

Article

Physicochemical characterization and FTIR analysis of pyrolysis oil derived from waste tires

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ABSTRACT

Waste tire pyrolysis has emerged as a promising thermochemical conversion technology for recovering valuable liquid fuels while addressing the environmental challenges associated with end-of-life tires. For this purpose, tire-derived fuel was pyrolyzed in a fixed-bed reactor at varying temperatures of 560 °C, 565 °C, 580 °C, 590 °C, and 600 °C. The maximum pyrolytic oil yield was achieved at 600 °C, producing approximately 45.56% liquid, 22.44% gas, and 32% solid residue. Increasing the temperature improved oil yield while reducing gas output. The physicochemical properties analyzed for the pyrolytic oil include calorific value, viscosity, density, flash point, fire point, and elemental composition. Fourier Transform Infrared Spectroscopy (FT-IR) analysis revealed various functional groups, including alkanes, alkenes, aromatics, and carbonyl compounds, indicating a complex hydrocarbon mixture. Thus, this study aims to produce tire pyrolysis oil (TPO) and assess its suitability as an alternative fuel for IC engines through yield analysis and fuel property characterization.

1. Introduction

Energy is fundamental to human development and plays a vital role in all aspects of socioeconomic activities worldwide. To meet these energy demands, people commonly use fossil fuels such as coal, gasoline, and natural gas, primarily by converting their chemical energy into thermal energy [1]. Rapid urbanization, rising car ownership, and expanding logistics networks have increased global energy demand. Concerns about climate change and environmental degradation have also prompted scientists and policymakers to look for more sustainable energy sources [2]. Energy security and environmental sustainability are two major 21st-century concerns because conventional fossil resources are finite, and their exploitation and use are associated with greenhouse gas emissions, air pollutants, and biodiversity loss [3]. Table 1 provides a comprehensive overview of global primary energy demand by source [4]. Diesel fuel, produced from crude oil, remains one of the most important energy carriers in the transport and industrial sectors due to its high energy density, established distribution infrastructure, and widespread engine technology. Despite their widespread use, diesel engines have several drawbacks. Diesel is a non-renewable energy source, and demand for diesel fuel rises as the number of diesel-powered vehicles increases. A considerable and steadily increasing number of diesel engines are in operation. Over 15 million commercial diesel trucks are on U.S. roads in 2025 [5]. Diesel engines are

renowned for their exceptional fuel efficiency, minimal CO₂ emissions, and high efficiency [6]. But they also produce NO_x and particulate matter (PM), which are currently controlled because they harm the environment and human health [7]. However, heavy dependence on diesel has drawbacks: volatile crude oil prices, geopolitical risks tied to oil supply, and stringent emission regulations that increasingly limit sulfur and aromatic content in fuels. Many countries, especially those that import a large fraction of their petroleum, face growing trade imbalances and economic vulnerability linked to diesel consumption, reinforcing the need to diversify fuel sources and partially replace conventional diesel with alternative or renewable fuels [8]. To reduce reliance on fossil fuels and emissions and use local resources, researchers have studied alternative fuels such as biodiesel, bioethanol, and various waste-derived oils. Among these alternatives, waste-derived fuels are of particular interest because they can address waste management and energy supply problems at the same time.

Abbreviations

TPO	Tire Pyrolysis Oil
TDF	Tyre-Derived Fuel
WTPO	Waste Tire Pyrolysis Oil
CO ₂	Carbon Dioxide
NO _x	Nitrogen Oxides
PM	Particulate Matter
DF	Diesel Fuel
CO	Carbon Monoxide
HC	Hydrocarbon
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
IP	Indicated Power
ME	Mechanical Efficiency
BSEC	Brake Specific Energy Consumption
FT-IR	Fourier Transform Infrared Spectroscopy

By harvesting energy from material that could end up in landfills, become a fire hazard, or require costly disposal, waste-to-fuel processes can support circular-economy goals and improve resource efficiency [9,10]. Waste tires from vehicles, trucks, buses, and off-road machinery constitute a large fraction of global solid waste. About 5×10^6 tons of tires are discarded on Earth's surface per year [11]. It is estimated that there are four billion tires currently in landfills, and that number could grow to fifty billion by 2030 [12]. At a 6% to 8% growth rate, China generates 13 million tons of waste tire annually [13]. Tires consist mostly of steel and other metals, carbon black, cross-linked rubber, and other substances that enhance mechanical performance and resist weathering [14]. To serve their original purpose and last a long time, tires are made of non-biodegradable materials [15]. Since 75% of a waste tire's volume is empty space, waste tires are also considered bulky waste [16]. Tire waste adversely affects land, human health, and the environment [17].

Waste tires provide a comfortable breeding ground for insects, vermin, and rodent plagues when they pile up in open environments for extended periods [18]. In the rainy season, discarded tires in third-world countries also serve as breeding sites for mosquitoes that spread diseases such as malaria [19]. Manufacturing a single tire emits 330 grams of CO₂, posing a substantial climate threat [20]. Millions of used tires are burned every day in the third world to free up land, causing black pollution [21]. Waste tires can be handled in several ways, each with its own advantages and disadvantages: mechanical recycling, retreading, co-processing in cement kilns, incineration, gasification, and pyrolysis. Pyrolysis has attracted increasing attention in recent years for converting waste tires into energy products [22]. It may be a promising alternative energy source with sustainable practices and good technological performance. Pyrolysis, a thermochemical conversion process carried out in the absence of oxygen, has emerged as an attractive option because it can convert tires into useful products, oil, gas, and solid char, while reducing waste volume and limiting harmful emissions compared with uncontrolled burning. Activated carbon is one of the many uses for pyrolyzed char in renewable energy [23]. Synonyms of activated carbon include activated charcoal and activated coal. It is a carbonaceous material used across various economic sectors [24].

Table 1. Global need for primary energy (Btoe) [4]

	1980	2004	2010	2015	2030	2004–2030 (%)
Coal	1785	2773	3354	3666	4441	1.8
Oil	3107	3940	4366	4750	5575	1.3
Gas	1237	2302	2686	3017	3869	2.0
Nuclear	186	714	775	810	861	0.7
Hydro	148	242	280	317	408	2.0
Biomass and waste	765	1176	1283	1375	1645	1.3
Other renewables	33	57	99	136	296	6.6
Total	7261	11,204	12,842	14,071	17,095	1.6

Because it produces a liquid fraction called tire pyrolysis oil (TPO) that can be used as fuel or refinery feedstock, pyrolysis is especially favorable from an energy perspective [25,26]. Pyrolysis oil from tires is generally a complex hydrocarbon mixture derived from the original tire formulation, containing sulfur-containing compounds along with aromatic, paraffinic, olefinic, and naphthenic chemicals. Although exact yields depend on reactor design, operating temperature, heating rate, feedstock characteristics, and catalyst use, previously reported pyrolysis processes yield approximately 30 to 65% oil, 25 to 45% char, and 5 to 20% gas. Since the oil fraction is the most valuable commodity, it can be upgraded in refineries to meet traditional gasoline specifications, blended with diesel to make diesel-gasoline-like hybrid fuels, or used directly as fuel in certain applications [27]. Second, by converting problematic solid waste into an alternative energy source, the technology supports waste tire management and reduces the environmental consequences of tire accumulation in landfills. Third, TPO could also create new pathways for valorization, supporting economic development and local energy security in regions with large tire waste flows and little to no fossil resources [28].

Nevertheless, effective application of TPO as an engine fuel or refinery feedstock requires a thorough understanding of its physical and chemical properties. To assess compatibility with engines and infrastructure, critical fuel-related properties such as density, viscosity, heating value, boiling range, flash point, and sulfur content must be characterized and compared with petroleum diesel and relevant standards. In addition, combustion characteristics, emissions (e.g., NO_x, CO, unburned hydrocarbons, particulate matter), and engine durability are strongly affected by the specific chemical composition. These include the relative proportions of aromatic and aliphatic hydrocarbons, olefins, and heteroatom-containing compounds [29]. Zhang et al. [30] investigated the properties of tire pyrolysis oil. TPO contains several high-value components, such as BTX and limonene, which are crucial for maintaining the economic competitiveness of this oil. Mirmiram et al. [31] identified three primary sources of WTPO: processing liquids used in tire formulation, tire additives, and products formed during tire pyrolysis.

