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Performance and emission of a spark-ignition engine using gasoline-plastic pyrolysis oil blends

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This article contributes to:
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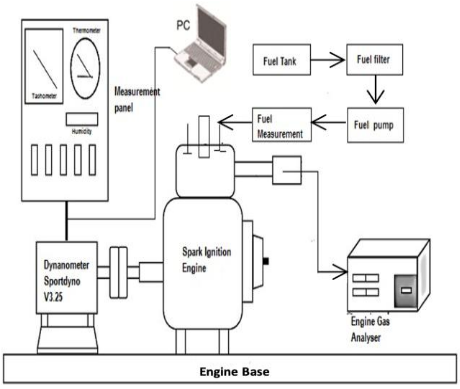

Highlights:

- This study investigates the performance and emissions of a spark-ignition engine using gasoline-plastic pyrolysis oil blends.
- Tests on 4-stroke motorcycles show that different mixtures of PPO and gasoline impact power, torque, and exhaust emissions.
- This research highlights the dual benefits of mitigating plastic waste accumulation and provides insight into the role of PPOs in driving a sustainable energy future.

Abstract

In response to the problem of plastic waste, this study investigates the conversion of PET waste plastics into Pyrolysis Plastic Oil (PPO) as an environmentally sustainable alternative energy source, aiming to tackle the pressing issue of plastic waste accumulation. Accordingly, the research comprehensively evaluates the physicochemical properties of PPO, examines its impact on engine performance, and determines the optimal concentrations for blending with gasoline. The investigation uncovers the potential of PPO through precise material preparation involving PET plastic waste pyrolysis, employing meticulous testing and analysis for comprehensive insights. Engine testing, conducted on a 125 cc, 4-stroke motorized vehicle, scrutinizes power, torque, and exhaust emissions under various PPO and gasoline blends. The findings reveal distinctive relationships between PPO ratios and engine behavior, emphasizing the need for nuanced fuel blending. The examination extends to fuel consumption and specific fuel consumption (SFC) testing, highlighting PPO's superior SFC. Exhaust emission testing demonstrates reduced emissions with heightened PPO concentration, showcasing its positive environmental impact. The results contribute valuable insights into PPO's viability as an alternative fuel source and its potential role in mitigating plastic waste. A comparative analysis with existing literature enriches our understanding of the field, emphasizing the need for careful consideration in fuel formulation. While PPO may not achieve performance parity with conventional gasoline, its environmental benefits and efficient waste utilization underscore its significance for a sustainable future. Further research is encouraged to optimize PPO properties and blending ratios, paving the way for an eco-friendlier energy landscape.

Keywords: Pyrolysis plastic oil; PET waste conversion; Blended fuel performance; Engine emissions analysis; Gasoline engine

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1. Introduction

The escalating global production and consumption of plastic, driven by its diverse advantageous properties, have led to unprecedented environmental challenges [1]. Plastic's ubiquity in daily life, owing to its strength, lightweight nature, flexibility, rust resistance, and excellent insulation, has propelled it into an indispensable role in household and industrial sectors

[2], [3]. However, the continuous demand for plastic, coupled with inadequate control measures, has resulted in the accumulation of plastic waste, emerging as a significant component of municipal solid waste [4]–[7].

The prodigious growth in plastic production over the past three decades, with an average of 129 million tons annually, has raised concerns about the environmental impact of plastic waste [8]. Current projections indicate a surge to 2.2 billion metric tons per year by 2025, emphasizing the urgency of addressing plastic waste management [8]. Household plastic waste, constituting polyolefin, polystyrene, PVC, PET, and other categories, exacerbates the environmental footprint and necessitates sustainable waste management strategies [9]. Efforts to mitigate the environmental impact of plastic waste are underway, with the 3R method (Reuse, Reduce, and Recycle) gaining attention [10]. Among these methods, plastic recycling stands out as a preferred approach, considering plastic waste as a cost-effective and abundant raw material. A particularly attractive avenue involves converting plastic waste into liquid fuel through the pyrolysis process, which is a thermal and chemical decomposition method conducted in the absence of oxygen [11], [12]. Pyrolysis has proven effective in harnessing the high calorific value of plastic waste for energy production [13].

Pyrolysis of plastic waste, such as PET, yields three main products: liquid, gas, and solid [14]. Operating at temperatures between 350-550 °C without oxygen, the pyrolysis process produces an optimal composition of 80.8% oil, 13% gas, and 6.2% char [15]. The resulting liquid fraction, known as pyrolysis plastic oil (PPO), is comprised of diverse hydrocarbons (C6 - C16), resembling the composition of conventional fuels like gasoline and diesel [16], [17]. This positions PPO as a promising alternative fuel source. However, the quality of PPO is contingent upon various parameters, including plastic waste type, pyrolysis reactor temperature, processing time, and the addition of catalysts [18]–[25]. Researchers have explored additives such as silica, alumina, Y zeolite, barium carbonate, and combinations thereof to enhance PPO quality [20]. The resulting improvements have elevated the calorific value of PPO to 43 - 45 MJ/kg, positioning it as a viable fuel for internal combustion engines [21]. The potential use of PPO as an alternative fuel introduces a novel solution to the global challenges of plastic waste and energy scarcity.

In response to the imminent depletion of fossil fuels and the environmental challenges inherent in their combustion, contemporary research endeavors are concentrated on the development of alternative fuels [26]–[28]. The extant literature has extensively examined various alternative fuels, with particular emphasis on gasoline-ethanol blends and their efficacy in internal combustion engines [29]. A considerable body of studies has been dedicated to exploring the potential of Pyrolysis Plastic Oil (PPO) in diesel engines, revealing noteworthy enhancements in fuel efficiency and a concurrent reduction in the levels of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx), coupled with a minimal sulfur content [21], [28], [30]. Despite these advancements, the application of PPO in spark-ignition engines, particularly within the context of PET waste plastics, remains an underexplored realm, presenting an avenue for further research and exploration.

