© JUN 2026 | IRE Journals | Volume 9 Issue 12 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I12-1718787

Engine Performance of Purified Pyrolytic Oil-Diesel Blends

IAN ANJELO B. CAJIDA[1], ANDREI DEREK P. MELENDREZ[2], JEROME V. PASAHOL[3]
[1,2,3]Department of Mechanical Engineering, Laguna University, Laguna Philippines

Abstract- ***This research project worked on seeing if pyrolysis oil (TPO) could be used as an alternate diesel fuel to meet increasing energy demand, inflation in fuel prices, and the problem of disposing of used tires. The purified TPO was then mixed with commercial diesel at 10%, 20%, and 30% ratios and tested for physical (fuel) properties, engine performance, and emissions from an engine using these blends as fuel. The results of the fuel tests indicate that all blends had acceptable fuel properties; they were stable when mixed; the flash points were within industry standards; the blends had low ash content and moisture levels, and the heat values were similar to commercial diesel. The engine tests indicated that each blend produced adequate combustion and maintained stability, especially with lower blend ratios; however, at higher concentrations of TPO, brake power and thermal efficiency were lower, and brake-specific fuel consumption was higher. Although performance was lower at high TPO blend ratios, results indicate that purified TPO may be a useful additive for diesel to support environmentally friendly ways to manage waste tires, reduce reliance on fossil fuels, and promote alternative energy use.***

Index Terms- ***Emission Characteristics, Engine Performance, Oil-Diesel Blend, Pyrolysis Oil, Waste Tire***

I. INTRODUCTION

Global energy demand is continuously increasing, as a result of industrialization, urbanization, and transportation development. This demand places greater reliance on petroleum-based fuels, especially diesel [1]. Diesel is still an important fuel for transportation, agriculture, marine operations and industrial applications because of its great fuel efficiency, reliability, and durability [2]. The combustion of diesel also generates emissions that result in environmental pollution. Some of these pollutants include nitrogen oxides, carbon monoxide, sulfur oxides, particulate matter, and unburned hydrocarbons. These concerns have increased the search for sustainable, environmentally friendly alternative fuels [3].

An alternative fuel that has potential is tire pyrolytic oil (TPO), which is produced from the pyrolysis of old tires in an environment with limited oxygen [4]. The pyrolysis of old tires produces a variety of products, including pyrolytic oil, carbon black, steel wire and combustible gases. TPO has similar hydrocarbon compositions and diesel-like fuel properties, which suggest the feasibility of using TPO or blending TPO with diesel fuel [5]. In addition to offering an alternative source of energy, TPO production provides a solution to the growing problem of disposing of used tires and contributes to the waste-to-energy and circular economy processes [6].

Growing fuel consumption and reliance on imported oil products in Southeast Asia have exacerbated energy security and waste management issues [7]. This is also true for the Philippines, which is strongly impacted by unstable fuel prices and a large volume of accumulated used tires. The conversion of used tires into Tire Pyrolysis Oil (TPO), has emerged as a viable alternative to reduce diesel dependence on imported sources of supply and provide an efficient way to manage waste tires. Previous research indicates that TPO can be used in low-percentage diesel fuel blends without significant modifications that will impact engine performance and efficiency. Therefore, additional research is needed to evaluate these fuels in terms of their physical and chemical properties, engine performance, and emissions [8, 9, 10].

II. LITERATURE REVIEW

Waste Tire Pyrolysis and Fuel Production: Tire pyrolysis is widely recognized as an effective thermochemical waste-to-energy process that converts discarded tires into valuable products such as tire pyrolysis oil (TPO), solid char, and pyro-gas under oxygen-limited conditions. The process typically operates at temperatures ranging from 400°C to 700°C, where complex vulcanized rubber polymers are broken down into smaller hydrocarbon chains suitable for fuel applications [11, 12, 13]. This technology is considered a sustainable solution to the growing environmental problem of waste tire accumulation, as tires are non-biodegradable and pose serious risks when improperly disposed of through open burning or landfilling.