This variety contributes to the complexity of WTPO composition. M.F. Laresgoiti [32] used one-dimensional gas chromatography (GC) to study more than 130 components in WTPO, while Rathasack [33] used GC-MS to examine several hundred constituents in the oil. WTPO's unique composition determines the refining procedure; the kinds of impurities determine the parameters, catalyst design, and refining techniques used. A liquid fuel's flashpoint, which indicates fire risks related to storage and transportation, is the lowest temperature at which it can catch fire when exposed to a flame. Waste tire pyrolysis oil (WTPO) often has a lower flashpoint than petroleum-based fuels like light oil (Flashpoint: 79°C) and diesel (Flashpoint: 75°C). Because WTPO contains more volatile hydrocarbons, its lower flashpoint makes it less safe to use undiluted [34]. A study by Ilkilic and Aydin [35] found that using WTPO in an engine resulted in substantial emissions of smoke, hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO₂). These emissions were attributed to WTPO's density, low cetane number, and poor atomization. WTPO's high viscosity, driven by its high molecular mass, likely leads to poor atomization [36]. Table 2 presents the key fuel properties of tire pyrolysis oil, offering valuable insights into its potential as an alternative energy source. Therefore, relatively little research has investigated TPO as an alternative fuel for IC engines. Murugan et al. [36] investigated the performance and combustion properties of engines powered by TPO. Their findings show that the engine can run on up to 90% distilled tire pyrolysis oil (DTPO) mixed with 10% diesel fuel (DF), but it does not perform well at 100% DTPO. Although it remains lower than pure diesel fuel, brake thermal efficiency rises as the DTPO blend percentage increases, with a roughly 3% drop. When DTPO80 and DTPO90 replace diesel fuel, NO_x emissions decrease by about 21% and 18%, respectively. DTPO mixes emit higher carbon monoxide (CO) and hydrocarbon (HC) emissions, most likely because DTPO contains unsaturated hydrocarbons. Compared with pure diesel fuel, DTPO-diesel mixtures emit more smoke. At full load, the ignition delay of DTPO-diesel blends is 2 to 2.5 degrees crank angle (°CA) longer than that of diesel fuel. Compared with diesel fuel, cylinder peak pressures for DTPO80 and DTPO90 are roughly 1.6 bar and 2 bar higher, respectively. In the early phases, DTPO-diesel blends exhibit faster heat release and pressure rise than diesel fuel, most likely because the blends have longer ignition delays. Numerous other researchers have also investigated the effectiveness and emissions of tire pyrolysis oil in diesel engines. Studies show that TPO–diesel blend performance is strongly influenced by blend ratio and engine load.

According to Pote et al. [43], brake power (BP), brake thermal efficiency (BTE), and mechanical efficiency (ME) generally increase with increasing TPO content and engine load, while the 10% TPO–90% diesel blend exhibits the lowest brake specific fuel consumption (BSFC), making it the most fuel-efficient blend. The improved BP and BTE are attributed to TPO's higher density, which enhances fuel availability during combustion. In contrast, Hariharan et al. reported that TPO blended with diethyl ether (DEE) exhibited lower BTE and higher brake specific energy consumption (BSEC) than diesel because of the lower heating value of TPO and reduced heat release during combustion [44]. Similarly, Uyumaz et al. observed that TPO–diesel blends showed higher BSFC than diesel fuel due to the higher density, viscosity, and lower calorific value of TPO, requiring greater fuel consumption to produce the same brake power [45]. The emission characteristics of TPO blends vary with fuel composition and engine operating conditions. According to Pote et al., increasing the TPO proportion in diesel blends generally reduces hydrocarbon (HC) emissions due to the higher oxygen content of TPO, which promotes more complete combustion [43].

Carbon monoxide (CO) emissions decrease at low loads but increase slightly at higher loads because oxygen deficiency during combustion increases CO formation. Although CO₂ emissions increase with engine load, they remain lower for TPO blends than for diesel because TPO has lower carbon content. Nitrogen oxides (NO_x) and smoke emissions initially decrease at lower TPO concentrations but increase with higher TPO content and engine load. In contrast, Hariharan et al. reported that TPO–DEE blends produced higher HC and CO emissions than diesel while significantly reducing NO_x emissions because DEE's cooling effect lowered the peak combustion temperature. However, smoke and particulate matter emissions increased because the fuel partially combusted unsaturated hydrocarbons [44]. Spectroscopic methods are essential for chemically analyzing TPO, providing information on molecular structure and functional groups that bulk physical properties alone cannot provide. Fourier-transform infrared (FTIR) spectroscopy, for example, is frequently used to analyze pyrolytic oils because it is rapid, relatively simple, and can detect vibrational bands characteristic of various functional groups.

Table 2. Fuel properties of TPO

Properties	Reference [37]	Reference [38]	Reference [39]	Reference [40]	Reference [41]	Reference [42]
Density (g/cm ³)	0.91	0.86	–	0.97	0.94	0.91
Viscosity (cSt)	3.35 (at 20 °C)	2.47 (at 40 °C)	2.44 (at 50 °C)	4.90 (at 30 °C)	4.62 (at 40 °C)	6.30 (at 40 °C)
Calorific value (MJ/kg)	38.1	41.74	41.7	40.8	38.0	42.1
Flash point (°C)	49.0	56.54	17.0	32.0	41.6	20.0
Cetane number	–	< 45	–	–	–	–
Carbon (%)	86.92	80.94	84.26	84.8	87.57	–
Hydrogen (%)	10.46	12.72	10.39	9.01	10.35	–
Nitrogen (%)	0.65	–	0.42	0.7	< 1.00	–
Sulfur (%)	0.95	1.54	1.54	1.36	1.35	1.45

Typical FTIR spectra of TPO show absorption bands assigned to aliphatic C–H stretching, aromatic C–H stretching and bending, C=C stretching in unsaturated compounds, and other functional moieties such as carbonyls, depending on the specific pyrolysis conditions and the type of feedstock. FTIR can differentiate the TPO content of aromatic and aliphatic matter, which is important for understanding ignition quality, the potential for soot formation, and the possible health effects of combustion products. By integrating FTIR data with other analytical results, such as gas chromatography–mass spectrometry (GC–MS) and elemental analysis, researchers can build a complete view of TPO chemical composition and identify upgrading routes, such as hydrodesulfurization or hydrogenation, to meet fuel standards. In addition, FTIR can monitor changes in TPO composition under different pyrolysis conditions to optimize the process for better fuel properties and reduced harmful chemicals [46].

Recent reviews and experimental studies show that TPO yield and quality depend strongly on reactor type (fixed bed, fluidized bed, spouted bed, rotary kiln), operating temperature, residence time, and catalyst type. Although shorter gas residence time and better heat transfer can provide a liquid fraction more suitable for refining or direct burning, high temperature and appropriate catalysts can not only maximize oil yield but also strongly influence oil composition, usually increasing aromatic content and altering sulfur speciation. These results demonstrate that thorough investigations, including spectroscopic measurements, detailed fuel characterization, and process optimization, are needed to fully exploit TPO as a diesel fuel alternative [28].

In this study, the effect of reactor temperature (560–600 °C) on the properties of the fuel and the yield is evaluated based on tire pyrolysis oil (TPO) derived from thermal decomposition of waste tire in a bench-scale reactor. The experiments used 2.5 kg batches of shredded tire feedstock, pretreated and dried at 110 °C, before pyrolysis. External heating of a cylindrical stainless-steel reactor was employed with an LPG burner under an argon atmosphere to avoid oxidation. The maximum oil yield was 45.56 wt% at 600 °C, with non-condensable gases and char as by-products. The obtained TPO was then tested for viability as an alternative to diesel fuel. The fuel density was 903 kg/m³, kinematic viscosity was 2.77 cSt, and the higher heating value was 43.37 MJ/kg. Moreover, the principal functional groups in the oil were determined, and its chemical nature was verified by FTIR spectroscopy.

