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Experimental study of engine performance using a blend of RON 90 gasoline and fractionated gasoline equivalent from plastic pyrolysis oil

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Abstract
This study investigated the performance and emission characteristics of a gasoline engine using a blend of commercial gasoline RON 90 and fractionated plastic pyrolysis oil (PPO). Almost all previous studies used unfractionated PPO in engine performance tests. The use of raw PPO in engine performance tests will result in poor engine performance, because the physicochemical properties of the fuel do not meet engine requirements and the ASTM D4814 standard (gasoline fuel properties standard). An innovative aspect of this study is that the raw PPO was first fractionated to separate the gasoline PPO fraction, the diesel PPO fraction, and other aromatic fractions. Gasoline-equivalent PPO was used in the engine performance test to ensure the fuel used met engine specifications. PPO is obtained from post-consumer plastic waste through a pyrolysis process, followed by fractionation to separate heavy fractions and complex aromatic compounds. Blends containing up to 40% fractionated PPO were tested to evaluate their effects on engine performance and emissions. Experimental results showed that the use of 40% PPO only reduced thermal efficiency 0.79%, which is very low compared to the results of previous studies. In terms of emissions, the use of a 40% fractionated PPO blend reduced CO emissions by 7%, reduced HC by 17%, and increased CO_2 by 17%. The reduction in CO_2 and HC emissions is an innovative aspect of this study. These findings differ from previous studies using raw PPO, which reported significant engine performance degradation and increased emissions due to poor combustion characteristics.

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INTRODUCTION

Plastic waste has become an environmental problem almost all over the world [1]. On the other hand, the world is also facing an energy crisis [2]. On a national scale, the number of motorized vehicles in Indonesia increases every year, of course the need for fuel also increases [3]. The transition to renewable energy sources is becoming increasingly urgent [4]. One effort that is expected to reduce the impact of these two problems is by converting plastic waste into fuel through the pyrolysis process [5]. According to Kabeyi & Olanrewaju, although pyrolysis oil from plastic waste has great potential to be used as an alternative fuel, there are still various challenges that need to be overcome [6]. Palanivelrajan Research et al. who used raw PPO as a fuel mixture concluded that the quality of Plastic Pyrolysis Oil (PPO) is still not equivalent to conventional fuels such as gasoline or diesel, both in terms of physico-chemical properties, performance, and exhaust emissions [7]. In terms of physico-chemical properties, Saha et al. concluded that raw PPO has a higher viscosity, varying cetane or octane numbers, and contains oxygen, olefins, and aromatic compounds that can affect fuel stability and combustion [8]. Figure 1 shows a Pyrolysis and fractionation reactors.

In terms of performance, Nandakumar et al. explained that some aromatic compounds in PPO often result in decreased combustion efficiency and increased carbon residue, which can cause the formation of deposits on engine components and reduce efficiency [9]. Maithomklang's research et al. explained that the combustion of raw PPO tends to produce higher exhaust gas emissions [10], such as carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NOx), which have the potential to increase environmental impacts if they do not undergo an adequate purification process [11].

Previous researchers have made various attempts to overcome the problems in using plastic pyrolysis oil as automotive engine fuel [12]. Several studies have explored mixing pyrolysis oil with biofuels, such as gasoline or diesel, to improve combustion stability and reduce exhaust emissions. As done by Tambunan, Ambarita, Sitorus, & Sebayang, (2024a), they mixed PPO equivalent to diesel with biodiesel derived from rubber seeds, the results showed improvements in several physicochemical properties, decreased viscosity, increased calorific value, but also decreased oxidation stability. However, this study only mixed PPO with biodiesel, not with gasoline fuel [1].

