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EMISSION PERFORMANCE ANALYSIS OF DIESEL BLENDED WITH WASTE PLASTIC OIL

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ABSTRACT

This work is investigation about the engine performance and emission of a single-cylinder variable compression ignition engine working on diesel blended with Waste Plastic Oil (WPO) under various load conditions. The blends containing 10%, 20%, 30%, 40%, and 50% WPO by volume were examined with pure diesel (D100). Results show a gradual decrease in Brake Thermal Efficiency (BTE) with increasing WPO volume while Exhaust Gas Temperature (EGT) rose with higher blends, peaking at 337 °C for D50WPO50.The emission of CO_2 found to be less by 33.3% at the highest blend, while CO and hydrocarbon (HC) increased by 32.7% and 51.3%. Emission of Nitrogen oxides (NO_x) showed a non-linear trend, initially decreasing at D80WPO20. D80WPO20 is the best-balanced blend keeping in mind optimum performance and emission. The findings are aligned with the past studies conducted in same fields.

KEYWORDS

Alternative fuel; Diesel–WPO blends; Emission characteristics; Greenhouse gas reduction; Pollution.

1. INTRODUCTION

We are living in most modern era and to achieve that we have exploited the environment so much that now we require a correction strategy to keep this beautiful earth a good living place for coming generation. Keeping that in mind this work proposed how to reduce the plastic waste while reusing them as a fuel. We all know that these wastes are non-degradable for long time so there is need or call to stop using them and converts whatever already dumped into fuels. By doing so we can achieve two objectives one eliminating the plastic waste from earth and secondly using it as a fuel therefore reducing dependency on fossil fuel.

The increasing demands for fuel around the globe is rising a concern about the overall impact on earth as the fossil fuels are limited and even if we keep on using them the pollution will increase causing global warming. Past few decades the generation and dumping of plastic has created a huge concern about environmental challenged that need to added as soon as possible because it has been delayed already too much. Beyond this the changes will be irreversible whether it is about land, water, air or food pollution.

Since plastic is non-degradable in nature it can live forever on earth causing serious threat to land and water ecosystems. Seeing this context conversion of plastic into energy is a great boon which can address energy crises and plastic wate disposal simultaneously. If we talk about the various methods of converting plastics into energy no doubt the pyrolysis method has gained popularity as an effective way to proves the plastic into energy. The various product released from this methods are in the form of liquids, gaseous and char under anaerobic condition. The liquid form obtained is mainly known as waste plastic oil whose properties are comparable to pure diesel since both are hydrocarbon compounds.

Despite the number of research done or going in this field there is doubt related to combustion emission characteristics and fuel stability in long term engine performance which limit the large-scale use, to make it viable a comprehensive study of WPO as a fuel need to be done for feasibility and long-term application without deteriorating the engine body. If we study previous studies done in tis field we found out that the waste plastic fuel (WPO) has demonstrated huge potential that can be generated from waste plastics.

The researcher Jahirul et al. (2023) found out in his study that plastics like as high-density polyethylene (HDPE), polystyrene (PS), and polypropylene (PP) generated fuels that have calorific values between 38.1 to 42.9 MJ/kg and cetane indices that meet automotive fuel requirements and same was reported by , Mikulski et al. (2022) while his investigation about tyre pyrolytic oil blends in a single-cylinder diesel engine and he observed stable performance up to 40% blending without engine, apart from increased particulate matter and sulphur-related content required the need for further fuel refinement