2. Materials and methods

2.1 Experimental setup

The waste tire pyrolysis oil (TPO) was prepared by the pyrolysis of waste tire using a laboratory-scale pyrolyzer. The shredded tire specimens were dried at 110 °C to remove moisture before pyrolysis. A cylindrical stainless-steel reactor (260 mm diameter, 310 mm height) with a maximum pressure of 16.7 bar and a temperature range of 500–600 °C was employed. To prevent oxidation, an argon atmosphere was maintained throughout, and a thermocouple monitored the reactor temperature. An LPG-burning burner under the reactor supplied heat. The generated vapors were condensed in a condenser to recover liquid TPO, while the remaining non-condensable gas was released separately. The process began by cutting scrap tires into smaller segments, then removing embedded materials such as fabric layers, steel wires, and beads.

The thick rubber sections from the tire edges were further sliced into smaller pieces, thoroughly cleaned, and oven-dried at 110 °C. These prepared samples were then placed into a mild steel pyrolysis reactor. The reactor, a fully insulated cylindrical chamber measuring 300 mm in height, 110 mm internal diameter, and 115 mm external diameter, was designed to withstand high-temperature operation. Before heating, inert gas displaced atmospheric oxygen, creating a vacuum environment to prevent unwanted combustion. An external burner heated the reactor, and a digital temperature controller precisely controlled the temperature.

The pyrolysis process was conducted at 400 °C to 450 °C for two and a half hours. The released vapors passed through a water-cooled condenser, where the liquid fuel condensed. The non-condensable air was vented to the atmosphere without issue. The liquid condensate, called TPO, was separated in crude form, while the solid char by-product was retained for possible secondary uses. Figure 1 represents a schematic arrangement of a pyrolysis unit in which the wastes were heat-decomposed inside a reactor at a predetermined heating. The generated vapors were condensed and separated into liquid fuel, non-condensable gases, and byproducts using several condensers, scrubbers, and collector units. The TPO was then analyzed in depth. Its calorific value was determined by a bomb calorimeter. Various physicochemical parameters, such as viscosity, density, flash point, and fire point, were also determined. Further examination of the oil by FTIR was carried out to identify the functional groups within it and improve understanding of its chemical structure. Figure 2 illustrates the experimental procedure flow diagram.

2.2 Analysis of pyrolysis oil

The pyrolysis oil obtained from waste tires was collected in a beaker. Several instruments had been employed to test the pyrolysis oil. The higher heating value (HHV) was determined by means of a digital bomb calorimeter. A controlled-temperature rotational viscometer with a 100 r/min speed and a Type-3 spindle measured dynamic viscosity. A Pensky–Martens closed-cup apparatus was used to determine flash and fire points. A Fourier Transform Infrared (FTIR) spectroscope was employed to analyze the TPO's chemical makeup and functional components within the 4000–400 cm^{−1} wavenumber range. This allowed for the identification of the main organic functional groups in the oil. Figure 3 illustrates the instruments used to perform physicochemical characterization of TPO.

3. Data collection and analysis

3.1 TPO yield calculation

The tire pyrolysis process has three major products: TPO, non-condensable gas, and solid char. In this study, we measured product yields precisely using a digital balance. The char yield was not measured. The gas yield was estimated indirectly from the initial feedstock weight and the weights of the recovered oil and char. In this study, different properties of the pyrolysis oil obtained were identified and investigated.

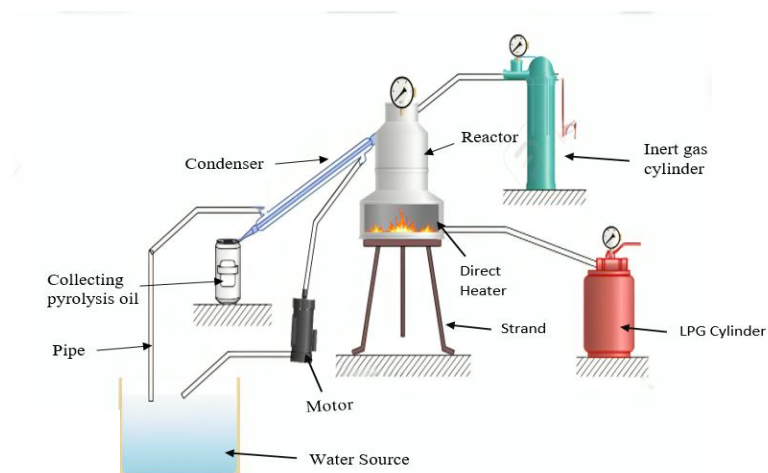


Figure 1. Experimental Setup for TPO drawn in EdrawMax

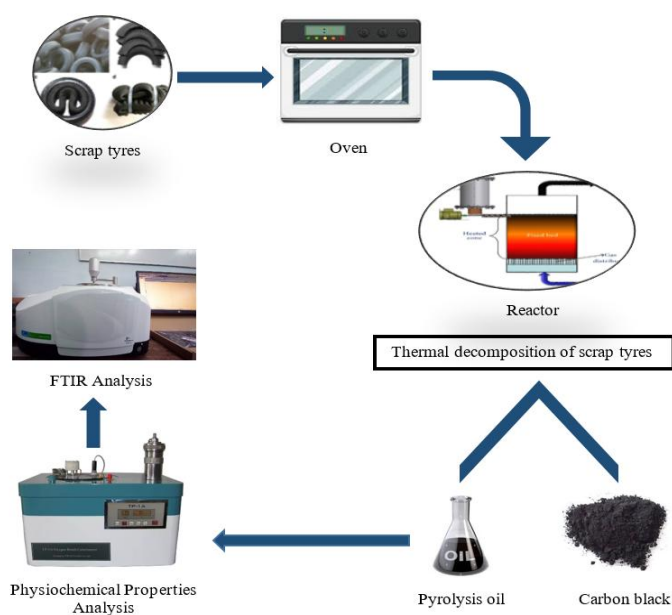


Figure 2. Flow diagram of the experimental procedure

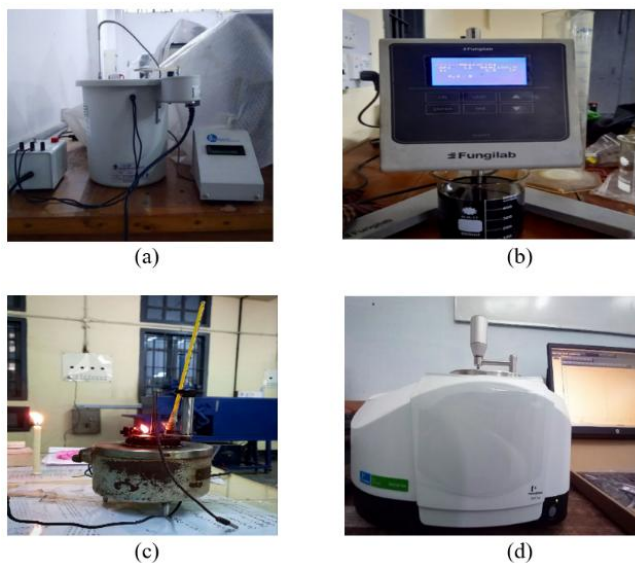


Figure 3. (a) Calorific value measurement using a bomb calorimeter. (b) Rotational viscometer. (c) Pensky-Martens closed-cup tester. (d) FTIR Spectrometer

The measured fuel properties included the calorific value, flash point, fire point, dynamic viscosity, kinematic viscosity, density, and specific gravity. Table 3 presents the experimental results, with each batch processed using 2.5 kg of waste tires as the feedstock. Murugan et al. [47] reported that pyrolysis at temperatures of 450 °C to 650 °C with a residence time of 90 min under vacuum produced a product distribution of around 50 wt% oil, 40 wt% gas, and 10 wt% char. In another work, Rok Vihar et al. [48] described that the vacuum pyrolysis of pre-treated waste tires (i.e., the tires were shredded and the steel wires and the fabric were removed) at 600 °C to 700 °C for 1 h resulted in ca. 40–50% TPO, 30–40 char, and 10–20% gas. Product yields can also change with temperature, system pressure, and feedstock preparation. R.N. Pote's research shows that feedstock size strongly influences product yield in tire pyrolysis. Using a 15×15×3 cm tire size, the oil, char, and gas yields were 33%, 56%, and 10.45%, respectively. Increasing the size to 20×20×3 cm raised the oil yield to 43%, while the char and gas yields dropped to 47% and 9.25%, respectively. Overall conversion efficiency remained high (99.5–99.75%), demonstrating the procedure's efficacy [49]. In this study, waste tire was pyrolyzed at different peak temperatures (310–350 °C) with a fixed feedstock amount of 2.5 kg per batch. Product yield varied slightly with temperature. Oil yield ranged from 37.4 to 45.56%, peaking at 350 °C. Char yield varied from 32 to 40%, and gas yield from 20.54 to 23.6%. The total product recovery was about 76.4–79.46%, indicating good conversion of tire feedstock into high-value products. This suggests that higher temperatures increased oil production and reduced solid residue, consistent with other studies. Figure 4 demonstrates the yield percentage of pyrolysis oil, gas, and char from TPO.