To build upon these findings and address the burgeoning issue of plastic waste, this research is dedicated to the conversion of PET waste plastics into PPO. The primary objectives include the comprehensive assessment of the physicochemical properties of PPO, its impact on engine performance, and the determination of optimal PPO concentrations in blended fuel compositions with gasoline. This research significantly contributes valuable insights into the application of PPO as a sustainable energy source, emphasizing its pivotal role in mitigating plastic waste and promoting environmentally friendly energy solutions by advancing our understanding of relevant aspects.

2. Materials and Methods

The study was conducted through a series of phases, encompassing the preparation of research materials, the assessment of plastic pyrolysis oil characteristics, experimentation with the fuel on the engine, and the subsequent analysis of the acquired data.

2.1. Materials Preparation

The pyrolysis process involved the conversion of plastic waste, specifically PET plastic waste sourced from plastic bottles, into fuel. This encompassed the preparation of PET plastic waste, which included cleaning, drying, and shredding. Subsequently, the plastic material was introduced into a pyrolysis reactor maintained at 400 °C in an oxygen-free environment. The schematic of the plastic waste pyrolysis process is shown in **Figure 1**. The resulting gas was then directed to a condenser unit for the condensation process, yielding pyrolysis plastic oil (PPO).

For the gasoline category, PPO was blended with gasoline (G) at various volume percentage ratios: PPO 100 vol% (G 0: PPO 100), PPO 10 vol% (G 90: PPO 10), PPO 30 vol% (G 70: PPO 30), PPO 50 vol% (G 50: PPO 50), and gasoline 100 vol% (G 100: PPO 0), as shown in **Figure 2b**. Tests were performed on both PPO and its blends, encompassing evaluations of calorific value, octane rating, density, viscosity, and flash point.

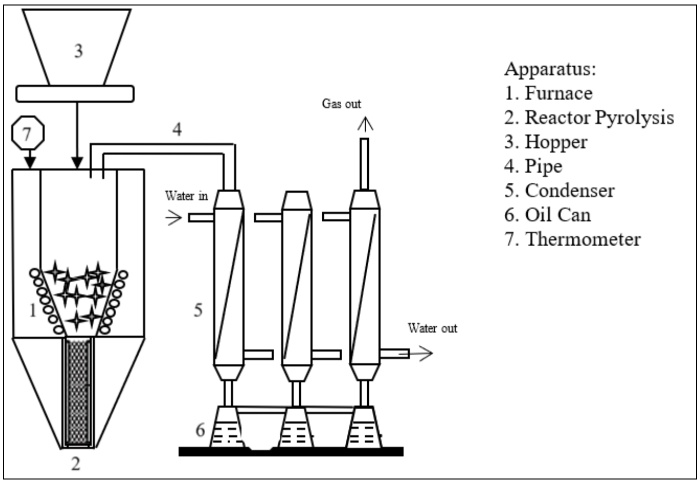

Figure 1. Schematic representation of the pyrolysis process

Figure 2. The pyrolysis process for plastic waste: (a) Plastic waste pyrolysis machine; (b) Variation in the mixture of PPO: Gasoline

2.2. Engine Testing

The evaluation of engine performance and exhaust emissions was conducted on a 1-cylinder, 4-stroke motorized vehicle with a 125-cc capacity, following standardized conditions as specified. **Table 1** provides a detailed overview of the specifications of the engine under scrutiny. Concurrently, **Table 2** delineates the environmental conditions during the assessment and testing workshop setup.

Table 1. Fuel properties of jatropha oil

Parameter	Specification
Machine Type	4 stroke petrol engine, SOHC, 1 cylinder
Capacity	124.8 cc
Diameter x Step	52.4 x 57.9 mm
Compression comparison	9.0 : 1
Maximum power	9.3 PS / 7000 rpm
Maximum torque	1.03 kgf. m/ 4000rpm
Cooling System	Air cooling
Ignition System	DC CDI
Fuel System	Carburetor
Fuel Tank Capacity	3.7 Liters

Table 2. Testing workshop setup

Parameter	Specification	Accuracy
Room temperature	31 °C	± 0.15 °C
Humidity	65%	± 0.75 %
Air pressure	1000 mbar	± 0.012 bar
Vehicle Weight	105 kg	± 0.5 kg
Rider Weight	70 kg	± 0.5 kg
Burette measurement	100 ml	± 0.1 ml

In the testing phase, the fuel utilized comprised Pyrolysis Plastic Oil (PPO) and a PPO-gasoline blend. Various volume ratios of these mixtures, denoted as PPO10, PPO30, PPO50, PPO100, and BP100, were formulated. To assess the fuel's characteristics and performance, a suite of equipment was employed, including a bomb calorimeter for calorific value assessment, an octane number tester, a pycnometer for density measurements, a viscometer for viscosity determination, a flash point tester, a Dynamometer Sport dyno V3.25 with a roller inertia of 1.446, and an Engine Gas Analyzer (Model 10174175).

The experimental procedure for assessing motor performance and exhaust emissions (**Figure 3**) aimed to elucidate the impact of PPO utilization and various PPO: Gasoline mixtures on power, torque, specific fuel consumption (SFC), and motorcycle exhaust emissions. The power and torque were evaluated by initiating the motorcycle in third gear on the dynamometer unit, followed by a spontaneous acceleration from 4000 rpm to the maximum motorbike rotation for a duration of 10 seconds. The measurement panel displayed a graph illustrating the power and motor torque values.

