

Article

Tribological Assessment of Synthetic Grease (PDPLG-2) Derived from Partially Degraded Low-Density Polyethylene Waste

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Abstract: This study focuses on addressing the pressing challenge of reusing plastic in an eco-friendly manner. This research aimed to produce synthetic grease through an environmentally friendly pyrolysis technique, utilizing 69% predegraded low-density polyethylene (LDPE) combined with visible-light-working TiO₂ thin film, protein-coated TiO₂ NPs, and *Lactobacillus plantarum* bacteria in a batch reactor. The optimized conditions of temperature (500 °C) and heating time (2 h) resulted in the creation of 166 gm of partially degraded polyethylene grease 2 (PDPLG2) with National Lubricating Grease Institute (NLGI 2) grade consistency. PDPLG2 grease exhibits a wide-range dropping point of 280 °C and effectively maintains lubrication under high friction and stress loads, thereby preventing wear. Thermal analysis using TG and DSC validated the grease's stability up to 280 °C, with minimal degradation beyond this point. Taguchi analysis using substance, sliding speed, and load as factors identified the ideal process parameters as aluminum, 1500 rpm, and 150 N, respectively. The present study revealed that sliding speed has the greatest impact, contributing 31.74% to the coefficient of friction (COF) and 11.28% to wear, followed by material and load. Comparative tribological analysis with commercially available grease (NLGI2) demonstrated that PDPLG2 grease outperforms NLGI2 grease. Overall, this innovative eco-friendly approach presents PDPLG2 as a promising alternative lubricant with improved anti-wear and friction properties, while also contributing significantly to plastic waste reduction.

Keywords: tribology; friction; wear; sputtering; pyrolysis-derived synthetic grease; thin films



Received: 15 January 2025

Revised: 10 February 2025

Accepted: 14 February 2025

Published: 18 February 2025

Citation: Dave, D.; Vaidya, Y.; Chauhan, K.; Rawal, S.; Khimani, A.; Chaki, S. Tribological Assessment of Synthetic Grease (PDPLG-2) Derived from Partially Degraded Low-Density Polyethylene Waste. *Lubricants* **2025**, *13*, 92. <https://doi.org/10.3390/lubricants13020092>

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1. Introduction

In the modern era, engineering is increasingly focused on the development of green technologies that can harness renewable energies and promote sustainable fuel processes. These initiatives have gained global recognition and are driving legislative actions to

safeguard the environment and mitigate carbon emissions. Although polymer manufacturing consumes a relatively small percentage of petroleum, ranging from 4% to 8% [1], the management of plastic solid waste (PSW) remains a pressing concern due to its potential environmental impact. Issues such as landscape degradation, contamination of environmental sinks, microplastic accumulation, and the reduction in valuable landfill space necessitate effective PSW management [2–5].

In response to the challenge of PSW, two primary approaches have emerged for its valorization: thermo-chemical conversion (TCC) and energy-generating processes [6]. TCC encompasses diverse techniques capable of converting plastic waste into valuable products, such as combustion gases, energy, monomers, and solid carbon black, while also minimizing carbon footprint and environmental impact. This approach enhances sustainability and presents favorable opportunities for the petroleum-refining industry [7].

The global reliance on plastics in everyday life has led to a staggering production volume of approximately 359 million tons in 2018, with an annual growth rate projected at 5% [8]. Among the TCC methods, pyrolysis has proven to be particularly effective in converting various polymers, including low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), and linear low-density polyethylene (LLDPE), into valuable fuels like petrol and diesel [9]. This clean and sustainable fuel generation approach is adaptable to market dynamics, influenced by fluctuating crude oil prices [2]. Moreover, TCC has shown significant success in transforming polyolefin polymers into value-added products, such as waxes and solid char, further promoting circularity and resource management [10–13].

Pyrolysis, a prominent short-term thermal waste-processing technique within TCC, involves treating feedstock at temperatures ranging from 350 to 900 °C under an inert gas medium, such as nitrogen, helium, or argon, in a closed environment without oxygen and at a high pressure [6]. The pyrolysis process yields liquid, solid, and gaseous fractions with high energy values, making it an efficient and cost-effective method for converting waste into valuable energy sources [14–17].

Various reactor and experimental designs have been explored for the pyrolysis of plastics, including conical spouted beds, fixed beds, molten salts, and fluidized beds [1,18,19]. Fixed-bed reactors, widely used for analytical classification of pyrolysis products, offer advantages in terms of convenience, construction, large-scale cost-effectiveness, ease of maintenance, and the accurate representation of slow pyrolysis kinetics [2,3,20]. These reactors have shown potential for producing fuel, light gases, and lubricants from 70% degraded polyethylene feedstock [9,18,21].

While researchers have explored pyrolysis wax and its potential as an acceptable commodity due to its high concentration of hydrocarbons and suitability for use in petroleum refineries, concerns related to the increased emission of SO_x, NO_x, and other toxic gases remain to be addressed. This study aimed to contribute to the understanding of pyrolysis wax production from partially degraded real-life PSW rescued from an active landfill, with a focus on reducing toxic gas emissions, an aspect which has not been extensively covered in previous research. The waxes were characterized through physiochemical testing as per NLGI standard (National Lubricating Grease Institute) to determine their fundamental properties and, importantly, their fuel-range constituents.

In conclusion, pyrolysis offers a zero-waste (ensuring that 70% yield refers to usable grease, while byproducts are repurposed) and cost-effective process with numerous potential applications, making it a promising technology within the concept of circularity for converting and recycling plastic waste. This study's exploration of synthetic grease production from rescued PSW seeks to advance the green and sustainable management of plastic waste and contribute to a cleaner and greener future.