3.2 Calorific value of the pyrolysis oil

The calorific value of the pyrolysis oil was determined using a digital bomb calorimeter. Table 4 indicates the values required for the calorific test.

$$\text{Higher calorific value} = [(\delta T \cdot W) - e_1 - e_2 - e_3] / m \quad (1)$$

The higher calorific value of the recovered pyro-oil is 43.37 MJ/kg.

The flash point and fire point were measured using a standard testing instrument. The flash point is the minimum temperature at which a volatile substance's vapor ignites in the presence of an ignition source. In contrast, the fire point is the lowest temperature at which the vapors sustain combustion even after the ignition source is removed. Table 5 summarizes the measured flash and fire point values.

3.4 Viscosity

The viscosity of the pyro-oil was measured by a rotating viscometer at 100 rpm. The measurement was taken at room temperature (33 °C). Viscosity values are shown in Table 6.

3.5 Density

Density is a substance's mass per unit volume. It was measured at room temperature 33°C. Test specifications for density are given below in Table 7. The density of tire pyrolysis oil is 903 kg/m³ at 33°C.

3.6 Specific gravity

At 33°C, water has a density of about 994.76 kg/m³ [41]. At 33 °C, the specific gravity of tire pyrolysis oil is 0.907 kg/m³.

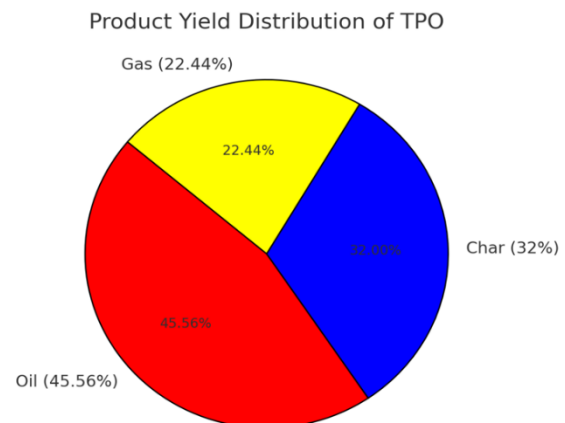


Figure 4. Yield percentage of pyrolysis oil, gas, and char from TPO

Table 3. Product yield from TPO

Peak Temp. (Top of Reactor) (°C)	Oil (kg)	Oil (%)	Char (kg)	Char (%)	Gas (kg)	Gas (%)	Total Yield (kg)	Total Yield (%)
560	0.909	37.4	0.9724	40	0.5496	22.6	1.8814	77.4
565	0.923	38	0.924	38.4	0.5842	23.6	1.847	76.4
580	1.05	42	0.8615	34.46	0.5885	23.54	1.9115	76.46
590	1.09	43.75	0.827	33.08	0.583	23.17	1.917	76.83
600	1.16	45.56	0.81	32	0.579	22.44	1.97	77.56

Table 4. Data of calorific value test

Weight of the pyrolysis oil, m(gm)	0.69
Length of nichrome wire, L(cm)	5
Length of cotton wire, l(cm)	10
The pressure of the oxygen inside the bomb, P(atm)	30
Volume of distilled water, V(ml)	2000
The energy equivalent of the calorimeter (considering consideration) under standardization, W (cal/°C)	2426
Initial temperature (°C)	27.604
Temperature rise δT (°C)	2.972

This study investigated different characteristics of pyro-oil, such as flash point, fire point, calorific value, density, kinematic viscosity, dynamic viscosity, and specific gravity. Table 8 summarises the net properties of pyrolysis oil.

3.8 FT-IR analysis

FT-IR spectroscopy was used to identify the functional groups present in the samples across three experimental runs (Run 1, Run 2, and Run 3). The FTIR spectra, shown in the figure below, plot transmittance (%) against wavenumber (cm^{-1}) and reveal several characteristic peaks that correspond to specific vibrational modes of chemical bonds. The spectra of all three runs show good agreement, indicating good sample composition and repeatability. The spectra, shown here as absorbance versus wavenumber (cm^{-1}), display unique, reproducible peaks for all samples, confirming that the pyrolysis was consistent.

Table 5. Flash and fire point

Flash Point ($^{\circ}\text{C}$)	44
Fire point ($^{\circ}\text{C}$)	65

Table 6. Viscosity of TPO

Dynamic viscosity (centipoise) (cP)	2.5
Kinematic viscosity (centistoke) (cSt)	2.77

Table 7. Density of TPO

Temperature ($^{\circ}\text{C}$)	33
Weight of 50ml beaker, M (gm)	34
Pyro-oil, V (ml)	50
Weight of 50ml beaker and pyro-oil, M' (gm)	79.15
Weight of pyro-oil, m= (M'-M) (gm)	45.15

Table 8. Fuel properties of pyrolysis oil

Calorific value (MJ/kg)	43.37
Flash Point ($^{\circ}\text{C}$)	44
Fire point ($^{\circ}\text{C}$)	65
Dynamic viscosity (centipoise) (cP)	2.5
Kinematic viscosity (centistoke) (cSt)	2.77
Density (kg/m^3)	903
Specific gravity	0.907

Table 9. Interpretation of FT-IR transmittance peaks for TPO

Wavenumber (cm^{-1})	Peak Intensity	Functional Group	Class of Compound
~3050-3000	Medium	=C-H (Aromatic or Alkene)	Aromatic hydrocarbons, Alkenes
~2950-2850	Strong	C-H (Aliphatic -CH ₃ , -CH ₂ -)	Alkanes, Saturated hydrocarbons
~1740-1700	Weak	C=O (Carbonyl)	Aldehydes, Ketones
~1600-1580	Medium	C=C (Aromatic ring)	Aromatic compounds
~1450-1375	Medium to Strong	C-H (Alkane CH ₂ , CH ₃)	Alkanes
~1260-1000	Variable	C-O, C-N, or S=O	Alcohols, Ethers, Sulfur compounds
~880-750	Sharp	=C-H (Aromatic)	Substituted benzenes

The functional groups detected show high consistency across the samples (three different runs), as shown by the transmittance spectra in Figure 5 of the TPO using FTIR. Table 9 provides a detailed interpretation of the FTIR spectra. The analysis identifies several distinct peaks corresponding to different functional groups, providing information about the chemical structure and sample content. Figure 6 shows the FTIR absorbance spectra of TPO samples from three runs and confirms good reproducibility of the peak patterns in chemical composition. The absorbance peaks provide insight into the functional groups present in the samples, as summarized in Table 10.