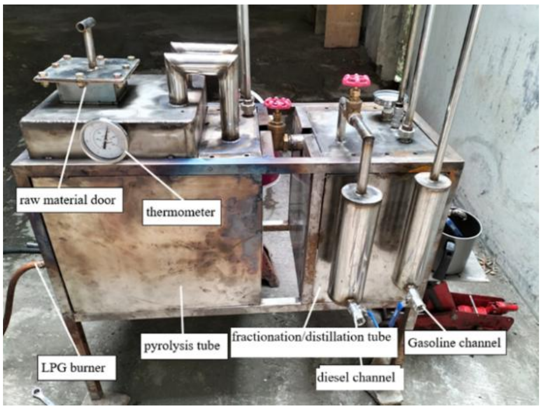


Figure 1. Pyrolysis and fractionation reactors

In addition, Jayanth et al. modified the engine to optimize the combustion characteristics of plastic pyrolysis oil in automotive engines, but this method was considered impractical, because the fuel performance was not optimal in standard engines [13]. The use of catalysts in the pyrolysis process can enhance the quality of PPO by lowering aromatic compounds and residues that affect engine performance, as noted by Kamali et al. However, the high cost of catalysts renders this method economically unviable [14].

Almost all previous studies have not used raw PPO in performance testing, without separating the plastic pyrolysis oil into fractions equivalent to diesel and gasoline, so the characteristics of the resulting fuel still vary and do not fully meet conventional fuel standards or ASTM D4814 namely the standard properties of gasoline fuel. The use of raw PPO is suspected of causing suboptimal engine performance and emissions. This study aims to enhance the quality of plastic pyrolysis oil (PPO) through a fractionation process to improve its suitability as an engine fuel.

Raw plastic pyrolysis oil has a very wide carbon chain distribution, consisting of a mixture of linear and branched hydrocarbons, and olefin and paraffin content that varies depending on the type of plastic from which it originates, for example polypropylene (PP) pyrolysis oil is rich in iso -olefins, while that from polyethylene (HDPE) is dominated by alpha-olefins [15]. After going through a fractionation or distillation process, plastic pyrolysis oil can be separated into fractions with a narrower carbon range, thus producing hydrocarbon fragments with more uniform purity and characteristics, such as diesel or naphtha fractions. [15]. Fractionation also increases the H/C ratio and decreases the O/C ratio in pyrolysis oil, so that its chemical properties become more similar to conventional petroleum fuels. [16]. In addition, fractionation significantly reduces the content of heavy hydrocarbons (e.g. >C23) and increases the proportion of light to medium fractions which are more desirable for fuel applications [17].

According to Apazhev et al. fractional composition of fuel has a significant impact on engine performance, including ignition, fuel cost, and chemical stability, as well as physical stability [18]. This fractionation process aims to obtain fuel with characteristics close to conventional fuel standards, so that it can be mixed homogeneously with conventional fuel and can be used more optimally in internal combustion engines [19].

In this study, the gasoline-range fraction derived from PPO fractionation was utilized for physicochemical characterization, such as density, viscosity, octane number, and energy content. In addition, the gasoline-equivalent fractionated PPO will be tested in a performance test on an electric generator engine to evaluate its thermal efficiency, output power, fuel consumption, and exhaust emissions to determine its suitability for use as an alternative fuel.

In this study, the oil obtained from the pyrolysis of plastic waste will be fractionated. using the distillation method based on the evaporation point to separate diesel and gasoline equivalent oil based on the evaporation point.

MATERIALS AND METHODS

Plastic pyrolysis oil (PPO) production

Various types of plastic waste were collected randomly from recycling facilities and then crushed using a shredder to produce plastic flakes measuring approximately 2 cm x 2 cm. Every 6000 grams of plastic flakes consisted of 25% each of: (1) used oil bottles (HDPE and PET), (2) refillable water gallon caps (LDPE and HDPE), (3) buckets and basins (PP, HDPE, LDPE, PP and ABS) and (4) jerry cans (HDPE) then pyrolyzed using the pyrolysis reactor in Figure 1 at temperatures of 250, 300, 350, and 400 °C, and the yield of PPO oil produced was calculated.