2. Materials and Methods

Sample Collection and Preparation

According to our pervious study [22], the photo-biodegradation of LDPE (30 microns) was performed in the presence of visible light for 21 days in ambient air. A light source and LDPE were located 5 cm away from each other. Furthermore, 50 watts visible lamps (wavelength range of 400–700 nm) were applied as a light source for photocatalytic activity. Each LDPE strip was weighed at regular periods. For the photo-biodegradation of the LDPE bag, visible-spectrum-working TiO_2 thin film, *Lactobacillus plantarum* MT477833 bacterial cell (10^6 cell/mL), and titania nanoparticles (10 mg) in the presence of NaOH (1M) as an alkaline agent were used. In continuation of our previous study, predegraded LDPE (69% degraded LDPE) was cleaned, dried, and then used for thermal pyrolysis.

Pyrolysis Experiments

Pyrolysis testing was conducted using an elevated horizontal tube furnace (Agni Electrical, MNF: Induction Furnace, Ahmedabad, Gujarat, India) equipped with connecting pipes to facilitate the transfer of necessary gases and products into and out of the reactor. This setup allowed for precise control over the operating parameters. To separate non-condensing and condensing gaseous products, an outgoing pipe was connected to a condensing flask maintained at 4 °C. The temperature within the reactor was monitored using a thermocouple mounted inside, and external regulation was achieved through a PID controller. Each pyrolysis reaction involved loading 50 g of partly degraded low-density polyethylene (LDPE) samples into a semi-batch reactor. The reactions were carried out for 2 h at 500 °C. To ensure the production of a higher-grade plastic, namely low-density polyethylene (LDPE), which is both cost-effective and environmentally beneficial without the release of hazardous oxides (e.g., CO_2 , CO), camphor was introduced into the process. By adding camphor (100 gm for 1 Kg LDPE) to the mixture during heating, it interacted with the reaction to consume oxides and prevent their release. The remaining camphor in the mixture eventually formed the grease. Further heating of the combination resulted in a semi-liquid compound, which solidified into grease upon cooling. This method proved to be far more cost-effective compared to industrial approaches and could be accomplished using easily available materials [23]. The thermal pyrolysis setup available at the Department of Physics, Sardar Patel University, is depicted in Figure 1. This innovative technique holds promise as a sustainable and accessible means to produce high-quality grease while minimizing harmful emissions.

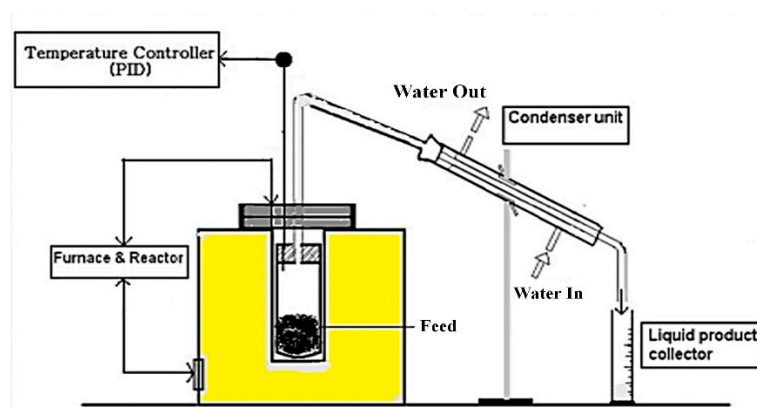


Figure 1. The thermal pyrolysis setup.

Physiochemical Testing Grease Consistency

All physiochemical properties were analyzed at the J. K. Analytical Laboratory & Research Center, Ahmedabad, Gujarat, India.

Grease Consistency

Grease hardness, also known as shear strength, was determined by ASTM D217, where a cone penetrometer measured the depth of penetration into a grease sample under specified conditions at 25 °C for 5 s. Softer grease resulted in deeper penetration, and the relative hardness was denoted by an NLGI consistency number ranging from 000 to 6. Higher NLGI numbers represented harder grease [24]. Table 1 illustrates the NLGI grease categories and their corresponding consistencies.

Table 1. Lubricating Grease Institute (NLGI) grease category based on consistency.

NLGI Number	ASTM Worked Penetration 0.1 mm (3.28×10^{-4} ft) at 25 °C (77 °F)	Consistency
000	445–475	Semi-fluid
00	400–430	Semi-fluid
0	355–385	Very soft
1	310–340	Soft
2	265–295	Common grease
3	Semi-hard	Semi-hard
4	175–205	Hard
5	130–160	Very hard
6	85–115	Solid

Dropping Point

The dropping point of grease refers to the temperature at which the grease transitions from a semi-solid state to a liquid state under specific test conditions. It represents the upper temperature limit at which the grease retains its structural integrity and can be effectively used in various applications. The test procedure, as per ASTM D 2265, involved placing a sample of the grease inside a cone-shaped cup, with a thermometer inserted without touching the grease [25]. This assembly was then immersed in a hot oil bath, which included a heat-resistant glass tube. The temperature at which the oil dropped through the cup's opening to the bottom of the test tube was measured and recorded. A higher dropping point temperature indicated that the grease provided greater protection and stability [26].

Four-Ball Testing

According to the ASTM-DIN 51350 standard procedure for extreme pressure, tribological testing for the synthesized grease PDPLG 2 was performed on a four-ball tester. The stress was delivered from a vertically downward direction in the four-ball tester. The rpm of the top ball rotated continuously. The temperature-controlled device kept the assembly's temperature at the required level. The EP test was conducted according to ASTM D 2596 to measure the load-carrying capability of the grease and its relative ability to prevent wear under applied loads. The load was increased stepwise in every run with a new set of balls, until seizure. The final seizure load involved the four balls becoming welded to each other, indicating the level of load-carrying ability of the applied grease [26]. The summary of the test parameters for the WP and EP tests is listed in Table 2.