Tunç et al. (2021) proposes that blending waste plastic oil with biogas and diesel can improve environmentally while reducing the cost and maintaining required acceptable engine performance across various load conditions taken by the engine. In line with same study, Shahir et al. (2020) found that 30% tyre pyrolytic oil blends increased brake thermal efficiency and reduced Nox although there was slight increase in the carbon monoxide and hydrocarbon emission. The great advancements in then pyrolysis techniques and fuel processing methods have further contributed to advancement in the quality and usability of waste-platic fuels. Ramanathan et al. (2019) studied on the combination of microwave-assisted pyrolysis of waste engine oil, with common rail direct injection (CRDI) systems, and found that fuel atomization enhanced and significantly reduced NO and smoke emissions. Venkatesan et al. (2018) work on that plastic oil derived from municipal waste conforms that it meets ASTM fuel standards and, when blended up to 30% with diesel shows higher in-cylinder pressures and improved brake thermal efficiency, with little bit of increased fuel consumption. Researchers like Wiriyaumpaiwong et al. (2017) has found out that fractional distillation also is an effective method for improving fuel quality, with demonstrating that lighter distillates obtained from mixed plastic pyrolytic oils possess properties comparable to gasoline, expanding the scope of application beyond diesel engines.

If we see the role of catalyst in this pyrolysis process many researchers in past has published number of paper discussing the role in optimization of the process. Mohanraj Chandran et al. (2020) during his studies on various catalytic pyrolysis found and concluded that appropriate catalyst selection improves hydrocarbon yield and fuel properties, although emissions of NO_x, CO, and unburned hydrocarbons may remain higher than in comparison to the diesel. Padmanabhan et al. (2022) whole addressing the balance between performance and emissions, found out improved brake thermal efficiency and reduced specific fuel consumption when incorporating multi-component blends waste plastic-derived fuels. Pal et al. (2019) observed lower brake thermal efficiency and increased unburned HC emissions, reinforcing the importance of optimised blending ratios while higher plastic oil blending ratios reduced CO_2 emissions and smoke opacity. Faisal et al. (2023) demonstrated that to improve pyrolytic oil quality post-treatment processes such as distillation and hydrotreatment plays significant role and improved engine performance at modest blending percentages.

Mohan et al. (2023) examined the catalytic co-pyrolysis reaction of low-density polyethylene (LDPE) with Pongamia pinnata seeds and found out diesel-like brake thermal efficiency with reduced CO and HC emissions, though a small increase in NO_x was observed at elevated combustion temperatures. Szwaja et al. (2022) found out that medium blending ratios can maintain high engine performance during his study of n-butanol–pyrolysis oil blends and without significant increase in emission, while higher proportions increased combustion duration and knock tendencies. Urban Žvar Baškovič et al. (2023) reported substantial reductions in NO_x and particulate matter emissions when waste plastic oil was used as a low-reactivity fuel component while implementing advanced concept like Reactivity Controlled Compression Ignition (RCCI).

Amit Kumar et al. (2024) studied optimisation techniques like response surface methodology to optimise plastic pyrolysis oil blends along with Al_2O_3 nanoparticles, demonstrating increase in brake thermal efficiency and reductions in brake-specific fuel consumption. Similarly, Santhoshkumar and Ramanathan (2020) also reported that microwave-assisted pyrolysis can significantly reduce energy consumption during fuel production while yielding fuel properties like diesel with improved emission characteristics. Additionally, research by Faisal et al. (2023) showed that neat pyrolysis oil exhibits delayed ignition and variable NO_x behaviour, while blended fuels offer substantial reductions in CO_2 emissions, highlighting the environmental benefits.

Mani et al. (2009) showed in his study that waste plastic oil could be used directly in a diesel engine without hardware modifications, achieving comparable brake thermal efficiency and significant smoke reduction. Research by Bharti and Singh (2022) highlighted the role of mechanical adaptability in optimising the performance and combustion for the alternative fuels and engines. Combining all these studies we van say that sustainable utilization od water plastic oil derived from plastics for CI engines can be boon but requires integrated approach encompassing fuel processing combustion strategy and engine optimisation.

A lot of research has been done till now but still gaps remains in understand the feasibility, engine modification, ratio of blending, performance and scale of production, The most challenging is identifying the optimal blends which balance performance and emission simultaneously. The current study tries toa address these gaps and give a picture for upcoming future research so that we all can get free from plastic choking the earth.

