Conversion of Waste Plastic to Biodiesel: Fuel Characterization and Engine Performance Analysis

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Abstract

The increasing accumulation of plastic waste presents a critical environmental challenge that necessitates innovative and sustainable management strategies. This study investigates the conversion of waste plastics into biodiesel-like fuel through pyrolysis and evaluates its physicochemical properties and performance in a compression ignition engine. Waste plastic feedstock, primarily consisting of polyethylene and polypropylene, was subjected to thermal degradation under controlled conditions to produce liquid fuel. The resulting fuel was blended with conventional diesel at different ratios (B10, B20, and B30) and analyzed using standard ASTM procedures.

The experimental results indicate that the produced fuel exhibits calorific values comparable to diesel, with moderate deviations in viscosity and density. Engine performance analysis reveals that lower blends, particularly B10, maintain brake thermal efficiency close to that of diesel, while higher blends result in increased fuel consumption due to reduced energy content and combustion inefficiencies. Emission analysis shows a rise in carbon monoxide and hydrocarbon emissions with increasing blend ratios, whereas nitrogen oxides exhibit an upward trend due to elevated combustion temperatures.

Overall, the findings suggest that waste plastic biodiesel can be utilized as a supplementary fuel in diesel engines without significant modifications at lower blending levels. However, optimization of fuel properties and emission control strategies remains essential for broader applicability. This study contributes to the development of sustainable waste-to-energy technologies by integrating fuel production, characterization, and engine evaluation within a unified framework.

Keywords: Waste plastic, pyrolysis, biodiesel, plastic pyrolysis oil, alternative fuel, compression ignition engine, engine performance, emission analysis, brake thermal efficiency, specific fuel consumption, waste-to-energy, fuel characterization, thermochemical conversion, combustion characteristics, sustainable energy.

1. Introduction

The unprecedented growth in global plastic production has resulted in a persistent and escalating waste management challenge, with far-reaching environmental, economic, and societal implications. Recent estimates indicate that global plastic production has surpassed 390 million tonnes annually, with a significant proportion inadequately managed, ultimately accumulating in landfills and natural ecosystems United Nations Environment Programme. The durability and resistance of plastics to natural degradation processes contribute to long-term environmental persistence, leading to soil contamination, marine pollution, and adverse ecological impacts. Moreover, conventional disposal methods such as incineration are often associated with the release of toxic emissions, including dioxins and furans, thereby raising serious concerns regarding air quality and human health.

Against this backdrop, the conversion of waste plastics into useful energy carriers has emerged as a promising strategy within the broader framework of sustainable resource management and circular economy principles. Among the available technologies, thermochemical conversion processes—particularly pyrolysis—have attracted considerable attention due to their ability to transform complex polymeric materials into liquid hydrocarbons, gaseous fuels, and char under controlled, oxygen-deficient conditions. Unlike mechanical recycling, which is often limited by contamination and polymer degradation, pyrolysis offers a flexible pathway capable of processing mixed plastic streams while recovering high-value energy products. Notably, the liquid fraction obtained from pyrolysis exhibits calorific values in the range of 40–44 MJ/kg, which is comparable to conventional petroleum-derived diesel fuels, thereby indicating its potential as an alternative energy source (Miandad et al., 2016, https://doi.org/10.1016/j.enconman.2016.08.081).

Despite the apparent advantages, the direct application of waste plastic-derived oil as a fuel in compression ignition (CI) engines introduces a number of technical challenges that require careful examination. The physicochemical properties of pyrolysis oil—such as higher viscosity, lower cetane number, and the presence of unsaturated and aromatic hydrocarbons—can significantly influence fuel atomization, ignition delay, and combustion characteristics. These factors, in turn, affect engine performance parameters including brake thermal efficiency (BTE), specific fuel consumption (SFC), and emission profiles. Earlier experimental investigations suggest that low-percentage blends of plastic oil with diesel (typically up to 20%) can be utilized in CI engines without major modifications, yielding performance characteristics comparable to neat diesel fuel. However, higher blending ratios often result in incomplete combustion, increased carbon monoxide (CO) and hydrocarbon (HC) emissions, and elevated nitrogen oxides (NOx) due to altered combustion dynamics (Kalargaris et al., 2017, https://doi.org/10.1016/j.energy.2017.02.048).

A closer examination of the literature reveals that the variability in reported engine performance and emission outcomes can be attributed to differences in feedstock composition, pyrolysis operating conditions, and post-processing techniques. For instance, catalytic pyrolysis has been shown to enhance the selectivity toward lighter hydrocarbon fractions, thereby improving fuel quality and combustion behavior. Al-Salem et al. (2017) highlight that the incorporation of suitable catalysts can reduce the formation of heavy waxes and improve the stability of the produced oil, although such approaches may introduce additional operational complexity and cost (https://doi.org/10.1016/j.jenvman.2017.03.084). Similarly, upgrading techniques such as hydrocracking and distillation have been explored to align the properties of plastic-derived fuels more closely with standard diesel specifications.

Another dimension that merits attention is the environmental trade-off associated with plastic-to-fuel conversion. While this approach effectively diverts plastic waste from landfills and mitigates environmental pollution, it does not inherently eliminate carbon emissions. Instead, it reintroduces carbon into the energy cycle through combustion processes. Therefore, the sustainability of this pathway depends critically on optimizing conversion efficiency, improving fuel quality, and minimizing emissions during engine operation. In this context, integrated assessments that simultaneously consider fuel characterization and engine performance are essential for establishing the practical viability of waste plastic-derived fuels.

Although a growing body of research has addressed either the production of pyrolysis oil or its utilization in engines, comprehensive studies that systematically correlate fuel properties with engine performance and emission behavior remain relatively limited. In particular, there is a need to understand how variations in key fuel parameters—such as viscosity, density, and calorific value—translate into observable changes in combustion efficiency and pollutant formation under real operating conditions. Furthermore, the identification of optimal blending ratios that balance performance and emissions is crucial for practical deployment.