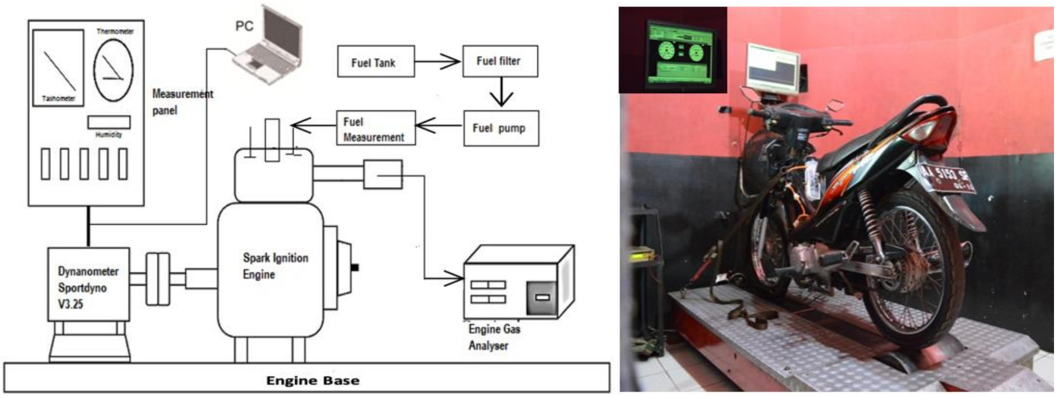

Figure 3. The schematic representation of the equipment setup and testing procedure

3. Results and Discussion

The pyrolysis of PET plastic waste undergoes a thermal breakdown, yielding various hydrocarbons via the chemical reaction $(C_{10}H_8O_4)_n \rightarrow C_nH_{2n+2} + C_nH_{2n} + C_nH_{2n-2}$ + others + residue [31]. This process results in the creation of continuous straight-chain hydrocarbons, such as propylene (C_3H_6), octene (1-C_8H_{16}), cetene (1-$C_{16}H_{32}$), and octacosene (1-$C_{28}H_{56}$), along with the formation of n 1-alkene molecules through the cleavage of n-1 C-C bonds within the polymer chain [32]. Several main compounds can be identified in pyrolysis-derived PET plastic oil (PPO). These primary compounds include ethane (C_2H_6), propane (C_3H_8), 2-Methyltetrahydrofuran ($C_5H_{10}O$), 2-Hexanone ($C_6H_{12}O$), Cyclohexane (C_6H_{12}), phenol (C_6H_6O), Heptane (C_7H_{16}), 4-Methylheptane (C_8H_{18}), 2,4-Dimethylheptane (C_9H_{20}), 2,3-Dimethyl-3-heptene (C_9H_{18}), 4-Methylnonane ($C_{10}H_{22}$), 6,6-Dimethylhepta-2,4-diene (C_9H_{16}), 3,3,5-Trimethylcyclohexene (C_9H_{16}), 3,5-Dimethyl-octane ($C_{10}H_{22}$), and Toluene (C_7H_8) [33]–[35]. These compounds encompass various groups such as aliphatic, cycloaliphatic, and aromatic, all of which play a crucial role in determining the properties of the fuel produced from plastic pyrolysis. To simplify the analysis, certain compound groups within PPO will be represented by hexane (C_6H_{14}), n-heptane ($CH_3(CH_2)5CH_3$), 2-Ethylhexylamine ($CH_3(CH_2)3CH(C_2H_5)\ CH_2NH_2$), n-Butylamine ($CH_3(CH_2)3NH_2$), liquid paraffin ($C_{12}H_{26}$), phenol ($C_6H_6O$), and toluene ($C_7H_8$).

The present study conducted a comprehensive FTIR spectral analysis of gasoline and Pyrolysis plastic oil (PPO) at varying concentrations (10%, 30%, 50%, and 100%), as shown in **Figure 4**. The investigation unveiled consistent "C=C Bending Alkene Disubstituted (cis)" structures in both gasoline and PPO within the 650-800 cm^{-1} region. A distinct "C=C Bending Alkene Vinylidene" peak at 888 cm^{-1} was exclusive to PPO, providing a unique identifier for this compound. Shared peaks for "O-H Bending Alcohol," "C-H Bending Alkane Methyl," "C-H Stretching Alkane," and "O-H Stretching Carboxylic Acid" were observed in both gasoline and PPO spectra across concentrations. Comparison with existing literature revealed alignment with findings, such as the expected functional groups in gasoline and the unique presence of "C=C Bending Alkene Vinylidene" in PPO.

This novel insight into the chemical composition of PPO adds valuable information not extensively covered in prior research on this compound. The implications of these findings extend to the quality of combustion within Otto engines. The exclusive identification of "C=C Bending Alkene Vinylidene" in PPO suggests that the combustion process of this compound might exhibit unique characteristics compared to conventional gasoline. The presence of shared functional groups, such as "O-H Stretching Carboxylic Acid," implies common combustion pathways for both gasoline and PPO. These insights are crucial for understanding the impact of compound additives on combustion efficiency and emissions in internal combustion engines. The study's strengths lie in its systematic FTIR analysis approach, offering a detailed examination of functional groups and their variations. However, limitations include the necessity for complementary analytical techniques to validate results and potential sample impurities. Future research could enhance the study by incorporating additional analytical methods and expanding the scope to include diverse fuel types and concentrations for broader applicability.

The successful conversion of PET waste plastics into pyrolysis oil underscores its potential as an alternative fuel source. Experimental testing systematically evaluates the physicochemical and thermal properties of Pyrolysis Plastic Oil (PPO). Application of PPO and its blends with gasoline in an unmodified Spark-Ignition (SI) engine is a focal point, leading to rigorous investigation into engine performance and exhaust emissions. This encompasses assessments of engine output, combustion characteristics, and exhaust emissions, with measurements on the engine brake providing a reference for data processing. Subsequent sections meticulously examine and discuss key findings, focusing on torque, power, specific fuel consumption, thermal efficiency, and exhaust gas emissions. A comprehensive comparative analysis between various blended fuels, featuring different PPO concentrations and pure gasoline, is provided for a thorough assessment.