From the yield calculation results, the pyrolysis temperature was obtained at 350 °C, so the next pyrolysis process was carried out at that temperature. Next, 2000 grams of PPO were fractionated at a temperature of 30-200 °C which was increased gradually. The distillation temperature was maintained at 200 °C until no more fractions evaporated. Fractions that evaporated at a temperature of 30 °C – 200 °C were considered equivalent to gasoline because their evaporation point was the same as the evaporation point of gasoline. Then the fractionation temperature was increased steadily until it reached a temperature of 350 °C, the fractions that evaporated at that temperature were considered equivalent to diesel, because their temperature was the same as the evaporation of diesel. Next, the mass of each fraction was weighed to calculate the yield of each fraction and the non-volatile residue.

Fuel preparation

The equivalent fraction of gasoline resulting from PPO fractionation is then filtered with filter paper, then mixed with Pertalite RON (Research Octane Number) 90 with compositions of 10%, 20%, 30%, and 40%. Pertalite is a trademark of gasoline fuel produced by Pertamina.

This state-owned enterprise is responsible for the management, production, and distribution of all oil and gas fuels in Indonesia. Each of these mixtures is denoted by P0, P10, P20, P30, and P40 (Figure 2). Each of these mixtures was examined for physical and chemical properties using methods in accordance with ASTM (Table 2).

Some of the equipment used to test the physicochemical properties of fuel samples and their performance test equipment are presented in Table 1, while the accuracy and uncertainty of the instruments used are presented in Table 3. The ASTM standards and the results of testing the physicochemical properties of fuel samples are presented in Table 2.

Figure 2. Tested fuel samples

Table 1. Testing equipment

Parameter	Equipment
Calorific value (J/g)	Cold properties viscometer SVM 3000 (Anton Paar, Austria)
Octane number	Cetane Koehler K88620-1 (United States)
Kinematic viscosity (mm ^{2}/s) at 40°C	Cold properties viscometer SVM 3000 (Anton Paar, Austria)
Density (kg/m ^{3} at 40°C	Cold properties viscometer SVM 3000 (Anton Paar, Austria)
Power (watts)	P06S-20 Type Power Monitor Cable (Huizhou More Green Light Co., Ltd, China)
Engine speed (rpm)	$^+$ digital tachometer (Shenzhen Bestone Industrial Co. Ltd, China)
Emissions (CO, CO$_2$, O$_2$, HC)	gas board 4020H 10076607 (Gehrmann GmbH)

Table 2. Physicochemical Properties of Fuel

Fuel testing	**Calorie value (kJ/ kg) ASTM D-4809-06**	**Octane number ASTM D 2699**	**Kinematic viscosity (mm ^{2} /second) ASTM D-445**	**Density (grams/ ml) ASTM D-2638-10**
P0	46.94	90	0.51	0.736
P10	48.73	82	0.45	0.713
P20	45.59	77	0.59	0.740
P30	50.44	81	0.63	0.746
P40	50.87	75	0.69	0.753

Table 3. Instrument Uncertainty

Measurement	**Accuracy**	**Uncertainty (%)**
Load	± 0.1 kg	± 0.2
Engine Speed	±10 rpm	± 0.3
Fuel consumption	± 0.1 ml	± 1
CO	± 0.02%	± 0.1
CO_2	± 0.02%	± 0.1
HC	± 5%	± 0.2
Opacity	± 0.1%	± 1
Time (stopwatch)	± 0.2 seconds	± 0.2

Engine performance test

4-stroke electric generator engine, maximum power 3 HP, 93 cc single cylinder, OHV valve, air-cooled, gasoline fueled, assembled with three 100 W bulbs as a load (Figure 3).

The fuel inlet hose was connected to a burette to measure fuel consumption per unit time using a timer. To detect engine power, a power meter was connected to the generator output cable, which was also connected to the bulb circuit as a 300-watt fixed load. A gas analyzer was installed in the engine exhaust to detect engine emissions. Table 4 shows the engine specifications used for the performance testing.

Each fuel sample in Table 2 was tested at engine speeds of 2800, 3000, 3200, 3400, and 3600 rpm. Each test was performed 3 times, and then the average was calculated. At each engine speed, the power detected by the power meter was recorded. A burette and timer were used to determine the fuel consumption rate per unit time.