2. MATERIALS AND METHODS

The material used in this study are obtained through thermos chemical pyrolysis technique in which plastic is decomposed in anaerobic method. This method breaks the plastics in to lower molecular hydrocarbon. This process is selected due to effectiveness in converting the plastic into fuel. The process of production is outlined below.

Feed Stock Selection: The Plastic feedstock collected mainly are high-density polyethylene

(HDPE), low-density polyethylene (LDPE), and polypropylene (PP). These plastics are collected from different sources like municipal waste stream are cleaned, shredded to remove dirt, labels etc. The plastic is shredded into small pieces to promote uniform heat transfer and thermal degradation.

Reactor Setup: The reactor used are batch types stainless steel so that no possibilities of any reaction which can reduce the fuel quality. The reactor is designed in a way to resist high pressure and temperature. The reactor is sealed to remove oxygen since ethe reaction take place in absence of oxygen.

Pyrolysis Process: The shredded feedstock is induced in the reactor and gradually headed temperature rises in a range between 350 to 450 °C. the heat source used is external. The long chain polymer molecules undergo thermal cracking due to high temperature which produces mixture of hydrocarbon vapours and gaseous product.

Condensation and Collection: This process is achieved by using water cooled condenser where vapour are condensed into liquid oil. This liquid is refereed as waste plastic oil.

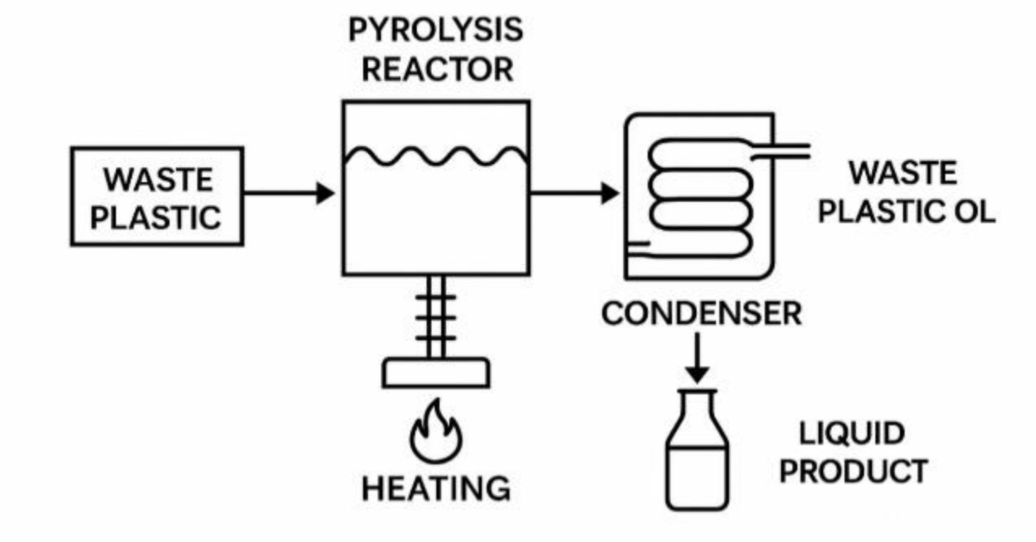

Fig. 1. Production stages of Waste Plastic Oil (WPO)

Oil Refining: After the collection of crude waste plastic oil, it is allowed to settle for some period of time to facilitate the separation of moisture and suspended impurities to further enhance the quality. This crude oil is made to undergo filtration and mild distillation prior to blending. Doing this process ensure the homogeneity and suitability of the product for combustion studies.

The fuels and blends oil used in the present study consist of pure diesel fuel and waste plastic oil (WPO). They are blended in various proportion to study the influence on engine performance and emission as shown in Table 1. The various properties of diesel and waste plastic oils are demonstrated in Table 2.