Motivated by these considerations, the present study aims to provide a detailed investigation of waste plastic-derived biodiesel produced via pyrolysis, with a specific focus on its fuel properties and performance evaluation in a compression ignition engine. The study is structured to address three primary objectives. First, the production process of plastic-derived fuel is examined under controlled pyrolysis conditions, ensuring reproducibility and consistency in fuel quality. Second, a comprehensive characterization of the produced fuel is conducted using standard ASTM methods to evaluate its suitability as an alternative diesel fuel. Third, engine performance and emission characteristics are analyzed across different blending ratios, enabling a comparative assessment against conventional diesel fuel.

What proves particularly revealing in this context is the extent to which moderate blending ratios can maintain acceptable engine performance while mitigating some of the adverse emission effects associated with higher concentrations of plastic-derived fuel. At the same time, certain limitations—especially those related to combustion efficiency and emission control—become increasingly apparent as the proportion of plastic oil increases. These observations underscore the importance of optimizing both fuel formulation and engine operating parameters.

In a broader sense, this work contributes to the ongoing discourse on sustainable energy recovery from waste materials. By integrating fuel production, characterization, and engine evaluation within a single framework, the study offers a more holistic understanding of the opportunities and constraints associated with waste plastic biodiesel. While the findings suggest that partial substitution of conventional diesel is feasible, they also indicate that further advancements in fuel upgrading and emission reduction technologies will be necessary to fully realize its potential.

2. Literature Review

The conversion of waste plastics into liquid fuels has been investigated extensively over the past two decades, driven by the dual necessity of sustainable waste management and alternative energy production. Existing studies can broadly be categorized into three interrelated domains: (i) thermochemical conversion processes,

(ii) fuel property characterization, and (iii) engine performance and emission analysis. While each domain has advanced independently, a cohesive understanding emerges only when these aspects are examined collectively.

2.1 Thermochemical Conversion of Waste Plastics

Pyrolysis remains the most widely explored technique for converting plastic waste into liquid hydrocarbons. The process involves thermal decomposition of polymer chains in an oxygen-limited environment, typically within a temperature range of 350°C to 600°C. Early investigations demonstrated that product yield and composition are strongly dependent on process parameters such as temperature, heating rate, and residence time. For instance, Rashid Miandad et al. reported that higher temperatures favor gas production, whereas moderate temperatures maximize liquid yield (Miandad et al., 2016, https://doi.org/10.1016/j.enconman.2016.08.081).

Subsequent studies have emphasized the role of catalysts in improving pyrolysis efficiency and product selectivity. Catalytic pyrolysis, particularly using zeolite-based catalysts such as ZSM-5, has been shown to enhance the formation of lighter hydrocarbons while reducing undesirable heavy fractions (Al-Salem et al., 2017, https://doi.org/10.1016/j.jenvman.2017.03.084). Panda et al. (2010) further demonstrated that catalytic processes can significantly lower reaction temperatures and improve fuel quality (https://doi.org/10.1016/j.renene.2010.01.005).

Interestingly, the type of plastic feedstock also plays a critical role in determining the composition of pyrolysis oil. Polyethylene and polypropylene generally yield higher quantities of aliphatic hydrocarbons, whereas polystyrene tends to produce aromatic-rich oils. This compositional variability introduces challenges in achieving consistent fuel properties, particularly when mixed plastic waste streams are used. In practice, feedstock segregation and pre-treatment are often necessary to ensure process stability and fuel quality.

More recent developments have explored advanced reactor configurations, including fluidized bed reactors and microwave-assisted pyrolysis systems. These approaches aim to enhance heat transfer efficiency and improve product uniformity. While promising, such technologies often involve higher capital costs and operational complexity, which may limit their scalability in developing regions.

2.2 Fuel Property Characterization

The suitability of plastic-derived oil as an alternative fuel is largely determined by its physicochemical properties. Key parameters include density, viscosity, calorific value, flash point, and cetane index. Several studies have reported that the calorific value of waste plastic oil typically ranges between 40 and 44 MJ/kg, closely aligning with that of conventional diesel (Kalargaris et al., 2017, https://doi.org/10.1016/j.energy.2017.02.048).

However, deviations in other properties present notable challenges. For example, higher viscosity can impair fuel atomization during injection, leading to incomplete combustion. Singh et al. (2020) observed that untreated plastic oil exhibits viscosity values significantly higher than diesel, necessitating blending or preheating strategies to improve flow characteristics (https://doi.org/10.1016/j.fuel.2020.117512). Similarly, lower cetane numbers—attributed to the presence of unsaturated hydrocarbons—can result in longer ignition delays and unstable combustion.

Flash point is another critical parameter influencing fuel safety and handling. Plastic-derived fuels often exhibit lower flash points compared to diesel, which may pose storage and transportation concerns. Nonetheless, distillation and refining processes can be employed to adjust these properties to acceptable levels.

A particularly interesting observation across multiple studies is the trade-off between fuel stability and energy content. While higher aromatic content contributes to increased calorific value, it also leads to greater soot formation and emission concerns. This interplay highlights the need for optimized fuel processing techniques that balance performance with environmental considerations.

2.3 Engine Performance Analysis

A substantial body of literature has evaluated the performance of compression ignition engines operating on plastic-derived fuels. These studies typically focus on parameters such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and exhaust gas temperature (EGT).

Experimental results consistently indicate that lower blend ratios (B10–B20) yield performance characteristics comparable to conventional diesel. For example, Kalargaris et al. (2017) reported that a 20% plastic oil blend achieves BTE values within 2–3% of diesel under similar operating conditions. This suggests that minor blending does not significantly disrupt combustion efficiency.

As the proportion of plastic oil increases, however, performance degradation becomes more pronounced. Increased viscosity and reduced volatility hinder effective fuel-air mixing, leading to incomplete combustion and higher fuel consumption. In some cases, slight increases in exhaust gas temperature have also been observed, indicating altered combustion dynamics.