From the measured power (BP) data, TE (Thermal Efficiency) is then calculated using (1).

$$TE = \frac{BP}{\dot{m}f \ x \ Q_{LHV}} \ (\%) \qquad (1)$$

Where $\dot{m}f$ is the fuel consumption rate (kg/h) and Q_{LHV} is the calorific value of fuel (kJ/kg). While the specific fuel consumption (*BSFC)* is calculated using (2).

$$BSFC = \frac{M_f}{BP} \ (kg/kWh) \qquad (2)$$

Table 4. Test machine specifications

Parameter	**Specification**
Brand/Model/Made in	Tiger /TG 2880/China
Engine type	Air-cooled, 4-stroke, OHV, Single Cylinder
Hole x Step	Size 56x38 mm
Compression ratio	8.5 : 1
Speed	2700 – 3600 revolutions per minute
output (kW/3600pm)	3.0 HP
Torque	4.4 Nm/2500 rpm

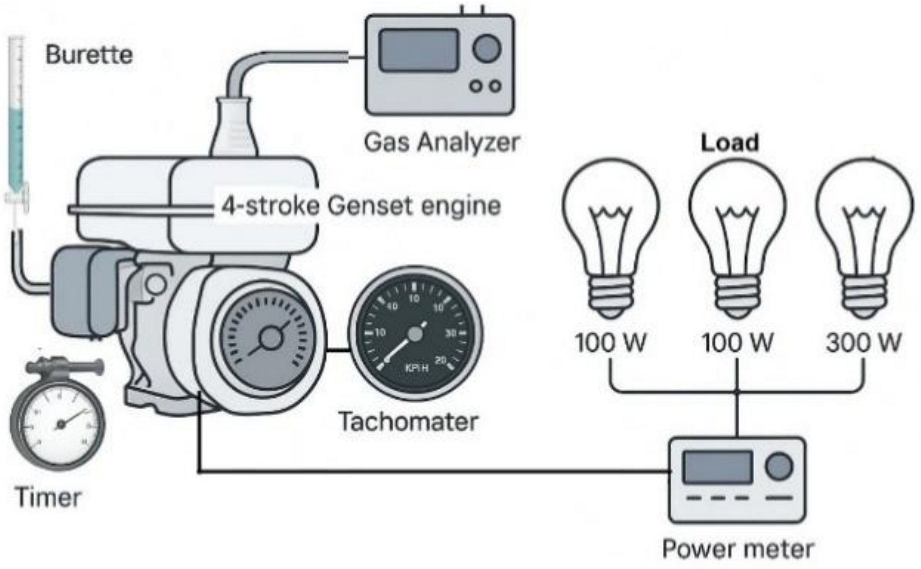


Figure 3. Engine performance test installation

RESULTS AND DISCUSSION

PPO Fractionation

When all the pyrolysis products were weighed, their composition in mass percentage is shown in Figure 4, with the oil fraction being 68.7%, the wax fraction 22.83%, the scale 7.17%, and the remaining gas and other fractions 1.33%. These results are very similar to findings by Mqsood et al., who found that 70% liquid oil was produced through the pyrolysis of various types of plastic waste in a batch reactor [20].

The composition of the PPO fractionation product is shown in Figure 5, consisting of 79.17% gasoline fraction, 16.67% diesel fraction, and 4.17% residue. Its physical appearance is shown in Figure 6. Furthermore, only the gasoline equivalent fraction was used as an RON 90 blend in engine performance testing.

Engine performance

Figure 7 shows the effect of variations in PPO mixtures (P0, P10, P20, P30, P40) on engine performance based on three main parameters: power (a), thermal efficiency (b), and specific fuel consumption or SFC (c) at various engine speeds. Figure 7 (a) shows that engine power increases with increasing engine speed, with P0 still showing the highest power.

