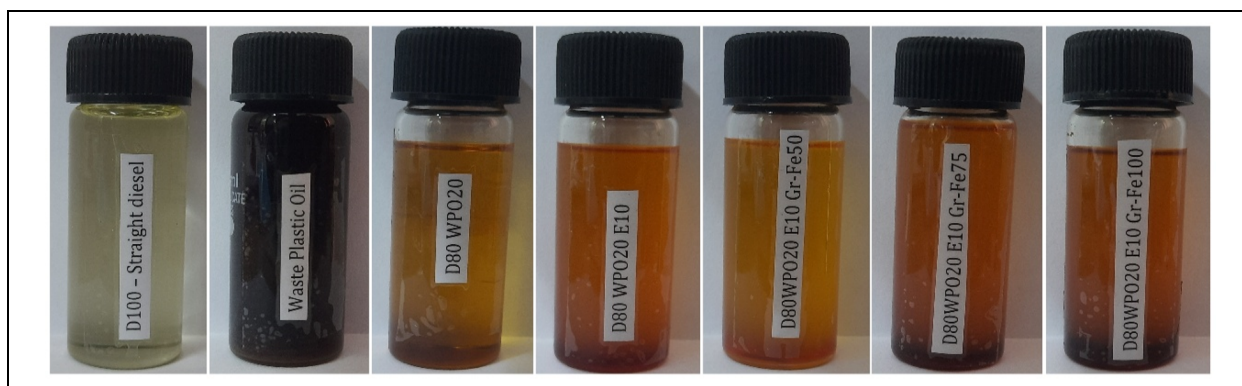


Fig. 4: Test fuel blends

2.4 Properties of Test Fuels

The physicochemical properties of the test fuels provide insight into the performance and behavior of the fuel combinations. These properties, including kinematic viscosity, calorific value, flash point, density, and ash content, were critically analyzed to assess their suitability for use in the CI engine. Kinematic viscosity is a vital parameter that affects the fuel spray pattern, fuel injection, and atomization, thereby influencing combustion efficiency. The lowest flammability limit, termed the flash point of the fuel, relates directly to the fuel's flammability and volatility. It also supports safer handling and storage. Generally, fuels with higher

calorific value are preferable for use in a CI engine to produce more power with limited fuel consumption. The quantity of inorganic carbon deposits after fuel combustion, termed ash content, is measured in weight %. This parameter influences the fuel's evaporation characteristics, which directly affect emission and performance parameters (Hariram *et al.* 2021). Table 2 illustrates the variation in the physicochemical properties with increasing Gr-Fe nanoparticle concentration in the diesel-WPO-ethanol blend.

2.5 Experimental Setup

A single-cylinder Kirloskar TV1 diesel engine was used in the present investigation (Fig. 5). It is a four-

stroke water-cooled compression ignition engine with an overall power of up to 5.2 kW at 1500 rpm. The volume of the engine is 661 cc with a bore and stroke length of 87.5 mm and 110 mm, respectively. The engine runs at the factory set compression ratio of 17.5, and the loading was accomplished with a water-cooled eddy current dynamometer. The combustion data were derived using a 5000-psi-range piezo sensor coupled with a crank angle encoder, which can resolve 1 degree at 5500 rpm. The piezo sensor is powered using an AX-409 piezo powering unit, and a NIUSB-6210 data acquisition system was employed to gather and segregate the engine data. RTD PT100, a K-type thermocouple-based temperature sensor, was used to identify the inlet and outlet temperatures of air and fuel, respectively. An AVL 444 five-gas analyzer was employed to measure HC, CO, CO₂, O₂, and NO_x. An AVL 437C smoke meter was used to measure the smoke levels.

Table 2. Physicochemical properties of the test fuels

Physicochemical Properties	Diesel (D100)	D80 WP O20	D80 WP O20 E10	D80 WP O20 E10 Gr-Fe 50	D80 WP O20 E10 Gr-Fe 75	D80 WP O20 E10 Gr-Fe 100	ASTM Standards
Kinematic viscosity (mm ² /s)	2.14	1.899	1.994	2.043	2.059	2.104	ASTM D445
Calorific value (MJ/kg)	43.5	43.84	44.02	44.57	45.41	45.98	ASTM D240
Flash point (°C)	51	44.7	45.3	46.1	46.9	47.3	ASTM D93
Density @ 15 °C (kg/m ³)	808	804.4	806.3	808.9	810.7	811.9	ASTM D4052
Ash content (wt.%)	0.01	0.024	0.025	0.019	0.018	0.019	ASTM D482