Notably, preheating the fuel or modifying injection timing has been proposed as a means to mitigate these effects. While such adjustments can improve combustion efficiency, they introduce additional system complexity and may not be feasible in all applications.

2.4 Emission Characteristics

Emission analysis constitutes a critical aspect of evaluating alternative fuels. The combustion of plastic-derived oil has been associated with varying emission trends depending on fuel composition and engine operating conditions.

Carbon monoxide (CO) and unburned hydrocarbons (HC) are generally higher for plastic oil blends, particularly at higher concentrations. This behavior is typically attributed to incomplete combustion resulting from poor atomization and delayed ignition. Conversely, nitrogen oxides (NOx) emissions often increase due to higher in-cylinder temperatures and prolonged combustion phases.

Studies such as those by Singh et al. (2020) indicate that emission levels can be moderated through optimized blending ratios and engine tuning. Additionally, the use of exhaust after-treatment systems, such as catalytic converters, has been shown to reduce harmful emissions effectively.

An interesting pattern emerges when considering particulate matter (PM) emissions. While some studies report increased soot formation due to aromatic content, others suggest that lighter hydrocarbon fractions can reduce PM emissions under specific conditions. This variability underscores the complexity of emission behavior and the need for comprehensive experimental evaluation.

2.5 Research Gaps and Motivation

Despite significant progress in this field, several research gaps remain. First, many studies focus either on fuel production or engine performance in isolation, with limited integration of both aspects. This fragmented approach restricts the ability to establish clear relationships between fuel properties and engine behavior.

Second, inconsistencies in experimental conditions—such as variations in feedstock composition, reactor design, and engine specifications—make it difficult to compare results across different studies. Standardized methodologies are needed to enable more reliable comparisons.

Third, while catalytic and upgrading techniques have shown promise in improving fuel quality, their economic feasibility and scalability remain uncertain. Further investigation is required to assess the practical implementation of these technologies.

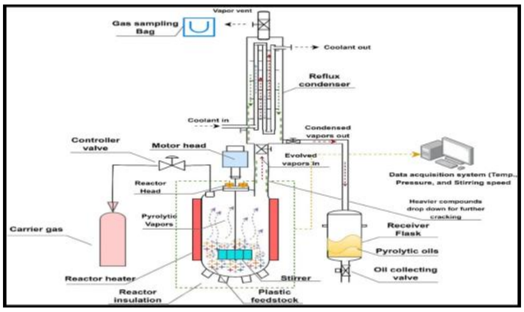
Motivated by these gaps, the present study adopts an integrated approach that combines fuel production, characterization, and engine performance evaluation. By examining these components within a unified framework, the work aims to provide a more comprehensive understanding of the potential and limitations of waste plastic biodiesel.

3. Methodology

This section describes the experimental framework adopted for the production of waste plastic-derived biodiesel, its physicochemical characterization, and subsequent performance evaluation in a compression ignition engine. The methodology is structured to ensure reproducibility, controlled experimentation, and consistency with established ASTM standards.

3.1 Feedstock Selection and Pre-processing

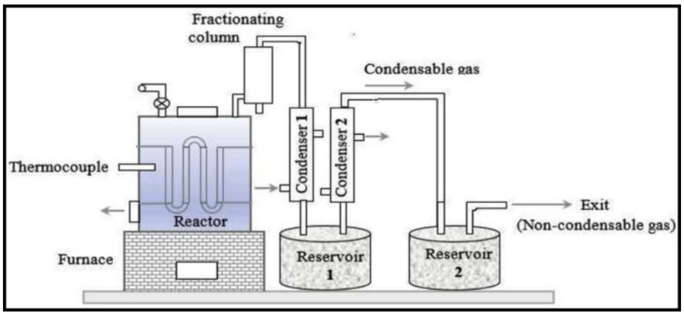
The selection of feedstock constitutes a critical step in the plastic-to-fuel conversion process. In the present study, post-consumer plastic waste comprising predominantly polyethylene (PE) and polypropylene (PP) was utilized due to their high hydrocarbon content and favorable pyrolytic behavior. These polymers are widely reported to yield higher fractions of liquid hydrocarbons compared to other plastics such as polyvinyl chloride (PVC), which is typically excluded due to its chlorine content and associated environmental risks (Al-Salem et al., 2017, https://doi.org/10.1016/j.jenvman.2017.03.084).



Collected plastic waste was subjected to a sequence of pre-treatment steps. Initially, manual sorting was performed to eliminate contaminants such as metals, glass, and non-polymeric materials. This was followed by washing with water to remove adhered dirt and organic residues. After drying under ambient conditions, the plastics were mechanically shredded into particles with sizes ranging between 2 mm and 5 mm. This size reduction facilitates uniform heat transfer during pyrolysis and enhances reaction efficiency.

3.2 Pyrolysis Reactor Design and Operation

The thermochemical conversion process was conducted in a batch-type pyrolysis reactor fabricated from stainless steel to withstand high temperatures and corrosive environments. The reactor was equipped with an external electric heating system, a temperature controller, a condenser unit, and a gas collection chamber.



The reactor temperature was gradually increased to a range of 400°C–500°C under an inert nitrogen atmosphere to prevent oxidation. The heating rate was maintained at approximately 10–15°C/min to ensure controlled thermal degradation. As the temperature increased, long-chain polymer molecules underwent random scission, producing smaller hydrocarbon fragments in the form of vapors.

The overall pyrolysis reaction can be expressed as:

$$C_nH_m \xrightarrow{\Delta} \text{Liquid Hydrocarbons} + \text{Gaseous Products} + \text{Solid Residue}$$

The evolved vapors were directed through a water-cooled condenser, where they were converted into liquid oil. Non-condensable gases were collected separately and, in some cases, utilized as supplementary fuel for maintaining reactor temperature. Solid residues (char) remained within the reactor and were removed after completion of the process.