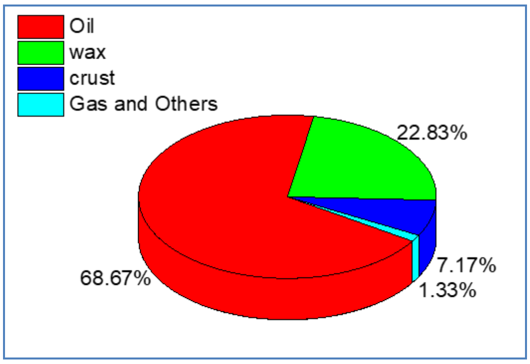


Figure 4. Composition of pyrolysis products.

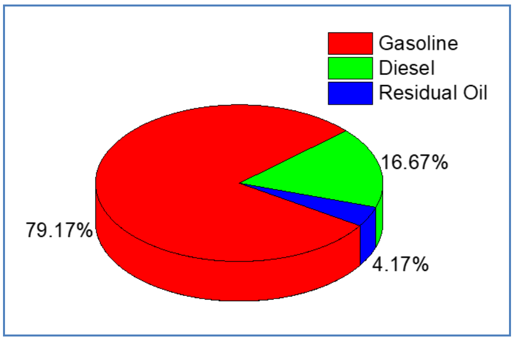


Figure 5. Product Composition of PPO

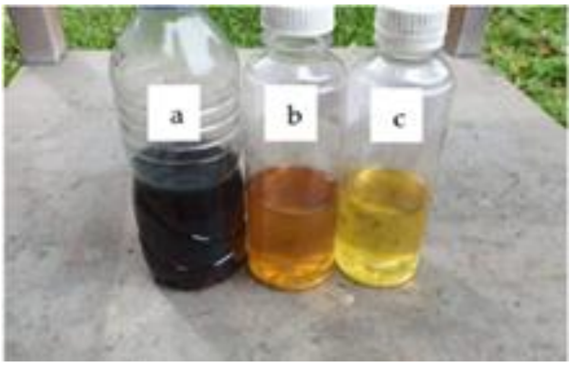
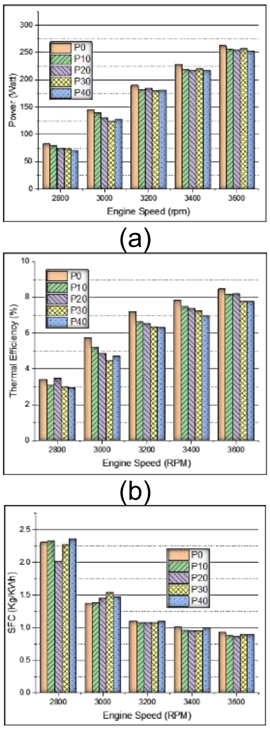


Figure 6. Physical appearance of PPO fractionation products: (a) Residual oil, (b) Diesel equivalent fraction, (c) Gasoline equivalent fraction



(a)

(b)

(c)

Figure 7. Engine performance graph: (a) power, (b) thermal efficiency, (c) SFC

A decrease in power also occurs with increasing portion of PPO in fuel, compared to P0, the average power at each engine speed decreases by 3.6% when using P10, 5.3% when using P20, 5.9% when using P30 and 6.8% when using P40, this power decrease is lower compared to the findings of Saputra & Effendy, (2023) who used PPO without fractionation, where there was a decrease in power of 8.6% when adding 30% PPO (P30) [21]. This decrease in power is likely caused by a decrease in Octane Number (RON) from P0 to P40, as seen in Table 3, where the fuel octane number decreases with the proportion of PPO. In accordance with the research results of Kumar & Sandhu, which states that the octane number affects the perfection of combustion and the torque produced by the engine, because fuel with a high octane produces higher pressure when burned in the engine combustion chamber [22].