Table 1: Diesel and WPO mixing ratio

Diesel (%)	Waste Plastic oil (WPO) (%)
90	10
80	20
70	30
60	40
50	50

Table 2: Comparison of Diesel and WPO properties

Property	Diesel	WPO	Reference
Calorific Value (MJ/kg)	46.5	44.34	(Chandran et al., 2020)
Density (g/cm³)	0.84	0.83	(Chandran et al., 2020)
Viscosity (cSt)	2.6–3.0	2.2–2.7	(Wiriyaumpaiwong et al., 2017)
Flash Point (°C)	60–80	45–60	(Pal et al., 2023)

2.1. Blend Preparation and Homogeneity Testing

The blends of diesel and waste plastic oil are prepared in a predetermined proportion ranging from 10% to 50%. The process of blending was done using magnetic stirrer at 1000 rpm to ensure uniform mixing for a period of 15 minutes. After the thar blend was subjected to homogeneity and phase stability to find out if any phase separation or stratification occurred before engine testing.

- Visual Inspection: For this each blend was left to rest for a day (24 hours) at room temperature to detect any visible phase separation, clouding or stratification.
- Density Consistency Test: Small samples were taken from the top, middle, and bottom of each stored blend after 24 hours. Their densities were measured using a hydrometer, and variations were within ±0.002 g/cm³, confirming uniform distribution.
- Repeatability Check: The blending and stability tests were repeated thrice for each formulation to confirm reproducibility.

2.2. Experimental Setup

The engine used for the experiment is single cylinder four-stroke diesel engine with electric-dynamometer.

Automotive Gas Analyzer (model- HG-540) was used to measure levels of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) in the blend of diesel and WPO.

Fig. 2. Gas Analyzer used in Experiment

Table 3: Experimental Engine Specification

Parameter	Specification
Bore Diameter	80mm
Related Power	7.5 kW(10HP)
Connecting Rod Length	234mm
Swept Volume	552.77 cc
Rated Torque	4.6kg-m
Stroke Length	110mm
Arm Length	150mm
Rated Speed	Rpm
Make	Kirloskar

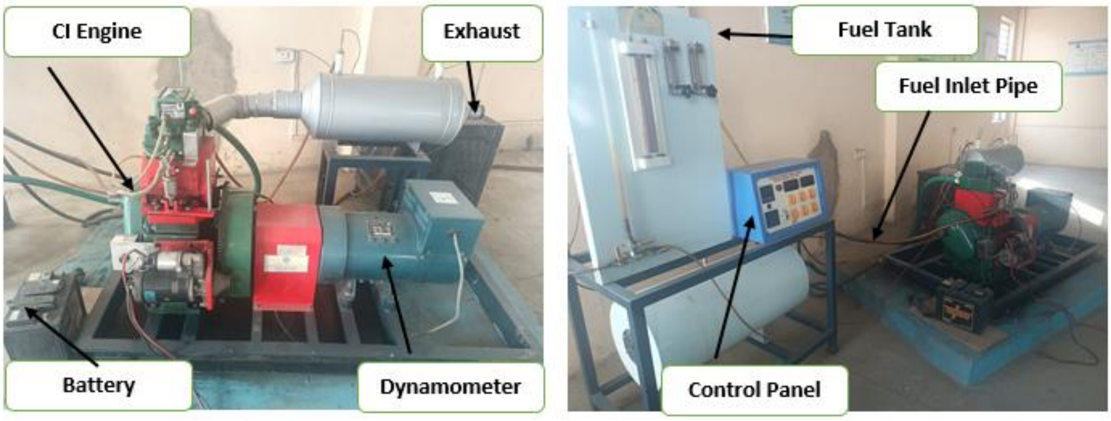

Fig. 3. Variable Compression Ratio CI engine Experimental Set-Up

2.3. Testing Procedure

To establish a reference point, the engine was first operated using 100% diesel fuel at 1500 rpm. Parameters such as CO, CO_2, NOx, HC, BTE, and EGT were recorded at different engine loads. After completing the baseline tests, the engine was run with each of the WPO-diesel blends (D90WPO10, D80WPO20, D70WPO30, D60WPO40, and D50WPO50).