Table 2. Test parameters for four-ball test.

Parameter	EP (ASTM DIN 51350-02)
Ball specimen	Steel balls, diameter 12.7 mm, Ra = 0.04 microns, HRC 65
Rotating speed	1450 rpm
Temperature	Ambient
Duration	60 ± 1 min
Load	Incremental load starting from 2000 N
Test duration	60 min

Thermal Characterization

To address reviewer comments, TG and DSC analyses were conducted to assess the thermal stability of PDPLG2 grease.

Tribological Properties of Partially Degraded Polyethylene Grease (PDPLG 2)

The tribological properties of partially degraded polyethylene grease (PDPLG 2) were measured using a pin-on-disk tribometer (Ducom Instruments Pvt. Ltd. at CHARUSAT, Gujarat, India, Changa) to confirm the compatibility of the PDPLG 2 and commercially available lithium-based NLGI 2 grease. The tribological tests were carried out as per ASTM G99 guidelines. Spherical pins of various materials such as aluminum (Al, ϕ 10 mm, 54 HRC), brass (Br, ϕ 10 mm, 62 HRC), and mild steel (Ms, ϕ 10 mm, 67 HRC) were examined against a disk made of hardened ground steel (EN-32, hardness 72 HRC, the surface roughness Ra = 0.07 μ m). The composition of the mild-steel pin (%W) was 0.06% aluminum, 0.25% copper, 0.15% carbon (C), 0.35% silicon (Si), and 0.03% sulfur (S). The brass pin consisted of 99.90% Br and 0.005% Zn. The aluminum pin was made of aluminum 98.71%, copper 0.05%, magnesium 0.45%, and silicon 0.33%. The average roughness (Ra) values of the aluminum, brass, and MS pins were 0.71, 0.40, and 0.95 μ m, respectively [27]. The tests were conducted with varying sliding velocities (1000, 1500, and 2000 rpm) with a track diameter of 80 mm and varying normal loads (100, 150, and 200 N). All the tests were performed on the same disk. In the current study, the effect of applied load on the wet-sliding wear of aluminum, brass, and MS pins against a hardened ground-steel disk at various sliding speeds was studied. The friction and wear tests were performed three times for 5 min each, and the average of three readings was taken as the result.

3. Results and Discussion

Physiochemical Properties of Partially Degraded Polyethylene Grease

The physicochemical properties of the selected greases are depicted in Table 3. It can be observed that the physicochemical behavior is qualitatively comparable between PDPLG 2 and NLGI 2 grease.

Grease PDPLG 2 and NIGL 2 have a similar appearance: gray and red brown color and in the form of viscous liquid. The fine, gray color might be due to the addition of dye coloring in LDPE. Regarding the grease consistency determined by unworked penetration, the PDPLG 2 grease had a semi-liquid structure with NLGI 2 grade, due to the cone penetrometer sinking to 268 tenths of a millimeter. Highly viscous base oil can form a thick lubrication layer between contact surfaces, promoting friction and wear reduction. The dropping point is the temperature at which the grease liquefies down to the liquid state, losing the desired consistency or rigidity. It is depended on the type of thickener used [28] and also indicates the grease's stability at a high temperature. In general, the dropping point indicates that the grease is operating at an optimal temperature. The dropping

point typically has to be at least 50 °C higher than the operational temperature. In our experiment, we observed that the dropping point of the PDPLG 2 grease remained stable up to a temperature of about 210 °C before the base oil dropped to the bottom of test tube, whereas the dropping point for commercially available NIGL2 grease was about >180 °C. Tribological testing was conducted using the four-ball test method. The extreme pressure performance of the synthesized PDPLG 2 was determined according to ASTM-DIN 51350. The weld load was calculated for synthesized PDPLG 2 and compared with commercially available NLGI 2 grease. The extreme pressure performance of the PDPLG 2 exhibited enhanced results compared to commercially available NLGI 2 grease. The percentage increase in the weld load PDPLG 2 was 7968%. Hence, PDPLG 2 can be a good lubricant replacement for industry and automobile parts to address environmental concerns.

Table 3. Physiochemical properties of PDPLG 2 and NLGI 2 greases.

Sr. No.	Physiochemical Properties	Test Method	PDPLG 2	NLGI 2
1	Appearance	-	Smooth and buttery	Smooth and buttery
2	Color		Gray	Red brown
3	Structure		Viscous liquid	Viscous liquid
4	NLGI grade	ASTMD 217	2	2
5	Worked penetration at 25 °C, 0.1 mm	DIN ISO 2137	268	265–295
6	Four-ball test	DIN 5130 pt. 4N	>7968	>7125
7	Dropping point (°C)	ASTMD 2265	280	>180
8	Viscosity @ 100 °C (cst)	ASTMD 446	14.8	11.0
9	Working temperature range (°C)	-	−25 to 210	−30 to 120

TG Analysis of Grease

The thermogravimetric analysis (TG) of the grease sample (Figure 2) revealed that an initial weight loss of approximately 2% occurred between 25 °C and 120 °C due to the evaporation of moisture and volatile components. A gradual weight loss of around 8% was observed from 120 °C to 280 °C, indicating the thermal degradation of minor organic additives. A major decomposition phase occurred between 280 °C and 450 °C, with a significant weight loss of approximately 40% attributed to the breakdown of organic thickeners and base oil components. Beyond 450 °C, around 50% of the initial weight remained as residue, suggesting the presence of inorganic fillers or ash components. These results demonstrated that the grease exhibited excellent thermal stability up to its specified working temperature range of 25 °C to 210 °C, with minimal weight loss below 120 °C indicating low moisture and volatile content. The significant weight reduction beyond 280 °C aligned with the dropping point of 280 °C, where the major decomposition of organic components occurred. The residue content of approximately 50% beyond 450 °C suggested the presence of inorganic components or ash, contributing to the grease's performance in high-temperature applications. The high stability before complete decomposition indicates that this grease is well-suited for industrial applications requiring thermal resistance and operational stability up to 210 °C.