Extensive literature highlights that TPO possesses hydrocarbon compositions similar to petroleum diesel, making it a promising alternative or blending component for compression-ignition engines [14]. Its relatively high heating value supports its potential use as a substitute fuel in industrial boilers, furnaces, and diesel engines. However, the quality and yield of TPO are strongly dependent on operational parameters such as reactor temperature, heating rate, residence time, and catalyst use, which significantly influence both chemical composition and overall fuel characteristics [15]. Studies also emphasize that improper pyrolysis conditions can lead to higher production of heavy aromatic compounds and impurities, reducing fuel quality and limiting direct engine applicability.

Purification and Conditioning of Tire Pyrolysis Oil: Raw tire pyrolysis oil is a complex mixture containing aliphatic and aromatic hydrocarbons along with undesirable components such as sulfur compounds, nitrogen species, ash, moisture, and fine carbon particulates. These impurities negatively affect combustion behavior, storage stability, and engine compatibility, making further refinement necessary before practical application. Without proper treatment, raw TPO can lead to injector clogging, incomplete combustion, higher emissions, and increased engine wear.

To address these issues, several purification techniques have been widely studied, including mild thermal treatment, gravitational settling, filtration, and activated carbon adsorption. Mild heating is used to reduce viscosity, remove light volatile fractions, and improve the overall thermal stability of the oil, making it more suitable for blending with diesel fuel [16]. Settling allows heavier suspended particles and carbon residues to naturally separate under gravity, serving as a low-cost preliminary cleaning step before further processing [11, 17]. Filtration methods, such as sand or paper filtration, further remove fine particulates and ash residues, improving clarity and preventing mechanical damage to fuel injection systems.

Activated carbon treatment plays a crucial role in upgrading TPO by adsorbing sulfur compounds, nitrogen-based contaminants, and heavy aromatic fractions. This process significantly improves fuel stability, reduces odor, and enhances combustion quality without requiring high-energy chemical processes [13, 18]. Collectively, these multi-stage purification techniques significantly enhance the physicochemical properties of TPO, including viscosity, density, flash point, and heating value, thereby improving its compatibility with conventional diesel fuel systems and making it more suitable for engine testing and real-world applications.

Engine Performance and Emission Characteristics of TPO-Diesel Blends: Numerous studies have investigated the performance of TPO-diesel blends in compression-ignition engines, particularly at low blending ratios ranging from 10% to 30%. Results consistently show that at these concentrations, TPO can be used without requiring significant engine modifications while still maintaining relatively stable combustion and acceptable engine performance [14, 19]. In many cases, brake thermal efficiency remains close to that of neat diesel, especially at lower load conditions, while fuel consumption remains within acceptable limits.

However, as the proportion of TPO increases in the blend, noticeable performance trade-offs begin to appear. Higher blending ratios tend to increase brake specific fuel consumption and reduce brake power output due to the higher viscosity, density, and aromatic content of TPO, which negatively affects fuel atomization and combustion efficiency. These changes often result in incomplete combustion and less efficient energy conversion within the engine cylinder.

In terms of emissions, studies report that higher TPO content generally leads to increased levels of NOx, CO, and particulate matter due to the presence of sulfur compounds and heavy hydrocarbons in the fuel matrix. Despite this, properly treated and refined TPO has been shown to significantly reduce these negative effects, especially when combined with optimized blending ratios and controlled engine operating conditions [20]. Overall, literature suggests that while performance and emission penalties exist at higher concentrations, carefully processed and properly blended TPO can still serve as a viable alternative fuel that supports waste tire recycling and reduces dependency on conventional diesel fuel.

III. METHODOLOGY

This study employed an experimental research design focused on the purification, blending, and evaluation of tire pyrolytic oil (TPO)-diesel fuel mixtures for compression-ignition engine application. The objective was to improve the fuel properties of crude TPO through multi-stage purification and assess its performance in a diesel engine under controlled laboratory conditions. The study also aimed to determine the effects of varying blend ratios (B10, B20, and B30) on engine performance and exhaust emissions compared to pure diesel fuel.