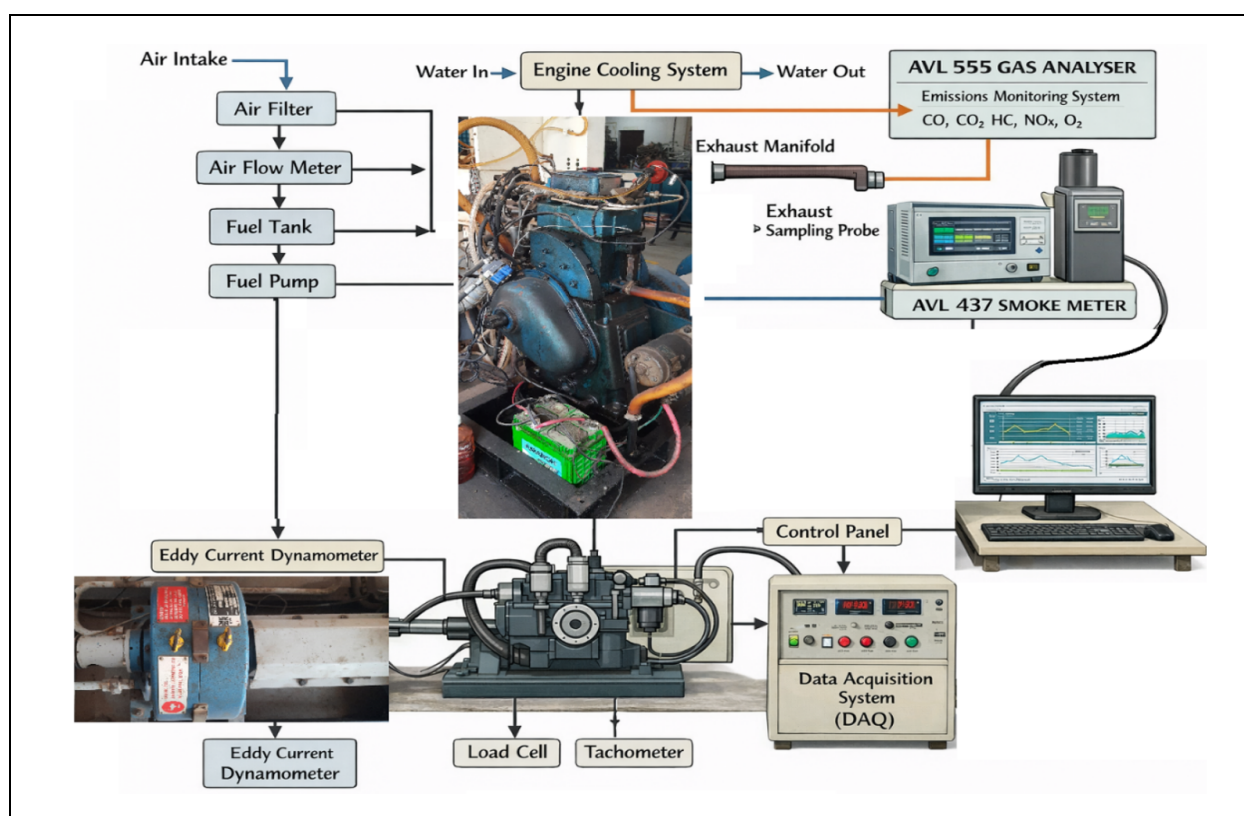


Fig. 5: Experimental setup

Baseline measurements of performance, emission, and combustion characteristics were obtained using D100 after the engine had been operated on straight diesel for 30 min to achieve steady-state conditions. Before testing each fuel blend listed in Table 1, the engine was operated on diesel fuel for 20 min at high load to eliminate residual fuel from the previous test and

minimize its influence on subsequent measurements. A warm-up period of 15 min was allowed before data acquisition for each fuel blend. The fuel injection pressure was maintained between 170 bar and 200 bar with 23° bTDC of injection timing. Engine output was recorded at no-load, low-load, part-load, and full-load conditions using a data acquisition system. BSFC and

BTE were evaluated to assess engine performance, whereas HC, CO, NO_x, CO₂, and smoke emissions were measured to evaluate emission characteristics.

2.6 Uncertainty Analysis

It is essential to estimate the uncertainty associated with the performance, combustion, and emission parameters evaluated in the present experimental study. The measurements may be subject to errors arising from human, environmental, instrumental, and standardization factors. Various researchers, including Faisal *et al.* (2023) and Janarthan *et al.* (2022), suggested the root-sum-square (RSS) method for estimating uncertainties using Eq. (1).

$$\text{Overall uncertainty } (Q) = \sqrt{\sum_{j=1}^n X_j^2} \quad \dots (1)$$

where X_j is the uncertainty associated with the j th measured parameter.

Table 3. Uncertainty analysis

Parameter	Range	Accuracy	Uncertainty (%)
Engine speed	0–500 rpm	± 100 rpm	± 0.20
Engine torque	0–11.2 Nm	± 0.2 Nm	± 0.15
CO emissions	0–5 g/kWhr	± 0.01 g/kWhr	± 0.02
HC emissions	0–8 g/kWhr	± 0.01 g/kWhr	± 0.02
CO ₂ emissions	0–15 g/kWhr	± 0.02 g/kWhr	± 0.04
NO _x emissions	0–15 g/kWhr	± 0.01 g/kWhr	± 0.04
BSFC	—	± 0.02 g/kWhr	± 0.12
BTE	—	± 0.05%	± 0.15
EGT	0–750 °C	± 5 °C	± 0.02

Thus, the overall uncertainty of the experimental investigation was found to be 1.72%.

3. RESULTS AND DISCUSSION

3.1 Brake Thermal Efficiency

The variation in BTE of the CI engine when fueled with the test fuels is shown in Fig. 6. Straight diesel (D100) exhibited BTE values of 21.68%, 30.6%, 33.47%, and 33.79% at low, part, three-quarter, and full load conditions, respectively. Addition of WPO up to 20% with straight diesel marginally increased the BTE at low load to 22.07%, but higher engine load showcased reduced BTE values of 29.12% and 31.95% at part and full load conditions. The addition of 10% ethanol to the

D80WPO20 fuel blend improved its ignition characteristics, resulting in a 4.34% increase in BTE under part- and full-load conditions. Amalgamating Gr-Fe nanoparticles with D80WPO20E10 fuel blend improved the thermal conductivity owing to its larger surface area, thereby contributing to enhanced premixing combustion phase. Infusing Gr-Fe up to 50 ppm exhibited BTE values of 19.196%, 27.819%, and 35.6035% at low, part, and full load conditions, respectively.

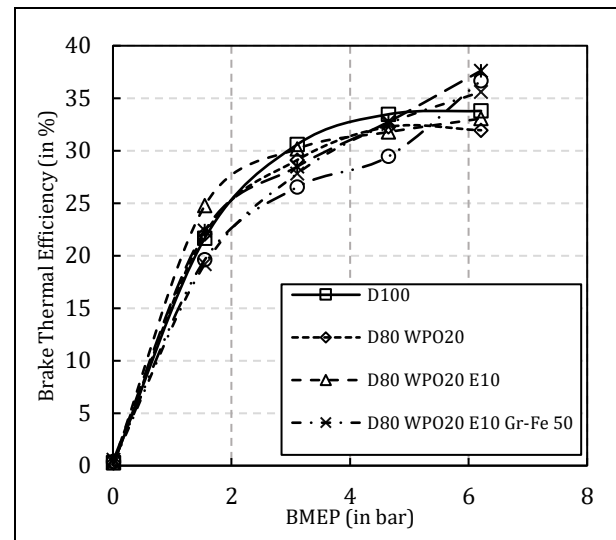


Fig. 6: Variation in BTE at all loads

Augmenting the Gr-Fe nanoparticles up to 75 ppm altered the physicochemical properties, leading to high localized temperature with reduced heat transfer between the in-cylinder wall membranes, especially during the premixed combustion phase. D80WPO20E10Gr-Fe75 exhibited a higher level of BTE at part-load and full-load conditions, as 28.49% and 37.623%, respectively. This may be due to the catalytic reaction between ethanol and Gr-Fe nanoparticles, enabling the disintegration of the HC atoms and thereby leading to enhanced combustion. This phenomenon was also reported by Hariram *et al.* (2018), Kalargaris *et al.* (2017), and Kumar *et al.* (2016) in their studies.

3.2 Brake Specific Fuel Consumption

The variation of BSFC with BMEP for the test fuels is shown in Fig. 7. D100 fuel exhibited BSFC values of 27.445 kg/kWhr, 3.025 kg/kWhr, 0.282 kg/kWhr, and 0.249 kg/kWhr at no, low, part, and full load engine operations, respectively. Blending 20% of WPO with straight diesel marginally increased the BSFC by 2.31%, 1.97% and 1.12%, as 3.126 kg/kWhr, 0.324 kg/kWhr, and 0.267 kg/kWhr at low, part, and full load operations respectively. Amalgamating 10% ethanol with D80WPO20 reduced the BSFC significantly by 3.92% at full load condition due to its improved calorific value. Infusing Gr-Fe nanoparticles with D80WPO20E10 fuel

blend considerably reduced the BSFC due to its lower latent heat of vaporization, higher surface area, and enhanced thermal conductivity, leading to combustion homogenization. The addition of Gr-Fe nanoparticles thereby reduced the quantity of fuel, notably to produce similar power output as that of other fuel combinations. Quicker combustion process and reduction in the rate of heat release in comparison with diesel-WPO-ethanol fuel blends may also be a reason for the reduction in BSFC. D80WPO20E10 Gr-Fe50 fuel blend exhibited BSFC values of 2.917 kg/kWhr, 0.521 kg/kWhr, and 2.031 kg/kWhr at low, part, and full load conditions, respectively, whereas the same fuel with 75 ppm of Gr-Fe nanoparticles showcased 2.888 kg/kWhr, 0.4856 kg/kWhr, and 1.879 kg/kWhr of BSFC at similar loads. Similar trends were reported by Kaimal *et al.* (2017), Kalargaris *et al.* (2017), Faisal *et al.* (2023), and Hariram *et al.* (2025).