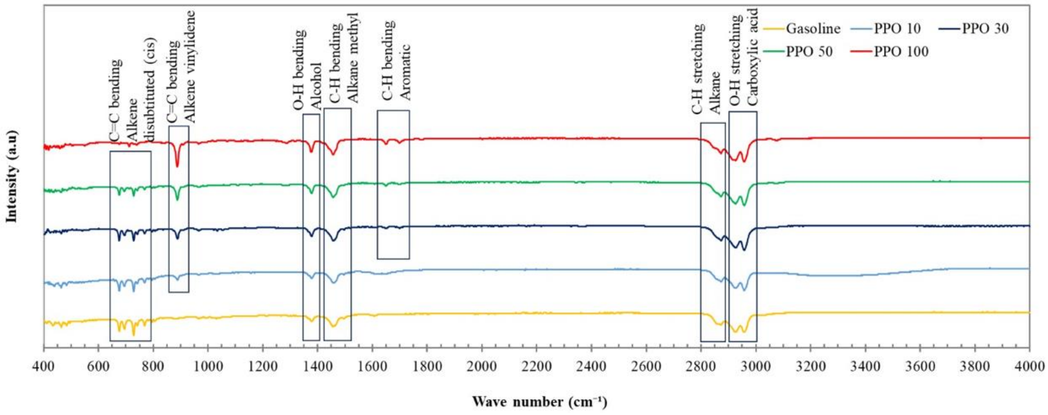

Figure 4. Comparison of FTIR spectral analysis of gasoline and pyrolysis plastic oil

3.1. Properties of Pyrolysis Plastic Oil

The investigation into pyrolysis plastic oil (PPO) properties, utilizing the ASTM method, offers valuable insights into its potential as an alternative fuel derived from PET plastic waste, as detailed in **Table 3**. The physical characteristics of PPO exhibit both similarities and distinctions in comparison to conventional fuels, particularly gasoline. The calorific value and density of PPO closely resemble those of gasoline, emphasizing its viability as a potential substitute for traditional fuels. The inherent high calorific value of plastics contributes to the energy content of PPO, aligning with previous findings [21], [36]. However, PPO demonstrates a lower octane rating and flash point compared to gasoline, deviating from typical fuel properties. Despite these variations, the lower octane rating positions PPO as a feasible alternative, akin to ethanol, suitable for use in gasoline motors [37]. The physicochemical properties of PPO play a pivotal role in influencing combustion characteristics and overall engine performance [38]. The observed trade-off in energy content and combustion efficiency, indicated by lower calorific value, density, and octane number with increased PPO percentage, suggests the need for a nuanced approach in fuel blending. The elevated viscosity and flash point further emphasize the importance of careful consideration in formulation.

The proportional relationship between characteristic properties of PPO-gasoline blends and the volume ratio is noteworthy. Higher PPO percentages result in decreased calorific value, density, and octane number, coupled with increased viscosity and flash point. This observation underscores the necessity for meticulous optimization in practical fuel applications. A comparative analysis with previous studies [39], specifically focusing on the Research Octane Number (RON) of gasoline, offers additional context. The varying RON values (88 to 100) in gasoline highlight the considerable diversity in its properties. This accentuates the importance of a nuanced evaluation when introducing PPO into gasoline blends, considering potential implications for overall fuel characteristics. Therefore, the properties of PPO exhibit promising alignment with conventional fuels, primarily gasoline, while introducing distinctive characteristics that necessitate careful consideration in fuel formulation.

Table 3. Properties testing of pyrolysis plastic oil (PPO)

Properties	Accuracy	Unit	Gasoline	PPO 10	PPO 30	PPO 50	PPO 100	Method
Calorific value	± 0.1%	± 0.15 °C	10886	10669	10499	10142	10140	Bomb Calorimeter
Density	± 0.001	± 0.75 %	0.749	0.749	0.752	0.757	0.756	ASTM D 1298
Viscosity	± 0.01	± 0.012 bar	0.509	0.539	0.601	0.664	0.85	ASTM D 445
Flashpoints	± 0.1	± 0.5 kg	< 7	< 7	< 9	< 11	< 21	ASTM D 93
Octane number	± 0.1	± 0.5 kg	93.0	92.5	91.5	90.2	87.9	ASTM D 613

3.2. Motor Performance Testing

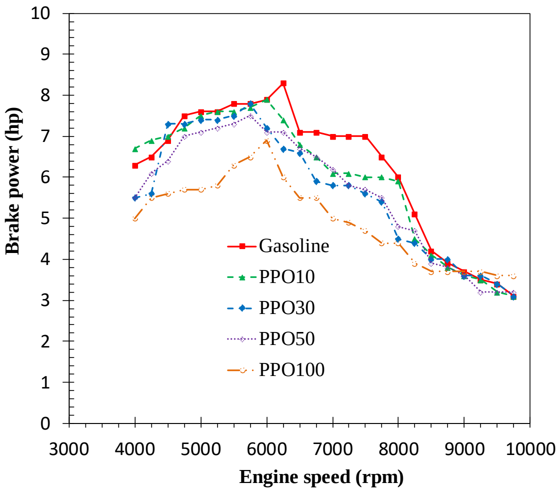

Figure 5. Relationship between brake power and engine speed

The motor performance testing, encompassing power, torque, and fuel consumption, reveals insights into the impact of pyrolysis plastic oil (PPO) on engine behavior. As depicted in **Figure 5**, variations in motor power with changing speeds exhibit a consistent pattern, reaching maximum power at 5000-6000 rpm, but notable alterations are observed with different PPO ratios. The reduction in motor power correlates with the higher PPO volume, indicating a decrease in energy output compared to gasoline [40]. The diminished motor power observed when employing pyrolysis plastic oil (PPO) in contrast to gasoline can be ascribed to a multitude of factors, encompassing various properties outlined in **Table 3**. The calorific value of PPO, consistently lower than that of gasoline across different concentrations (PPO 10, PPO 30, PPO 50, and PPO 100), signifies a reduced energy content. Furthermore, the altered combustion characteristics of PPO, evidenced by lower flashpoints and octane numbers, contribute to inefficient combustion processes, negatively impacting motor power. The increase in viscosity with PPO concentration poses a challenge to proper fuel atomization during injection, resulting in incomplete combustion.