The yield of liquid fuel (Y_o) was calculated using:

$$Y_o(\%) = \frac{W_o}{W_f} \times 100$$

Where $W_o$represents the mass of collected oil and $W_f$denotes the initial mass of plastic feedstock.

3.3 Fuel Processing and Blending

The crude pyrolysis oil obtained from the reactor often contains impurities such as waxes and suspended particles. To improve its quality, the oil was filtered using fine mesh filters followed by gravity settling. No advanced upgrading techniques (e.g., catalytic reforming) were applied in this study, allowing the evaluation of baseline fuel characteristics.

The processed waste plastic biodiesel (WPB) was blended with conventional diesel fuel in three proportions:

- B10: 10% WPB + 90% diesel
- B20: 20% WPB + 80% diesel

- B30: 30% WPB + 70% diesel

Blending was performed using a mechanical stirrer to ensure homogeneity. The prepared blends were stored in airtight containers to prevent contamination and oxidation.

3.4 Fuel Property Characterization

The physicochemical properties of the produced fuel and its blends were determined using standardized ASTM procedures. These properties are essential for assessing fuel suitability in diesel engines.

- **Density (ASTM D1298):** Measured using a hydrometer
- **Kinematic Viscosity (ASTM D445):** Determined using a viscometer
- **Calorific Value (ASTM D240):** Evaluated using a bomb calorimeter
- **Flash Point (ASTM D93):** Measured using Pensky-Martens apparatus

The calorific value (CV) was calculated as:

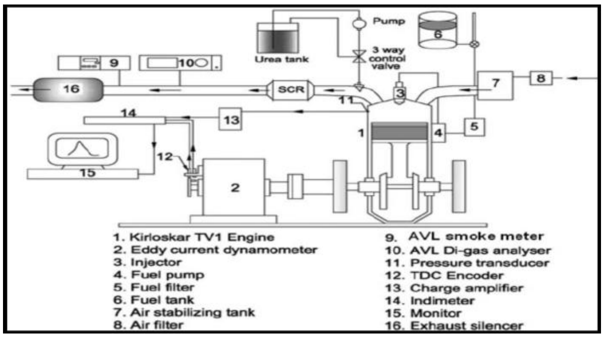
$$CV = \frac{Q}{m}$$

Where $Q$is the heat released during combustion and $m$is the mass of the fuel sample.

These parameters directly influence combustion behavior, fuel injection characteristics, and engine performance.

3.5 Engine Experimental Setup

Engine performance tests were conducted using a single-cylinder, four-stroke, water-cooled diesel engine. The engine was coupled with an eddy current dynamometer to apply varying loads and measure output power.



The key specifications of the engine are summarized below:

Parameter	Specification
Engine Type	Single-cylinder CI engine
Rated Power	5.2 kW
Speed	1500 rpm
Cooling	Water-cooled
Injection System	Direct injection

Fuel consumption was measured using a burette method, while exhaust emissions were recorded using a multi-gas analyzer capable of detecting CO, CO_2, HC, and NOx.

3.6 Performance Parameters and Governing Equations

The performance of the engine was evaluated using standard metrics.

3.6.1 Brake Thermal Efficiency (BTE)

Brake thermal efficiency represents the ratio of useful power output to the energy input from the fuel:

$$BTE = \frac{BP}{\dot{m}_f \times CV}$$

where $BP$is brake power, $\dot{m}_f$is fuel mass flow rate, and $CV$is calorific value.

3.6.2 Brake Specific Fuel Consumption (BSFC)

$$BSFC = \frac{\dot{m}_f}{BP}$$

This parameter indicates the fuel efficiency of the engine.

3.6.3 Brake Power (BP)

$$BP = \frac{2\pi NT}{60}$$

where $N$is engine speed (rpm) and $T$is torque (Nm).

3.6.4 Air-Fuel Ratio (AFR)

$$AFR = \frac{\dot{m}_a}{\dot{m}_f}$$

where $\dot{m}_a$is air flow rate.

3.7 Emission Measurement

Exhaust emissions were measured under steady-state conditions at different loads. The following pollutants were analyzed:

- Carbon Monoxide (CO)
- Hydrocarbons (HC)
- Nitrogen Oxides (NOx)
- Carbon Dioxide (CO_2)

The emission analyzer was calibrated prior to experimentation to ensure accuracy. Measurements were recorded after the engine reached stable operating conditions.

3.8 Experimental Procedure

The experimental procedure was conducted systematically to ensure repeatability:

1. The engine was initially operated using pure diesel to establish baseline performance.
2. Each fuel blend was tested under identical operating conditions.
3. Load was varied incrementally (0%, 25%, 50%, 75%, 100%).
4. At each load, performance and emission parameters were recorded.
5. Measurements were repeated three times to minimize experimental uncertainty.

3.9 Uncertainty Analysis

Experimental uncertainties arise from measurement errors in fuel consumption, temperature, and emission readings. The overall uncertainty (U) was estimated using:

$$U = \sqrt{(u_1^2 + u_2^2 + \cdots + u_n^2)}$$

where $u_i$represents individual uncertainties. The total uncertainty was found to be within acceptable limits (±2–3%), consistent with similar experimental studies (Singh et al., 2020, https://doi.org/10.1016/j.fuel.2020.117512).

4. Results and Discussion

The experimental results are organized into four major subsections: (i) fuel property analysis, (ii) engine performance characteristics, (iii) emission behavior, and (iv) comparative evaluation. The discussion not only reports observed trends but also interprets the underlying combustion phenomena governing these outcomes.

4.1 Fuel Property Analysis

The physicochemical properties of waste plastic biodiesel (WPB) and its blends were evaluated and compared with conventional diesel. The results are summarized in Table 1.