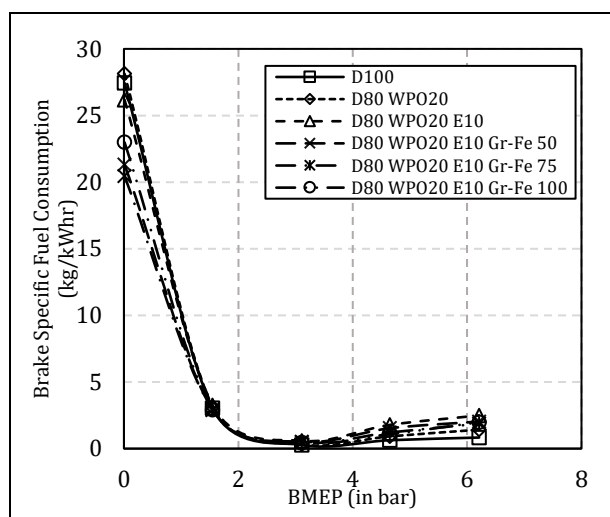


Fig. 7: Variation in BSFC at all loads

3.3 Engine Exhaust Emissions

3.3.1 Unburnt Hydrocarbon Emissions

Improper air-fuel mixing, poor atomization, and sub-optimal combustion phenomena may lead to incomplete combustion, resulting in the discharge of unburnt hydrocarbon atoms to the environment through the exhaust. Fig. 8 depicts the variation in UBHC emissions of various test fuels. Straight diesel (D100) exhibited a UBHC emission of 0.305 g/kWhr, 0.249 g/kWhr, and 0.164 g/kWhr at low, part, and full load operations. Blending WPO up to 20% with diesel had a significant effect on the UBHC emissions (0.312 g/kWhr, 0.245 g/kWhr and 0.2015 g/kWhr), which is 3.19% 4.2% increase in UBHC emissions. Adding 10% ethanol in diesel-WPO fuel blend reduced the UBHC emissions by 3.167%. This may be due to the supply of additional oxygen atoms, which may have contributed to the oxygenation process during the combustion phenomenon. At low, part, and full load conditions, the

fuel blend with Gr-Fe50 ppm exhibited UBHC emissions of 0.3001 g/kWhr, 0.2179 g/kWhr and 0.1846 g/kWhr, whereas an increase in Gr-Fe concentration up to 75 ppm showcased reduced UBHC emissions of 0.2875 g/kWhr, 0.2015 g/kWhr and 0.1789 g/kWhr at the same loading condition. This can be attributed to higher surface area and improved catalytic reaction of Gr-Fe nanoparticles, thereby leading to enhanced combustion process (Kaimal and Vijayabalan, 2017). Further increase in Gr-Fe concentration up to 100 ppm showcased a marginal increase in UBHC emissions, especially during the part load operation owing to the dissolution effect of Gr-Fe in the diesel-WPO-ethanol fuel blend.

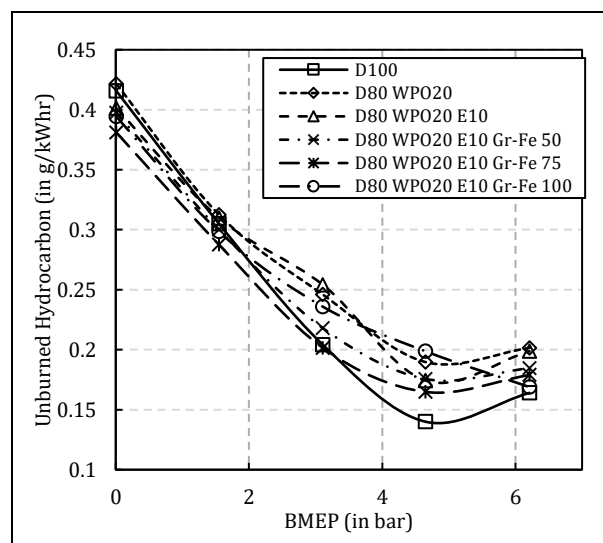


Fig. 8: Variation in UBHC emissions at all loads

3.3.2 Carbon Monoxide Emissions

Availability of surplus oxygen, which contributes to completing the combustion process have significant effect on CO emissions. Fig. 9 demonstrates the variation in CO emissions when the CI engine is fueled with D100, D80WPO20, D80WPO20E10, D80WPO20E10 Gr-Fe50, D80WPO20E10Gr-Fe75, and D80WPO20E10Gr-Fe100. Blending WPO of 20% with straight diesel significantly increased the CO emissions by 2.12%, 1.97% and 1.45%, as 12.95 g/kWhr, 10.98 g/kWhr and 7.47 g/kWhr at low, part, and full load conditions respectively. Ethanol addition up to 10% with D80WPO20 fuel marginally reduced the CO emissions by 3.15%, 2.97% and 2.43%, as 12.01 g/kWhr, 10.67 g/kWhr and 6.47 g/kWhr at the above loads respectively, which may be due to the supply of surplus oxygen during the premixed combustion phase as a result of oxidizing the carbon molecules to form CO₂, thereby achieving a better combustion process. Furthermore, the addition of oxygen-bearing Gr-Fe nanoparticles up to 50 ppm in D80WPO20E10 fuel blend notably reduced the CO emissions by promoting the oxidation of CO to CO₂. D80WPO20E10Gr-Fe50 exhibited CO emissions of 11.79 g/kWhr, 9.72 g/kWhr, and 6.18 g/kWhr at low, part,

and full load conditions, respectively, whereas increasing the Gr-Fe concentration up to 75 ppm further reduced the CO emissions to 10.98 g/kWhr, 9.49 g/kWhr, and 5.78 g/kWhr. This indicates the enhanced oxidation of CO to CO₂ due to the increased thermal conductivity and the availability of surplus oxygen during the combustion process, resulting in lower CO emissions (Faisal *et al.* 2023). Increasing the Gr-Fe nanoparticle concentration up to 100 ppm showcased a marginal increase in CO emission up to 1.02%, as shown in Fig. 9.