The reoccurrence of spikes in the 7000-8500 rpm range during brake power testing for gasoline, PPO 10, and PPO 30, in contrast to their absence in PPO 50 and PPO 100, can be ascribed to the intricate molecular interactions and compositional disparities highlighted in **Table 3**. The diverse molecular forces at play in the gasoline-PPO blend, such as London dispersion forces, dipole-dipole interactions, and potential hydrogen bonding, are integral to understanding these variations. This is supported by the fact that gasoline exhibits a higher calorific value (10886 Cal/g) and lower viscosity (0.509 mm^2/s) compared to PPO 10 (10669 Cal/g, 0.539 mm^2/s) and PPO 30 (10499 Cal/g, 0.601 mm^2/s), indicating potentially superior combustion efficiency for gasoline. The involvement of toluene, an aromatic compound present in both gasoline and PPO, introduces dipole-dipole interactions, which may contribute to combustion stability in gasoline. Conversely, the elevated viscosity and distinct oxygenated compounds in PPO 10 and PPO 30, such as methyltetrahydrofuran and phenol, could lead to inefficient combustion, manifesting as spikes in the brake power results. The absence of spikes in PPO 50 and PPO 100 may be attributed to the higher concentration of toluene and the potential mitigation of combustion challenges due to their unique compositions, as outlined in the additional information. These findings underscore the pivotal role of molecular interactions and fuel composition in shaping combustion dynamics and engine performance [33]–[35], [41]–[45].

Motor torque testing, as illustrated in **Figure 6**, highlights a noteworthy phenomenon where torque steadily increases with rising RPM until reaching 5000 RPM, after which it rapidly decreases. This distinctive pattern contrasts with the absence of spikes in torque measurements, in stark contrast to the presence of spikes observed in power measurements. The substantial torque reduction, especially pronounced in PPO100 with a 17% decrease compared to gasoline, can be correlated with the intricate molecular structures [46] and properties outlined in **Table 3**. The complex intermolecular forces at play between gasoline and PPO, including London dispersion

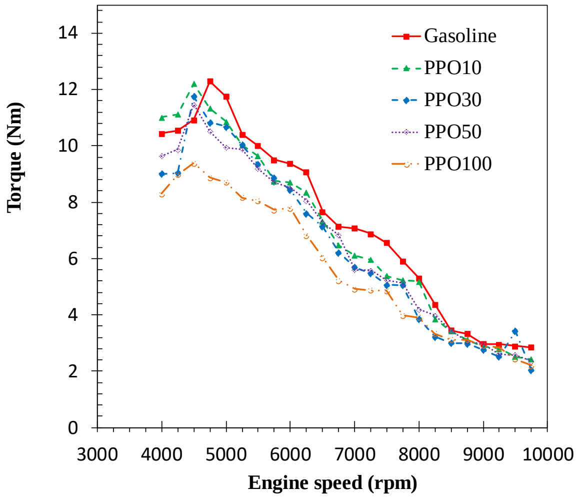

Figure 6. Relationship between torque and engine speed

forces, dipole-dipole interactions, and potential hydrogen bonding, significantly impact combustion dynamics. Hydrocarbons in gasoline, particularly alkanes and aromatics, contribute to London dispersion forces, affecting the miscibility and homogeneity of the gasoline-PPO blend. Furthermore, toluene, present in both fuels, introduces dipole-dipole interactions, enhancing overall molecular cohesion. The absence of torque spikes, unlike the observed power spikes, underscores the nuanced influence of molecular interactions on combustion efficiency. This phenomenon suggests that while the combustion process is affected by the intricate molecular dynamics of the fuel blend, torque measurements may not exhibit the same abrupt fluctuations as power measurements. This analysis emphasizes the need to consider specific engine parameters and their responses to molecular interactions for a comprehensive understanding of the impact of plastic-derived fuels on engine performance.

The persistent decrease in engine power and torque with an escalation in PPO (pyrolysis plastic oil) volume ratios can be thoroughly elucidated by scrutinizing the ignition temperatures of diverse compounds present in both gasoline and PPO. Although the calorific values of gasoline and PPO may approximate each other, the distinct ignition characteristics of individual components play a pivotal role in shaping combustion dynamics. The analysis of **Table 3**, outlining the properties testing of pyrolysis plastic oil (PPO), may reveal the presence of aromatic compounds [47] like toluene, methyltetrahydrofuran, and phenol in PPO. A critical factor contributing to the observed decline in engine performance lies in the disparate ignition temperatures of these compounds compared to those in gasoline. Toluene, a prevalent aromatic compound in PPO, exhibits an ignition temperature of approximately 552 °C, significantly higher than the ignition temperature of iso-octane (396 °C) found in gasoline. This elevated ignition temperature of toluene can induce delayed ignition and incomplete combustion, thereby contributing to the observed reduction in engine power and torque with increasing PPO ratios. Additionally, the presence of phenol in PPO, characterized by an ignition temperature of around 79.4 °C, indicates a compound with a lower ignition temperature than most components in gasoline, potentially leading to premature ignition or inconsistent combustion. In conclusion, the consistent decrease in engine power and torque as PPO volume ratios rise is intricately linked to the higher ignition temperatures of aromatic compounds such as toluene and potential variations in the ignition characteristics of other PPO components, collectively impacting the combustion efficiency and overall engine performance.

