

Article

Physicochemical, Thermal, and Tribological Characteristics of Pyro-Oils Obtained from Plastics and Tires: A Comparative Study and Assessment

Abdullah A. Alazemi ^{1,*} , Abdullah F. Alajmi ¹  and Sultan M. Al-Salem ² ¹ Department of Mechanical Engineering, College of Engineering and Petroleum, Kuwait University, Sabah Al Salem University City, P.O. Box 5969, Safat 13060, Shadadiya, Kuwait; abdullah.alajmi1@ku.edu.kw² Environment & Life Sciences Research Centre, Kuwait Institute for Scientific Research, P.O. Box 24885, Safat 13109, Kuwait; ssalem@kisr.edu.kw

* Correspondence: a.alazemi@ku.edu.kw

Abstract

The escalating global accumulation of plastic waste (PW) poses a critical obstacle to environmental sustainability, necessitating the development of viable valorization strategies. Pyrolysis process offers a thermo-chemical conversion pathway capable of transforming waste plastics into a potentially functional liquid product. This work presents a systematic and comprehensive investigation of the physicochemical, wettability, thermal stability, rheological, and tribological properties of pyrolysis oil (i.e., pyro-oil) derived from virgin linear low-density polyethylene (LLDPE) pellets to mimic the behavior of common polymers in such thermo-chemical conversion processes. Pyro-oil was produced under controlled slow pyrolysis conditions in a fixed-bed reactor at 700 °C, and its properties were benchmarked against tire-derived pyro-oil and a commercial engine oil. Chemical and structural characterization was conducted via Fourier transform infrared spectroscopy (FTIR), wavelength dispersive X-ray fluorescence (WDXRF), and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS). Wettability was evaluated through temperature-dependent contact angle measurements, and thermal stability was assessed by thermogravimetric analysis (TGA). Rheological profiling of the plastic pyro-oil was investigated using a rheometer apparatus at different temperatures. Lastly, the tribological properties of plastic pyro-oils at various temperatures were examined using a tribometer instrument in a ball-on-disk configuration. Results demonstrate that plastic-derived pyro-oil exhibits a hydrocarbon-dominant chemical composition similar to that of tire pyro-oil and engine oil. Its absolute viscosity is nearly similar to that of the tire pyro-oil and is lower than that of engine oil across different temperatures. Tribological testing revealed that the plastic pyro-oil results in lower friction at elevated temperatures compared to both tire pyro-oil and commercial engine oil. However, the thermal examinations showed that plastic pyro-oil has lower thermal stability than tire pyro-oil and engine oil. Overall, these findings indicate that plastic pyro-oil holds promise as a functional lubricant for low-load and moderate-temperature industrial applications, positioning PW pyrolysis as a viable contributor to circular economy strategies in the lubricants sector.



Received: 18 June 2026

Revised: 22 July 2026

Accepted: 27 July 2026

Published: 31 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: plastic waste; pyrolysis oil; tribology; rheology; thermal stability; circular economy; lubrication

1. Introduction

Plastic waste (PW) constitutes one of the most pressing environmental challenges of the twenty-first century, affecting societies across all stages of economic development [1]. The environmental consequences of plastic pollution are well-documented, with ever-increasing levels of PW in terrestrial, marine, and water bodies environmental sinks [2]. To address this issue, researchers have explored various recycling and recovery routes for plastics, with a particular emphasis on waste generated from single-life-cycle plastic products [1]. The four main routes for treating plastic solid waste are primary, secondary, tertiary, and quaternary recycling [1,3]. Primary recycling involves re-introducing converted scraps back into the processing line to produce similar products but is rarely used among conventional recyclers, as the recycled materials often lack the required quality [1]. Secondary recycling, or mechanical/physical recycling, involves processing PW into new products without substantial modifications to the material's chemical structure [4]. Tertiary recycling, commonly referred to as chemical recycling, involves the breakdown of plastic polymers into their original monomers or other valuable chemical products through processes such as thermo-chemical conversion (TCC) for fuels or monomer recovery [3,5]. Quaternary recycling, also known as energy recovery, includes the incineration of PW to produce heat or electricity [6].

Among the various recycling and recovery routes, the pyrolysis process stands out as a promising solution for the sustainable management of PW. This process, which involves the treatment of plastics in inert atmospheres, leads to the decomposition of the material into smaller hydrocarbon (HC) molecules [4]. The resulting hydrocarbon products serve as valuable chemical feedstocks, suitable for repolymerization, fuel blending, or lubricant formulation [7]. Life cycle assessment studies suggest that pyrolysis can reduce the climate change impact of plastic waste management by up to 50% relative to other waste management methods, such as energy recovery and mechanical recycling [8]. Furthermore, due to the absence of oxygen, the pyrolysis process can have a lower carbon footprint since no dioxins are being produced, which reduces the emissions of carbon monoxide and dioxide [3]. As research in this area continues to advance, the pyrolysis process is predicted to become a key component of circular economy strategies for addressing the global plastic waste crisis.

Global demand for industrial lubricating oils continues to rise, creating both economic incentives and environmental imperatives for the development of alternative feedstocks. Therefore, using plastic pyrolysis oil (pyro-oil) as an oil lubricant could meet the goals of providing an environmentally friendly and commercially competitive oil lubricant. The management of PW locally, within the State of Kuwait, poses a serious challenge that has governmental entities focusing their efforts on this issue. This is apparent within the new strategic plans of the State of Kuwait, whereby sponsored White Papers were published alongside a new strategic plan for the Kuwait Environment Public Authority (KEPA) to tackle this issue in particular, which accumulates to some 300 ktpa from municipal sources alone [9,10]. Thus, valorizing PW, which could be a sustainable route in developing a local circular economy, presents an important aspect for Kuwait's strategic plans in the near future, especially for engine oil production, which offsets petroleum-based pollution and crude-based products.

While the present work is framed within Kuwait's national waste management strategy, the underlying valorization concept of converting polyolefin-rich plastic waste into a lubricant feedstock via pyrolysis is, in principle, transferable to other regions facing similar plastic waste management challenges, particularly where municipal solid waste streams are polyethylene-rich and centralized waste-sorting infrastructure exists. However, the specific economic and operational viability of this pathway is expected to vary interna-

tionally with feedstock composition (i.e., the proportion of polyolefins relative to other polymers, such as PET or PVC, in the local waste stream), the existing scale of plastic collection and sorting infrastructure, regional energy costs, and the prevailing regulatory or carbon-pricing framework governing waste valorization. In regions lacking organized plastic waste segregation, feedstock heterogeneity would likely necessitate additional pre-treatment or catalytic upgrading steps, which increase the cost and complexity of large-scale implementation relative to the controlled single-polymer feedstock investigated here.

Recently, there has been considerable attention given to oils produced from municipal solid waste (MSW) for economic and environmental reasons [11,12]. Due to its optimized energy efficiency and scalable operational conditions, the pyrolysis process is increasingly utilized to convert solid waste into economically viable outputs that mimic the properties of crude oil fractions [3]. Alazemi et al. [13,14] investigated the potential use of pyro-oil produced from recycling end-of-life tires (ELTs) as an oil lubricant and as an additive to commercial engine oil. They concluded that tire pyro-oils exhibited similar chemical and tribological properties in comparison to commercial engine oil, but with lower rheological and thermal properties. Furthermore, they demonstrated that ELTs pyro-oil can be added to commercial engine oil up to 10 wt.% without affecting its rheological and tribological performance. Alternatively, plastic pyro-oil has gained a lot of attention in recent years as an environmentally friendly and economically feasible oil lubricant [15–18]. Nevertheless, a main gap in the literature exists (and accordingly, is studied in this work) regarding a comprehensive study of the physicochemical, thermal, and tribological characteristics of plastic pyrolysis oil as a standalone industrial lubricant in boundary and mixed lubrication regimes. The present work constitutes a distinct and novel investigation in three key respects: (i) it is, to our knowledge, the first study to comprehensively characterize plastic (PE)-derived pyro-oil as a standalone lubricant rather than as a fuel additive or blending component; (ii) all plastic pyro-oil and benchmark data presented herein were generated using identical instrumentation, sample handling, and test protocols, enabling a rigorous, like-for-like comparison that is not achievable when benchmarking against literature values reported under disparate experimental conditions; and (iii) the work establishes, for the first time, a side-by-side physicochemical, thermal, and tribological dataset directly comparing two distinct waste-derived pyro-oil feedstocks (plastic versus tire) against the same commercial reference oil.