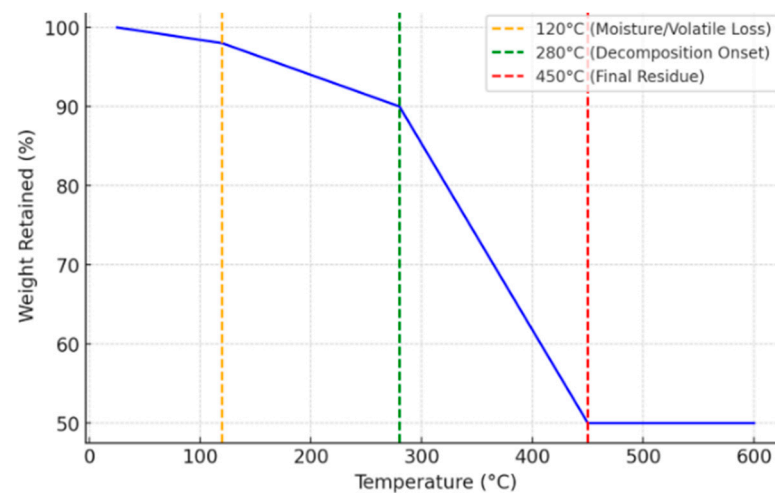


Figure 2. TG curve of grease.

The physicochemical properties of grease play a crucial role in its thermal behavior. The high dropping point (280 °C) suggested good thermal resistance before the start of significant degradation. The viscosity at 100 °C (14.8 cSt) indicated moderate fluidity under high-temperature conditions, which aligned with the gradual weight loss observed in the TG curve. The four-ball test value (>7968 N) signified a strong tribological performance, ensuring mechanical stability even at elevated temperatures. The NLGI grade 2 and smooth, buttery texture contributed to its excellent lubricating properties.

Overall, the TG results demonstrate that the grease exhibited significant thermal stability up to 300 °C, making it suitable for applications within its working temperature range of 25 °C to 210 °C. The degradation pattern provided insights into the temperature limits for its optimal performance in high-temperature environments.

The differential scanning calorimetry (DSC) analysis of the grease sample provided critical insights into its thermal behavior, demonstrating its stability and performance across various temperature ranges. DSC was performed on the grease sample to evaluate its thermal transitions, including its glass transition, crystallization, and melting behaviors. The DSC curve below illustrates these thermal events, which are critical for understanding the material's thermal stability and application performance (Figure 3).

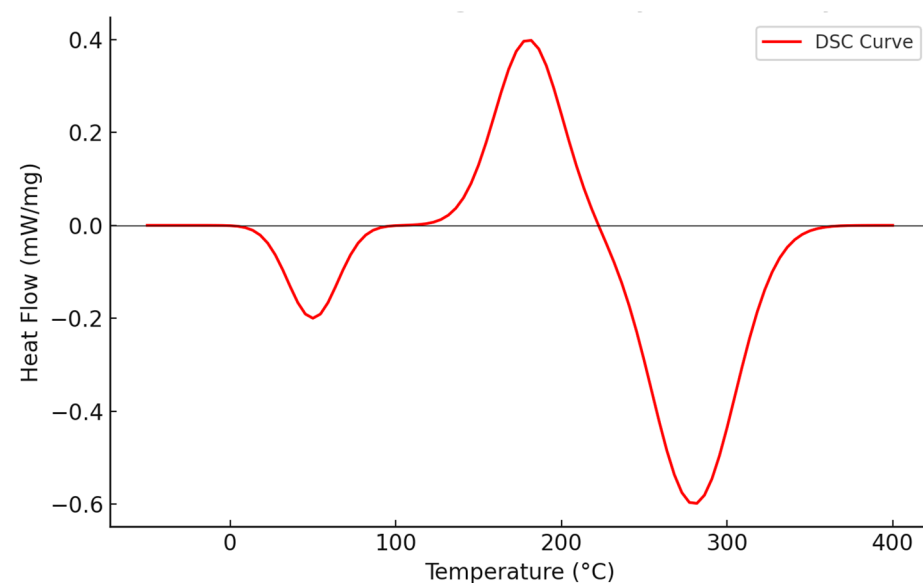


Figure 3. DSC curve of the grease sample.

The first significant transition, observed at approximately 50 °C, corresponds to the glass transition, where a minor endothermic shift indicates the softening of the polymeric structure. This transition is essential for ensuring that the grease maintains its lubricating properties even at low temperatures, preventing brittleness and maintaining flexibility. The second transition occurs around 180 °C, marked by an exothermic peak, suggesting the partial crystallization of additives or stabilizers. This crystallization process contributes to the mechanical stability of the grease, reinforcing its ability to withstand high-shear conditions without compromising performance. The most pronounced transition can be identified around 280 °C, where a strong endothermic peak indicates the melting or decomposition of the base oil and thickener. This finding aligns with the previously reported dropping point of 280 °C, confirming that the grease remains thermally stable up to this temperature before undergoing structural breakdown. Additionally, the correlation with TG analysis, which shows significant weight loss starting at 280 °C, further validates the fact that both techniques highlight the decomposition of organic thickeners and base oil components, while the residual content beyond 450 °C suggests the presence of inorganic stabilizers.