3.3. Fuel Consumption Examination and Specific Fuel Consumption (SFC) Testing

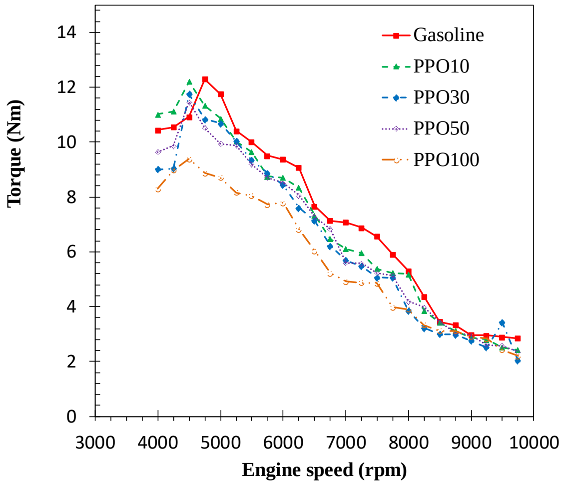

Figure 7. Relationship between fuel consumption and engine speed

In the evaluation of fuel consumption and specific fuel consumption (SFC), the study employed a comprehensive approach to assess the performance of the engine using various volume ratios of pyrolysis plastic oil (PPO) in comparison to gasoline. Fuel consumption is a critical parameter for evaluating internal combustion engine efficiency and performance. The dataset shown in **Figure 7** presents fuel consumption in kilograms per hour (kg/h) across various engine speeds (rpm) for different fuel types, including Gasoline, PPO10, PPO30, PPO50, and PPO100. Generally, fuel consumption increases with higher engine speeds, a common characteristic due to the elevated power output demand. Gasoline consistently demonstrates the lowest fuel consumption at each engine speed, while PPO100 tends to have higher consumption rates. PPO10 and PPO30 exhibit variations compared to PPO100, generally showing lower consumption. Specific observations at different engine speeds highlight the varying fuel efficiency of each fuel type. Recommendations include operating the engine within a moderate speed range for better efficiency, considering factors like cost and availability when selecting a fuel type, and exploring engine tuning options to optimize performance.

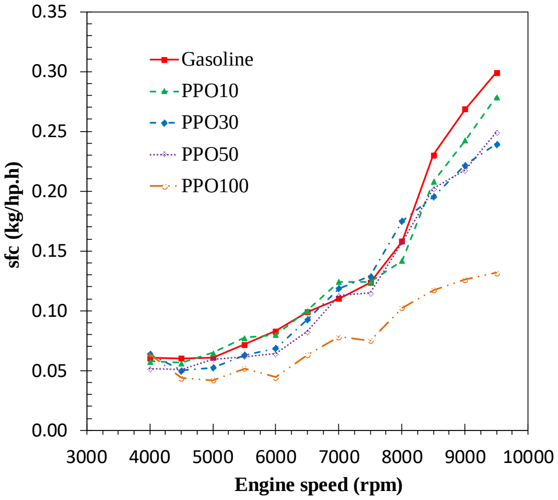

Figure 8. Relationship between SFC and engine speed

The specific fuel consumption, a key metric reflecting the efficiency of internal combustion engines, is analysed in correlation with engine speed for various fuel types—Gasoline, PPO10, PPO30, PPO50, and PPO100. The SFC values, measured in kilograms per horsepower-hour (kg/hp·h), demonstrate discernible trends across different engine speeds (**Figure 8**). At 4000 rpm, Gasoline exhibits the lowest SFC, indicating higher fuel efficiency compared to the PPO blends. Notably, PPO50 records the lowest SFC among the plant oil-based fuels, suggesting a favourable balance between engine speed and fuel consumption.

As engine speed increases to 4500 rpm, Gasoline maintains a competitive SFC, while PPO100 displays the highest SFC among the fuels. This trend persists at 5000 rpm, with PPO100 consistently recording the highest SFC values. The data at 5500 rpm reveals an overall increase in SFC for all fuels, with Gasoline still showcasing relatively lower consumption, emphasizing its efficiency at higher engine speeds. Moreover, the rising trend in SFC continues up to 9500 rpm, reinforcing the general understanding that higher engine speeds demand more fuel. Gasoline consistently exhibits lower SFC compared to PPO blends, indicating its superior efficiency across various operating conditions.

To explain these SFC variations, the molecular interactions between gasoline and PPO, influenced by intermolecular forces, must be considered. London dispersion forces, dipole-dipole interactions, and potential hydrogen bonding play a pivotal role in shaping the combustion characteristics of these fuels. The chemical makeup of gasoline, primarily straight-chain alkane compounds, forms London dispersion forces crucial for combustion efficiency in Otto engines. Conversely, PPO, comprising benzene derivatives, aliphatic hydrocarbons, and oxygenated compounds, engages in diverse intermolecular forces, including dipole-dipole interactions and hydrogen bonding. These forces affect the vaporization and combustion characteristics of the fuel mixture, impacting ignition timing and, consequently, SFC.

Therefore, the analysis of SFC at different engine speeds underscores the significance of fuel type and its molecular interactions. Gasoline consistently demonstrates lower SFC values, emphasizing its efficiency across a range of engine speeds. The interplay of intermolecular forces contributes to these variations, highlighting the need for a comprehensive understanding of molecular interactions to optimize fuel formulations and enhance overall engine performance. Further research in this direction is crucial for refining fuel blends and promoting more efficient and environmentally friendly internal combustion engines.