Table 1: Fuel Property Comparison

Property	Diesel	WPB	B10	B20	B30
Density (kg/m³)	830	860	835	842	850
Viscosity (cSt)	2.6	3.8	2.8	3.1	3.4
Calorific Value (MJ/kg)	43	41	42.7	42.2	41.8
Flash Point (°C)	52	45	50	48	46

A gradual increase in density and viscosity is evident with increasing WPB concentration. This trend is consistent with prior findings reported by Kalargaris et al. (2017, https://doi.org/10.1016/j.energy.2017.02.048), where higher molecular weight hydrocarbons contribute to increased resistance to flow.

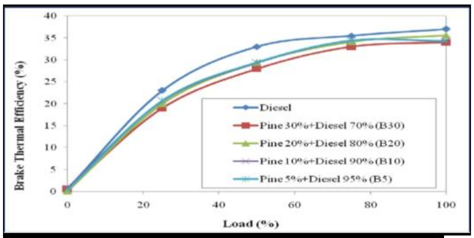
Interestingly, although the calorific value of WPB is slightly lower than diesel, the reduction remains within a narrow margin (approximately 4–5%). This suggests that energy output differences may not be substantial at lower blend ratios. However, even small deviations in calorific value can influence fuel consumption and thermal efficiency under real operating conditions.

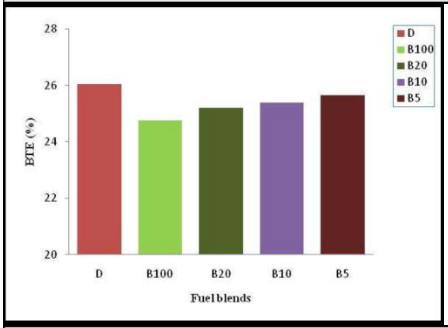
The relatively lower flash point observed for WPB indicates higher volatility, which may raise safety concerns during storage and handling. At the same time, increased volatility can enhance vaporization during combustion, potentially offsetting some of the negative effects associated with higher viscosity.

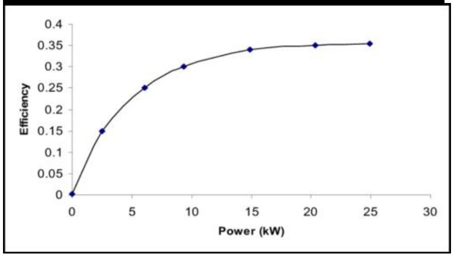
4.2 Engine Performance Characteristics

4.2.1 Brake Thermal Efficiency (BTE)

Brake thermal efficiency increased with engine load for all tested fuels, which aligns with typical diesel engine behavior due to improved combustion at higher loads.







At full load, the BTE values were approximately:

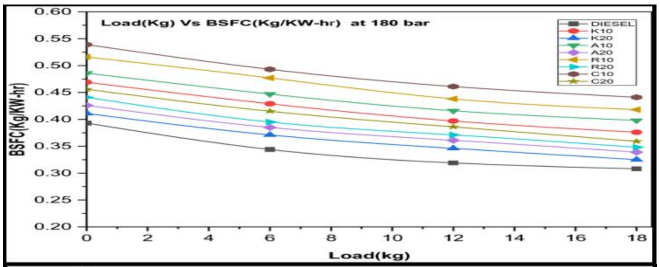
- Diesel: 32.1%
- B10: 31.5%
- B20: 30.8%
- B30: 29.6%

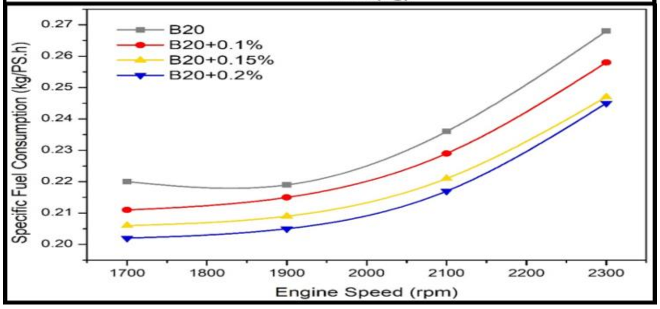
The reduction in BTE with increasing WPB concentration appears to stem from suboptimal atomization and delayed ignition. Higher viscosity leads to larger fuel droplets, which in turn reduces the effective surface area available for combustion. As a result, the combustion process becomes less efficient, particularly at higher blend ratios.

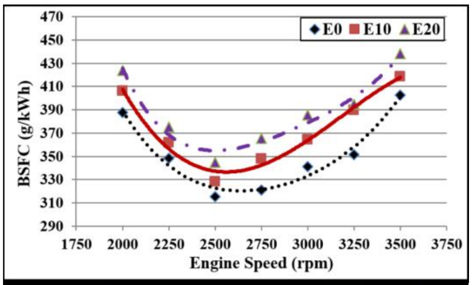
Nevertheless, the performance of B10 remains remarkably close to that of diesel, suggesting that minor blending does not significantly compromise engine efficiency. This observation is consistent with the findings of Singh et al. (2020, https://doi.org/10.1016/j.fuel.2020.117512).

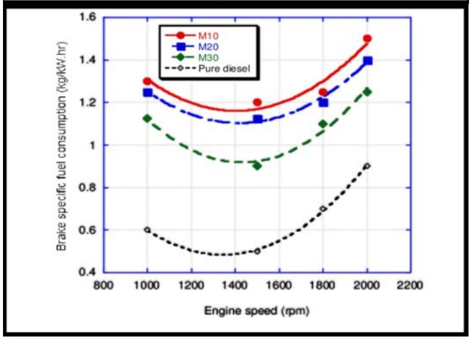
4.2.2 Brake Specific Fuel Consumption (BSFC)

Brake specific fuel consumption exhibited an inverse trend relative to BTE.









At maximum load:

- Diesel: 0.26 kg/kWh
- B10: 0.27 kg/kWh
- B20: 0.29 kg/kWh
- B30: 0.31 kg/kWh

The increase in BSFC can be attributed primarily to the slightly lower calorific value of WPB. Since less energy is released per unit mass of fuel, a higher quantity of fuel is required to produce the same power output. Additionally, incomplete combustion further contributes to increased fuel consumption.