For each blend:

- The engine was warmed up to operating temperature.
- Emissions data were collected under the same load conditions as the diesel tests.

The experimental trials were conducted at incremental load conditions of 0.5, 1.0, 1.5, 2.0, and 2.5 kW while maintaining a constant engine speed of 1500 rpm, in order to evaluate the influence of waste plastic oil blending across the entire operating range of the engine. The experiment was repeated three times for each load and blends and average values out of all three experiment was collected for analysis. The variation in all the three reading of different load and blend was minimal confirming the reliability of the data.

The results were presented in graph form for analysis purpose and better representation of trends of blends. The key performance and emission indicators such as brake thermal efficiency, exhaust gas temperature, carbon dioxide, carbon monoxide, hydrocarbons, and nitrogen oxides, were evaluated in detail.

2.3.1. CERTAINTY AND REPEATABILITY ANALYSIS

To ensure the correctness and reliability of the experimental outcomes, all measuring instruments were calibrated and checked before starting the experiment. The reliability and repeatability of fuel blending data and procedures, emission measurements, and temperature readings was examined and found to exhibit negligible deviation, as summarised in Table 4, which conforms the correctness and reliability of the data.

Table 4 Certainty Analysis

Parameter	Instrument/ Method Used	Accuracy	Repeatability / Deviation	Remarks
Fuel Measurement (Diesel & WPO)	Graduated Beaker	±1 ml	< ±2% across trials	Consistent volume maintained in all blends
Emission Measurement (CO, HC, NO_x)	Automotive Gas Analyzer (HG-540)	Manufacturer-calibrated (ppm accuracy)	±3% variation observed across repetitions	Emissions taken after engine reached stable temp
CO_2 Measurement	Automotive Gas Analyzer (HG-540)	±0.01%	±2.5% variation	Inline with literature-reported deviation
Exhaust Gas Temperature (EGT)	Thermocouple in exhaust pipe	±1 °C	±2% variation	Temperature sensor calibrated before testing
Engine Load	Electric Dynamometer	±0.1 kW	Consistent load increments from 0.5 to 2.5 kW	Same load pattern used for all blends
Blend Homogeneity Check	Magnetic Stirring (1000 RPM, 15 mins) + Visual + Density	±0.002 g/cm³ (hydrometer)	No phase separation identical top/mid/bottom densities	Confirmed phase stability over 24 hours
Repetition of Tests	All experiments repeated thrice	–	Average used for reporting; deviation within limits	Ensures statistical reliability of results

3. RESULTS AND DISCUSSION

The emission and performance behaviour evaluation of the diesel–waste plastic oil (WPO) blends was conducted by examining key parameters, such as brake thermal efficiency, exhaust gas temperature, carbon dioxide, carbon monoxide, unburned hydrocarbons, and nitrogen oxides. The major observations derived from the experimental results are summarised below.

3.1. Brake Thermal Efficiency (BTE)

BTE decreased with increasing WPO content in the fuel blend Fig. 6.

BTE represents how effectively the chemical energy of the fuel is converted into useful mechanical work.

Reasons:

- Lower cetane number of WPO leads to delayed combustion and less efficient energy conversion.
- Incomplete combustion due to higher viscosity and poorer atomization reduces effective pressure generation.
- Higher aromatic content in WPO burns less efficiently, lowering overall thermal efficiency.
- Volatility mismatch between diesel and WPO can also lead to poor air-fuel mixing and sub-optimal combustion, particularly at low loads.

3.2. Exhaust Gas Temperature (EGT)

EGT increased with both engine load and WPO blending ratio Fig. 5.