3.4. Brake Thermal Efficiency

The evaluation of brake thermal efficiency, depicted in **Figure 9**, elucidates a decline in thermal efficiency for PPO100 compared to other PPO blends and gasoline. The observed decline in thermal efficiency for PPO100, compared to other PPO blends and gasoline, can be attributed to multifaceted factors rooted in the properties of the fuels. Initially, the persistently lower calorific value of PPO100 (10142 Cal/g), in contrast to other blends and gasoline, suggests a reduced energy content, aligning with findings from a previous study [48]. This lower calorific value translates into reduced heat output during combustion, thereby diminishing the thermal efficiency of the engine. The altered combustion characteristics of PPO, exemplified by lower flashpoints and octane numbers, contribute to inefficient combustion processes. The increase in viscosity with higher PPO concentrations hampers fuel atomization during injection, resulting in incomplete combustion and a subsequent decrease in thermal efficiency. Furthermore, the intricate molecular interactions within the gasoline-PPO blend, such as London dispersion forces and dipole-dipole interactions, significantly influence combustion dynamics. Gasoline, exhibiting a higher calorific value and lower viscosity, displays potentially superior combustion efficiency compared to PPO blends. This discrepancy in combustion efficiency contributes to a decline in thermal efficiency, especially noticeable in PPO100. In essence, the thermal efficiency reduction in PPO100 is intricately linked to its lower calorific value, altered combustion characteristics, and the complex interplay of molecular forces affecting combustion efficiency.

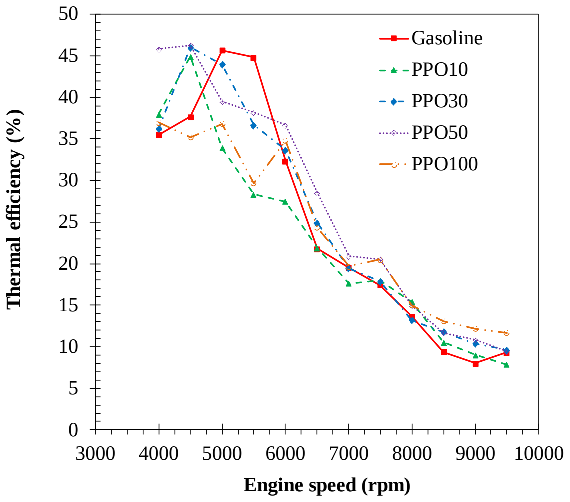

Figure 9. Relationship between thermal efficiency and engine speed

In general, errors are correlated with any experimentally acquired values. The main causes of measurement errors include instrument selection and calibration, as well as the effects of environmental and human errors. The uncertainty of the measurements is calculated based on the error related to the discrete parameters [13]. The uncertainty of this thermal efficiency measurement is calculated based on the error associated with using calculated discrete parameters of 0.22%.

$$BTE\ Uncertainty\ (\%) = \pm\sqrt{\left(\frac{AP}{P}\right)^2 + \left(\frac{\Delta t}{t}\right)^2 + \left(\frac{\Delta\rho}{\rho}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta LHV}{LHV}\right)^2} \tag{1}$$

3.5. Exhaust Emission Testing

The exhaust emission analysis, covering hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and air-fuel ratio (AFR) during the exhaust emission test, provides crucial insights into the influence of Pyrolysis Plastic Oil (PPO) on engine performance and emissions. Gasoline exhibits the lowest HC emissions at 152 ppm, indicating efficient combustion, while increasing PPO concentration correlates with a general decrease in HC emissions, reaching a minimum of 96.25 ppm for PPO100. This reduction is attributed to specific PPO compounds fostering more complete combustion, aligning with prior research [49]. Notably, all tested fuels, including PPO, are expected to meet or exceed emission standards due to their low HC emission levels.

The exhaust emission data highlights variations in carbon monoxide (CO) emissions across different fuel blends, including Gasoline, PPO10, PPO30, PPO50, and PPO100. Gasoline, serving as the baseline, exhibits a CO emission rate of 1.8%. The introduction of 10% Pyrolysis Plastic Oil (PPO10) results in a marginal increase in CO emissions to 1.84%. However, a notable trend emerges as the PPO concentration rises. PPO30 demonstrates a decrease in CO emissions to 1.3%, indicating a potential correlation between higher PPO content and reduced CO levels. This trend persists with PPO50, where CO emissions further drop to 1.45%. The most substantial reduction is observed in the PPO100 blend, displaying a CO emission rate of 1.11%, significantly lower than Gasoline. The consistent decrease in CO emissions with higher PPO concentrations suggests a positive impact on combustion efficiency. The molecular composition of PPO, enriched with oxygenated compounds and aromatic hydrocarbons, potentially contributes to enhanced combustion, resulting in reduced CO emissions.

Moreover, CO_2 emissions rise with higher PPO concentrations, peaking at 6.8% for PPO50. This increase is linked to PPO's composition, rich in carbon compounds, leading to enhanced CO_2 production during combustion [50]. The observed surge in carbon dioxide aligns with the molecular information of PPO compounds, emphasizing improved combustion efficiency. Importantly, CO_2 emissions remain within acceptable ranges, given their association with complete combustion and lenient standards.

Regarding oxygen content, Gasoline has the highest at 10.58%, while PPO100 has the lowest at 8.05%. The decline in oxygen content with increasing PPO concentration is attributed to specific

PPO compounds consuming more oxygen during combustion. The molecular information of PPO compounds aligns with this observation, elucidating the surge in carbon dioxide levels. As combustion efficiency improves with higher PPO ratios, oxygen is more comprehensively consumed during the process, resulting in a depletion of oxygen levels in the exhaust gas. Despite the decrease, observed values fall within typical ranges for internal combustion engines, and oxygen content is not typically regulated. Furthermore, analysis of air-fuel ratio (AFR) and lambda (λ) reveals that PPO50 exhibits the lowest AFR, indicating a rich mixture, while PPO100 has the highest λ, indicating a lean mixture. Rich mixtures may contribute to incomplete combustion and higher CO emissions, while lean mixtures can reduce CO but may increase NOx emissions. Adjustments are required to ensure AFR and λ values comply with specified ranges in emission standards for each fuel type.