The transformation of plastic materials to oil via the pyrolysis method has substantial environmental and economic advantages. Our research work explores several properties (e.g., chemical, rheological, thermal, tribological, etc.) of the pyrolysis oil extracted from locally sourced plastic resin that mimics the main component in PW. Furthermore, these properties are compared to those of tire pyro-oil and commercial engine oil. This work specifically addresses the gap identified above by establishing whether plastic pyro-oil can function as a standalone industrial lubricant under boundary and mixed lubrication regimes, rather than solely as a fuel or blending component. Accordingly, this research provides a comprehensive assessment of plastic pyrolysis oil's physicochemical, thermal, and tribological behavior and examines the viable use of oil derived from PW as a liquid lubricant.

2. Experimental Design

2.1. Sample Acquisition

Samples of pyro-oil were extracted from a batch pyrolysis process depicted in detail elsewhere (Al-Salem et al. [19]). The pyro-oils are a result of the treatment of virgin linear low-density polyethylene (LLDPE) pellets supplied through a local agent from EQUATE Petrochemical Company with a 0.918 g.cm^{-3} density (ρ) and a 124°C melting point (T_m).

The material was used as is in the form of white translucent pellets (3 mm). The properties of the polymer are reported in Al-Salem and Dutta [20] and Al-Salem et al. [19]. Slow pyrolysis conditions were applied in the patented technology used in the production of the pyro-oils [21], whereby 100 g was subjected to thermal pyrolysis utilizing three temperature heating regions by the reactor's casing. Chilling temperature was maintained at 20 °C, and the pyro-oils were collected post-condensation (less than 3 h of pyrolysis time) [19]. A heating rate (β) equal to 5 °C/min was used to produce oil samples under a 50 mL/min nitrogen gas flow rate and an operating temperature of 700 °C. All experiments were conducted in duplicates, and the oil mass balance was at about 25% of the original feedstock with no char produced, indicating completion of full pyrolysis. The samples extracted were spotty and viscous with apparent oil-like features and brownish/blackish in color. Samples of pyro-oils were compared to commercial engine oil for physicochemical, thermal, and tribological properties. The commercial engine oil (5W-30 Engine Oil) utilized in the current investigation was manufactured by Valvoline Corporation, Lexington, KY, USA (CAS no. 64742-65-0). Tire pyro-oil samples were also used for comparative assessment, which was discussed elsewhere (Alazemi et al. [13,14]).

It should be noted that virgin LLDPE pellets, rather than a real mixed plastic waste stream, were deliberately selected as the feedstock in order to isolate the intrinsic pyro-oil properties of polyethylene, which is the single largest polymer fraction typically present in municipal plastic waste streams, from confounding variables introduced by feedstock heterogeneity, such as co-mingled PET, PVC, or PP, food and dirt contamination, or variable additive packages. This controlled, single-polymer approach is consistent with prior fundamental pyrolysis-oil characterization studies that likewise rely on virgin or single-polymer feedstocks to establish baseline structure-property relationships [19,20,22]. Likewise, the batch, fixed-bed slow-pyrolysis configuration used here is widely reported in bench- and pilot-scale plastic pyrolysis literature [3,4,19,21] and is mechanistically representative of larger continuous or semi-continuous reactor designs operating under comparable temperature and residence-time regimes, although absolute yields and oil composition are known to vary with reactor geometry, heating rate, and feedstock blend [3]. Consequently, while the present results establish a robust baseline for polyethylene-derived pyro-oil as a lubricant candidate, pyro-oils derived from real, mixed plastic waste streams are expected to exhibit broader compositional variability (e.g., higher aromatic content from PET/PS fractions, chlorine from PVC, or elevated sulfur from rubber or PVC contamination), and their lubricant performance should be validated separately.

2.2. Characterization Methods

2.2.1. Physicochemical Characterization

The oil samples were examined for their physicochemical characteristics. Molecular structure was characterized by FTIR (Cary 630, Agilent Technologies Inc., Santa Clara, CA, USA). The quantitative identification of major and minor atomic constituents based on infrared absorption in the spectral range of 500 to 4000 cm^{-1} was detected using this technique. Additionally, elemental analysis was performed using WDXRF (Rigaku ZSX Primus IV, Tokyo, Japan) spectrometer. This spectrometer is equipped with a high-power 4 kW Rhodium X-ray tube positioned above the sample stage. For each XRF measurement, a 5 mL oil sample was introduced into a liquid unit and analyzed to quantify the elemental composition of the examined oil sample. The rheological properties were studied via a rheometer apparatus (ARES-G2, TA Instruments, New Castle, DE, USA) using a 10 mL oil sample for each test. The absolute viscosity of each oil sample was measured over 5–60 °C.

2.2.2. Morphology

The morphological and surface chemistry analyses of the particles within the pyro-oils were conducted using a field emission scanning electron microscopy (SEM). Before imaging, each sample was sputter-coated with gold (Au) using an auto fine sputter coater (JFC-1600, JEOL, Tokyo, Japan) to mitigate charging effects. Elemental examination for carbon, hydrogen, nitrogen, and sulfur (CHNS) was carried out via a Vario MacroCube analyzer (Elementar, Frankfurt, Germany). This instrument operates via dynamic combustion, where the sample is incinerated at high temperatures (≥ 1050 °C), decomposing it into simpler gaseous compounds. These gases—CO₂, H₂O, N₂, and SO₂—are transported by helium (He) as a carrier gas through a chromatographic column maintained at a uniform, modular temperature. The individual components are subsequently separated and quantified using a thermal conductivity detector.

2.2.3. Wettability

Wettability measurements of the oil samples were executed by a Drop Shape Analyzer (DSA100, Krüss GmbH, Hamburg, Germany), following the methodology outlined by Alazmi et al. [23]. Measurements were conducted on polished stainless-steel substrates at four discrete temperatures: 20 °C, 35 °C, 50 °C, and 75 °C. A droplet volume of 4 µL was dispensed at a rate of 0.1 µL/s for each measurement. The stainless-steel substrates were prepared with a nominally isotropic (random, multidirectional polished) surface finish rather than a directionally textured surface; this distinction is relevant because surface texture orientation and scale relative to the contact line have recently been shown to influence dynamic contact angle and hysteresis on anisotropic surfaces [24]. Because the substrate texture used here is isotropic, the measured CA values are not expected to depend on droplet orientation relative to a preferential polishing direction. Contact angle (CA) values were determined using the instrument's integrated image analysis software, and the temperature-dependent wettability response of each oil sample was evaluated. All CA measurements, as well as the other characterization tests reported in this study, were repeated three times per condition, and results are reported as mean $\pm$ standard deviation.

2.2.4. Thermal Stability Investigation

The thermal stability of oil samples was assessed following ASTM E2550 standards via a thermogravimetric analyzer (TGA) (METTLER TOLEDO, Model TGA 2, Columbus, OH, USA), and sample analysis was conducted using STARe Software (version 16.20, Mettler Toledo). Before testing, the chamber in the TGA instrument was purged by dry air for 60 min to ensure a stable baseline. About 10 mg of the oil sample was placed in a platinum container with a volume capacity of 70 µL. Thermal degradation profiles (i.e., thermograms) were obtained by heating the oil samples from 25 °C up to 600 °C under a heating rate of 10 °C/min in a nitrogen gas (N₂) atmosphere, maintained at a flow rate of 50 mL/min.

2.2.5. Tribological Investigation

Tribological performance was evaluated using an MFT-5000 Multi-Function Tribometer (Rtec Instruments, San Jose, CA, USA) with 10 mL lubricant per test, at three temperatures (25 °C, 50 °C, 75 °C) spanning the typical operational range of industrial lubricants (40–80 °C) [25]. The tribological tests were conducted following ASTM G99 standards [26] in a ball-on-disk configuration. A normal load of 20 N was maintained on a 9.5 mm diameter stationary steel ball, producing 1.3 GPa maximum Hertzian contact pressure—representative of severe tribological situations of boundary and mixed lubrication regimes [27]. A rotating steel disk (50 mm in diameter) was used, with the ball-disk contact occurring at a sliding radius of 12.5 mm. The disk rotational speed varied from

0 to 1500 rpm. The testing procedure involved heating the system to the target temperature within 1 min, followed by a speed ramp-up to 1500 rpm over 2 min. Subsequently, the speed was reduced in discrete steps to assess the lubrication behavior across varying regimes. Each test was conducted over a total duration of 74 min. Post-test analysis involved examining wear scars on both the ball and disk using an optical profilometer at 10× and 20× magnifications. The coefficient of friction (COF) was continuously recorded, and Stribeck curves were generated to assess the lubrication characteristics of the plastic pyro-oil relative to tire pyro-oil and commercial engine oil.