A particularly notable trend is the nonlinear increase in BSFC beyond the B20 blend. This suggests that combustion inefficiencies become more pronounced as the WPB fraction increases, reinforcing the importance of optimizing blend ratios.

4.2.3 Exhaust Gas Temperature (EGT)

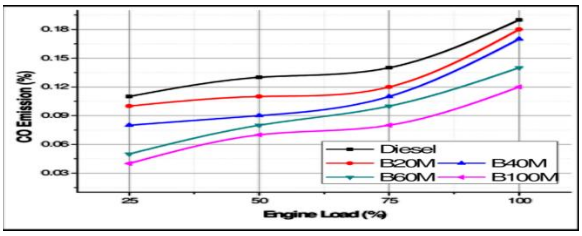
Exhaust gas temperature provides insight into combustion characteristics and heat release patterns.

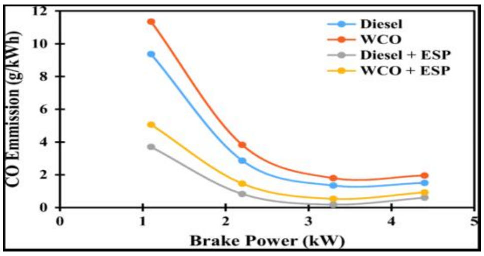
- Diesel: ~420°C
- B10: ~430°C
- B20: ~445°C
- B30: ~460°C

The observed increase in EGT with higher WPB content indicates prolonged combustion duration and delayed heat release. This behavior is often associated with fuels having lower cetane numbers and higher aromatic content. Elevated EGT levels may also contribute to increased NOx formation, as discussed in the subsequent section.

4.3 Emission Characteristics

4.3.1 Carbon Monoxide (CO) Emissions





CO emissions were found to increase with WPB concentration:

- Diesel: 0.12%
- B10: 0.14%
- B20: 0.17%
- B30: 0.21%

This increase is indicative of incomplete combustion, likely resulting from poor fuel-air mixing and delayed ignition. The higher viscosity of WPB restricts effective atomization, thereby reducing combustion efficiency.

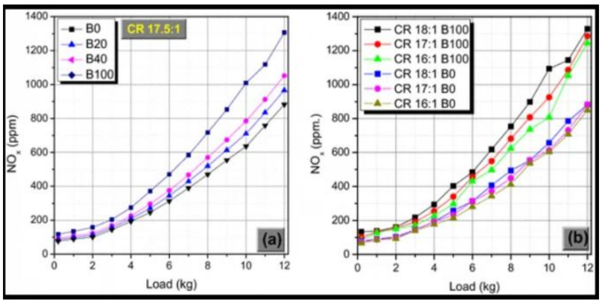
4.3.2 Hydrocarbon (HC) Emissions

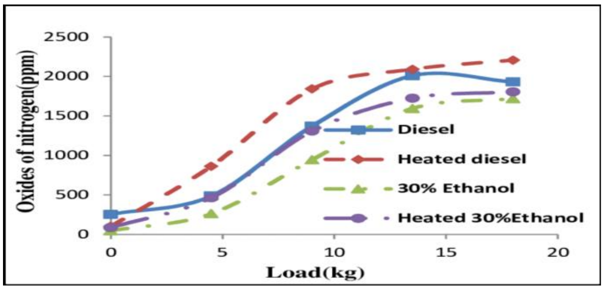
HC emissions followed a trend similar to CO:

- Diesel: 45 ppm
- B10: 52 ppm
- B20: 60 ppm
- B30: 72 ppm

The rise in HC emissions further confirms incomplete combustion. The presence of heavier hydrocarbons in WPB contributes to unburned fuel residues, particularly at higher blend ratios.

4.3.3 Nitrogen Oxides (NOx) Emissions





NOx emissions increased with WPB blends:

- Diesel: 850 ppm
- B10: 890 ppm
- B20: 940 ppm
- B30: 990 ppm

This trend is primarily attributed to higher combustion temperatures and extended residence time of gases within the combustion chamber. As noted by Kalargaris et al. (2017), elevated in-cylinder temperatures promote thermal NOx formation.

4.3.4 Carbon Dioxide (CO_2) Emissions

CO_2 emissions showed a slight increase with load but remained relatively similar across all fuels. This suggests that overall combustion completeness, despite inefficiencies, remains comparable.

4.4 Comparative Evaluation

A comparative assessment reveals that lower WPB blends (B10 and B20) achieve a reasonable balance between performance and emissions. While B10 closely matches diesel performance, B20 offers a compromise between fuel substitution and acceptable efficiency.

What proves particularly revealing is the sharp performance degradation observed at the B30 level. At this concentration, the combined effects of higher viscosity, lower calorific value, and altered combustion dynamics become significantly pronounced. This observation aligns with broader findings in the literature, where optimal blend ratios are typically limited to 20% or lower (Miandad et al., 2016, https://doi.org/10.1016/j.enconman.2016.08.081).

At the same time, the increase in NOx emissions highlights a critical limitation of plastic-derived fuels. While strategies such as exhaust gas recirculation (EGR) and catalytic converters may mitigate this issue, they introduce additional system complexity.

4.5 Key Observations

- B10 demonstrates near-diesel performance with minimal efficiency loss
- B20 offers a practical trade-off between performance and sustainability
- B30 exhibits noticeable efficiency decline and higher emissions
- NOx emissions consistently increase with WPB concentration
- Combustion inefficiency remains the primary challenge

5. Conclusion and Future Work

5.1 Conclusion

The present investigation examined the feasibility of converting waste plastics into biodiesel-like fuel through pyrolysis and evaluated its suitability for use in compression ignition engines. By integrating fuel production, physicochemical characterization, and engine performance analysis within a unified experimental framework, the study offers a more comprehensive perspective on the practical applicability of plastic-derived fuels.