The experimental fuel was prepared using crude tire pyrolytic oil sourced from Flygon Trading, which underwent a multi-stage purification process consisting of mild thermal treatment, activated carbon adsorption, gravitational settling, and filtration. These processes were applied to reduce moisture, suspended solids, sulfur compounds, and heavy aromatic content, improving the stability and combustion characteristics of the oil. The purified TPO was then blended with commercial diesel fuel at volumetric ratios of 10%, 20%, and 30% to form the test fuel samples, while pure diesel served as the control fuel.

Figure 1. *Purification process of the tire pyrolytic oil and blending with diesel: (a) heat treatment, (b) filtration, (c) blending with diesel*

Fuel property testing was conducted at the Department of Energy National Petroleum Laboratory to evaluate key characteristics such as flash point, heating value, moisture content, and ash content. These properties were compared against standard diesel fuel specifications to determine the suitability of the blends for engine application. The results provided baseline indicators of how purification and blending affected the physicochemical behavior of the fuel.

Figure 2. *10%,20%,30 Blends of Tire Pyrolytic Oil-Diesel Fuel for Testing*

Engine performance testing was conducted at the Agricultural Machinery Testing and Evaluation Center (AMTEC), University of the Philippines Los Baños, using a KINGSTONE TF80NL single-cylinder compression-ignition engine. Each fuel blend was tested under controlled load conditions, and performance parameters such as brake power, brake thermal efficiency, brake specific fuel consumption, exhaust gas temperature, and emission gases (CO, CO_2, NO_x, and O_2) were recorded using calibrated instruments and a flue gas analyzer.

Figure 3. *Engine Performance Testing at AMTEC UP Los Baños*

The collected data were compared with pure diesel fuel to determine performance deviations and emission behavior across different blending ratios. The analysis focused on identifying trends in engine efficiency and combustion characteristics as the proportion of TPO increased. This experimental approach provided a systematic evaluation of the feasibility of using purified TPO-diesel blends as an alternative fuel, ensuring consistent laboratory conditions for valid comparison and reliable results.

IV. RESULTS AND DISCUSSION

The developed tire pyrolytic oil (TPO)-diesel fuel blends were evaluated in terms of fuel properties, engine performance, and emission characteristics to determine their suitability as alternative fuels for compression-ignition engines. The study utilized 10%, 20%, and 30% pyrolytic oil-diesel blends, which were compared against pure commercial diesel fuel as the baseline. The evaluation covered physical and chemical fuel properties, engine load performance, and exhaust gas emissions under controlled operating conditions.

Fuel Testing Results

Fuel Verification of 10%, 20%, and 30% Pyrolytic Oil-Diesel Blends

The fuel quality of the TPO-diesel blends was first assessed through laboratory verification tests conducted at the Department of Energy National Petroleum Testing Laboratory. The objective was to determine whether the blends satisfy standard fuel requirements in terms of stability, safety, and combustion suitability.

Table 1. *Fuel Testing Result of 100% Commercial Diesel and Diesel blends*

Test Analysis	Test Method	Sample Label 100% Commercial Diesel	Sample Label 10% Pyrolytic Oil	Sample Label 20% Pyrolytic Oil	Sample Label 30% Pyrolytic Oil
Flash Point (PMCC), °C	PNS ASTM D93 - Proc A	80.5	77.5	75.5	73.5
Water, %v/v	PNS ASTM D6304 - Proc A	0.01	0.03	0.04	0.02
Ash, %m/m	ASTM D482	<0.001	<0.001	<0.001	<0.001
Heating Value, Gross BTU/lb	ASTM D4809	19,692	19,611	19,484	19,406

The fuel properties of 100% commercial diesel and 10%, 20%, and 30% pyrolytic oil–diesel blends were evaluated in terms of flash point, water content, ash content, and heating value to determine their suitability for diesel engine operation. The results show that all fuel samples complied with standard requirements and remained within acceptable limits for compression-ignition applications.

Across all samples, a gradual decreasing trend was observed in flash point and heating value as the proportion of pyrolytic oil increased. Commercial diesel recorded the highest flash point at 80.5°C and the highest heating value at 19,692 BTU/lb, while the 10%, 20%, and 30% blends showed progressively lower values of 77.5°C, 75.5°C, and 73.5°C for flash point, and 19,611, 19,484, and 19,406 BTU/lb for heating value, respectively. Despite this reduction, all values remained within safe operating and combustion requirements, indicating that the blends still retain sufficient energy content for engine use.