3. Results and Discussion

3.1. FTIR Analysis and Elemental Composition of Oil Samples

FTIR transmittance spectra for all three oil samples are presented in Figure 1. This illustrates the transmittance of key functional groups for plastic-derived pyro-oil compared to those identified in the tire-derived pyro-oil and commercial engine oil. The observed spectral bands in oil samples correspond to molecular vibrations, plotted as a function of wavenumber (cm^{-1}). A prominent peak at 3200 cm^{-1} was apparent for the plastic and tire pyro-oil samples, indicating the existence of the O-H stretching functional group. This points towards the development of oxides and hydroxides [28]. A band near 3400 cm^{-1} also shows the =C-H stretching characteristic, which is consistent with the presence of alkenes and anticipated for the case of PE [29]. The peak at 1710 cm^{-1} was distinctive for the plastic pyro-oil and was attributed to the C=O vibrational bonding. The same was previously reported in [30] for PE samples.

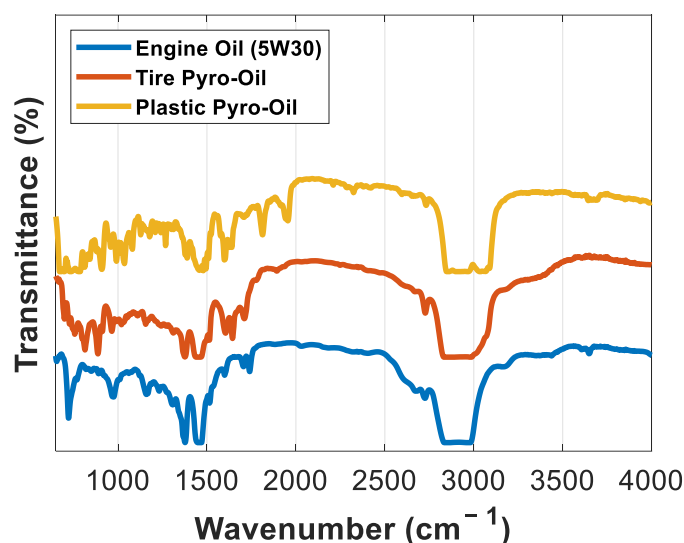


Figure 1. FTIR transmittance spectrum of plastic pyro-oil, tire pyro-oil, and engine oil.

To assess the chemical composition of oils derived via pyrolysis process, an elemental analysis of engine oil and plastic and tire pyro-oils was performed using a Vario MacroCube analyzer (see Table 1). Regarding the sulfur content, the engine oil and plastic pyro-oil had no sulfur, whereas the tire-derived variant exhibited a sulfur concentration of 0.74%. The elevated sulfur concentration observed in tire-derived pyro-oil is ascribed to the vulcanization stage of tire fabrication, where sulfur is introduced to facilitate polymer cross-linking.

The presence of micro-sized solid agglomerates was identified in the plastic pyro-oil and characterized by SEM-EDS to determine their shape, size, and chemical characteristics. SEM imaging confirmed a heterogeneous population of micron-scale clusters with irregular morphology, as shown in Figure 2. The elemental chemical composition of the solid particles was studied by energy-dispersive X-ray spectroscopy (EDS) connected to SEM apparatus.

The EDS investigation confirmed that the particles consist of 86% carbon and 14% oxygen by weight, as shown in Figure 2c. Note that the Au element is discarded in the EDS analysis, as the sample was sputter-coated by Au in order to picture the non-conducting plastic solid particles within the pyro-oil.

Table 1. Chemical elemental examination results for engine oil and plastic and tire pyro-oils.

Sample	Carbon (C, %)	Hydrogen (H, %)	Nitrogen (N, %)	Sulfur (S, %)
Engine Oil	85.02	14.126	0.91	0
Plastic pyro-oil	91.71	8.125	0	0
Tire pyro-oil	91.51	6.35	0.40	0.74

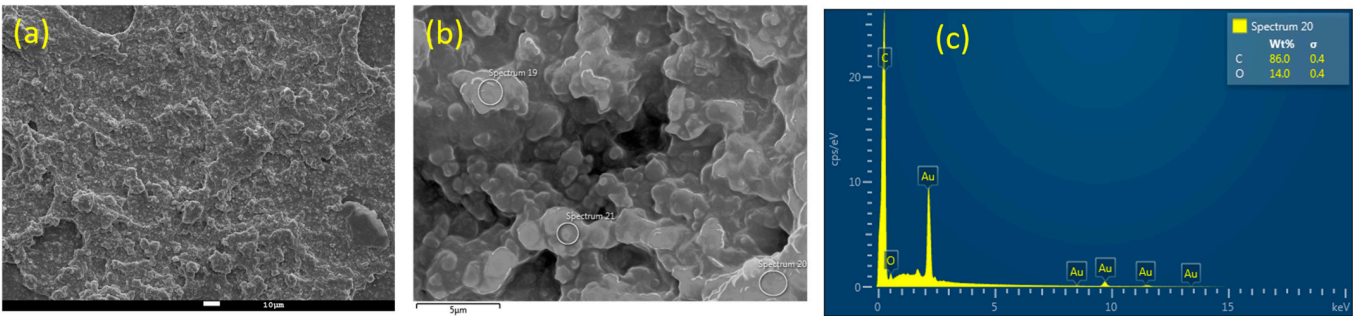


Figure 2. (a,b) SEM images and (c) EDS analysis chart for plastic pyro-oil solid particles.

Further chemical examination of the plastic and tire pyro-oils with their solid particles was performed using the XRF instrument. The XRF investigation also confirms the existence of carbon as the predominant component of both pyro-oil samples. In addition, only tire pyro-oil sample was found to contain sulfur (see Figure 3). Also, it was revealed that the liquid tire pyro-oil contained more than double the sulfur content of the solid particles within the tire pyro-oil. The micro-sized agglomerates of solid particles in the plastic pyro-oil are carbon-based, as revealed by XRF analysis. This is expected since at a pyrolysis temperature of 700 °C, the formation of carbonaceous char via secondary gas-phase reactions is common.

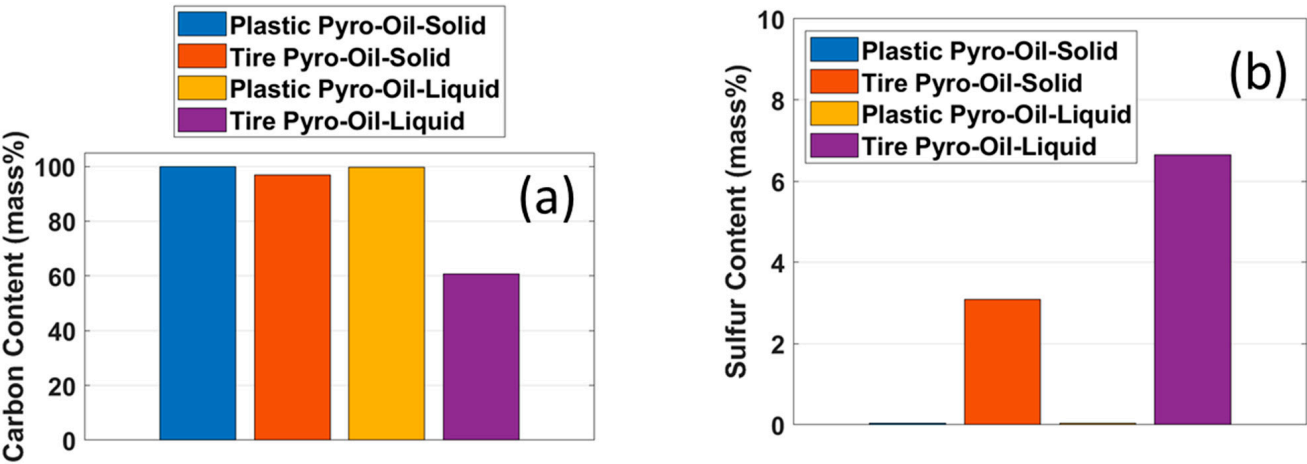


Figure 3. XRF analysis results of the (a) carbon and (b) sulfur content in the liquid and solid particles within the plastic and tire pyro-oil samples.

3.2. Wettability and Thermal Stability Analyses

The wettability of a lubricant on a metal surface directly governs the quality and continuity of the lubricating film, with lower contact angles reflecting stronger oleophilic affinity and enhanced surface coverage. Conventional engine oils are predominantly derived from petroleum or mineral sources and are formulated with different additives to optimize lubrication characteristics. Historically, modifications to engine oils have been aimed at improving their wetting capabilities on metal surfaces [23]. This section presents a comparative wettability study of plastic and tire pyrolysis oils against a commercial engine oil across different temperatures. Wettability was evaluated through contact angle (CA) measurements, which serve as a primary indicator of the interfacial interactions between the oil lubricant and the metal surface. For the present comparison, the industrially relevant operating window for boundary and mixed-regime lubrication is approximately 40–80 °C [25], coinciding with the 50 °C and 75 °C conditions used in this work and with the tribological test temperatures. Accordingly, the CA behavior captured at 50 °C and 75 °C is considered most representative of in-service wetting conditions, whereas the lower-temperature data points (20 °C and 35 °C) primarily establish the baseline wetting trend rather than inform application-relevant performance.