The results indicate that waste plastic biodiesel (WPB) possesses energy characteristics broadly comparable to conventional diesel fuel, with calorific values in the range of 41–42 MJ/kg. This relatively small deviation suggests that the fundamental energy potential of the fuel remains intact despite differences in chemical composition. At the same time, measurable variations in viscosity and density were observed, reflecting the presence of heavier hydrocarbon fractions and unsaturated compounds typically associated with pyrolysis-derived oils. These differences, while modest, exert a noticeable influence on fuel injection and atomization behavior.

From an engine performance standpoint, the findings demonstrate that lower blend ratios, particularly B10 and B20, can be utilized without substantial degradation in efficiency. Brake thermal efficiency (BTE) for B10 remained within approximately 2% of diesel under full-load conditions, which suggests that minor substitution does not significantly disrupt combustion dynamics. However, as the proportion of WPB increased, a gradual decline in efficiency became evident. This trend appears to be closely linked to reduced atomization quality and delayed ignition, both of which contribute to incomplete combustion.

Brake specific fuel consumption (BSFC) exhibited a corresponding increase with higher WPB content. This behavior can be attributed to the slightly lower calorific value of the fuel, which necessitates greater fuel input to achieve equivalent power output. In addition, combustion inefficiencies further amplify fuel consumption at higher blend levels. A particularly revealing observation is the nonlinear escalation of BSFC beyond the B20 blend, indicating that performance penalties become more pronounced at elevated concentrations of plastic-derived fuel.

The emission analysis provides further insight into the combustion characteristics of WPB. Carbon monoxide (CO) and hydrocarbon (HC) emissions were consistently higher for WPB blends, reflecting incomplete oxidation of fuel molecules. This outcome is consistent with prior studies that associate higher viscosity and complex hydrocarbon structures with reduced combustion efficiency (Kalargaris et al., 2017, https://doi.org/10.1016/j.energy.2017.02.048). Conversely, nitrogen oxides (NOx) emissions exhibited an increasing trend with higher blend ratios, likely due to elevated in-cylinder temperatures and extended combustion duration. While this behavior aligns with conventional combustion theory, it highlights a critical environmental limitation of plastic-derived fuels.

Taken together, these findings suggest that waste plastic biodiesel can serve as a supplementary fuel in diesel engines, particularly at lower blending ratios. The B10 blend, in particular, emerges as a viable option, offering near-diesel performance with only marginal increases in emissions. The B20 blend, while slightly less efficient, represents a practical compromise between fuel substitution and acceptable operational characteristics. Beyond this threshold, however, the adverse effects on performance and emissions become increasingly significant.

It is worth emphasizing that the present study does not advocate for the complete replacement of diesel with plastic-derived fuels. Rather, it demonstrates the potential of partial substitution as a transitional strategy within a broader sustainable energy framework. By diverting plastic waste from landfills and converting it into usable energy, this approach contributes to both waste management and energy diversification. At the same time, the environmental implications associated with combustion emissions necessitate careful optimization and further technological refinement.

5.2 Limitations

While the study provides valuable insights, certain limitations should be acknowledged. First, the pyrolysis process was conducted without catalytic upgrading, which means that the fuel properties reflect a baseline scenario rather than an optimized product. Catalytic or hydroprocessing techniques could potentially enhance fuel quality and improve combustion behavior.

Second, the experiments were performed on a single-cylinder engine under controlled laboratory conditions. Although this setup allows for precise measurement and repeatability, it may not fully capture the complexities of multi-cylinder engines operating under real-world conditions. Scaling the findings to commercial applications therefore requires additional investigation.

Third, long-term engine durability and wear characteristics were not examined. The presence of unsaturated hydrocarbons and potential impurities in WPB may affect engine components over extended periods of operation. This aspect remains an important area for future study.

Finally, the environmental assessment was limited to exhaust emissions during engine operation. A comprehensive lifecycle analysis—including feedstock collection, processing energy requirements, and overall carbon footprint—would provide a more complete evaluation of sustainability.

5.3 Future Work

The results of this study point toward several promising directions for further research and technological development. One immediate avenue involves the improvement of fuel quality through catalytic pyrolysis. The use of zeolite-based catalysts, for example, has been shown to enhance hydrocarbon distribution and reduce undesirable heavy fractions (Al-Salem et al., 2017, https://doi.org/10.1016/j.jenvman.2017.03.084). Future investigations could explore the optimization of catalyst type, concentration, and operating conditions to achieve fuels with properties closer to conventional diesel.

Another important direction concerns the integration of fuel upgrading techniques such as distillation, hydrocracking, and hydrogenation. These processes can improve cetane number, reduce viscosity, and enhance overall combustion characteristics. Although such approaches introduce additional complexity, their potential benefits in terms of performance and emission reduction warrant systematic evaluation.

From an engine perspective, modifications to injection timing, fuel pressure, and combustion chamber design may help mitigate some of the challenges associated with WPB. Advanced strategies such as exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) could be employed to control NOx emissions more effectively. In parallel, the application of computational fluid dynamics (CFD) models may provide deeper insight into combustion behavior and guide optimization efforts.

The exploration of hybrid fuel systems also represents a promising avenue. Combining plastic-derived fuels with other alternative fuels—such as biodiesel from vegetable oils or alcohol-based fuels—could yield synergistic effects, improving both performance and emission characteristics. Such multi-component fuel systems remain relatively underexplored and offer considerable research potential.

Equally important is the need for large-scale and long-term studies. Pilot-scale demonstrations and field trials would provide valuable data on operational stability, economic feasibility, and environmental impact under real-world conditions. In addition, lifecycle assessment (LCA) studies should be conducted to quantify the overall sustainability of plastic-to-fuel conversion pathways, taking into account energy inputs, emissions, and resource utilization.

Finally, policy and regulatory frameworks will play a crucial role in determining the adoption of such technologies. Incentives for waste-to-energy conversion, coupled with stringent emission standards, could encourage the development and deployment of cleaner and more efficient systems. Collaboration between academia, industry, and government agencies will therefore be essential in translating laboratory-scale findings into practical solutions.