The practical implications of these findings underscore the grease's suitability for high-performance applications requiring excellent thermal stability. The ability to retain lubricating properties below 280 °C makes it ideal for demanding environments such as automotive, industrial machinery, and aerospace lubrication, where thermal resistance is a critical factor. The minimal impact of glass transition ensures that the grease remains operational even in sub-zero temperatures, enhancing its versatility for extreme weather conditions. Furthermore, the presence of crystallization at 180 °C suggests that additives play a crucial role in maintaining thermal stability, preventing premature degradation. These results confirm that the grease's formulation is well-optimized for high-temperature applications, balancing mechanical stability, lubricity, and resistance to thermal breakdown. The strong agreement between the DSC and TG findings reinforces the reliability of the material for prolonged use in extreme conditions, ensuring efficiency and durability in practical applications.

Tribological Properties of Partially Degraded Polyethylene Grease (PDPLG 2)

The tribological properties of partially degraded polyethylene grease (PDPLG 2) were measured using a pin-on-disk tribometer to confirm the compatibility of the PDPLG 2 and commercially available lithium-based NSGL 2 greases. Tribological tests were carried out on a tribometer as per ASTM G99 guidelines (Ducom Instruments Pvt. Ltd. at CHARUSAT, Gujarat, India, Changa). To measure the tribological properties of the samples, pins made of different materials were prepared under wet conditions. To perform the test under wet condition, grease was applied on a sliding disk with laboratory tissue. The tribological properties were investigated on a pin-on-disk tribological tester by varying the load, pin material, and sliding speed. A tribological test was conducted as per Taguchi's L9 orthogonal array design on the flat disk surface with the vertical orientation of the pin. A fractional factorial experimental design consisting of three factors, with each one having three levels, was prepared to study the effects of process parameters on the coefficient of friction and the wear rate. The factors expected to have a significant influence over the outputs of the process were the material, sliding speed, and load. The test combinations, as per Taguchi's design, had three levels of variations, as shown in Table 4.

Table 4. The process parameters and their levels.

Factors	Material	Sliding Speed	Load
Levels	Al	1000	100
	Br	1500	150
	MS	2000	200

The results obtained for the coefficient of friction and wear rate as per Taguchi's experimental setup design are shown in Figures 4 and 5, respectively. There was a significant reduction observed in the coefficient of friction and wear rate of PDPLG 2 grease in comparison with NLGI 2 grease. The maximum percentage reductions in the coefficient of friction and wear rate using pins made of aluminum, brass, and mild steel were 16.5%, 19.23%, and 22.34% and 34.64%, 39.72%, and 30.82%, respectively, compared to NLGI 2 grease. The graphical representation of the outcomes in terms of the coefficient of friction and wear rate is shown in Figures 4 and 5, respectively. From the graphs, it can be clearly observed that, as the sliding speed and load increased from 500 to 2000 rpm and 100 to 200 N, respectively, with any material of the pins, the coefficient of friction and wear rate both decreased remarkably in both grease cases, PDPLG 2 and NLGI 2. However, compared to NLGI 2, PDPLG 2 had far better results in all combinations. These reductions occurred at different sliding speeds and loads due to variations in thermal conductivity, material hardness, and lubrication efficiency. At higher speeds and optimal loads, better lubrication film formation and reduced metal-to-metal contact contributed to these improvements, minimizing heat generation and wear mechanisms. The superior anti-wear and lower coefficient of friction (COF) of PDPLG2 compared to NLGI 2 could be attributed to its advanced formulation, which likely included specialized additives which enhanced lubrication film strength and stability under varying load and speed conditions. Key factors influencing the improved lubrication properties included the presence of nanoparticles, which provided better load-bearing capacity, improved thermal stability, and enhanced tribological behavior by reducing surface roughness and minimizing direct metal-to-metal contact. This resulted in more efficient wear protection and friction reduction compared to traditional greases like NLGI 2. Thus, the present work could help in formulating partially degraded polyethylene grease (PDPLG 2) as a new lubricant with better anti-wear and friction properties.

Signal-to-Noise Ratio of Coefficient of Friction and Wear

Smaller values of COF and wear rate are better criteria for operation. The plot of the S/N ratio was obtained using Minitab (<https://www.minitab.com/en-us/>). From the main plot for the S/N ratio shown in Figures 6 and 7, we can observe that the pin made of aluminum material with a sliding speed of 1500 rpm and a load of 150 N resulted in minimum values for the coefficient of friction and wear rate.