Water content remained very low across all fuels, ranging from 0.01% in commercial diesel to 0.02–0.04% in the blends, indicating minimal risk of moisture-related combustion issues or corrosion. Similarly, ash content remained consistently below 0.001% for all samples, confirming the effectiveness of the purification process and indicating low potential for deposit formation inside the engine.

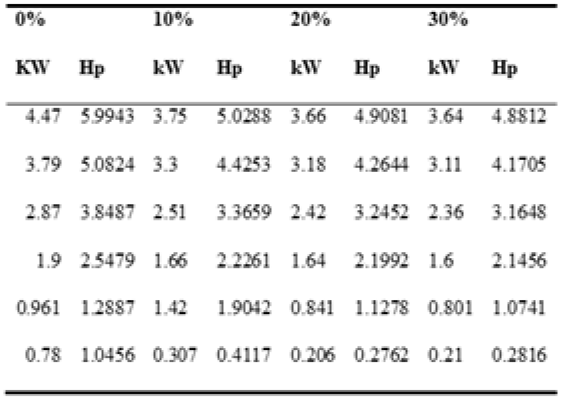
Overall, the results demonstrate that while the addition of pyrolytic oil slightly reduces flash point and energy content, the changes remain marginal and do not compromise fuel usability. The 10%, 20%, and 30% blends maintain comparable properties to commercial diesel, confirming their suitability for engine testing and compression-ignition operation under standard conditions.

Engine Performance Results

Brake Power Performance

The brake power output of the engine was evaluated under varying load conditions using different fuel blends.

Table 2. *Brake power of engine using 0%, 10%, 20%, and 30% blends*



0%		10%		20%		30%	
KW	Hp	kW	Hp	kW	Hp	kW	Hp
4.47	5.9943	3.75	5.0288	3.66	4.9081	3.64	4.8812
3.79	5.0824	3.3	4.4253	3.18	4.2644	3.11	4.1705
2.87	3.8487	2.51	3.3659	2.42	3.2452	2.36	3.1648
1.9	2.5479	1.66	2.2261	1.64	2.1992	1.6	2.1456
0.961	1.2887	1.42	1.9042	0.841	1.1278	0.801	1.0741
0.78	1.0456	0.307	0.4117	0.206	0.2762	0.21	0.2816

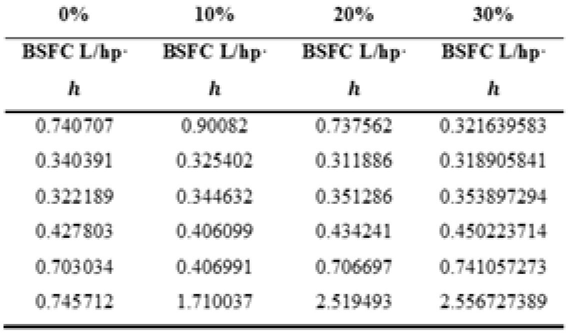
Results show that brake power decreased as the proportion of pyrolytic oil increased. The 10% blend produced the closest performance to commercial diesel, while the 30% blend recorded the lowest power output. This trend is attributed to the lower heating value and higher viscosity of pyrolytic oil, which slightly reduces combustion efficiency.

Despite this reduction, all blends maintained stable engine operation across all load conditions, indicating that the engine can safely utilize up to 30% TPO without operational instability.

Brake Specific Fuel Consumption (BSFC)

Fuel consumption behavior was analyzed to determine efficiency under different loads.