Reasons:

- Higher engine load: More fuel is injected, leading to more combustion and higher heat release, raising exhaust gas temperatures.
- Higher WPO content:
  - Aromatic content and lower cetane number cause delayed ignition and rapid post-ignition combustion, raising peak temperatures.
  - Post-flame oxidation of unburned hydrocarbons contributes to elevated EGT.
  - Extended combustion duration due to WPO's slower burning rate leads to more heat carried into the exhaust.
  - This trend indicates more intense combustion and heat retention in the exhaust gases with WPO blends, especially at higher proportions.

3.3. Carbon Dioxide (CO_2) Emissions

CO_2 emissions decreased with increasing WPO content Fig. 4.

Reasons:

- CO_2 is a product of complete combustion. Diesel combusts more completely, producing more CO_2.
- WPO's hydrocarbon irregularities (long chains, aromatics, impurities) reduce combustion efficiency, causing oxygen deficiency and incomplete oxidation, thus lowering CO_2 formation.
- This corresponds with increased CO and HC emissions, signs of incomplete combustion.

3.4. Carbon Monoxide (CO) Emissions

CO emissions increased with increasing WPO content Fig. 4.

Reasons:

- CO forms from incomplete combustion in oxygen-deficient conditions.

- WPO's structure (complex hydrocarbons, residues, aromatics):
  - Requires higher activation energy to break down
  - Forms localized rich zones with low oxygen
  - Causes incomplete oxidation of carbon, producing CO instead of CO_2
- At higher blends like D50WPO50, low volatility and cetane number hinder smooth ignition and flame propagation, worsening CO formation.

3.5. Hydrocarbon (HC) Emissions

HC emissions increased with increasing WPO content Fig. 4.

Reasons:

- HC emissions result from unburned or partially burned fuel.
- WPO contains:
  - Unsaturated and branched hydrocarbons resistant to oxidation
  - Contaminants disrupting flame stability
  - Lower cetane number, delaying ignition and increasing incomplete combustion
- Higher blends (e.g., D50WPO50) produce poor vaporization and mixing, leaving unburned fuel that exits as HC.
- In diesel engines, atomization and vaporization are crucial. WPO's higher viscosity and lower volatility hinder these, especially under low pressure or cold conditions.

3.6. Nitrogen Oxides (NO_x) Emissions

NO_x emissions followed a non-linear trend — initially decreasing, then increasing Fig. 4.

Reasons:

- NO_x formation depends on combustion temperature and oxygen availability.
- With initial WPO increase:
  - Combustion temperature drops due to incomplete combustion
  - Oxygen deficiency occurs due to poor fuel-air mixing
  - Both reduce NO_x formation
- Beyond D70WPO30:
  - Delayed ignition causes fuel accumulation, leading to rapid and hotter post-ignition combustion
  - Local spikes in in-cylinder temperature increase NO_x despite poor combustion
  - Aromatics in WPO may contribute to localized thermal NO_x formation

This U-shaped NO_x behavior is common with alternative fuels, where initial poor ignition suppresses NO_x, but delayed, high-temperature combustion later increases it.

3.7. Effect of Load on All Emissions

Higher loads involve more fuel, higher pressures, and elevated temperatures. Effects:

- Increases combustion rate, but not necessarily combustion completeness (especially with WPO).
- Amplifies CO and HC due to richer mixtures and possible flame quenching.
- Raises NO_x due to higher in-cylinder temperatures and pressures.