In Figure 7 (b) it can be seen that in each fuel mixture, thermal efficiency shows an increasing trend along with increasing engine speed, this certainly shows normal symptoms according to the theory presented by Mohammed et al. , (2021) in his paper [23], even though the calorific value of P0 is lower (as seen in Table 3), P0 shows the best thermal efficiency, this can be caused by the octane number of the mixed fuel (P10, P20, P30 and P40) being lower, so that not all the heat contained in this fuel can be converted into pressure that pushes the piston and into torque on the crankshaft, as explained in Zhou's research. et al. , (2021) [24]. However, in this study, the average decrease in thermal efficiency at P40 compared to P0 was only 0.79%, which is very low compared to the results of previous studies in Table 5.

Figure 7 (c) regarding SFC shows that at low engine speed (2800 rpm), all fuel variations have high SFC, with P40 showing the highest fuel consumption. As engine speed increases, for all fuels, the SFC value decreases significantly, but the SFC value increases slightly with increasing PPO portion. Overall, it can be concluded that despite a slight downward trend in performance, blending PPO in RON 90 fuel still shows quite good performance and is able to compete with pure RON 90 (P0).

This research strengthens the findings of several recent studies on the potential use of plastic pyrolysis oil as a blended fuel, especially after pre-treatment processes such as fractionation. In research conducted by Sunaryo et al., Thomas et al., and Sharma et al., fractionated PPO exhibits better physical characteristics, such as reduced viscosity and increased calorific value, which directly impact thermal efficiency and engine performance [25, 30, 31].

This study is also in line with the results of Singh et al., who found that fractionated PPO can provide engine performance almost equivalent to pure gasoline when used at concentrations up to 20% [32]. Furthermore, research by Faisal et al. (2023) confirmed that PPO pretreatment can improve combustion stability and reduce knock potential, especially in gasoline engines [33].

The decrease in engine performance with the addition of PPO in this study is likely due to the lower octane number of PPO compared to RON 90 gasoline, as shown in Table 2.

Table 5. Comparison of Thermal Efficiency test results from several references

References	PPO Mixture	Thermal Efficiency
This study	40%	↓ 0.79%
[25]	40%	↓ 3.5%
[26]	40%	↓ 2.1%
[27]	40%	↓ 2.8%
[28]	40%	↓ 4.0%
[29]	40%	↓ 1.5%

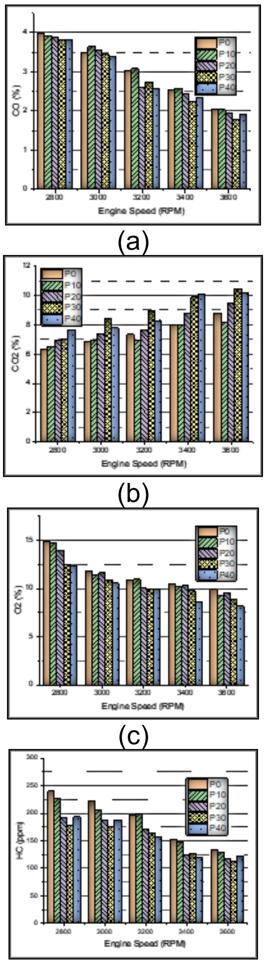
This assumption is in accordance with the results of research conducted by Kumar & Sandhu, (2021) who evaluated the combustion and emission characteristics of various fuel mixtures with different octane numbers in a constant volume vessel.

The results showed that the combustion of fuel mixtures with higher octane numbers resulted in better combustion efficiency, characterized by an increase in peak pressure and a reduction in combustion duration [22]. This is supported by research conducted by Zhou et al., who found that increasing RON consistently increases engine thermal efficiency [24]. In addition, increasing RON also reduces fuel consumption [34].

Exhaust emissions

The overall emission test results indicate that mixing gasoline with fractionated plastic pyrolysis oil (PPO) significantly affects the exhaust emission characteristics at various engine speeds. Figure 8 (a) shows that carbon monoxide (CO) emissions decrease with increasing engine speed; the relationship between engine speed and CO emissions in this study is in accordance with the theory, as explained by Elnajjar. et al. and Mohammed et al. in their research results [35][23]. CO also decreased with the addition of fractionated PPO to the fuel. The average CO emission at P0 was 3% while the average CO emission at P40 was 2.8%. This shows that oxygen requirements are met due to the higher oxygen content in PPO.