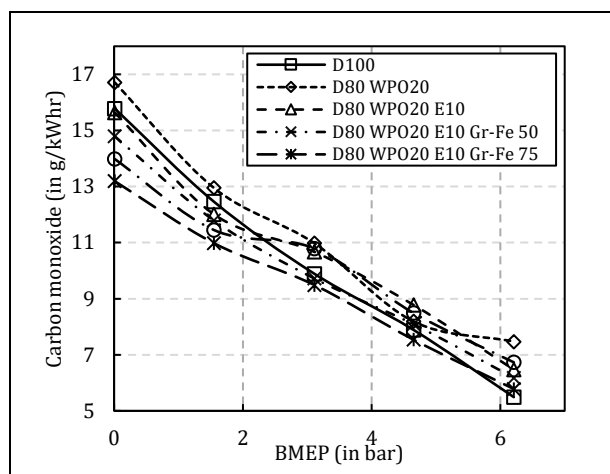


Fig. 9: Variation in CO emissions at all loads

3.3.3 Oxides of Nitrogen (NO_x) Emissions

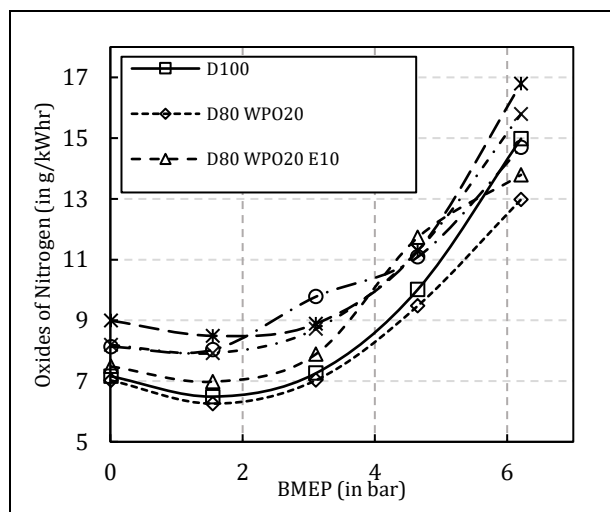


Fig. 10: Variation in NO_x emissions at all loads

Blending waste plastic oil up to 20% with straight diesel represented a marginal decrement in NO_x emissions at all engine loads. D100 fuel showcased NO_x emissions of 6.489 g/kWhr, 7.26 g/kWhr and 14.98 g/kWhr at low, part, and full loading conditions, whereas D80WPO20 represented 6.257 g/kWhr, 7.03 g/kWhr, and 12.98 g/kWhr, respectively (Fig. 10). Amalgamating ethanol upto 10% in D80WPO20 fuel blend improved the combustion phenomenon, while relatively raising the

peak flame temperature, thereby producing a higher concentration of NO_x when compared with straight diesel at low and part engine loads, with a marginal decrement at the full load condition. The addition of Gr-Fe nanoparticles significantly increased NO_x emissions due to the improved combustion efficiency promoted by the nanoparticles. Stable combustion process and quicker propagation of combustion flame during the premixed combustion phase favored superior combustion (Faisal *et al.* 2023; Yaqoob *et al.* 2023). It can be observed that D80WPO20E10Gr-Fe50 test fuel registered NO_x emissions of 7.92 g/kWhr, 8.719 g/kWhr and 15.79 g/kWhr at low, part, and full load conditions, respectively. A further increase in Gr-Fe concentration to 100 ppm resulted in a slight decrease in NO_x emissions, with values of 8.03, 9.78, and 14.69 g/kWhr under low, part, and full load conditions, respectively.

3.3.4 Smoke Emissions

Pyrolysis reaction inside the combustion chamber, instead of hydrocarbon oxidation, results in the formation of soot particles in the form of smoke. Fig. 11 depicts the variation in engine smoke emissions for various test fuels, plotted against BMEP. An AVL 437 smoke meter was employed in the present investigation, and the quantification of engine smoke was carried out using FSN (Filter Smoke Number). D100 test fuel emitted 1.49, 3.19, and 8.23 FSN of smoke at low, part, and full load conditions, respectively, whereas amalgamating straight diesel with WPO up to 20% increased the smoke emissions to 5.24%, 4.97% and 3.78% (i.e., 1.59, 2.89, and 8.99 FSN at low, part and full loads respectively). Adding ethanol up to 10% in D80WPO20 significantly reduced smoke emissions by 3.92% due to the additional oxygen supplied during the diffusion combustion phase, thereby promoting cleaner combustion (Karagoz *et al.* 2020; Ananthakumar *et al.* 2017).

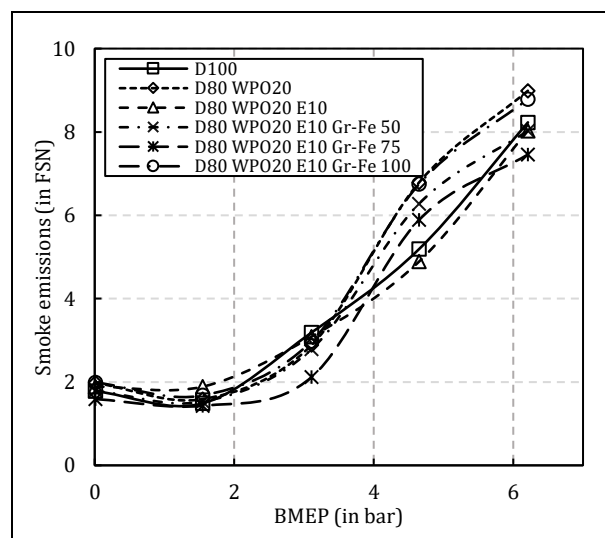


Fig. 11: Variation in smoke emissions at all loads

Further adding Gr-Fe nanoparticles improved the catalytic effect in oxidizing the available hydrocarbons, thereby ensuring limited formation of smoke. Supply of surplus oxygen by Gr-Fe nanoparticles may also be a reason for reduced engine smoke at part and full load conditions. It can be noted that D80WPO20E10Gr-Fe50 test fuel emitted the smoke values of 1.53, 2.79, and 8.03 FSN at low, part, and full load conditions, respectively. Further increase in the concentration of Gr-Fe up to 75 ppm limited the NO_x emissions by 2.12%, 1.94% and 1.57% (i.e., 1.43, 2.12, and 7.46) at low, part and full loads respectively. When Gr-Fe concentration was increased up to 100 ppm, the smoke emissions increased by 2.92% at full load conditions (Pote and Patil, 2019; Yusuf *et al.* 2024).

3.3.5 CO₂ Emissions

A complete combustion process indicates the liberation of more CO₂ in the engine exhaust. The variation in CO₂ emissions for various test fuels is plotted against BMEP (Fig. 12). D100 fuel exhibited lower CO₂ emissions of 0.679 g/kWhr, 0.548 g/kWhr and 0.619 g/kWhr at low, part, and full load conditions, respectively. The addition of WPO up to 20% in straight diesel lowered the CO₂ emissions by 1.12%, 2.43% and 2.99% at low, part and full load condition. Amalgamating ethanol up to 10% (D80WPO20) improved the combustion efficiency by liberating a higher quantity of CO₂ of 0.712 g/kWhr, 0.554 g/kWhr and 0.601 g/kWhr at low, part, and full load conditions, respectively.