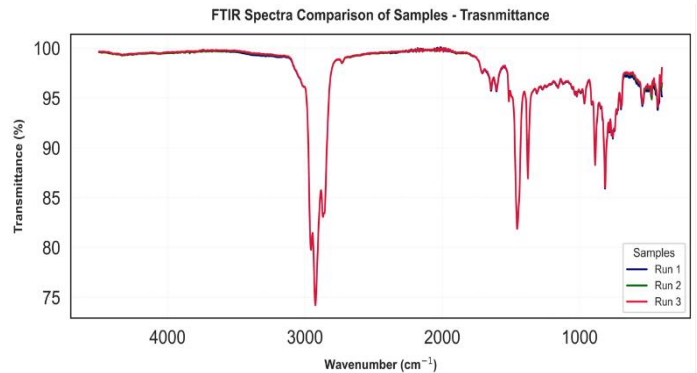


Figure 5. FT-IR transmittance spectra of TPO samples

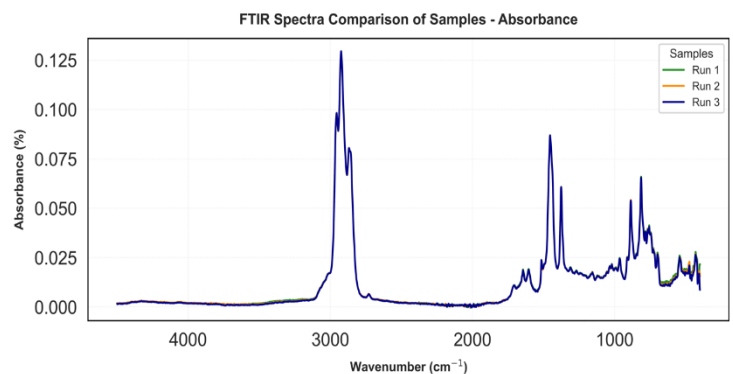


Figure 6. FT-IR absorbance spectra of TPO samples

Table 10. Interpretation of FT-IR absorbance peaks for TPO

Wavenumber (cm ⁻¹)	Peak Type	Functional Group	Class of Compound
3000–2850	C–H stretching	Alkanes (–CH ₂ –, –CH ₃)	Saturated hydrocarbons
~1740	C=O stretching	Carbonyl (Ketones, esters)	Oxygenated compounds
~1600–1650	C=C stretching	Alkenes / Aromatics	Unsaturated/aromatic hydrocarbons
~1450	CH ₂ bending	Alkanes	Saturated hydrocarbons
~1375	CH ₃ bending	Alkanes	Branched hydrocarbons
1300–1000	C–O stretching	Alcohols / Ethers	Oxygenated compounds
900–700	=C–H bending	Aromatic rings	Aromatic hydrocarbons

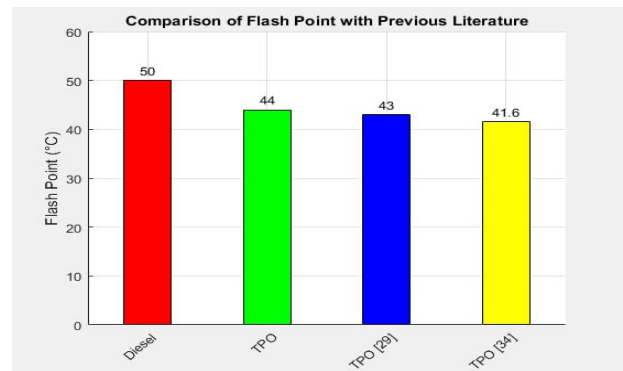
4. Results and discussion

Table 11 presents the physicochemical characteristics of TPO and diesel, along with related values from earlier reports. Graphs provide a very natural way to capture relationships and to analyze complex systems. When applying comparison methods, graphs help us understand, analyze, and derive useful insights. This helps us better understand the data and make more informed decisions. The bar chart compares the Density (g/cm³) of four substances: diesel, TPO, TPO [29], and TPO [34], with each substance represented by a color-coded bar. Diesel has the lowest density at 0.85 g/cm³, followed by TPO at 0.903 g/cm³. TPO [29] has the highest density at 0.9239 g/cm³, and TPO [34] has a density of 0.901 g/cm³. The density values of these materials fall within a narrow range from 0.85 to 0.9239 g/cm³, indicating relatively minor variation. Figure 7 compares the density values of diesel and TPO with values from previous literature.

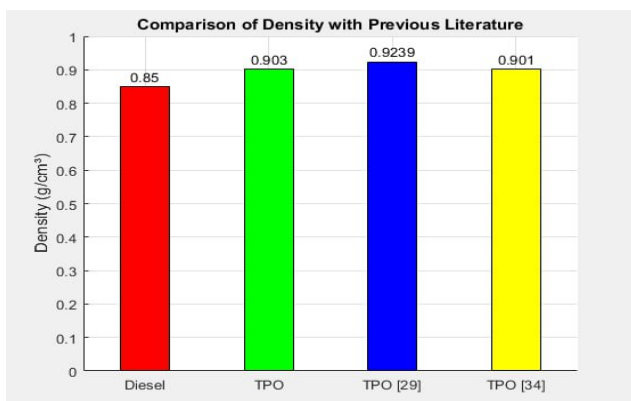
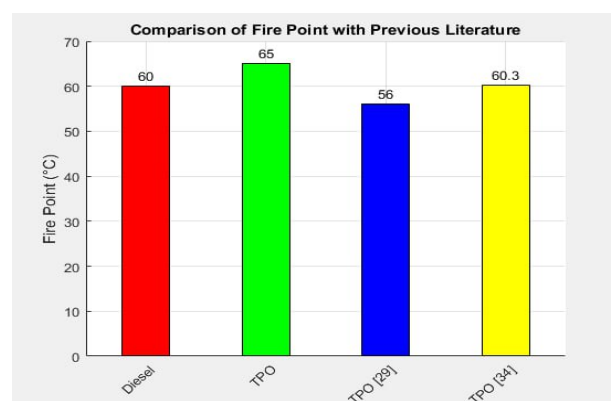
Table 11. Comparison of fuel properties with obtained pyrolysis oil

SL No.	Property (Unit)	Diesel [50]	TPO	TPO [37]	TPO [42]
1.	Density (g/cm ³)	0.850	0.903 (33°C)	0.9239	0.901
2.	Flash point (°C)	50	44	43	41.6
3.	Fire point (°C)	60	65	56	60.3
4.	Calorific value (MJ/kg)	45	43.37	41.74	42.1
5.	Kinematic viscosity (cSt)	3	2.77	3.35	2.47
6.	Specific gravity	0.85	0.907 (33°C)	0.916	0.904

A substance's fire point is the temperature at which it will continue to burn after it has been ignited, whereas its flash point is the lowest temperature at which its vapors will ignite when exposed to an open flame. The bar charts compare the fire point and flash point of four substances: diesel, TPO, TPO [29], and TPO [34]. In the flash point graph, Diesel presents the highest flash point of 50°C, TPO follows with 44°C, TPO [29] at 43°C, and TPO [34] at 41.6°C. Diesel in the fire point graph again has the highest fire point of 60°C, with TPO at 65°C, TPO [29] at 56°C, and TPO [34] at 60.3°C. The flash and fire points of these materials are within normal ranges for oils and biodiesels, suggesting the values are expected. TPO flash and fire points are somewhat lower than those of diesel, possibly related to chemical makeup. Differences in raw materials or processing methods may explain the observed differences between TPO and its varieties. Overall, the evidence suggests that minor formulation fluctuations are likely responsible. Figure 8 compares the flash point and fire point values of diesel and TPO with values from previous literature.



(a)

**Figure 7.** Comparison of the density of diesel and TPO with previous literature

(b)

Figure 8. Comparison of flash point (a) and fire point (b) of diesel and TPO with previous literature

Calorific value is the amount of energy released when a substance is completely combusted, typically measured in MJ/kg. The bar chart compares the calorific value of four substances: diesel, TPO, TPO [29], and TPO [34]. Diesel (red) has the highest calorific value at 45 MJ/kg, followed by TPO (43.37 MJ/kg), TPO [34] (42.1 MJ/kg), and TPO [29] (41.74 MJ/kg). The calorific values are within the expected range for fuels, with Diesel having the highest value, which is typical for fossil fuels. The lower values for TPO and its variations may reflect differences in chemical composition. These variations in calorific value could also reflect differences in production processes or raw materials. Overall, the differences are small and can be attributed to the different nature and production procedures of each material. Figure 9 compares the calorific values of diesel, TPO, and those reported in the literature.