The **Figure 10** comparison of exhaust emission levels validates trends, showcasing the association between higher PPO ratios and reduced CO and HC levels, coupled with elevated CO_2 levels and reduced O_2 concentrations. This correlation is explained by the molecular composition of PPO, with oxygenated compounds and aromatic hydrocarbons enhancing combustion efficiency. The findings align with prior research on ethanol-containing fuels [49], highlighting the environmental advantages of using PPO.

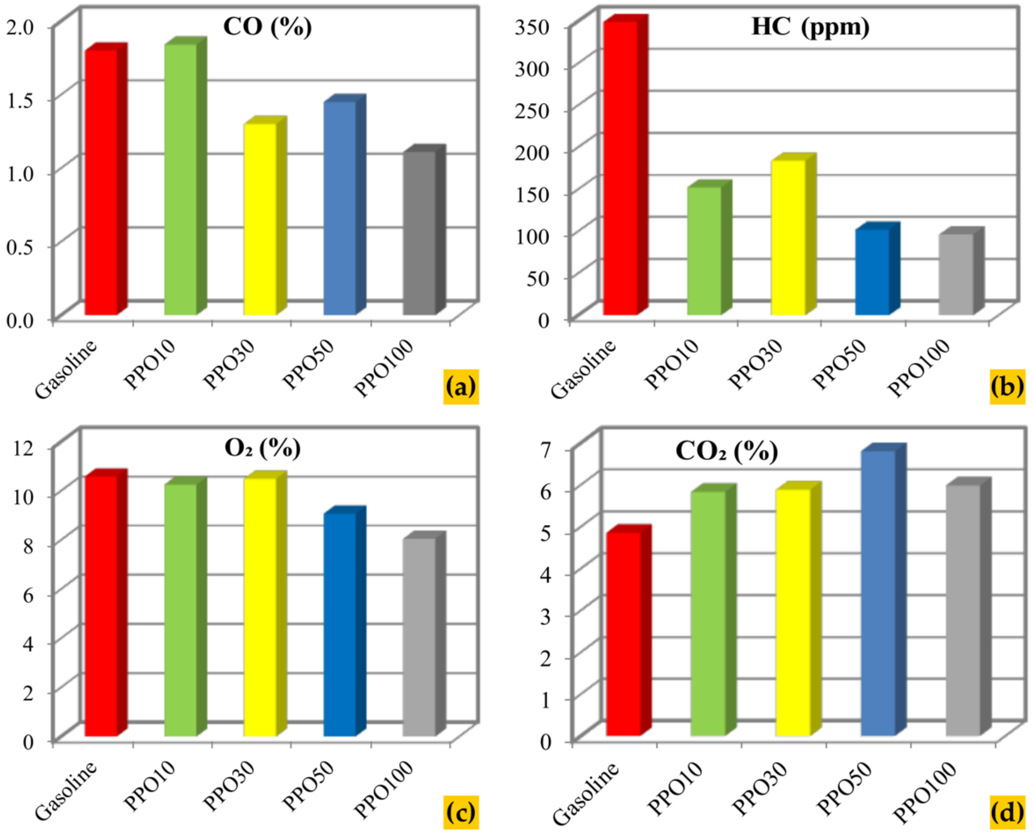

Figure 10. Comparison of exhaust emission levels: (a) Carbon monoxide content; (b) Hydrocarbon content; (c) Oxygen content; (d) Carbon dioxide

The molecular interaction between gasoline and PPO involves complex intermolecular forces, including London dispersion forces, dipole-dipole interactions, and potential hydrogen bonding. These forces significantly influence vaporization, combustion characteristics, and overall performance. The diverse composition of hydrocarbons in gasoline engages in interactions with PPO components, impacting blend miscibility and homogeneity. Additionally, oxygenated compounds in PPO may contribute to hydrogen bonding, adding complexity to the interaction. Comparatively, the chemical makeup of gasoline, primarily straight-chain alkane compounds, differs from PPO, which comprises benzene derivatives, aliphatic hydrocarbons, and oxygenated compounds. The diverse intermolecular forces, including London dispersion forces, dipole-dipole interactions, and hydrogen bonding, influence combustion quality, efficiency, and overall engine performance. For instance, the interaction between toluene and air introduces dipole-dipole interactions, impacting combustion efficiency and mitigating knocking. Therefore, a comprehensive understanding of exhaust emissions, molecular interactions, and chemical compositions provides valuable insights into PPO's performance as a fuel source.

4. Conclusion

The pyrolysis of PET plastic waste produces pyrolysis plastic oil (PPO), a potential alternative fuel source. The physicochemical properties of PPO, including calorific value and density, align closely with traditional fuels. However, variations in octane rating, flash point, and viscosity necessitate careful fuel blending. Motor performance testing indicates a reduction in power and torque with higher PPO concentrations, linked to lower energy content and altered combustion characteristics. Thermal efficiency declines, primarily in PPO100, due to its lower calorific value and complex molecular interactions. Specific fuel consumption (SFC) analysis reveals that gasoline consistently demonstrates lower SFC values, emphasizing its efficiency. Exhaust emission testing shows decreased hydrocarbon and carbon monoxide emissions with higher PPO concentrations, indicating enhanced combustion efficiency. CO_2 emissions rise, reflecting the carbon-rich composition of PPO. Oxygen content decreases, and air-fuel ratio variations highlight the impact of molecular interactions on combustion. PPO exhibits potential as an environmentally friendly alternative fuel, but challenges such as reduced thermal efficiency and altered combustion characteristics require further research for optimization.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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