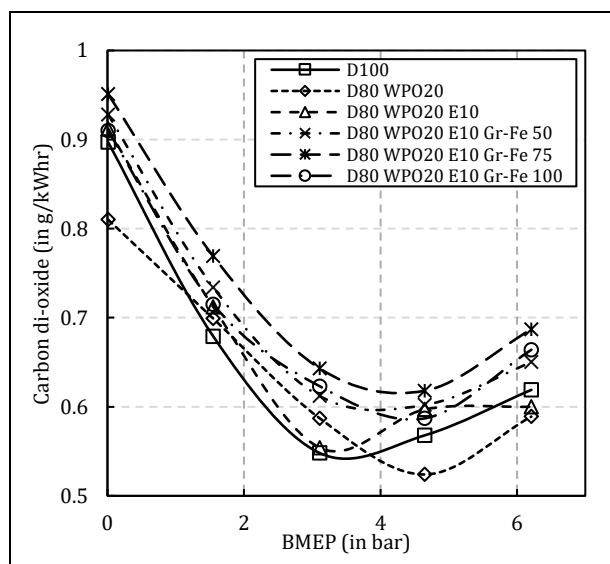


Fig. 12: Variation in CO₂ emissions at all loads

The addition of Gr-Fe nanoparticles to the test fuel blends promoted increased CO₂ formation, indicating more complete oxidation of the fuel, thereby improving the combustion efficacy. D80WPO20E10Gr-Fe50 test fuel showcased CO₂ emissions of 0.734 g/kWhr, 0.612 g/kWhr and 0.656 g/kWhr at low, part, and

full load conditions, respectively (Geo *et al.* 2018; Venkatesan *et al.* 2017). Further increase in Gr-Fe concentration up to 100 ppm marginally reduced the CO₂ formation by 0.62%.

3.4 Combustion Characteristics

This experimental investigation primarily focuses on the key combustion parameters, namely, in-cylinder pressure and heat release rate. The plots illustrate the effect of Gr-Fe nanoparticles on ethanol-oxygenated diesel-WPO blends.

3.4.1 In-cylinder Pressure and Rate of Heat Release

Fig. 13 depicts the variation of in-cylinder pressure against crank angle for the test fuel blends at full load. In-cylinder pressure is a critical combustion parameter that reflects combustion efficiency during both the uncontrolled and controlled combustion phases. The peak in-cylinder pressure for straight diesel was recorded as 66.521 bar, whereas D80WPO20 exhibited 63.932 bar, corresponding to a 4.05% reduction. Blending ethanol up to 10% in D80WPO20 fuel blend improved the in-cylinder pressure by 3.15% up to 65.627 bar. This may be due to enhanced lowering in the ignition delay period, leading to enhanced premixing combustion phase (Arjharanw *et al.* 2022). Amalgamating Gr-Fe nanoparticles up to 50 ppm in D80WPO20E10 improved the in-cylinder pressure by 1.8% due to enhanced oxidative kinetic reaction of Gr-Fe nanoparticles at reduced ignition delay. Increasing the Gr-Fe nanoparticles up to 100 ppm affected the fuel oxidative reaction, thereby prolonging the ignition delay slightly at full load conditions. D80WPO20E10Gr-Fe100 ppm exhibited a higher in-cylinder pressure of 66.08 bar. At the outset, it can be noted that Gr-Fe nanoparticle concentration up to 75 ppm in diesel-WPO-ethanol fuel blend significantly improved the combustion phenomena (Catizane *et al.* 2023; Hariram *et al.* 2018).

Fig. 14 illustrates the variation of the heat release rate against crank angle for D100, D80WPO20, D80WPO20E10, D80WPO20E10Gr-Fe50, D80WPO20E10Gr-Fe75, and D80WPO20E10Gr-Fe100 fuel blends at full load conditions. Analysis of the heat release rate is important because it influences NO_x formation, which is commonly explained by the Zeldovich mechanism. It can be noted that D100 exhibited a heat release rate of 58.521 J/CAD at full load conditions (Fig. 14). Blending WPO up to 20% in diesel marginally improved the heat release rate up to 53.661 J/CAD at the same load, which may be due to a slight prolongation in the ignition delay period. Amalgamating ethanol up to 10% in diesel-WPO fuel improved the heat release rate to 56.672 J/CAD, attributed to a prolonged progressive combustion phase due to more fuel accumulation. Infusing Gr-Fe nanoparticles up to 50 ppm released more thermal conduction ability uniformly

throughout the fuel, enhancing the surface reactivity of the fuel atoms. This enabled a superior progressive combustion phase releasing an enormous amount of heat energy (Gopinath and Devan, 2020). Further increase in Gr-Fe nanoparticles to 75 ppm and 100 ppm in the diesel-WPO-ethanol fuel blend increased the heat release rate to 60.8485 J/CAD and 60.021 J/CAD, respectively, under full-load conditions.

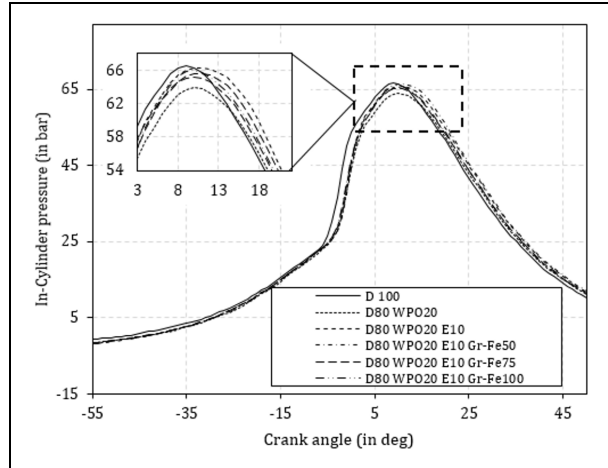


Fig. 13: Variation in In-cylinder pressure

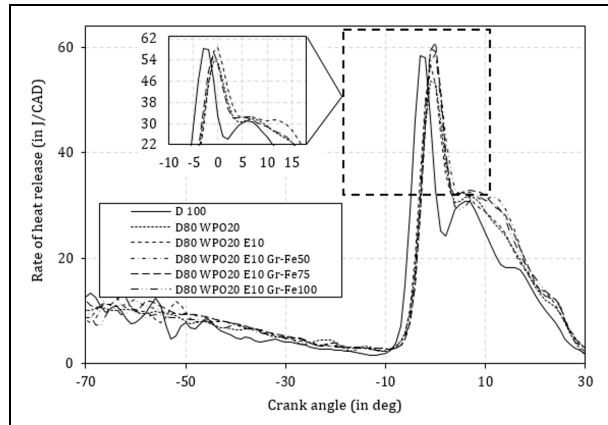


Fig. 14: Variation in heat release rate

3.5 Energy Analysis

The first law of thermodynamics forms the basis for the energy analysis performed in the present study to understand the distribution of input chemical energy among brake power, cooling losses, exhaust gas losses, frictional losses, and other heat losses. The input chemical energy was determined from the fuel mass flow rate and calorific value, whereas the useful output energy was obtained from the brake power delivered at the engine crankshaft. The losses considered in the energy analysis include cooling losses through the engine jacket, exhaust gas energy losses, frictional losses associated with mechanical components, and losses arising from incomplete combustion (Kumar *et al.* 2016; Kumar *et al.*