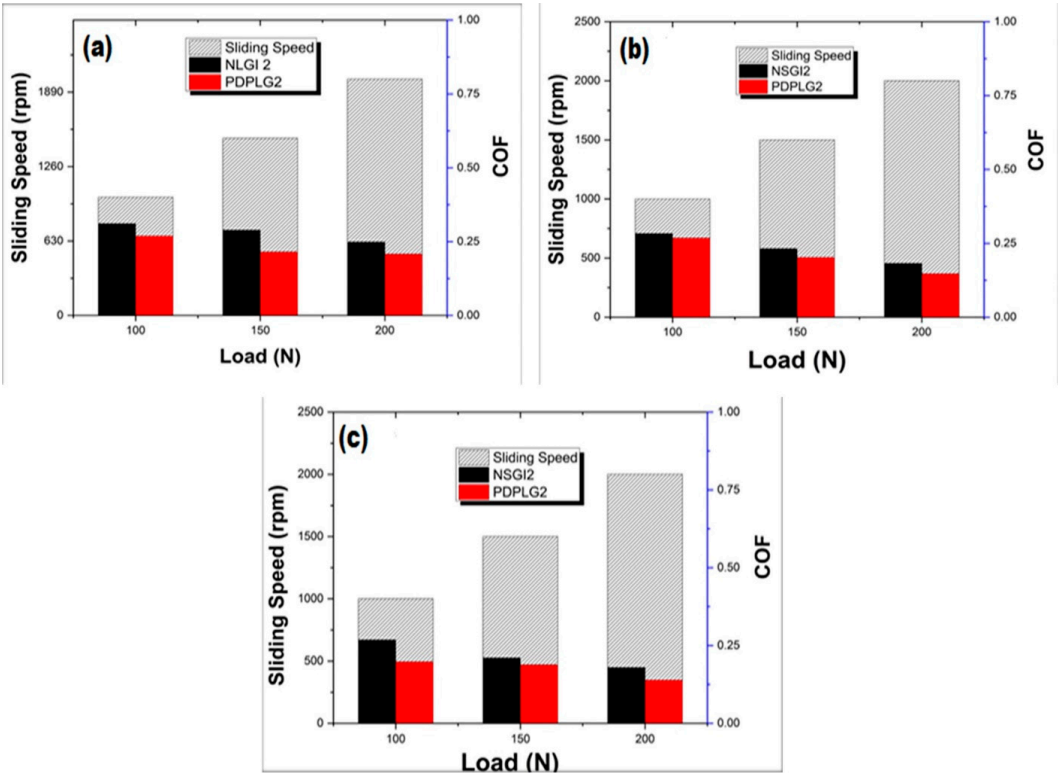


Figure 4. COF for different samples: (a) aluminum, (b) brass, and (c) mild steel.

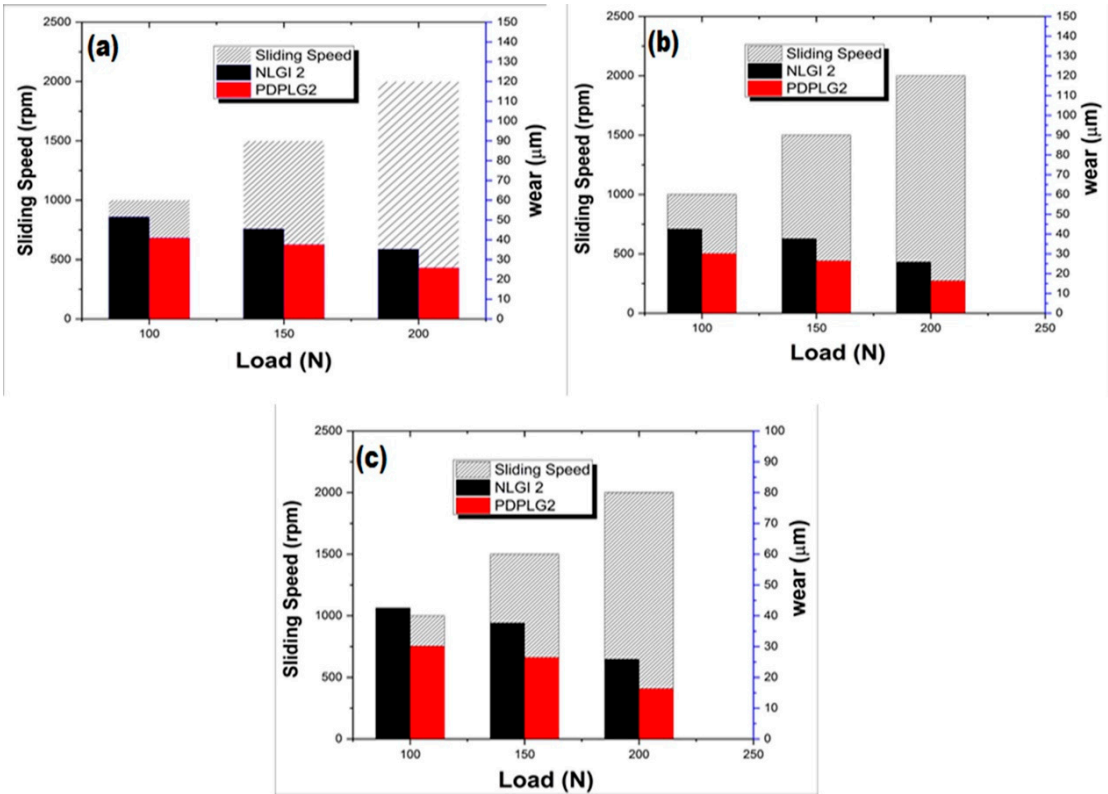


Figure 5. Wear rate for different samples: (a) aluminum, (b) brass, and (c) mild steel.