Temperature-dependent CA results of all oil samples are presented in Figure 4. At 20 °C, both plastic and tire pyro-oils displayed lower CA values compared to the engine oil, indicating superior wettability. Upon increasing the temperature to 35 °C, the CA values of both pyro-oil samples increased, whereas the engine oil showed a large decrease. Further temperature elevations to 50 °C and 75 °C resulted in a reduction in the CA values for the pyro-oils, while the engine oil experienced a marginal increase. This increase in CA with temperature for the commercial engine oil can be ascribed to the complex formulation of the oil and additive depletion at elevated temperatures.

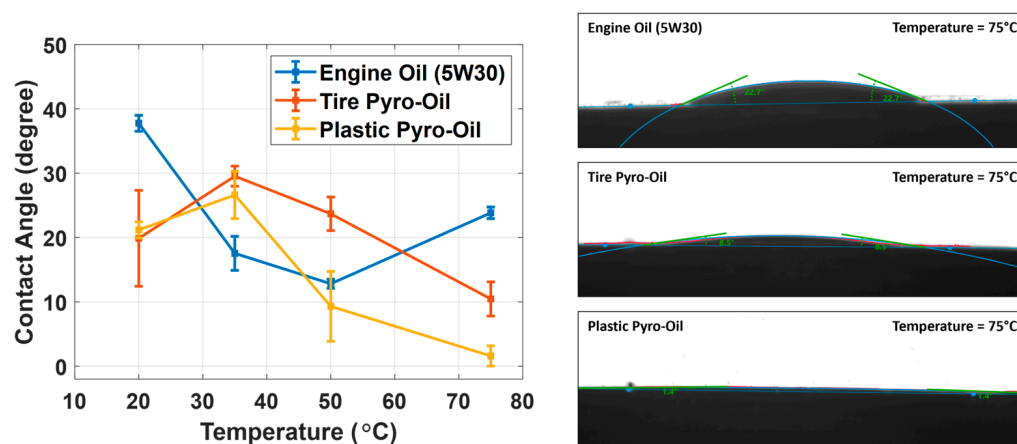


Figure 4. Comparison of contact angle values versus temperature on stainless-steel substrate for plastic pyro-oil, tire pyro-oil, and engine oil (left). Representative droplet image of all samples at 75 °C (right).

Notably, at elevated temperatures, plastic pyro-oil consistently demonstrated lower CAs than tire pyro-oil. The superior high-temperature wettability of both pyro-oils compared to the engine oil is ascribed to the carbonaceous solid particles dispersed within the oils, as revealed by the SEM and XRF analyses. Regarding the proposed mechanism, the improved high-temperature wettability is not attributed to an intrinsic hydrophilicity of the carbonaceous particles themselves, as pristine carbon char is typically hydrophobic. Rather, the mechanism is proposed to be geometric/physical in nature: micro- and sub-micron carbon particles present at the oil–metal interface may locally roughen and fill the asperities of the polished stainless-steel substrate, increasing the effective solid–liquid contact area

and pinning the contact line, which is an effect previously reported for carbon-particle-modified lubricants on metal substrates [23,27]. This asperity-filling/contact-line-pinning mechanism is proposed as a plausible explanation of the observed reduction in CA values compared to the commercial engine oil.

The thermal stability of plastic pyro-oil was evaluated and compared to that of tire pyro-oil and commercial engine oil by analyzing the thermogravimetric (TG) thermograms, as illustrated in Figure 5. Thermal stability is a critical property for lubricants exposed to elevated operating temperatures and is primarily influenced by the chemical composition of the oil. This property is typically characterized by the onset decomposition temperature, which marks the beginning of thermal degradation following moisture evaporation. Thermal decomposition is reflected as a change in mass, indicated by a deviation from the initial mass baseline [31].

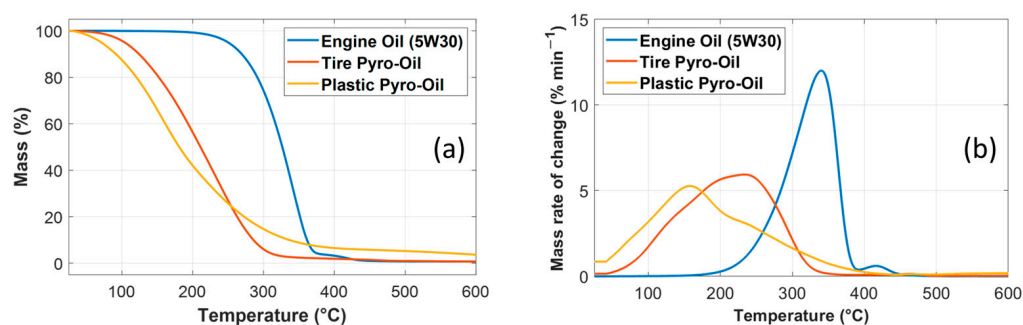


Figure 5. (a) Weight loss versus temperature and (b) mass rate of change versus temperature for plastic pyro-oil, tire pyro-oil, and engine oil.

As shown in Figure 5a, the TGA curves for all tested oils exhibit three distinct phases. During the first phase, a minor mass loss of approximately 1% is detected, corresponding to moisture evaporation. The temperature at which this initial weight loss occurs is defined as the onset temperature [32]. The second phase is marked by a rapid decline in mass, with the midpoint temperature representing the point at which 50% mass loss occurs. Then, the third phase begins once the rate of weight change significantly drops, approaching a plateau with a small residual mass remaining.

Among the tested samples, engine oil demonstrated superior thermal stability, initiating decomposition at an onset temperature of 208 °C. In contrast, plastic and tire pyro-oils began to decompose at significantly lower onset temperatures of 43 °C and 68 °C, respectively. The first derivative thermogravimetric (DTG) curves, presented in Figure 5b, further highlight the differences in thermal behavior. The peak in the DTG curve denotes the highest decomposition rate temperature, after which the rate of mass loss declines toward a stable baseline. The DTG results reaffirm the higher thermal stability of the engine oil compared to the pyro-oils.

Table 2 summarizes the thermal properties of the examined oil samples, including onset temperatures and weight loss percentages at the end of the second phase. High-temperature pyrolysis at 700 °C favors the production of light hydrocarbons in the naphtha and diesel ranges (C₅–C₁₆), which have high volatility. In contrast, commercial engine oils are composed of heavier base stocks (C₂₀–C₅₀). The presence of these light, unsaturated fractions and potentially oxidized components significantly reduces thermal stability. Therefore, fractional distillation or hydrogenation would be required to make the plastic pyro-oil industrially viable. However, given that many engineering lubrication systems operate within a typical temperature range between 40 °C and 80 °C [25], the relatively low thermal stability of pyro-oils poses limitations for their use in high-temperature appli-

cations. Nevertheless, these pyrolysis-derived oils may still serve as viable lubricants for systems operating under moderate or low-temperature conditions.

Table 2. Thermogravimetric outcomes for plastic pyro-oil, tire pyro-oil, and engine oil.

Parameter	Plastic Pyro-Oil	Tire Pyro-Oil	Engine Oil
Mass loss (%)	94.5	98.1	96.6
Onset temperature (°C)	43.3	68.8	208.3
Midpoint temperature (°C)	180.9	210.9	326.4
Maximum decomposition rate temperature (°C)	158.2	233.3	340.2

3.3. Rheological Investigation

A comprehensive rheological analysis was conducted to assess the flow behavior of plastic pyro-oil relative to tire pyro-oil and commercial engine oil across varying temperatures and shear rates. Viscosity measurements were implemented at 25 °C, 50 °C, and 75 °C and over a shear rate range of 1 to 100 s^{−1}. As illustrated in Figure 6, the viscosity of all samples remained relatively constant across the tested shear rates, indicating Newtonian behavior. However, a slight shear thinning at low shear rates and temperatures is observed for the plastic pyro-oil. This is likely due to the presence of the suspended solid agglomerates, which form weak networks that break under shear stress. Among the tested samples, plastic pyro-oil exhibited slightly lower viscosity than tire pyro-oil and approximately one order of magnitude less than that of the commercial engine oil. Previous research supports the finding that 700 °C pyrolysis produces low-viscosity oils dominated by light aliphatic and aromatic species [22].