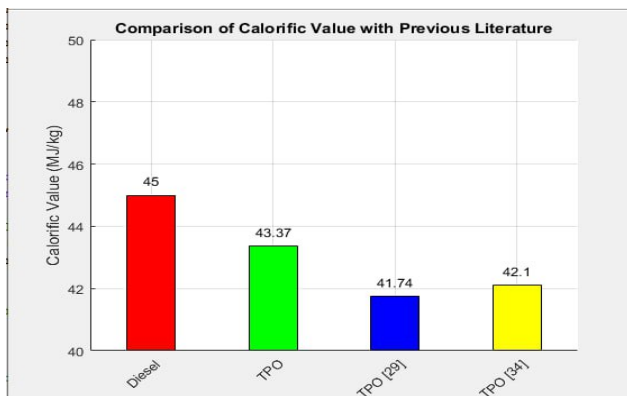


Figure 9. Comparison of calorific value of diesel and TPO with previous literature

Kinematic viscosity measures a fluid's resistance to flow under gravity and is commonly represented as cSt. The bar chart compares the kinematic viscosity of four substances: Diesel, TPO, TPO [29], and TPO [34]. Diesel has a kinematic viscosity of 3 cSt, the highest among the substances, followed by TPO [29] at 3.35 cSt, TPO at 2.77 cSt, and TPO [34] at 2.47 cSt. Figure 10 compares the kinematic viscosity of diesel and TPO with values from previous literature. The kinematic viscosity values fall within the typical range for oils and biodiesels, with diesel generally exhibiting higher viscosity than biodiesel mixtures. The variation observed in TPO and its subtypes may reflect differences in composition or production processes. Differences in chemical structure could explain the higher viscosity of TPO [29] compared to TPO [34], whereas the lower value for TPO [34] may be due to its composition. Overall, the results align with the expected viscosity ranges for these material classes, with small variations due to different formulations or raw materials.

Specific gravity is a dimensionless quantity that represents the ratio of a substance's density to that of a reference substance, usually water. The bar chart compares the specific gravity of four substances: Diesel, TPO, TPO [29], and TPO [34]. Diesel has the lowest specific gravity at 0.85, followed by TPO at 0.907, TPO [29] at 0.916, and TPO [34] at 0.904. Figure 11 compares the specific gravity values of diesel and TPO with corresponding literature values. The density values are within the normal range for oils and biodiesels, with Diesel having a higher density than TPO. The specific gravity differences for TPO, TPO [29], and TPO [34] are small. Overall, the results fit what one would expect for the specific gravity ranges of these materials, and any small deviations are likely due to raw material formulations and/or processing.

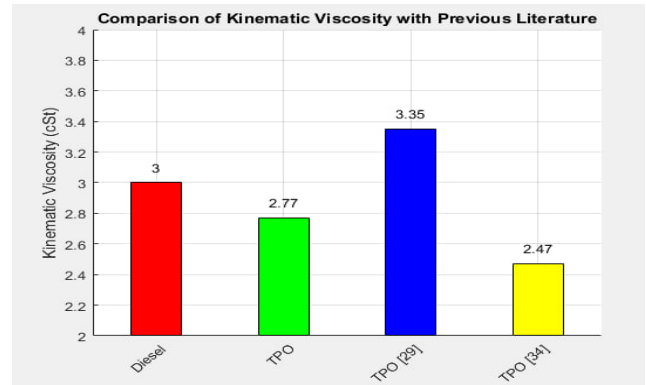


Figure 10. Comparison of kinematic viscosity of diesel and TPO with previous literature

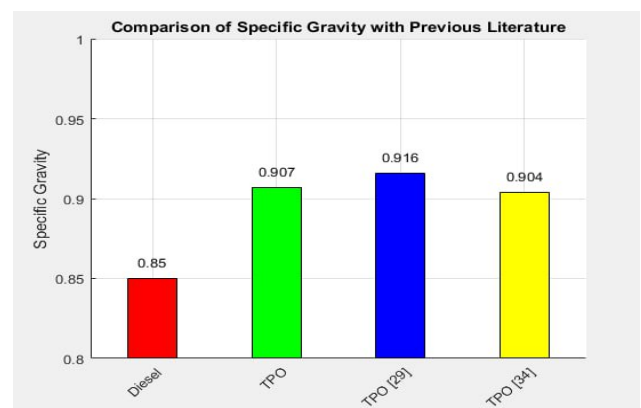


Figure 11. Comparison of specific gravity of diesel and TPO with previous literature

4.1 Compositional analysis by FT-IR spectroscopy

FT-IR Spectroscopy was performed to identify the functional groups present in the TPO. Measurements were made under ~vacuum, in absorbance and transmittance mode, over the wavenumber range 4500–400 cm^{-1} . The FT-IR spectra showed strong vibrational bands associated with different chemical groups in tire rubber, generated during thermal depolymerization. Strong bands at 3000–2850 cm^{-1} from C–H stretching vibrations of long-chain aliphatic hydrocarbons confirmed that saturated alkanes were predominant. A weak or absent peak at 1740–1700 cm^{-1} (C=O stretching) suggests few oxygenated species and extensive thermal cracking with minimal oxidation. Table 12 lists the FTIR peak assignments and functional groups detected in TPO. The presence of rings in aromatics also produced moderate-intensity bands at about 1600–1580 cm^{-1} (C=C stretching), indicating that the rubber matrix degraded into polyaromatic radicals. 1450–1375 cm^{-1} : bending vibration of CH₂ and CH₃ groups, with matching presence of branched and straight hydrocarbons. A multi-component shoulder was observed in the 1300–1000 cm^{-1} region, assigned to overlapping C–O, C–N, and S=O stretching vibrations that may be associated with additives and/or sulfur-based vulcanizing agents. Substituted aromatics were identified by strong, sharp out-of-plane bending peaks (880–750 cm^{-1}).

Table 12. Interpretation of FT-IR peaks and corresponding functional groups in TPO

Wavenumber (cm ⁻¹)	Peak Type	Functional Group	Compound Class
3000–2850	C–H stretching	Alkanes (–CH ₂ –, –CH ₃)	Saturated hydrocarbons
~1740–1700	C=O stretching	Carbonyl	Oxygenated compounds
1600–1580	C=C stretching	Aromatics	Aromatic hydrocarbons
1450–1375	CH ₂ and CH ₃ bending	Alkenes	Branched and linear hydrocarbons
1300–1000	C–O / C–N / S=O stretching	Alcohols, ethers, sulfur groups	Heteroatomic groups from additives
880–750	=C–H bending	Aromatics	Substituted benzenes

The absorbance mode seems more favorable for quantifying peak magnitudes, at least at ~2920 and ~2850 cm⁻¹. TPO was predominantly made of saturated and aromatic hydrocarbons, with trace amounts of oxygenated and sulfurous species that could be from the tire additives/vulcanizing agents.

5. Conclusion

To evaluate the pyrolysis oil derived from waste tires' suitability as a substitute liquid energy source, FT-IR analysis and physicochemical characterization were performed. Waste tires weighing 2.5 kg were pyrolyzed in batches between 560 and 600 °C, and the effects of temperature on the main characteristics of the oil and the product yields were thoroughly examined. These are the outcomes of the experimental research:

- The discarded tires were thermally depolymerized to produce three main products: non- condensable gas, solid char, and liquid oil, or TPO. Liquid TPO yield correlated positively with process temperature, peaking at 45.56 wt% at 600 °C, up from 37.4 wt% at 560 °C. Good thermal processing of the tire feedstock was indicated by the weight-based total product recovery of 76.4–77.56 wt%.
- Recovery TPO's high calorific value of 43.37 MJ/kg is quite similar to that of ordinary diesel fuel (45 MJ/kg). At 33 °C, the oil density was 903 kg/m³ (0.903 g/cm³), well within the permissible range for commercial fuel standards and indicating a strong chance of using the oil as a solid fuel in fields with high thermal energy demands.
- Commercial diesel has a flash point of 50 °C and a fire point of 60 °C, while TPO has a flash point of 44 °C and a fire point of 65 °C. These findings suggest the product has good volatility and ignition properties, and indicate handling and storage risks at room temperature.
- In contrast to several of the biomass-based oils, the TPO demonstrated good flow performance. At 33 °C, the kinematic viscosity was 2.77 cSt (dynamic viscosity of 2.5 cP). This indicates excellent flow and atomization characteristics without harsh pretreatment, as it is extremely close to, yet slightly below, typical diesel (3 cSt).
- FT-IR analysis of the TPO sample confirmed that it primarily consists of saturated aliphatic and aromatic hydrocarbons. A number of peaks at 1600–1580 cm⁻¹ and 880–750 cm⁻¹ belonged to aromatic ring systems, while vibrations at 3000–2850 cm⁻¹ and 1450–1375 cm⁻¹ indicated the existence of many alkanes.
- The finding that the peak intensity in the carbonyl region (1740–1700 cm⁻¹) is weak to insignificant suggests that a modest quantity of oxygenated species indicates a high degree of thermal cracking with minimal oxidation. However, traces of S, N, and oxygenated species from tire additives and vulcanizing chemicals are responsible for the complicated bands around 1300–1000 cm⁻¹.