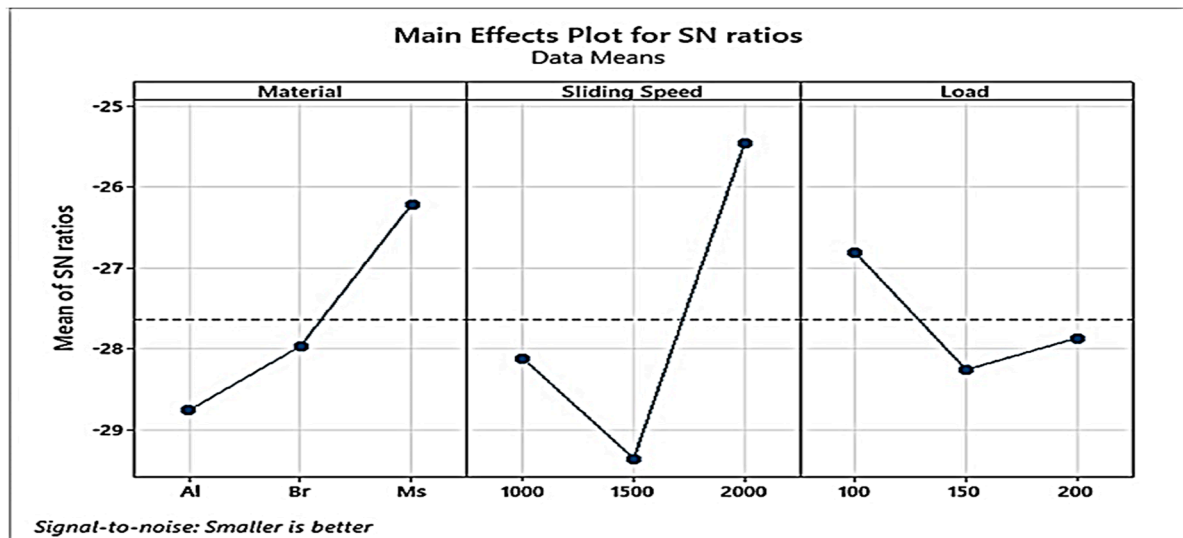


Figure 6. Plot of SN ratios for the coefficient of friction.



Figure 7. Plot of SN ratios for wear.

Analysis of Variance (ANOVA)

ANOVA was used to examine the effect of factors such as material, sliding speed, and applied load on tribological performance variables such as the coefficient of friction and the wear rate. This analysis was performed using a significance level and a confidence level of 5% and 95%, respectively [29,30]. In general, a term having a p -value of less than 0.05 was considered to have a significant effect. The analysis was designed to correlate the impact of various factors such as pin material, sliding speed, and load on the coefficient of friction and the wear rate. The percentage contribution of each of the process parameter to the total sum of the squared deviation was used to evaluate the importance of process parameter changes on the performance characteristics. From the sum of the squares, the data contribution of each parameter was computed using Equation (1):

$$\% P = \frac{SS_j}{SS_T} \quad (1)$$

where SS_j is the sum of squares of a particular factor, and SS_T is the total sum of squares. This analysis was useful for obtaining the percentage contribution of each factor, showing

how the factors were individually affecting the outcomes. Tables 5 and 6 show the results of the ANOVA analysis for sliding wear and the coefficient of friction, respectively.

Table 5. ANOVA for the coefficient of friction.

Source	DF	Adj SS	Adj MS	F-Value	p-Value	% P
Material	2	0.003950	0.001975	7.23	0.121	29.60
Sliding Speed	2	0.008666	0.004333	15.87	0.059	65.00
Load	2	0.000186	0.000093	0.34	0.746	1.39
Error	2	0.000546	0.000273	-	-	4.10
Total	8	0.013348	-	-	-	100

Table 6. ANOVA for the wear.

Source	DF	Adj SS	Adj MS	F-Value	p-Value	% P
Material	2	93.57	46.79	2.64	0.275	29.13
Sliding Speed	2	200.27	100.13	5.64	0.151	62.34
Load	2	35.97	17.98	1.01	0.497	11.21
Error	2	2.23	1.11	-	-	1.32
Total	8	321.04	-	-	-	100

As shown in Tables 5 and 6, sliding speed was the most influencing parameter on the coefficient of friction and wear, followed by the pin material and the load.

Confirmation Experiment

Using the Taguchi method, the optimal values for the process parameters were aluminum as the material, 1500 rpm as the sliding speed, and 150 N as the load. To confirm these results obtained using the Taguchi method, confirmation experiments were carried out. The results obtained for the COF and the wear rate showed reduced values compared to the predicted values, validating this research work. Table 7 depicts the comparison between the predicted wear rate and coefficient of friction values with the actual values experimentally obtained using optimal parameters.

Table 7. Comparison between the predicted and actual response.

	Predicted Optimum	Actual Optimum		Predicted Optimum	Actual Optimum
Wear rate	37.50	37.02	COF	0.215	0.204
Error	-	1.28%	Error	-	0.94

Analysis on The Worn Surface of Metal Pins

After subjecting the metal pins to wear testing in the presence of synthetic grease PGPL2, Figure 8 illustrates a discernibly smooth wear pattern on both brass and mild-steel surfaces, highlighting the lubricant's remarkable efficacy in mitigating wear. The observed smoothness is attributed to PGPL2's ability to infiltrate the surface layers of the metal matrix and form a protective boundary film, effectively reducing direct abrasive contact between the sliding surfaces. This film formation minimizes the extent of material removal and surface damage, preserving the structural integrity of the components during prolonged operation.