2020). The energy analysis was conducted using Eqs. 3–10. Fig. 15 depicts the variation in energy efficiency with engine brake power. D100, D80WPO20, D80WPO20E10, D80WPO20E10Gr-Fe50, D80WPO20E10Gr-Fe75, and D80WPO20E10Gr-Fe100 test fuels exhibited energy efficiencies of 28.9%, 27.92%, 29.71%, 28.23%, 29.05% and 27.91% at low load, whereas at 3.11 kW brake power, the energy efficiency was increased to 34.9%, 34.59%, 35.79%, 35.19%, 36.79% and 35.70%, respectively; at full loading conditions, the energy efficiency shows higher values of 40.9%, 37.9%, 39.48%, 39.74%, 38.1%, 41.98%, and 38.90%. Generally, it could be observed that energy efficiency was increased considerably in the presence of Gr-Fe nanoparticles at all loading conditions, with a notable reduction in engine exhaust emissions.

$$\sum Xn_{in} = \sum Xn_{out} \quad (I \text{ law analysis}) \quad \dots (2)$$

$$Ex_{air} + Ex_{fuel} = Ex_w + Ex_{exh} + Ex_{loss} \quad \dots (3)$$

$$Ex_{air} = m_{air}h_{air} = p_{air}v_{air}h_{air} \quad \dots (4)$$

$$Ex_{fuel} = m_{fuel}H_u \quad \dots (5)$$

$$Ex_w = \omega T \quad \dots (6)$$

$$W = \frac{2\pi n}{60} \quad \dots (7)$$

$$Ex_{exh} = \sum_{j=1}^n m_i h_i = m_{co}h_{co} + m_{NO_x}h_{NO_x} + m_{co_2}h_{co_2} \quad \dots (8)$$

$$n_{en} = \frac{Ex_w}{Ex_{air} + Ex_{fuel}} \quad \dots (9)$$

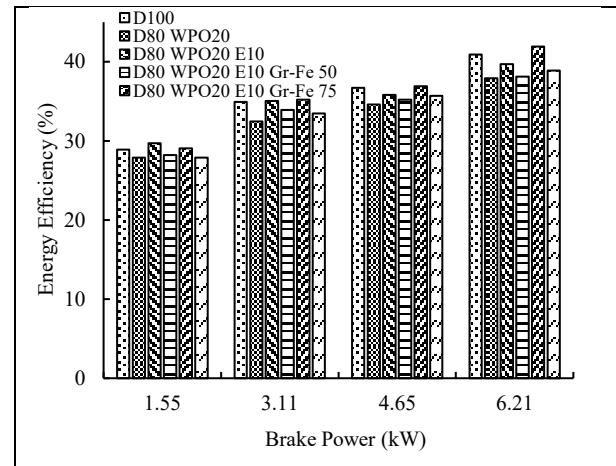


Fig. 15: Variation in energy efficiency at all loads

3.6 Exergy Analysis

Exergy analysis of the CI engine was carried out based on the second law of thermodynamics. Fig. 16 depicts the variation in exergy efficiency with engine brake power for various test fuels at all loading conditions. The total measure of molecular disorder in the

system increases with time and, in turn, influences the spontaneity of the process. Exergy efficiency further indicates the degree of useful energy conversion and irreversibility in the system. In the presence of external work input, heat transfer from a colder region to a hotter region can occur, consistent with the second law of thermodynamics. Eqs. 11–17 present the exergy efficiency analysis of the investigation (Kalargaris et al. 2016; Kaimal et al. 2017, John et al. 2017). It was observed that exergy efficiency increased with increasing engine load. At low load, the engine exhibited exergy efficiencies of 25.79%, 21.7%, 24.9%, 26.7% 27.16% and 27.90% for D100, D80WPO20, D80WPO20E10, D80WPO20E10Gr–Fe50, D80WPO20E10Gr–Fe75, and D80WPO20E10Gr–Fe100, respectively; with an increase in engine load to 4.65 kW, the test fuels exhibited values of 31.92%, 28.46%, 32.30%, 34.50%, 35.71% and 34.95%, respectively. A further increase in the engine load increased the exergy efficiency to 38.4–41.89%, particularly for Ge–Fe nanoparticles, which exhibited enhanced combustion and reduced exhaust emissions. Improved air–fuel mixing and fuel atomization may also contribute to the higher exergy efficiency at elevated load conditions.

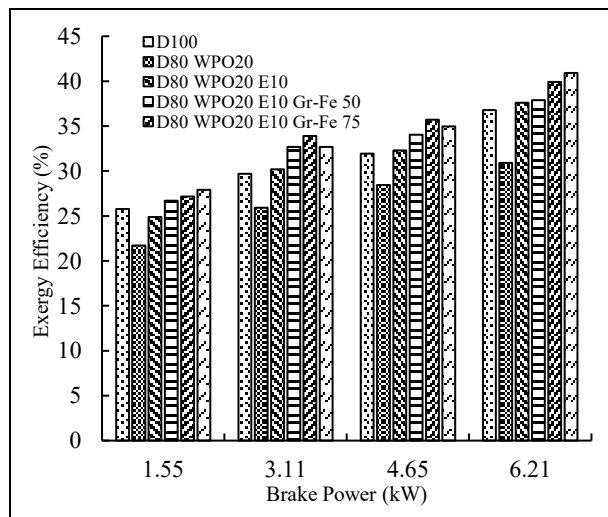


Fig. 16: Variation in exergy efficiency at all loads

$$\sum En_{in} = \sum En_{out} + \sum En_{dest} \text{ (II law analysis)} \dots (10)$$

$$En_{air} + En_{fuel} = En_w + En_{exh} + En_{loss} + En_{dest} \dots (11)$$

$$En_{air} = m_{air} C_{p,air} [(T_{air} - T_0) - T_0 \ln \left(\frac{T_{air}}{T_0} \right)] \dots (12)$$

$$En_w = Ex_w - \omega T \dots (13)$$

$$En_{exh} = \sum_{i=1}^n m_i (ex_{tm,i} + ex_{ch,i}) \dots (14)$$

$$en_{ch,i} = RT_0 \ln \left(\frac{y_i}{y_{env,i}} \right) \dots (15)$$

$$\psi = \frac{Ex_w}{Ex_{air} + Ex_{fuel}} \dots (16)$$

3.7 Regulatory Framework and Fuel Standardization for Waste Plastic Oil–diesel Blends

Globally, alternatives to conventional petroleum fuels are being extensively researched. In this study, WPO–diesel blends were investigated in a compression ignition engine, with the aim of complying with existing fuel quality standards and emission regulations to ensure legal acceptability and environmental safety. Although the fuel is currently in the research phase, its commercialization would require compliance with BS VI emission norms and Bureau of Indian Standards (BIS) fuel specifications, particularly IS 1460. Globally, the fuel quality is under frameworks such as the European Union EN 590 and the U.S. Environmental Protection Agency (EPA) fuel regulations. Therefore, the successful development and commercialization of such fuels requires certification, life-cycle assessment, and approval from statutory regulatory bodies to ensure environmental compatibility (Gopinath and Devan, 2020). Hence, systematic standardization, regulatory clearance, and engine compliance testing are essential to legally position Gr–Fe nanoparticle-infused WPO blends as viable supplementary diesel fuels in the current energy scenario. Future work could focus on improving fuel quality to meet or surpass existing standards.