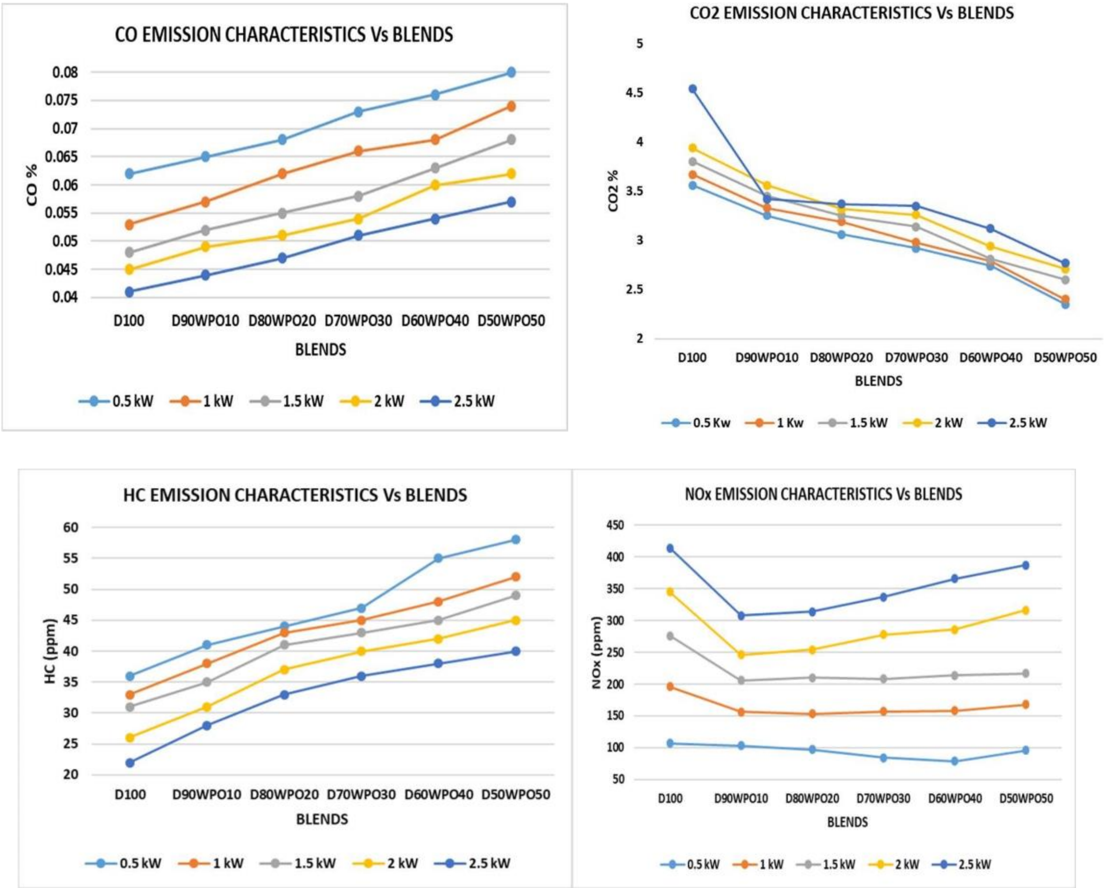

Fig. 4. Emission characteristics of HC, CO2, NOx and CO

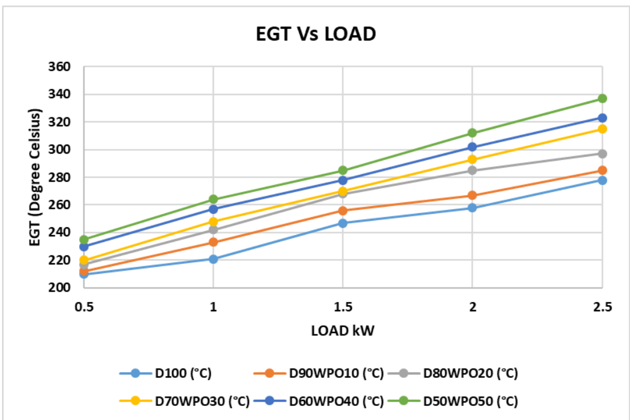

Fig. 5. EGT Trend

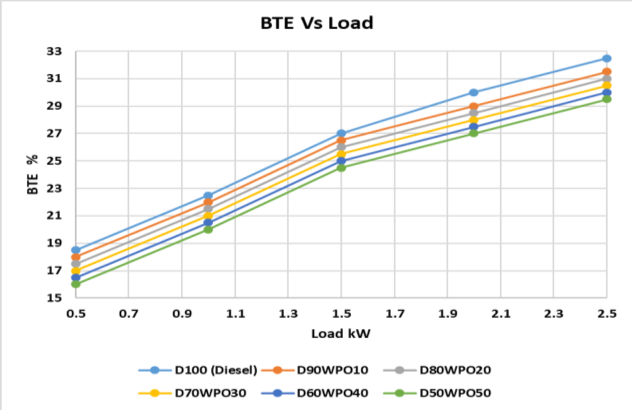

Fig. 6. BTE Trend

4. VALIDATION

The performance and emission trends observed in this investigation are in agreement with previously reported studies on diesel–waste plastic oil (WPO) blends. Venkatesan et al. (2018) documented a 6.9% reduction in brake thermal efficiency (BTE) when using pure WPO compared to diesel, which aligns with the observed decrease in BTE with increasing WPO content in the present study. Faisal et al. (2023) and Pal et al. (2023) showed that at 20–30% WPO blends optimal engine performance occurs, while higher proportions of blending leads to a notable decline in thermal efficiency due to combustion inefficiencies. The D80WPO20 blend in this study demonstrated optimum performance closest to pure diesel, confirming its suitability as an optimal blend. Additionally, Mani et al. (2009) and Palanivelrajan et al. (2024), also recommended a 20% WPO blend for maintaining efficiency under varying operating conditions.

The observed reduction in emission of CO_2 with increasing WPO volume align with results reported by Kumar et al. (2013) and Das et al. (2023). The rise in carbon monoxide (CO) and hydrocarbons (HC) at higher WPO blending levels is aligned with the findings published in Energy Conversion and Management (Kumar et al., 2013) and Journal of Mechanical Science and Technology (2016). Amar Kumar Das and Panda (2023), highlighting the non-liner trends of Nox and sensitivity of NO_x formation to both combustion temperature and fuel composition. Overall, these validations support the reliability and credibility of the present experimental outcomes.

5. CONCLUSION