Overall, the findings show that pyrolysis of scrap tires is an appealing and practical way to convert problematic rubber waste into high-energy liquid fuels. The produced TPO's low viscosity, high calorific value, and moderate flash point make it a good substitute for traditional diesel. To commercialize this technology, the following research avenues are recommended:

- Research on how heating rates, residence periods, carrier gas flow rates, and vacuum pressures affect liquid yield and product distribution should be done methodically.
- Relevant research on catalyst upgrading, desulfurization, and distillation is highly recommended in order to eliminate the sulfurous compounds (produced from vulcanizing agents) and to meet environmental emission regulations.
- To examine the brake thermal efficiency, fuel consumption, and exhaust emission characteristics, the TPO-diesel blends should undergo extensive testing in internal combustion engines.
- To evaluate the commercial feasibility and net environmental advantages of waste tire pyrolysis at an industrial level, extensive scale-up modeling, techno-economic assessments, and LCA are essential.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

References

- [1] O. E. Ajala, F. Aberuagba, T. E. Odetoeye, and A. M. Ajala, "Biodiesel: Sustainable Energy Replacement to Petroleum-Based Diesel Fuel – A Review," *ChemBioEng Rev.*, vol. 2, no. 3, pp. 145–156, Jun. 2015, doi: 10.1002/cben.201400024.
- [2] G. A. Mansoori et al., "Fuels of the Future for Renewable Energy Sources (Ammonia, Biofuels, Hydrogen)," 2021, arXiv. doi: 10.48550/ARXIV.2102.00439.
- [3] N. H. Zerín, M. G. Rasul, M. I. Jahirul, and A. S. M. Sayem, "End-of-life tyre conversion to energy: A review on pyrolysis and activated carbon production

- processes and their challenges," *Sci. Total Environ.*, vol. 905, p. 166981, Dec. 2023, doi: 10.1016/j.scitotenv.2023.166981.
- [4] B. S. Chauhan, R. K. Singh, H. M. Cho, and H. C. Lim, "Practice of diesel fuel blends using alternative fuels: A review," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1358–1368, 2016.
- [5] How Many Truckers Are in the US? A Deep Dive into the American Trucking Industry. Website: <https://www.rapidresponsestl.com/how-many-truckers-are-in-the-us/> (August 2026)
- [6] M. I. Arbab, H. H. Masjuki, M. Varman, M. A. Kalam, S. Imtenan, and H. Sajjad, "Fuel properties, engine performance and emission characteristic of common biodiesels as a renewable and sustainable source of fuel," *Renew. Sustain. Energy Rev.*, vol. 22, pp. 133–147, 2013.
- [7] A. K. Agarwal, T. Gupta, and A. Kothari, "Particulate emissions from biodiesel vs diesel fuelled compression ignition engine," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 3278–3300, 2011.
- [8] M. Staff, "43% of US Commercial Trucks Powered by Diesel," *MHL News*. Accessed: Jul. 19, 2026. [Online]. Available: <https://www.mhlnews.com/transportation-distribution/article/22055876/43-of-us-commercial-trucks-powered-by-diesel>
- [9] "Use of diesel - U.S. Energy Information Administration (EIA)." Accessed: Jul. 19, 2026. [Online]. Available: <https://www.eia.gov/energyexplained/diesel-fuel/use-of-diesel.php>
- [10] "The percentage of commercial diesel trucks that are near-zero emissions grows." Accessed: Jul. 19, 2026. [Online]. Available: <https://www.fleetequipmentmag.com/57-of-all-commercial-diesel-trucks-on-the-roads-are-near-zero-emissions-models/>
- [11] S. Boxiong, W. Chunfei, L. Cai, G. Binbin, and W. Rui, "Pyrolysis of waste tyres: The influence of USY catalyst/tyre ratio on products," *J. Anal. Appl. Pyrolysis*, vol. 78, no. 2, pp. 243–249, Mar. 2007, doi: 10.1016/j.jaap.2006.07.004.
- [12] B. S. Thomas and R. Chandra Gupta, "Properties of high strength concrete containing scrap tire rubber," *J. Clean. Prod.*, vol. 113, pp. 86–92, Feb. 2016, doi: 10.1016/j.jclepro.2015.11.019.
- [13] S. Doja, L. K. Pillari, and L. Bichler, "Processing and activation of tire-derived char: A review," *Renew. Sustain. Energy Rev.*, vol. 155, p. 111860, Mar. 2022, doi: 10.1016/j.rser.2021.111860.
- [14] "Federal Register, Volume 65 Issue 107 (Friday, June 2, 2000)." Accessed: Jul. 19, 2026. [Online]. Available: <https://www.govinfo.gov/content/pkg/FR-2000-06-02/html/00-12952.htm>
- [15] J. Xu et al., "High-value utilization of waste tires: A review with focus on modified carbon black from pyrolysis," *Sci. Total Environ.*, vol. 742, p. 140235, Nov. 2020, doi: 10.1016/j.scitotenv.2020.140235.
- [16] P. Lahijani, Z. A. Zainal, A. R. Mohamed, and M. Mohammadi, "Co-gasification of tire and biomass for enhancement of tire-char reactivity in CO₂ gasification process," *Bioresour. Technol.*, vol. 138, pp. 124–130, Jun. 2013, doi: 10.1016/j.biortech.2013.03.179.
- [17] M. Nehdi and A. Khan, "Cementitious Composites Containing Recycled Tire Rubber: An Overview of Engineering Properties and Potential Applications," *Cem. Concr. Aggreg.*, vol. 23, no. 1, pp. 3–10, Jun. 2001, doi: 10.1520/CCA10519J.
- [18] J. Zhang, I. Jones, M. Zhu, Z. Zhang, J. Preciado-Hernandez, and D. Zhang, "Pore Development During CO₂ and Steam Activation of a Spent Tyre Pyrolysis Char," *Waste Biomass Valorization*, vol. 12, no. 4, pp. 2097–2108, Apr. 2021, doi: 10.1007/s12649-020-01165-4.
- [19] I. Hita, M. Arabiourrutia, M. Olazar, J. Bilbao, J. M. Arandes, and P. Castaño, "Opportunities and barriers for producing high quality fuels from the pyrolysis of scrap tires," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 745–759, Apr. 2016, doi: 10.1016/j.rser.2015.11.081.
- [20] A. J. Bowles and G. D. Fowler, "Assessing the impacts of feedstock and process control on pyrolysis outputs for tyre recycling," *Resour. Conserv. Recycl.*, vol. 182, p. 106277, Jul. 2022, doi: 10.1016/j.resconrec.2022.106277.
- [21] Z. Derakhshan et al., "A new recycling technique for the waste tires reuse," *Environ. Res.*, vol. 158, pp. 462–469, Oct. 2017, doi: 10.1016/j.envres.2017.07.003.
- [22] J. D. Martínez, N. Puy, R. Murillo, T. García, M. V. Navarro, and A. M. Mastral, "Waste tyre pyrolysis – A review," *Renew. Sustain. Energy Rev.*, vol. 23, pp. 179–213, Jul. 2013, doi: 10.1016/j.rser.2013.02.038.
- [23] E. L. K. Mui, D. C. K. Ko, and G. McKay, "Production of active carbons from waste tyres—a review," *Carbon*, vol. 42, no. 14, pp. 2789–2805, 2004, doi: 10.1016/j.carbon.2004.06.023.
- [24] P. T. Williams, "Pyrolysis of waste tyres: A review," *Waste Manag.*, vol. 33, no. 8, pp. 1714–1728, Aug. 2013, doi: 10.1016/j.wasman.2013.05.003.
- [25] "The percentage of commercial diesel trucks that are near-zero emissions grows." Accessed: Jul. 19, 2026. [Online]. Available: <https://www.fleetequipmentmag.com/57-of-all-commercial-diesel-trucks-on-the-roads-are-near-zero-emissions-models/>
- [26] "More of America's Truck and Bus Fleets Powered by Advanced." Accessed: Jul. 19, 2026. [Online]. Available: <https://www.globenewswire.com/news-release/2026/05/06/3288779/0/en/More-of-America-s-Truck-and-Bus-Fleets-Powered-by-Advanced-Diesel-Engines-Than-Ever-Before.html>
- [27] E. T. Forum, "More of America's Truck and Bus Fleets Powered by Advanced Diesel Engines Than Ever Before," *GlobeNewswire News Room*. Accessed: Jul. 19, 2026. [Online]. Available: <https://www.globenewswire.com/news-release/2026/05/06/3288779/0/en/More-of-America-s-Truck-and-Bus-Fleets-Powered-by-Advanced-Diesel-Engines-Than-Ever-Before.html>