Table 3. *BSFC results for all fuel blends*



0%	10%	20%	30%
BSFC L/hp·h	BSFC L/hp·h	BSFC L/hp·h	BSFC L/hp·h
0.740707	0.90082	0.737562	0.321639583
0.340391	0.325402	0.311886	0.318905841
0.322189	0.344632	0.351286	0.353897294
0.427803	0.406099	0.434241	0.450223714
0.703034	0.406991	0.706697	0.741057273
0.745712	1.710037	2.519493	2.556727389

$$BSFC = \frac{4.44L/h}{5.99427hp} = 0.740707L/hp \cdot h$$

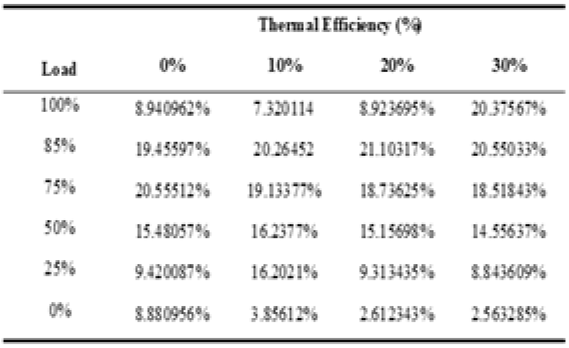
The results indicate that BSFC was lower at higher loads and increased significantly at lower loads across all blends. This behavior is expected due to increased frictional losses and incomplete combustion at low load operation.

Higher TPO content resulted in slightly higher BSFC values, particularly at light loads, indicating reduced fuel utilization efficiency due to poorer atomization and combustion characteristics.

Brake Thermal Efficiency

Thermal efficiency was used to evaluate the energy conversion performance of the engine.

Table 4. *Brake thermal efficiency of all blends*



	Thermal Efficiency (%)			
Load	0%	10%	20%	30%
100%	8.940962%	7.320114	8.923695%	20.37567%
85%	19.45597%	20.26452	21.10317%	20.55033%
75%	20.55512%	19.13377%	18.73625%	18.51843%
50%	15.48057%	16.2377%	15.15698%	14.55637%
25%	9.420087%	16.2021%	9.313435%	8.843609%
0%	8.880956%	3.85612%	2.612343%	2.563285%

$$\eta = \frac{4.47}{0.00192 \times 45803.59} \times 100 = 8.940962\%$$

The results show that thermal efficiency peaked at medium load conditions for all fuels. The 10% and 20% blends followed trends similar to diesel, while the 30% blend showed localized improvements at specific load points but unstable performance at low loads. Overall, all blends performed best under moderate load conditions where combustion stability is highest.

Emission Testing Result

Oxygen (O_2)

Table 5. *O_2 Emission test result of the engine*

Load	0%	10%	20%	30%
100%	12.5	7.3	4.9	6.8
85%	15.3	9.6	6.5	9.3
75%	16.6	12.2	8.7	11.1
50%	18.4	15.6	11	13.1
25%	19.6	19.2	18.2	18.6
0%	20.9	19.9	21.3	22.1

O_2 concentration generally decreased as engine load increased, indicating greater oxygen consumption during combustion. The 20% blend recorded the lowest O_2 concentration at full load (4.9%), suggesting more efficient oxygen utilization and improved combustion compared to the other fuel blends.

Carbon Dioxide (CO_2)

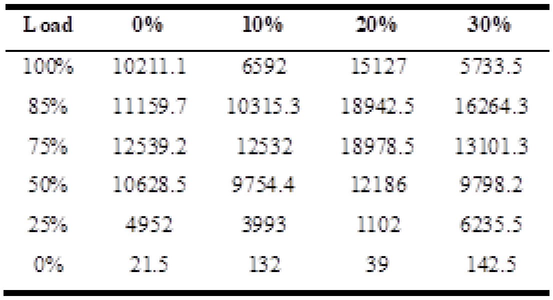
Table 6. *CO_2 Emission test result of the engine*

Load	0%	10%	20%	30
100%	6.2	2.6	22.3	3.2
85%	5.6	3.1	11.7	7.7
75%	4.2	2.8	9.5	7.4
50%	3.4	4.5	6.3	5.3
25%	2.2	4.6	2.8	1.9
0%	0.9	5.2	0	0.6

CO_2 emissions were generally higher at increased engine loads, reflecting more complete combustion. The 20% blend produced the highest CO_2 concentration, reaching 22.3% at full load, indicating superior fuel oxidation and combustion efficiency among the tested blends.