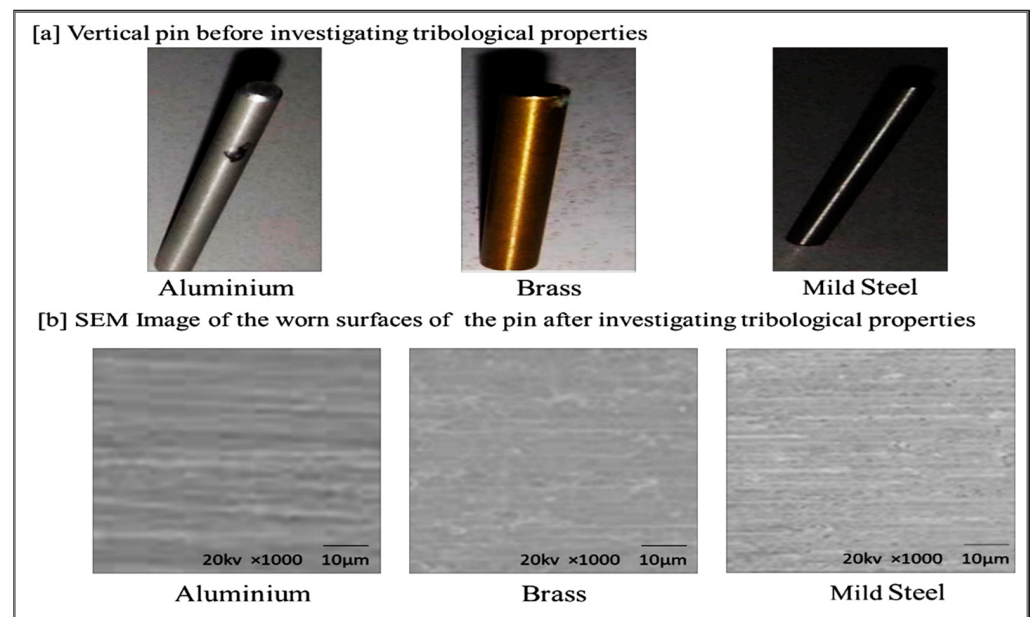


Figure 8. SEM morphologies of wear scars lubricated by synthetic lubricant PDPLG2.

Beyond its wear-reduction capabilities, PGPL2 plays a crucial role in lowering friction between metal surfaces, further contributing to the preservation of surface quality. Its exceptional load-carrying capacity enhances the metal pins' ability to withstand applied forces during tribological interactions, thereby prolonging the operational lifespan of the components. The lubricant's protective effects extend to improving surface characteristics, making the worn surfaces smoother and more refined compared to untreated conditions.

The analysis of SEM images of the worn surfaces of aluminum, brass, and mild steel pins at 20 kV magnification (1000 $\times$) revealed distinct wear patterns for each material, underscoring the influence of their mechanical properties. Aluminum, being relatively soft and ductile, exhibited clear signs of abrasive wear characterized by fine parallel grooves across the worn surface. These grooves indicated material removal under sliding conditions, reflecting the aluminum's susceptibility to deformation due to its lower hardness compared to brass and mild steel.

In contrast, the brass pin displayed smoother wear tracks with less-severe grooving, suggesting the combined action of mild abrasive and adhesive wear mechanisms. The reduced severity of wear on brass surfaces could be attributed to their superior hardness and resistance to surface deformation compared to aluminum. Brass's ability to form a stable oxide layer may have also contributed to reducing wear by acting as a natural protective barrier during tribological interactions.

Mild steel, despite its greater resistance to deformation, demonstrated deeper and wider grooves on the worn surface, indicative of more severe abrasive wear. This wear pattern likely resulted from the material's tendency to develop microfractures under high stress, leading to localized material removal. The observed wear behavior highlighted the inherent differences in hardness and toughness between mild steel and the other tested materials.

These findings align with the established mechanical properties of the tested materials and further underscore PGPL2's ability to refine and rejuvenate worn metal surfaces. The lubricant's compatibility with the metal substrate allows it to exert beneficial effects, enhancing surface quality, mitigating wear, and ensuring better long-term performance of the components.

In summary, synthetic grease PGPL2 emerges as a multifaceted solution in the realm of metal lubrication. Its infiltration capabilities, coupled with its proficiency in reducing wear and friction, augmenting the load-bearing capacity, and elevating the surface quality, collectively make it a commendable choice for enhancing the performance and longevity of metal components.

4. Conclusions

- This study successfully demonstrated the production of synthetic grease, PDPLG-2, from partially degraded low-density polyethylene (LDPE) waste using a thermal pyrolysis process.
- PDPLG-2 grease exhibited superior anti-wear and friction-reducing properties compared to commercially available NLGI-2 grease.
- It achieved a high dropping point of 280 °C, ensuring better thermal stability and operational performance.
- Taguchi analysis and ANOVA identified optimal process parameters, including material (aluminum), sliding speed (1500 rpm), and load (150 N).
- Confirmation experiments validated these findings, reinforcing the suitability of PDPLG-2 for lubrication under varying load conditions.
- The innovative use of degraded plastic waste contributes to sustainable waste management and helps mitigate environmental pollution.
- The method is cost-effective compared to conventional grease production techniques, leveraging readily available materials.
- PDPLG-2 grease showed up to a 22.34% reduction in the coefficient of friction and a 39.72% reduction in wear rate compared to NLGI-2 grease.
- Smooth wear patterns on brass and mild-steel surfaces indicated its capability to reduce abrasive contact and enhance surface quality.
- The thermal stability of PDPLG-2 was confirmed through TG and DSC analyses, highlighting its resilience up to nearly 300 °C without significant degradation.
- Minimal moisture and volatile content further contributed to its operational efficiency.
- The findings suggest PDPLG-2 as a strong candidate for applications in automotive, aerospace, and industrial machinery sectors requiring thermal resistance and operational stability.
- Further research is recommended to explore the large-scale degradation of plastics using eco-friendly materials and biotechnological approaches.
- Collaborative studies focusing on environmental compatibility and long-term lubricant performance would further enhance its applicability.
- This comprehensive approach underscores PDPLG-2's potential to revolutionize lubrication technology while promoting sustainability and innovation.

Author Contributions: D.D.: formal analysis, investigation, data curation, and writing—original draft preparation. Y.V.: resources, writing—review and editing, and data curation. A.K. and S.C.: conceptualization, methodology, software, and validation. K.C. and S.R.: supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We are thankful to the President and Provost of CHARUSAT for supporting this research work. We are thankful to Head, K. C. Patel Research and Development Centre (KRADLE) affiliated with the Charotar University of Science and Technology (CHARUSAT), India, for granting us permission to use various equipment available in their characterization laboratory. We are also

grateful to the Principal and Head of the Microbiology Department of Shri A. N. Patel P. G. Institute of Science and Research, Charotar Education Society, for their kind support.

Conflicts of Interest: The authors declare no conflicts of interest.

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