- [28] "The percentage of commercial diesel trucks that are near-zero emissions grows." Accessed: Jul. 19, 2026. [Online]. Available: <https://www.fleetequipmentmag.com/57-of-all-commercial-diesel-trucks-on-the-roads-are-near-zero-emissions-models/>
- [29] E. T. Forum, "More of America's Truck and Bus Fleets Powered by Advanced Diesel Engines Than Ever Before," GlobeNewswire News Room. Accessed: Jul. 19, 2026. [Online]. Available: <https://www.globenewswire.com/news-release/2026/05/06/3288779/0/en/More-of-America-s-Truck-and-Bus-Fleets-Powered-by-Advanced-Diesel-Engines-Than-Ever-Before.html>
- [30] G. Zhang et al., "Properties and utilization of waste tire pyrolysis oil: A mini review," *Fuel Process. Technol.*, vol. 211, p. 106582, Jan. 2021, doi: 10.1016/j.fuproc.2020.106582.
- [31] S. Mirmiran, H. Pakdel, and C. Roy, "Characterization of used tire vacuum pyrolysis oil: nitrogenous compounds from the naphtha fraction," *J. Anal. Appl. Pyrolysis*, vol. 22, no. 3, pp. 205–215, 1992.
- [32] M. F. Laresgoiti, B. M. Caballero, I. De Marco, A. Torres, M. A. Cabrero, and M. J. Chomón, "Characterization of the liquid products obtained in tyre pyrolysis," *J. Anal. Appl. Pyrolysis*, vol. 71, no. 2, pp. 917–934, 2004, doi: 10.1016/j.jaap.2003.12.003.
- [33] P. Rathack, A. Rieger, R. Haseneder, D. Gerlach, J.-U. Repke, and M. Otto, "Analysis of pyrolysis liquids from scrap tires using comprehensive gas chromatography-mass spectrometry and unsupervised learning," *J. Anal. Appl. Pyrolysis*, vol. 109, pp. 234–243, 2014.
- [34] A. M. Cunliffe and P. T. Williams, "Composition of oils derived from the batch pyrolysis of tyres," *J. Anal. Appl. Pyrolysis*, vol. 44, no. 2, pp. 131–152, 1998.
- [35] C. İlkılıç and H. Aydın, "Fuel production from waste vehicle tires by catalytic pyrolysis and its application in a diesel engine," *Fuel Process. Technol.*, vol. 92, no. 5, pp. 1129–1135, May 2011, doi: 10.1016/j.fuproc.2011.01.009.
- [36] S. Murugan, M. C. Ramaswamy, and G. Nagarajan, "Performance, emission and combustion studies of a DI diesel engine using Distilled Tyre pyrolysis oil-diesel blends," *Fuel Process. Technol.*, vol. 89, no. 2, pp. 152–159, 2008, doi: 10.1016/j.fuproc.2007.08.005.
- [37] A. Sharma and S. Murugan, "Potential for using a tyre pyrolysis oil-biodiesel blend in a diesel engine at different compression ratios," *Energy Convers. Manag.*, vol. 93, pp. 289–297, 2015.
- [38] M. Karagöz, "Investigation of performance and emission characteristics of an CI engine fuelled with diesel-waste tire oil-butanol blends," *Fuel*, vol. 282, p. 118872, 2020.
- [39] S.-Q. Li, Q. Yao, Y. Chi, J.-H. Yan, and K.-F. Cen, "Pilot-scale pyrolysis of scrap tires in a continuous rotary kiln reactor," *Ind. Eng. Chem. Res.*, vol. 43, no. 17, pp. 5133–5145, 2004.
- [40] M. R. Islam, M. Tushar, and H. Haniu, "Production of liquid fuels and chemicals from pyrolysis of Bangladeshi bicycle/rickshaw tire wastes," *J. Anal. Appl. Pyrolysis*, vol. 82, no. 1, pp. 96–109, 2008.
- [41] S. Ucar, S. Karagoz, A. R. Ozkan, and J. Yanik, "Evaluation of two different scrap tires as hydrocarbon source by pyrolysis," *Fuel*, vol. 84, no. 14–15, pp. 1884–1892, 2005.
- [42] P. T. Williams, R. P. Bottrill, and A. M. Cunliffe, "Combustion of tyre pyrolysis oil," *Process Saf. Environ. Prot.*, vol. 76, no. 4, pp. 291–301, 1998.
- [43] R. N. Pote and R. K. Patil, "Combustion and emission characteristics analysis of waste tyre pyrolysis oil," *SN Appl. Sci.*, vol. 1, no. 4, p. 294, Apr. 2019, doi: 10.1007/s42452-019-0308-8.
- [44] S. Hariharan, S. Murugan, and G. Nagarajan, "Effect of diethyl ether on Tyre pyrolysis oil fueled diesel engine," *Fuel*, vol. 104, pp. 109–115, Feb. 2013, doi: 10.1016/j.fuel.2012.08.041.
- [45] A. Uyumaz et al., "Production of waste tyre oil and experimental investigation on combustion, engine performance and exhaust emissions," *J. Energy Inst.*, vol. 92, no. 5, pp. 1406–1418, Oct. 2019, doi: 10.1016/j.joei.2018.09.001.
- [46] "Diesel Engines Market 2025 to 2032." Accessed: Jul. 19, 2026. [Online]. Available: <https://www.intelmarketresearch.com/diesel-engines-market-14196>
- [47] S. Murugan, H. Sundaramoorthi, G. Nagarajan, and B. Horak, "A comparative study on some methods to use tyre pyrolysis oil as an alternative fuel in a DI diesel engine," *Exergy Better Environ. Improv. Sustain.* 2 Appl., pp. 405–420, 2018.
- [48] U. Ž. Baškovič, T. Seljak, and T. Katrašnik, "Combustion and emission formation phenomena of tire pyrolysis oil in a common rail Diesel engine," *Energy Convers. Manag.*, vol. 149, pp. 706–721, 2017.
- [49] R. N. Pote and R. K. Patil, "Combustion and emission characteristics analysis of waste tyre pyrolysis oil," *SN Appl. Sci.*, vol. 1, no. 4, p. 294, Apr. 2019, doi: 10.1007/s42452-019-0308-8.
- [50] S. V. Ghadge and H. Raheman, "Biodiesel production from mahua (*Madhuca indica*) oil having high free fatty acids," *Biomass Bioenergy*, vol. 28, no. 6, pp. 601–605, 2005.



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