This work shows that there is effect of blending of pure diesel and waste plastic oil. The brake thermal efficiency reduces as the volume of waste plastic oil increases. The exhaust gas temperature increases as the waste plastic oil volume percentage increases keeping engine efficiency close to that of pure diesel.

When it comes to emission characteristics CO_2 level decreases as waste plastic oil increases while CO and HC level increases for the same. The NO_x emission shows a U-shaped trend initially decreasing then increasing with the increase of waste plastic oil.

Table 5 Summary of Key Engine Performance and Emission Trends for Diesel and WPO Blends

Parameter	D100 (Diesel)	D80WPO20	D50WPO50
Brake Thermal Efficiency (%)	32.5	31.0	29.5
Exhaust Gas Temperature (°C)	278	297	337
CO_2 Emissions (%)	3.6	3.1	2.4
CO Emissions (%)	0.055	0.062	0.073
HC Emissions (ppm)	37	45	56
NO_x Emissions (ppm)	~390	315	385
Overall Assessment	Baseline	Optimal Blend	Unfavorable

This study focuses only on short term analysis of performance and emission characteristics. There is a need to analysis long-term effect of blends on engine parts like pump, injector etc. Past research showed that there may be deposits in fuel systems and accelerated wear and tear. These aspects give a scope of future investigation and research opportunities for future research.

6. FUTURE WORK SCOPE

1. Conduct long-term durability studies on diesel engines operating with different WPO blends to evaluate wear and potential damage to fuel injectors, pumps, and other critical components.
2. Examine the influence of WPO blends on fuel system cleanliness and deposit formation over prolonged operation.
3. Investigate combustion dynamics and emission behaviour of WPO–diesel blends under transient engine loads and varying speeds.
4. Explore advanced refining or post-treatment techniques to improve the physicochemical properties of waste plastic oil, enhancing its compatibility and performance in diesel engines.

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