4. CONCLUSION

The present investigation highlights two key factors: one is the conversion of heterogeneous waste plastic material into its pyrolytic oil, and the other is the potential capability of Gr–Fe nanoparticles to influence the combustion, emission, and performance characteristics in a compression ignition engine. The effects of Gr–Fe nanoparticles in diesel–WPO blends, in comparison with straight diesel, can be summarized as follows:

- The developed batch-type pyrolysis reactor yielded 1.69 L of waste plastic oil (WPO) in a single batch using 8 kg of preprocessed heterogeneous waste plastics.
- The brake thermal efficiency (BTE) of D80WPO20E10Gr–Fe75 was 37.623% at full load, which is 7.62% lower than straight diesel. Diesel–WPO–ethanol fuel blend also exhibited a 2.12% higher BTE compared to straight diesel.
- Unburned hydrocarbon (UBHC) emissions showed a decreasing trend with increasing engine load. D80WPO20E10 with Gr–Fe nanoparticle addition up to 75 ppm exhibited a higher UBHC emission of 0.1789 g/kWhr, which was lower than that of D80WPO20. A similar trend was observed in carbon monoxide emission, with a 2.92% reduction for D80WPO20E10Gr–Fe75 compared to straight diesel. However, NO_x emissions

increased with engine load. Gr-Fe-infused fuel blends exhibited higher NO_x emissions due to improved oxidation and catalytic activity.

- Improved premixed combustion resulted in higher in-cylinder pressure for Gr-Fe-infused fuels, along with a higher heat release rate due to enhanced combustion duration and progressivity.
- The findings also highlight that, beyond performance and emission improvements, regulatory compliance and certification are critical for the large-scale adoption of Gr-Fe nanoparticle-infused WPO blends.

It can be concluded that the infusion of Gr-Fe nanoparticles with oxygenated diesel-WPO fuel blends provides a sustainable alternative to conventional fuels. Future efforts could focus on compliance with BS VI emission norms, BIS IS 1460 standards, and international fuel quality frameworks to ensure environmental safety and legal acceptability.

NOMENCLATURE

PPO	Plastic Pyrolysis Oil
CI	Compression Ignition
WPO	Waste Plastic Oil
FTIR	Fourier Transform Infrared
ASTM	American Society for Testing and Materials
CO	Carbon monoxide
HC	Hydrocarbon
NO _x	Oxides of Nitrogen
O ₂	Oxygen
CO ₂	Carbon dioxide
BTE	Brake Thermal Efficiency
GQD	Graphene Quantum Dot
HDPE	High-density Polyethylene
LDPE	Low-density Polyethylene
PE	Polyethylene
PS	Polystyrene
ANOVA	Analysis of Variance
SEM	Scanning Electron Microscope
TDC	Top Dead Centre
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
BMEP	Brake Mean Effective Pressure

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCE

- Arjhar, W., Liplap, P., Maithomklang, S., Thammakul, K., Chuepeng, S. and Sukjit, E., Distilled waste plastic oil as fuel for a diesel engine: fuel production, combustion characteristics, and exhaust gas emissions, *ACS Omega*, 7(11), 9720-9729 (2022). <https://doi.org/10.1021/acsomega.1c07257>
- Ananthakumar, S., Jayabal, S. and Thirumal, P., Investigation on performance, emission and combustion characteristics of variable compression engine fuelled with diesel, waste plastics oil blends, *J. Brazilian Soc. Mech. Sci. Eng.*, 39(1), 19-28 (2017). <https://doi.org/10.1007/s40430-016-0518-6>
- Bisrul, H. T., Himsar, A., Tulus, B. S. and Abdi, H. S., Experimental study of the use of plastic pyrolysis oil as an additive to improve physicochemical properties and performance of rubber seed biodiesel, *Case Stud. Chem. Environ. Eng.*, 10, 100924(2024). <https://doi.org/10.1016/j.csee.2024.100924>
- Catizane, C., Jiang, Y. and Sumner, J., Improving plastic pyrolysis oil quality via an electrochemical process for polymer recycling: a review, *Energy Adv.*, 3(2), 366-388 (2024). <https://doi.org/10.1039/D3YA00389B>
- Chacko, N. and Jeyaseelan, T., Comparative evaluation of graphene oxide and graphene nanoplatelets as fuel additives on the combustion and emission characteristics of a diesel engine fuelled with diesel and biodiesel blend, *Fuel Proce. Technol.*, 204, 106406 (2020). <https://doi.org/10.1016/j.fuproc.2020.106406>
- Faisal, F., Rasul, M. G., Chowdhury, A. A., Jahirul, M. I. and Hazrat, M. A., Performance and emission characteristics of a CI engine with post-treated plastic pyrolysis oil and diesel blend, *Energy Rep.*, 9, 87-92 (2023). <https://doi.org/10.1016/j.egy.2023.09.142>
- Faisal, F., Rasul, M. G., Jahirul, M. I. and Ashfaq, A. C., Waste plastic pyrolytic oil is a source of diesel fuel: A recent review on diesel engine performance, emissions and combustion characteristics, *Sci. Tot. Environ.*, 886, 163756 (2023). <https://doi.org/10.1016/j.scitotenv.2023.163756>