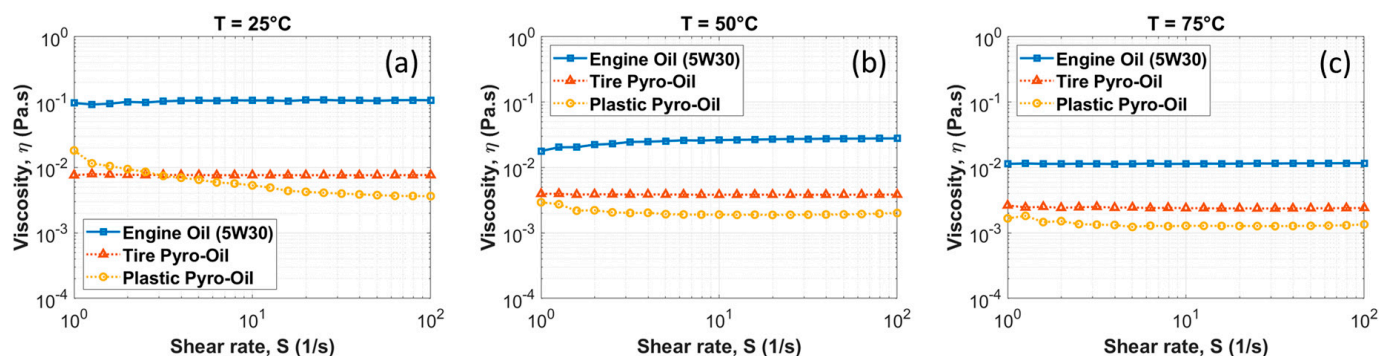


Figure 6. Viscosity against shear rate for plastic pyro-oil, tire pyro-oil, and engine oil at temperatures of (a) 25 °C, (b) 50 °C, and (c) 75 °C.

Further rheological assessments examined the relationship between shear stress and shear rate at multiple temperatures. As shown in Figure 7, a linear correlation was observed for all samples, further confirming their Newtonian nature. Both pyro-oils displayed lower shear stress values than the engine oil across all shear rates and temperatures. However, the disparity in shear stress between pyro-oils and engine oil diminished with increasing temperature.

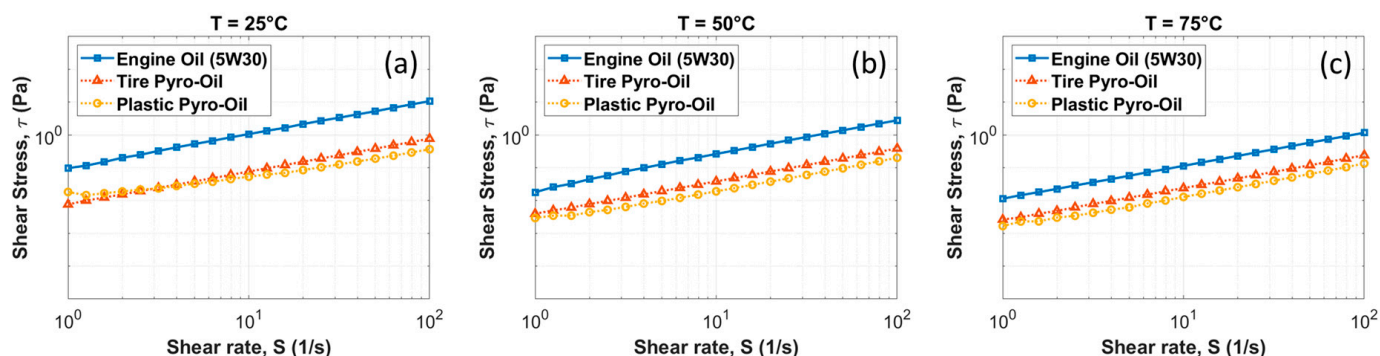


Figure 7. Shear stress versus shear rate for plastic pyro-oil, tire pyro-oil, and engine oil at temperatures of (a) 25 °C, (b) 50 °C, and (c) 75 °C.

The temperature-dependent viscosity behavior of the oil samples was also investigated over a broader temperature range (5 °C to 60 °C), as depicted in Figure 8. Results showed that plastic and tire pyro-oils had comparable viscosity profiles, except at low temperatures, where plastic pyro-oil exhibited slightly higher viscosity. Nevertheless, both pyro-oils consistently demonstrated significantly lower viscosity compared to that of engine oil across the entire temperature range. At elevated temperatures, the viscosity of pyro-oils showed increased instability, likely due to the presence of solid particles, as identified through SEM analysis.

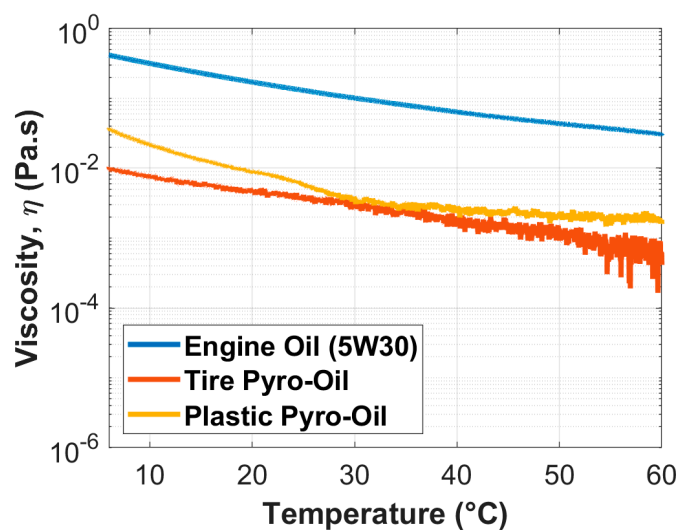


Figure 8. Viscosity against temperature for plastic pyro-oil, tire pyro-oil, and engine oil.

Viscosity is a critical parameter in lubricant performance, directly influencing the load-bearing capability and frictional losses in any tribological system. The markedly lower viscosity of pyro-oils—approximately an order of magnitude less than that of the engine oil—suggests their suitability for applications involving low mechanical loads. Based on the rheological findings, pyro-oils may be considered as potential lubricants in industrial systems operating under moderate temperature and low-load conditions.

3.4. Tribological Study

The present investigation evaluated the lubrication performance of plastic- and tire-derived pyro-oils against a commercial engine oil across a range of velocities and temperatures. As shown in Figure 9, the lubrication performance was characterized by monitoring the coefficient of friction (COF) as a function of rotational speed at 25 °C, 50 °C, and 75 °C for all three oils. Figure 9 reveals the consistent decline in COF with speed increments,

signifying the operation within the mixed lubrication regime for all tested oil samples. At 25 °C, plastic pyro-oil exhibits an unstable and fluctuating COF with the change in rotational speed, while the tire pyro-oil and the engine oil produce stable COF values and slightly decreased with the increase in rotational speed (see Figure 9a). At 50 °C, the plastic pyro-oil had a stable and the lowest COF value compared to the other two oil samples (see Figure 9b). At 75 °C, the plastic pyro-oil also exhibited the lowest COF relative to the other two oil samples, with some fluctuations with the change in rotational speed (see Figure 9c). This unstable COF behavior for the plastic pyro-oil is attributed to the presence of the agglomerated micro-sized particles within the oil, as seen in the SEM analysis; at elevated temperatures these particles contribute positively via tribofilm formation. This non-monotonic instability pattern—unstable at 25 °C and 75 °C but stable at 50 °C—is consistent with a viscosity- and temperature-dependent particle-suspension behavior. At 25 °C, the comparatively higher oil viscosity is insufficient to keep the micro-agglomerates uniformly dispersed under shear, promoting intermittent particle bridging and momentary disruption of the boundary film within the contact, which manifests as COF fluctuations. At 50 °C, the combination of reduced viscosity and sufficient thermal energy is hypothesized to allow more uniform particle redistribution and stable tribofilm formation. At 75 °C, however, the further-reduced viscosity may favor renewed particle agglomeration and intermittent particle expulsion from the contact zone, compounded by the onset of oil thermal/oxidative degradation noted in Section 3.2 (TGA onset temperature of 43 °C), re-introducing instability. Mitigation strategies such as fine filtration or centrifugation prior to use could reduce the population of large agglomerates and improve COF consistency across the full temperature range, while dispersant-type additives could stabilize the particle suspension without removing the beneficial carbonaceous tribofilm-forming particles. These approaches are recommended as a direction for future formulation work on plastic pyro-oil-based lubricants.