This is in accordance with the research results of Kabeyi & Olanrewaju, which concluded that CO emissions decreased with the addition of PPO due to the higher oxygen content in PPO [6]. Conversely, in Figure 8 (b), carbon dioxide (CO_2) emissions increased as the PPO content in the fuel mixture increased. The average CO_2 emission was 7.4% when using P0, increasing to 8.7% when using P40. The decreasing trend of unburned oxygen (O_2) content in Figure 8 (c) also supports this finding, where the O_2 concentration is lower in the PPO mixture compared to P0, most of the oxygen has reacted with the fuel.



(a)

(b)

(c)

(d)

Figure 8. Exhaust gas emissions (a) CO, (b) CO_2, (c) O_2, (d) HC

Hydrocarbon (HC) emissions, which are the result of incomplete combustion, in Figure 8 (d) also show a decrease with increasing engine speed and the addition of PPO to the fuel. The average HC emission is 189 ppm at P0, decreasing to 156 at P40.

This is lower than the results of the study by KV Kumar et al., who used the iridium spark plug method, which is 175 ppm at P20 [36]. Overall, these results indicate that PPO is suitable for use as an alternative fuel, both in terms of engine performance and exhaust emissions.

This finding confirms the results of several previous studies, such as those conducted by Nandakumar et al., Alawa & Chakma, and Dhamodaran et al., which reported that the presence of natural oxygenates in PPO improves the combustion process, resulting in lower CO and HC emissions, and increased CO_2 emissions due to more complete carbon oxidation [7, 35, 36]. Decreased free oxygen (O_2) levels in the emissions are also consistent with their research findings, which indicate that the oxygen in PPO plays an active role in the combustion reaction.

Interestingly, compared to previous studies, these results show improved combustion stability at high engine speeds. Some previous studies reported instability with increasing engine load, while in this study, PPO maintained low emissions up to high engine speeds.

Further research is needed to further investigate the carbon chain structure of each PPO distillate product and compare it with the carbon chain structure of gasoline and diesel. Research aimed at improving the octane rating of PPO is also needed.

CONCLUSION

This study shows that blending gasoline with distillate- based PPO has a positive impact on engine performance and emissions. Blends of up to 40% PPO (P40) produce power and torque comparable to those produced with pure gasoline. This small performance difference is believed to be due to the PPO distillation process before use, which separates gasoline-like fuel fractions based on their vaporization points. This process produces PPO with a density and viscosity close to that of gasoline, improving mixture homogeneity and enhancing fuel injection atomization. Better atomization results in more complete fuel combustion, improving combustion efficiency and overall engine response. These findings suggest that with proper pretreatment, PPO is a viable alternative fuel because it maintains engine performance close to that of pure gasoline and improves exhaust emissions.

From an emissions perspective, the study also shows that refined gasoline-PPO blends produce cleaner exhaust emissions than pure gasoline. There is a decrease in carbon monoxide (CO) and hydrocarbon (HC) emissions, and an increase in carbon dioxide (CO_2) emissions, indicating More complete combustion. The low O_2 emissions remaining in the exhaust also indicate that the oxygen in PPO plays an active role in the combustion process. This improvement is likely due to the characteristics of refined PPO, which resemble gasoline in terms of density, volatility, and viscosity, thereby improving fuel mixing quality and atomization efficiency in the combustion chamber. Thus, refined PPO not only addresses the environmental challenges of plastic waste processing but also opens up opportunities as an environmentally friendly fuel with competitive emission performance compared to conventional fossil fuels.

The limitation of this research is that it only conducted tests on an electric generator and a maximum load of 300 watts, it needs to be tested on a larger load, or a performance test on a machine assembled with a dynamo meter.

Further research is needed to further investigate the carbon chain structure of each PPO distillate product and compare it with the carbon chain structure of gasoline and diesel. Research aimed at improving the octane rating of PPO is also needed.

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