- Faisal, F., Rasul, M. G., Jahirul, M. I. and Chowdhury, A., Waste plastics pyrolytic oil is a source of diesel fuel: a recent review on diesel engine performance, emissions, and combustion characteristics, *Sci. Tot. Environ.*, 886, 163756 (2023). <https://doi.org/10.1016/j.scitotenv.2023.163756>
- Geo, V. E., Sonthalia, A., Aloui, F. and Femilda Josephin, J. S., Study of engine performance, emission and combustion characteristics fueled with diesel-like fuel produced from waste engine oil and waste plastics, *Front. Environ. Sci. Eng.*, 12(4), 8 (2018). <https://doi.org/10.1007/s11783-018-1063-6>
- Gopinath, S. and Devan, P. K., Optimization and Prediction of Reaction Parameters of Plastic Pyrolysis Oil Production Using Taguchi Method, *Iran. J. Chem. Chem. Eng.*, 39(2), 91-103(2020). <https://doi.org/10.30492/IJCCE.2020.33965>
- Gopinath, S., Chidambaranathan, B., Ashok, K. R., Arunkumar, S., Rajesh, K., Yuvarajan, D. and Ruby, M., Synergistic effects of graphene quantum dot additives in waste plastic oil blends: combustion stability and emission reductions analysis, *Res. Eng.*, 25, 104130 (2025). <https://doi.org/10.1016/j.rineng.2025.104130>
- Gopinath, S., Devan, P. K. and Pitchandi, B. C. K., Influence of retarded injection timing on thermal performance and emission characteristics of a diesel engine fuelled with an optimized pyrolytic blend, *Energy Environ.*, 33(6), 1039-1060 (2021). <https://doi.org/10.1177/0958305X211033970>
- Hariram, V., John, J. G., Seralathan, S. and Micha, P. T., Comparative analysis of combustion, performance and emission phenomenon of a CI engine fuelled with algal and cotton seed biodiesel, *Int. J. Amb. Energy*, 42(6), 636-647(2018). <https://doi.org/10.1080/01430750.2018.1562977>
- Hariram, V., Prakash, S., Seralathan, S. and Micha Premkumar, T., Data set on optimized biodiesel production and formulation of emulsified Eucalyptus teriticornis biodiesel for usage in compression ignition engine, *Data Brief*, 20, 6-13(2018) <https://doi.org/10.1016/j.dib.2018.07.053>
- Hariram, V., Sathishbabu, R., Godwin, J. J., Kailiappan, N., Vijayakumar, K., Sangeeth, K. E. and Kamakshi, P., Enhanced combustion and emission characteristics of diesel-algae biodiesel-hydrogen blends in a single-cylinder diesel engine, *Res. Eng.*, 26, 104676(2025). <https://doi.org/10.1016/j.rineng.2025.104676>
- Hariram, Venkatesan., C, Dhanush., K, Ezhil Maran., K, Akilandabharathi., A, Md. Faizaan., Seralathan, Sivamani, K, L, Vasudev., Micha Premkumar T. Performance assessment of artificial neural network on the prediction of Calophyllum inophyllum biodiesel through two-stage transesterification, *Energy Sources, Part A: Recovery, Utiliz. Environ. Eff.*, 43(9), 1060-1072 (2021). <https://doi.org/10.1080/15567036.2019.1634164>
- Haseeb, Y., Hafiz, M. A., Uzair, S. and Khalid, H., Investigating the potential of plastic pyrolysis oil-diesel blends in diesel engine: performance, emissions, thermodynamics and sustainability analysis, *Res. Eng.*, 24, 103336 (2024). <https://doi.org/10.1016/j.rineng.2024.103336>
- Janarthanan, K. and Sivanandi, P., Extraction and characterization of waste plastic pyrolysis oil for diesel engines, *J. Clean. Prod.*, 366, 132924 (2022). <https://doi.org/10.1016/j.jclepro.2022.132924>
- Jayashri, N., Nair, T., Nagadurga, Dhana, R. V., Harish, V., Sameer, A., Sarfaraz, K., Amir, I. A. A., Abdul, R. and Narasimha, M., Impact of fuel additives on the performance, combustion and emission characteristics of diesel engine charged by waste plastic bio-diesel, *Case Stud. Therm. Eng.*, 67 105755 (2025). <https://doi.org/10.1016/j.csite.2025.105755>
- John, Godwin., Hariram, V., Seralathan, S., Jaganathan R. Effect of oxygenate on emission and performance parameters of a CI engine fuelled with blends of diesel-algal biodiesel. *Int. J. Rene. Energy Res.*, 7(4), 2041-2047 (2017).
- Kaimal, V. K. and Vijayabalan, P., A detailed investigation of the combustion characteristics of a DI diesel engine fuelled with plastic oil and rice bran methyl ester, *J. Energy Inst.*, 90(2), 324-330(2017). <https://doi.org/10.1016/j.joei.2015.11.005>
- Kalargaris, I., Tian, G. and Gu, S., Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil, *Fuel Process. Technol.*, 157, 108-115 (2017) <https://doi.org/10.1016/j.fuproc.2016.11.016>
- Karagoz, M., Uysal, C., Agbulut, U. and Saridemir, S., Energy, exergy, economic and sustainability assessments of a compression ignition diesel engine fueled with tire pyrolytic oil-diesel blends, *J. Clean. Prod.*, 264, 121724 (2020). <https://doi.org/10.1016/j.jclepro.2020.121724>
- Kumar, K. S. and Muniamuthu, S., Assessment of performance, combustion, and emission characteristics of single cylinder diesel engine fuelled by pyrolysis oil + CeO₂ nanoparticles and 1-butanol blends, *Int. J. Amb. Energy*, 45 (1), 2344568 (2024). <https://doi.org/10.1080/01430750.2024.2344568>
- Kumar, R., Mishra, M. K., Singh, S. K. and Kumar, A., Experimental evaluation of waste plastic oil and its blends on a single cylinder diesel engine, *J. Mech. Sci. Technol.*, 30, 4781-4789(2016) <https://doi.org/10.1007/s12206-016-0950-7>
- Kumar, Y. R., Deshmukh, K., Sadasivuni, K. and Pasha, S. K. K., Graphene quantum dot-based materials for sensing, bio-imaging and energy storage applications: a review, *RSC Adv.*, 10, 23861-23898 (2020). <https://doi.org/10.1039/D0RA03938A>

- Mohammed, A. J., Anish, M., Jayaprabakar, J., Yashashwini, S., Vivek, A. A., Karthick, M., Ankur, B., Mohammad, K., Muraliraja, R. and Vimal R., Performance optimization of CI engine using python with blends of waste oil biodiesel, plastic pyrolysis oil and diesel, *Res. Chem.*, 18, 102769 (2025). <https://doi.org/10.1016/j.rechem.2025.102769>
- Pote, R. N. and Patil, R. K., Combustion and emission characteristics analysis of waste tyre pyrolysis oil, *SN Appl. Sci.*, 1(4), 294 (2019). <https://doi.org/10.1007/s42452-019-0308-8>
- Soudagar, M. E. M., Nik-Ghazali, N. N., Abul, K. M., Badruddin, I. A., Banapurmath, N. R. and Akram, N., The effect of nano-additives in diesel-biodiesel fuel blends: a comprehensive review on stability, engine performance and emission characteristics, *Energy Convers. Manage.*, 178, 146-177(2018). <https://doi.org/10.1016/j.enconman.2018.10.019>
- Suresh, V., Davannendran, C., Ravikumar, V., Krishnamoorthy, R., Raghunatha, R. and Revathi, R., Maximizing waste plastic oil yield and enhancing energy and environmental metrics through pyrolysis process optimization and fuel modification, *Res. Eng.*, 22, 102066 (2024). <https://doi.org/10.1016/j.rineng.2024.102066>
- Venkatesan, H., Sivamani, S., Bhutoria, K. and Vora, H. H., Assessment of waste plastic oil blends on performance, combustion and emission parameters in direct injection compression ignition engine, *Int. J. Amb. Energy*, 40(2), 170-178(2019). <https://doi.org/10.1080/01430750.2017.1381155>
- Yaqoob, H., Ali, H. M., Abbas, H. Abid, O., Jamil, M. A. and Ahmed, T., Performance and emissions characteristics of tire pyrolysis oil in diesel engine: an experimental investigation, *Clean Technol. Environ. Policy*, 25, 3177-3187 (2023). <https://doi.org/10.1007/s10098-023-02586-0>
- Yusuf, A. A., Veza, I., Ampah, J. D., Afrane, S., Sarikoç, S., Mujtaba, M. A. and Yahuza, I., Experimental study on emissions and particulate characteristics of diesel engine fueled with plastic waste oil, acetone-butanol-ethanol and diesel blends, *Process Safe. Environ. Protect.*, 191, 1419-1431 (2024). <https://doi.org/10.1016/j.psep.2024.09.060>