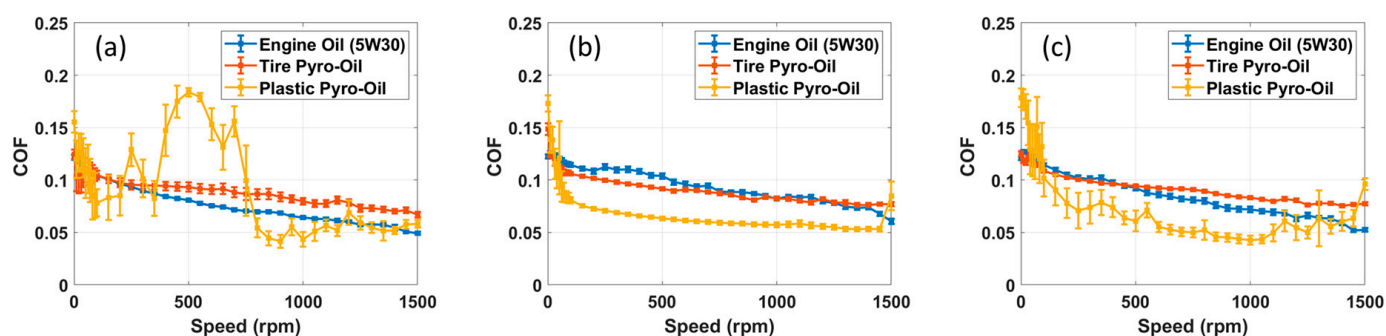


Figure 9. COF versus rotational speed for tribotesting using plastic pyro-oil, tire pyro-oil, and engine oil at operating temperatures of (a) 25 °C, (b) 50 °C, and (c) 75 °C.

Post-test wear characterization was performed on both ball and disk specimens to further evaluate the anti-wear performance of the plastic pyro-oil, and the obtained results were compared against the tire pyro-oil and engine oil from the authors' prior study [13]. Ball specimen wear scar diameters after tribotesting at 25 °C, 50 °C, and 75 °C using plastic pyro-oil were measured to be 440 µm, 320 µm, and 420 µm, respectively (Figure 10). The minimum scar size at 50 °C coincides with the lowest and stable COF value. Plastic pyro-oil produced slightly larger ball scars (~9–29%) than those under tire pyro-oil or engine oil lubrication. Figure 11 shows disk wear tracks following tribological testing at operating temperatures of 25 °C, 50 °C, and 75 °C. Plastic pyro-oil resulted in a wide disk wear track with a dark layer deposited on it. The wear track on the disk was found to have a width between 300 µm and 400 µm. The depth of the disk wear track was determined via

profilometric analysis, utilizing a line profile oriented perpendicularly to the wear track developed after tribotesting using the plastic pyro-oil. The obtained results demonstrate that the wear scars on the disk surface were very shallow, characterized by depths below $0.1\text{ }\mu\text{m}$ across the different temperatures. Interestingly, the wear track on the disk contained a thin layer ($\sim 0.2\text{ }\mu\text{m}$) adhered to its surface.

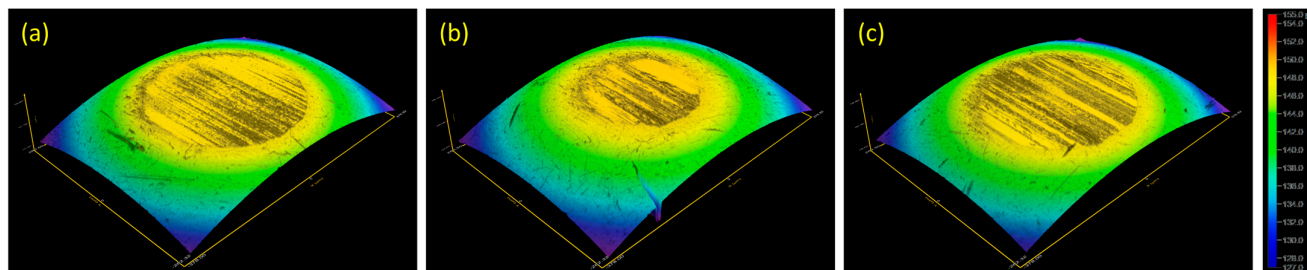


Figure 10. Wear scars image on the ball specimen after tribotesting using plastic pyro-oil at (a) $25\text{ }^{\circ}\text{C}$, (b) $50\text{ }^{\circ}\text{C}$, and (c) $75\text{ }^{\circ}\text{C}$ temperatures.

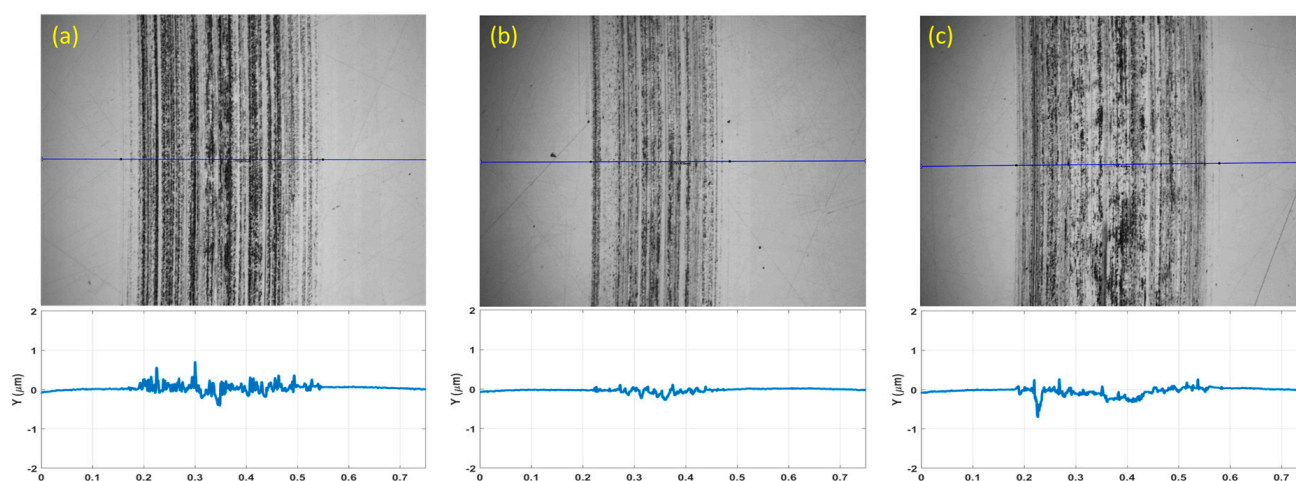


Figure 11. Wear scars image on the disk specimen with a line profile across the wear scar after tribotesting using plastic pyro-oil at (a) $25\text{ }^{\circ}\text{C}$, (b) $50\text{ }^{\circ}\text{C}$, and (c) $75\text{ }^{\circ}\text{C}$ temperatures.

Further chemical and structural analyses of the disk wear scar were performed using SEM-EDS. Figure 12 shows an SEM image, EDS mapping, and EDS spectrum on the disk specimen before tribotest, as well as after tribotesting using plastic pyro-oil at $25\text{ }^{\circ}\text{C}$, $50\text{ }^{\circ}\text{C}$, and $75\text{ }^{\circ}\text{C}$. The results showed a rise in the carbon content from 0.7 wt.% (pre-test) to 1.1 wt.% within the wear track after tribotesting with plastic pyro-oil at $50\text{ }^{\circ}\text{C}$ and $75\text{ }^{\circ}\text{C}$. This suggests that a carbon-based layer adhered to the surface of the disk within the wear track and protected the disk specimen from wear damage and minimized friction between sliding surfaces. It should be noted that while the carbon-based layer prevented deep scarring on the disk, it failed to match the anti-wear performance of commercial engine oil on the ball specimen, where ZDDP-type additive provides superior protection.

Overall, the tribological assessment demonstrates that the plastic-derived pyro-oil exhibits a lubrication performance comparable to or superior to that of both tire-derived oil and commercial engine oil, particularly at rotational speeds around 1000 rpm and moderate temperatures.