Carbon Monoxide (CO)

Table 7. *CO Emission test result of the engine*



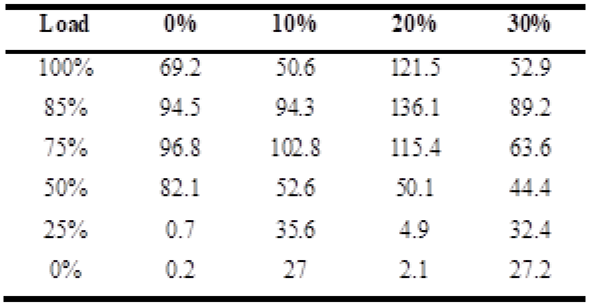
Load	0%	10%	20%	30%
100%	10211.1	6592	15127	5733.5
85%	11159.7	10315.3	18942.5	16264.3
75%	12539.2	12532	18978.5	13101.3
50%	10628.5	9754.4	12186	9798.2
25%	4952	3993	1102	6235.5
0%	21.5	132	39	142.5

CO emissions varied with engine load and blend ratio. The 20% blend showed lower CO emissions at lighter loads, indicating improved combustion efficiency. However, elevated CO levels at some higher load conditions suggest occasional incomplete combustion. The 30% blend exhibited comparatively moderate CO emissions across most operating conditions.

Nitrogen Oxides (NO_x)

NO_x emissions increased with engine load due to higher combustion temperatures. The 20% blend generated the highest NO_x concentration, reaching 121.5 ppm at full load, indicating more complete and intense combustion. The 10% and 30% blends produced lower NO_x levels, while pure diesel showed a gradual increase in NO_x emissions as load increased.

Table 8. *NOx Emission test result of the engine*



Load	0%	10%	20%	30%
100%	69.2	50.6	121.5	52.9
85%	94.5	94.3	136.1	89.2
75%	96.8	102.8	115.4	63.6
50%	82.1	52.6	50.1	44.4
25%	0.7	35.6	4.9	32.4
0%	0.2	27	2.1	27.2

Overall Emission Performance. Among the tested fuel formulations, the 20% TPO-diesel blend demonstrated the most favorable combustion characteristics, as evidenced by lower residual O_2, higher CO_2 production, and improved combustion efficiency. Although this blend produced higher NO_x emissions, the results suggest that the 20% blend provides the best overall combustion performance compared to the 10%, 30%, and pure diesel fuel conditions.

V. CONCLUSION

The 10% and 20% blends demonstrated the most balanced performance in terms of efficiency, combustion behavior, and emissions. While the 30% blend is still usable, it exhibited more noticeable variations in performance and emission characteristics. Therefore, lower to moderate blending ratios are recommended for optimal engine performance and environmental compatibility.

Key outcomes of the study include:

Fuel Compatibility and Stability: Purified tire pyrolytic oil (TPO) was successfully blended with commercial diesel at 10%, 20%, and 30% without phase separation, indicating good fuel compatibility and stability.

Acceptable Fuel Properties: All blends met operational diesel fuel requirements. Flash point ranged from 80.5°C (diesel) to 73.5°C (B30), while heating value slightly decreased from 19,692 BTU/lb to 19,406 BTU/lb, remaining suitable for engine use.

Gradual Reduction in Energy Content: Increasing TPO concentration resulted in a consistent decrease in heating value, showing lower energy density compared to pure diesel.

Engine Performance Behavior: Brake power decreased and BSFC increased with higher blend ratios, indicating reduced combustion efficiency as TPO content increased.

Emission Characteristics Trend: NOx and CO_2 emissions generally increased with higher blends, while oxygen levels decreased under load, reflecting stronger combustion activity and oxygen consumption.

Best Performing Blends: The 10% and 20% blends demonstrated the most balanced performance in terms of engine efficiency, fuel consumption, and emission behavior compared to B30.

Sustainable Fuel Utilization: The study confirms that waste tire-derived pyrolytic oil can be utilized as an alternative diesel extender, promoting waste recycling and energy recovery.

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