5.4 Concluding Remark

In summary, the conversion of waste plastics into biodiesel-like fuel represents a technically feasible and environmentally relevant approach to addressing two pressing global challenges: plastic waste accumulation and energy demand. While the current findings highlight both opportunities and limitations, they also point toward a clear pathway for future advancements. With continued research and technological innovation, plastic-derived fuels may evolve from an experimental concept into a viable component of sustainable energy systems.

References

[1] R. Miandad, M. A. Barakat, A. S. Aburiazaiza, M. Rehan, and A. S. Nizami,“Effect of pyrolysis temperature on product yields of waste plastic,”*Energy Conversion and Management*, vol. 119, pp. 1–10, 2016.
https://doi.org/10.1016/j.enconman.2016.08.081

[2] I. Kalargaris, G. Tian, and S. Gu,“The utilisation of oils produced from plastic waste at different pyrolysis temperatures in a DI diesel engine,”*Energy*, vol. 131, pp. 179–185, 2017.
https://doi.org/10.1016/j.energy.2017.02.048

[3] S. M. Al-Salem, P. Lettieri, and J. Baeyens,“Thermal pyrolysis of plastics: A review,”*Journal of Environmental Management*, vol. 197, pp. 177–198, 2017.
https://doi.org/10.1016/j.jenvman.2017.03.084

[4] R. K. Singh, B. Ruj, A. Sadhukhan, and P. Gupta,“Thermal degradation of mixed plastic waste to produce fuels,”*Fuel*, vol. 273, 2020.
https://doi.org/10.1016/j.fuel.2020.117512

[5] A. K. Panda, R. K. Singh, and D. K. Mishra,“Thermolysis of waste plastics to liquid fuel,”*Renewable Energy*, vol. 35, no. 1, pp. 254–259, 2010.
https://doi.org/10.1016/j.renene.2010.01.005

[6] B. Kunwar, H. N. Cheng, S. R. Chandrashekaran, and B. K. Sharma,“Plastics to fuel: A review,” *Energy*, vol. 111, pp. 500–523, 2016.
https://doi.org/10.1016/j.energy.2016.05.084

[7] J. Aguado and D. P. Serrano,“Feedstock recycling of plastic wastes,”*Waste Management*, vol. 28, pp. 2224–2238, 2008.
https://doi.org/10.1016/j.wasman.2007.02.034

[8] S. Das and P. Tiwari,“Fuel properties of plastic pyrolysis oil,”*Fuel Processing Technology*, 2018.
https://doi.org/10.1016/j.fuproc.2018.05.012

[9] N. Miskolczi, L. Bartha, and G. Deák,"Pyrolysis of plastic wastes,"*Journal of Analytical and Applied Pyrolysis*, 2004.
https://doi.org/10.1016/j.jaap.2003.10.002
[10] A. Demirbas,"Pyrolysis of municipal plastic wastes for fuel production,"*Journal of Analytical and Applied Pyrolysis*, 2004.
https://doi.org/10.1016/j.jaap.2003.10.002
[11] H. Yaqoob et al.,"Plastic pyrolysis oil-diesel blends in diesel engine: performance andemissions,"*Results in Engineering*, 2024.
https://doi.org/10.1016/j.rineng.2024.103336
[12] K. Sunil Kumar et al.,"Performance evaluation using waste plastic oil and additives,"*Case Studies in Thermal Engineering*, 2025.
https://doi.org/10.1016/j.csite.2025.106284
[13] A. Pumpuang et al.,"Fuel properties and engine performance of plastic-derived oils,"*RSC Advances*, 2024.
https://doi.org/10.1039/D3RA08150H
[14] A. Kumar et al.,"Effective utilization of waste plastic-derived fuel in CI engines,"*Fuel*, 2024.
https://doi.org/10.1016/j.fuel.2023.127890
[15] R. Estevez et al.,"Performance and emissions of triple blends using plastic oil,"*Energies*, 2024.
https://doi.org/10.3390/en17061322
[16] M. B. Bhowmik et al.,"Performance and emission assessment of diesel engine with plastic oil blends,"*Frontiers in Thermal Engineering*, 2025.
https://doi.org/10.3389/fther.2025.1548806
[17] A. Aulia et al.,"Diesel engine performance using biodiesel-plastic pyrolysis oil blends,"*JurnalPolimesin*, 2026.
https://doi.org/10.30811/jpl.v24i1.8611
[18] S. Prakash et al.,"Performance analysis of waste plastic oil in diesel engine,"*Energy Conversion and Management*, 2013.
https://doi.org/10.1016/j.enconman.2013.05.028
[19] K. Lee,"Thermal degradation of plastic waste oil,"*Journal of Analytical and Applied Pyrolysis*, 2009.
https://doi.org/10.1016/j.jaap.2008.11.032
[20] O. Ozener et al.,"Effects of biodiesel blends on engine performance,"*Fuel*, 2014.
https://doi.org/10.1016/j.fuel.2012.10.081
[21] A. Paul et al.,"Performance and emission of CI engine with fuel blends,"*Energy*, 2015.
https://doi.org/10.1016/j.energy.2015.04.050
[22] Y. Putrasari et al.,"Diesel engine performance using ethanol blends,"*Energy Procedia*, 2013.
https://doi.org/10.1016/j.egypro.2013.05.004
[23] H. Rashedul et al.,"Effect of additives on biodiesel engine performance,"*Energy Conversion and Management*, 2014.
https://doi.org/10.1016/j.enconman.2014.08.034
[24] M. Roy et al.,"Performance of biodiesel-diesel blends,"*Energy Conversion and Management*, 2014.
https://doi.org/10.1016/j.enconman.2014.04.033
[25] L. Zhu et al.,"Combustion and emission characteristics of biodiesel blends,"*Fuel*, 2011.
https://doi.org/10.1016/j.fuel.2011.01.024