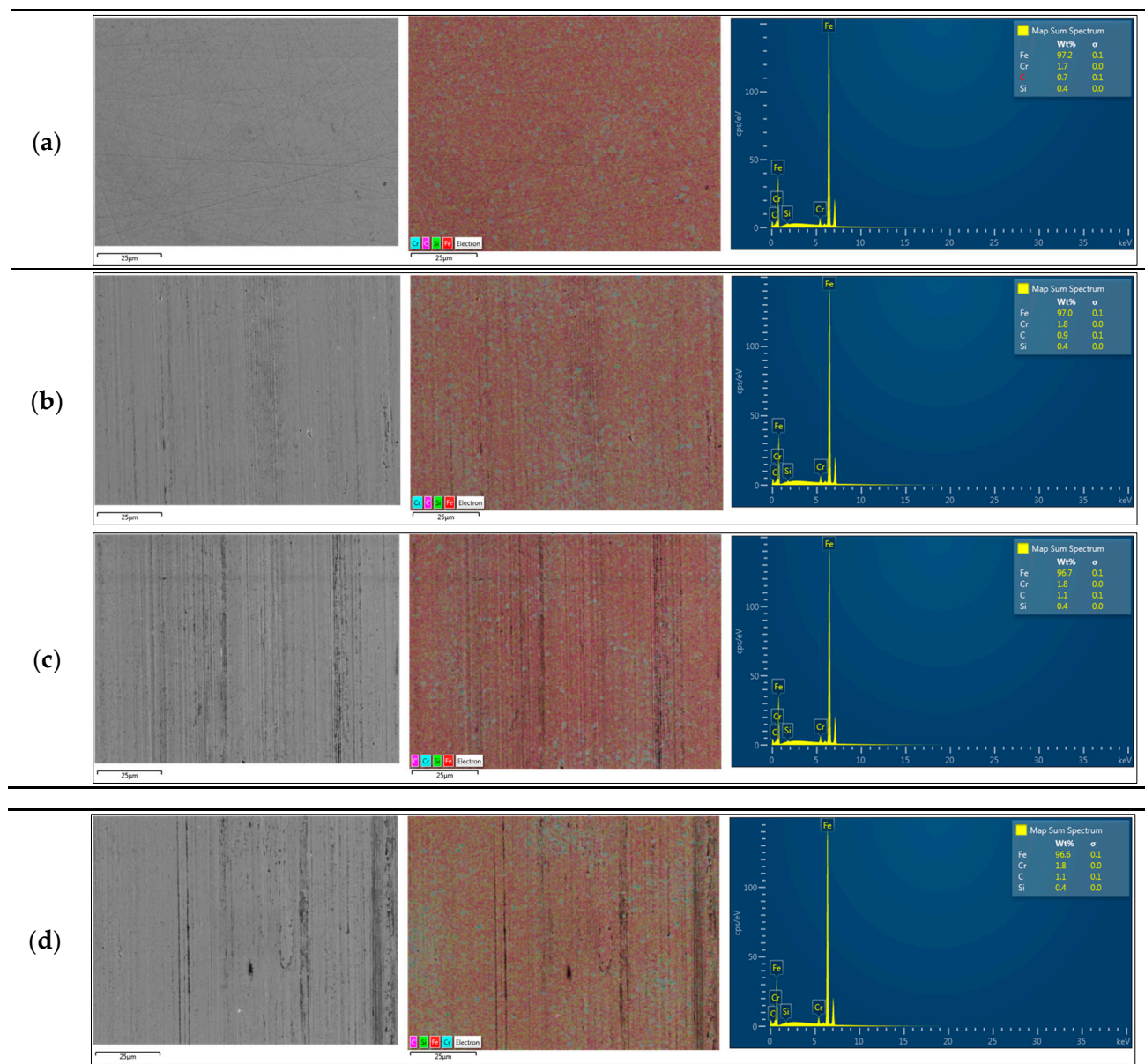


Figure 12. SEM image, EDS mapping, and EDS chemical element chart on the disk specimen (a) before tribotest and after tribotesting using plastic pyro-oil at (b) 25 °C, (c) 50 °C, and (d) 75 °C temperatures.

3.5. Evaluation of Environmental and Economic Implications

Despite widespread awareness and efforts, the global accumulation of plastic waste poses a significant environmental challenge, with nearly 79% of plastics ending up in landfills and the natural environment [33]. Diverting even a fraction of this stream toward pyrolysis-derived lubricant applications—rather than only the fuel-range applications more commonly proposed in the literature—would extend the value-recovery options available for plastic waste management and is environmentally preferable to landfilling, which contributes to groundwater contamination and forecloses resource recovery [34]. Given the relatively low thermal stability and ball-wear performance identified in Sections 3.2 and 3.4, the plastic pyro-oil characterized in this work is best positioned for low-load, moderate-temperature niche lubrication applications (e.g., chain, slideway, or hydraulic systems operating below ~80 °C) rather than as a drop-in engine oil replacement, which narrows—but does not eliminate—its practical valorization pathway.

From an economic perspective, the production of pyrolysis oil from waste plastics holds substantial promise. It presents an opportunity to develop a low-cost, domestically sourced alternative to petroleum-based lubricants and fuels. While the initial investment for a pyrolysis plant can be significant, the long-term economic viability is compelling [35]. The market value of the primary product, plastic pyrolysis oil, can range from \$600 to \$900 per ton [36]. Economic feasibility is further enhanced by the marketability of solid char and non-condensable gases, which can be used to power the pyrolysis process itself, reducing operational costs. Therefore, while upgrading processes are often necessary to meet industry specifications, investment in such steps can be justified by the enhanced value and broader market applicability of the final product. It should be emphasized that a rigorous techno-economic and life-cycle assessment that incorporates capital and operating costs, upgrading requirements, and a process-specific carbon balance is identified as a necessary direction for future work before definitive economic or environmental claims can be made for this specific lubricant application.

4. Conclusions

This study presents a comprehensive characterization of LLDPE-derived plastic pyro-oil benchmarked against tire-derived pyro-oil and a commercial engine oil. The principal conclusions are: (1) FTIR, CHNS, and WDXRF analyses confirmed a predominantly aliphatic, sulfur-free hydrocarbon composition comparable to both benchmarks. (2) SEM-EDS identified micron-scale carbonaceous agglomerates with irregular structures. (3) Plastic pyro-oil exhibits superior high-temperature wettability on stainless steel, attributed to surface asperity-filling by carbonaceous particles. (4) Thermal stability analysis revealed that the plastic pyro-oil and tire pyro-oil start the decomposition process at onset temperatures of 43 °C and 68 °C, respectively, substantially lower than the engine oil, which has an onset temperature of 208 °C. (5) The rheological profiles of both plastic and tire pyro-oils were found to be comparable, with both fluids displaying a viscosity roughly ten times lower than the commercial engine oil. (6) Plastic pyro-oil achieved lower COF than both benchmarks at 50 °C and 75 °C; this was attributed to the carbonaceous tribofilm developed on the disk wear track.

Collectively, the results demonstrate that while plastic pyro-oil cannot serve as a drop-in replacement for commercial engine oil in high-temperature or high-load applications due to its inferior thermal stability and anti-wear characteristics on ball specimens, it presents a viable and sustainable lubricant candidate for engineering systems operating under light loads, moderate rotational speeds, and moderate working temperatures. The employment of pyro-oil derived from plastic waste for the lubrication of engineering systems offers a sustainable utilization of cumulative plastic solid waste that poses a serious environmental hazard.

Author Contributions: A.A.A.: Conceptualization, Methodology, Testing, Analysis, Validation, Writing—Original Draft, Preparation, Supervision, Writing—review and editing. A.F.A.: Conceptualization, Methodology, Analysis, Writing—review and editing. S.M.A.-S.: Conceptualization, Methodology, Testing, Analysis, Validation, Resources, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Kuwait University grant number RE04/24.

Data Availability Statement: Data will be made available on request.

Acknowledgments: The authors would like to thank the Research Sector at Kuwait University for funding this research project through Research Grant No. RE04/24. We gratefully acknowledge the support of Kuwait University General Facilities through Grant No. GE 01/07, Grant No. GE 03/08, and Grant No. GS 01/05. The authors are also grateful for the support of the Kuwait Institute for Scientific Research (KISR), the Kuwait Foundation for the Advancement of Sciences (KFAS), and the General Supreme Council for Planning of Kuwait; for their support of Projects P-KISR-06-11 and EM96C.

Conflicts of Interest: The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

References

1. Al-Salem, S.M.; Lettieri, P.; Baeyens, J. Recycling and recovery routes of plastic solid waste (PSW): A review. *Waste Manag.* **2009**, *29*, 2625–2643. [CrossRef]
2. Garcia, J.M.; Robertson, M.L. The future of plastics recycling. *Science* **2017**, *358*, 870–872. [CrossRef] [PubMed]
3. Al-Salem, S.M.; Antelava, A.; Constantinou, A.; Manos, G.; Dutta, A. A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). *J. Environ. Manag.* **2017**, *197*, 177–198. [CrossRef] [PubMed]
4. Al-Salem, S.M.; Lettieri, P.; Baeyens, J. The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals. *Prog. Energy Combust. Sci.* **2010**, *36*, 103–129. [CrossRef]
5. Constantinou, A.; Hafeez, S.; Harkou, E.; Adamou, P.; Pallari, E.; Manos, G.; Webb, A.; Kotha, R.; Morgen, O.V.; Walls, L.E.; et al. Fuel Quality from Thermochemical Conversion and Biological Treatment of Biomass. *Ind. Eng. Chem. Res.* **2024**, *63*, 18699–18723. [CrossRef]
6. Al-Salem, S.M.; Evangelisti, S.; Lettieri, P. Life cycle assessment of alternative technologies for municipal solid waste and plastic solid waste management in the Greater London area. *Chem. Eng. J.* **2014**, *244*, 391–402. [CrossRef]
7. Al-Salem, S.M.; Van Haute, M.; Karam, H.J.; Hakeem, A.; Meuldermans, W.; Patel, J.; Hafeez, S.; Manos, G.; Constantinou, A. Fuel range properties of oil and wax obtained from catalytic pyrolysis of linear low-density polyethylene in a fluidized bed reactor (FBR). *Ind. Eng. Chem. Res.* **2022**, *61*, 16383–16392. [CrossRef]
8. Ángeles-Hurtado, L.A.; Rodríguez-Reséndiz, J.; Salazar-Colores, S.; Torres-Salinas, H.; Sevilla-Camacho, P.Y. Viable disposal of post-consumer polymers in Mexico: A review. *Front. Environ. Sci.* **2021**, *9*, 749775. [CrossRef]
9. Alshawaf, M.; Alwaeli, M.; Pikon, K.; Alolayan, M. The Characterization of Municipal Solid Waste in Kuwait: A Pathway to Reform the Waste Management Sector. *Discov. Sustain.* **2025**, *6*, 208. [CrossRef]
10. Lyons, B.; Al-Salem, S.M.; Al-Snafi, F.; Al-Nakib, D.; Al-Ghadban, A.N.; Al-Said, T.; Ali, M.T.; Shivshanker, V.S.; Langston, W.J. *Marine Litter in the Arabian Gulf with a Specific Focus on the State of Kuwait: Current Knowledge, Research Gaps & Recommendations. A White Paper on the Role of KFAS in Addressing Challenges & Identifying Knowledge Gaps*; Kuwait Foundation for the Advancement of Sciences (KFAS): Kuwait City, Kuwait, 2022. Available online: [https://www.kfas.org/media\(MediaArchive:47d3e484-6c37-4f76-8bc4-d7adc51ba263\)](https://www.kfas.org/media(MediaArchive:47d3e484-6c37-4f76-8bc4-d7adc51ba263)) (accessed on 30 May 2026).
11. Kunwer, R.; Pasupuleti, S.R.; Bhurat, S.S.; Gugulothu, S.K.; Rathore, N. Blending of ethanol with gasoline and diesel fuel—A review. *Mater. Today Proc.* **2022**, *69*, 560–563. [CrossRef]
12. Rajesh, B.; Rajesh, K. Experimental investigation on single cylinder four stroke tri-charged diesel engine using pyrolysis oil at different proportions. *Mater. Today Proc.* **2022**, *52*, 675–682. [CrossRef]
13. Alazemi, A.A.; Alajmi, A.F.; Al-Salem, S.M. Investigation of Chemical, Physical, and Tribological Properties of Pyrolysis Oil Derived from End-of-Life Tires (ELTs) against Conventional Engine Oil. *Lubricants* **2024**, *12*, 188. [CrossRef]
14. Alazemi, A.A.; Alajmi, A.F.; Al-Salem, S.M. Viable Use of Tire Pyrolysis Oil as an Additive to Conventional Motor Oil: A Tribological and Physical Study. *Lubricants* **2025**, *13*, 64. [CrossRef]
15. Sikdar, S.; Siddaiah, A.; Menezes, P.L. Conversion of waste plastic to oils for tribological applications. *Lubricants* **2020**, *8*, 78. [CrossRef]
16. Awang, M.S.N.; Zulkifli, N.W.M.; Abbas, M.M.; Zulkifli, S.A.; Kalam, M.A.; Yusoff, M.N.A.M.; Daud, W.M.A.W.; Ahmad, M.H. Effect of diesel-palm biodiesel fuel with plastic pyrolysis oil and waste cooking biodiesel on tribological characteristics of lubricating oil. *Alex. Eng. J.* **2022**, *61*, 7221–7231. [CrossRef]
17. Pumpuang, A.; Klinkaew, N.; Wathakit, K.; Sukhom, A.; Sukjit, E. The influence of plastic pyrolysis oil on fuel lubricity and diesel engine performance. *RSC Adv.* **2024**, *14*, 10070–10087. [CrossRef] [PubMed]
18. Cappello, V.; Sun, P.; Zang, G.; Kumar, S.; Hackler, R.; Delgado, H.E.; Elgowainy, A.; Delferro, M.; Krause, T. Conversion of plastic waste into high-value lubricants: Techno-economic analysis and life cycle assessment. *Green Chem.* **2022**, *24*, 6306–6318. [CrossRef]

19. Al-Salem, S.; Chandrasekaran, S.R.; Dutta, A.; Sharma, B.K. Study of the fuel properties of extracted oils obtained from low and linear low density polyethylene pyrolysis. *Fuel* **2021**, *304*, 121396. [[CrossRef](#)]
20. Al-Salem, S.M.; Dutta, A. Wax recovery from the pyrolysis of virgin and waste plastics. *Ind. Eng. Chem. Res.* **2021**, *60*, 8301–8309. [[CrossRef](#)]
21. Al-Salem, S.M. Pyrolysis Reactor System for the Conversion and Analysis of Organic Solid Waste. U.S. Patent 10,364,395 B2, 30 July 2019.
22. Williams, P.T.; Williams, E.A. Fluidised bed pyrolysis of low density polyethylene to produce petrochemical feedstock. *J. Anal. Appl. Pyrolysis* **1999**, *51*, 107–126. [[CrossRef](#)]
23. Alazemi, A.A.; Alzubi, F.G.; Alhazza, A.; Dysart, A.; Pol, V.G. Rheological and wettability properties of engine oil with a submicron spherical carbon particle lubricant mixture. *Int. J. Automot. Technol.* **2020**, *21*, 1475–1482. [[CrossRef](#)]
24. Peta, K.; Kubiak, K.J.; Brown, C.A. Multiscale geometric analysis of dynamic wettability on complex, fractal-like, anisotropic surfaces. *Measurement* **2026**, *264*, 120328. [[CrossRef](#)]
25. Aberoumand, S.; Jafarimoghaddam, A. Experimental study on synthesis, stability, thermal conductivity and viscosity of Cu–engine oil nanofluid. *J. Taiwan Inst. Chem. Eng.* **2017**, *71*, 315–322. [[CrossRef](#)]
26. ASTM G99-17; Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. ASTM International: West Conshohocken, PA, USA, 2017.
27. Alazemi, A.A.; Etacheri, V.; Dysart, A.D.; Stacke, L.E.; Pol, V.G.; Sadeghi, F. Ultrasmooth submicrometer carbon spheres as lubricant additives for friction and wear reduction. *ACS Appl. Mater. Interfaces* **2015**, *7*, 5514–5521. [[CrossRef](#)] [[PubMed](#)]
28. Alawa, B.; Chakma, S. Insight into the engine performance of pyro-oil synthesized through catalytic co-pyrolysis of mixed waste plastics in the presence of dolomite modified with silica and ZSM-5. *Fuel* **2023**, *354*, 129190. [[CrossRef](#)]
29. Rajendran, K.M.; Kumar, D.; Lamba, B.Y.; Ghodke, P.K. Production and characterization of plastic oil from mixed plastic waste through the pyrolysis process. *Mater. Today Proc.* **2023**. [[CrossRef](#)]
30. Al-Salem, S.M.; Behbehani, M.H.; Al-Hazza'a, A.; Arnold, J.C.; Alston, S.M.; Al-Rowaih, A.A.; Asiri, F.; Al-Rowaih, S.F.; Karam, H. Study of the degradation profile for virgin linear low-density polyethylene (LLDPE) and polyolefin (PO) plastic waste blends. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 1106–1122. [[CrossRef](#)]
31. Kalam, M.A.; Masjuki, H.H.; Cho, H.M.; Mosarof, M.H.; Mahmud, M.I.; Chowdhury, M.A.; Zulkifli, N.W.M. Influences of thermal stability, and lubrication performance of biodegradable oil as an engine oil for improving the efficiency of heavy duty diesel engine. *Fuel* **2017**, *196*, 36–46. [[CrossRef](#)]
32. Nik, W.W.; Ani, F.N.; Masjuki, H.H. Thermal stability evaluation of palm oil as energy transport media. *Energy Convers. Manag.* **2005**, *46*, 2198–2215. [[CrossRef](#)]
33. Upadhyay, K.; Bajpai, S. Microplastics in Landfills: A Comprehensive Review on Occurrence, Characteristics and Pathways to the Aquatic Environment. *Nat. Environ. Pollut. Technol.* **2021**, *20*, 1935–1945. [[CrossRef](#)]
34. Al-Salem, S.M. Valorisation of end of life tyres (ELTs) in a newly developed pyrolysis fixed-bed batch process. *Process. Saf. Environ. Prot.* **2020**, *138*, 167–175. [[CrossRef](#)]
35. Kim, D.; Anderson, N.M.; Chung, W. Financial performance of a mobile pyrolysis system used to produce biochar from sawmill residues. *For. Prod. J.* **2015**, *65*, 189–197. [[CrossRef](#)]
36. Hasan, M.M.; Haque, R.; Jahirul, M.I.; Rasul, M.G. Pyrolysis of plastic waste for sustainable energy Recovery: Technological advancements and environmental impacts. *Energy Convers. Manag.* **2025**, *326*, 119511. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.