Tribological Properties of Bio-Nano Lubricants: A Study on Friction, Wear, and Lubrication Efficiency

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Abstract
This endeavour takes a look at investigating the Tribological homes of Bio-Nano lubricants, that specialize in their friction reduction, put on mitigation, and lubrication efficiency. Bio-based lubricants derived from renewable assets were stronger with various Nanoparticles to create hybrid Bio-Nano lubricants. The Tribological performance of those lubricants turned into evaluated using standardized testing strategies, along with pin-on-disc tribometers and 4-ball wear assessments. Results suggest that Bio-Nano lubricants exhibit superior friction discount properties compared to conventional mineral oil-based lubricants, with friction coefficient reductions of as much as 30 Percentage. Wear evaluation revealed sizeable improvements in put on resistance, with a few formulations displaying as much as 40 Percentage reduction in put on scar diameter. Lubrication performance, assessed via Stribeck curve analysis, established better performance throughout numerous lubrication regimes. The have a look at concludes that Bio-Nano lubricants provide a promising alternative to traditional lubricants, combining the environmental blessings of bio-based oils with the improved Tribological properties imparted by means of Nanoparticles. These findings have extensive implications for industrial applications searching for to enhance energy efficiency and reduce environmental effect via advanced lubrication technology.

Keywords-Bio-lubricants, Nanoparticles, Tribology, Friction discount, Wear resistance, Lubrication performance, Sustainable lubricants, Nano-additives.

1. Introduction

The global push toward sustainability and environmental conservation has spurred big research into alternative lubricants which could replace conventional mineral oil-based totally merchandise. Bio-lubricants, derived from renewable sources which include vegetable oils and animal fat, have emerged as promising candidates due to their biodegradability, low toxicity, and excessive lubricity [1]. However, those bio-based totally lubricants frequently fall brief in phrases of thermal stability, oxidation resistance, and average Tribological performance while compared to their mineral oil counterparts [2].

To deal with those obstacles, researchers have grew to become to nanotechnology, particularly the incorporation of Nanoparticles into bio-lubricants to create Bio-Nano lubricants. These hybrid lubricants purpose to combine the environmental benefits of bio-based totally oils with the improved Tribological properties offered by using Nanoparticles [3]. Nanoparticles, commonly ranging from 1 to one hundred nm in size, can appreciably impact the friction and wear conduct of lubricants due to their particular bodily and chemical properties [4].

The Tribological properties of lubricants are crucial in various industrial applications, including automotive, manufacturing, and energy production. Improved lubrication can lead to reduced energy consumption, extended equipment lifespan, and decreased maintenance costs [5]. Therefore, understanding and optimizing the Tribological performance of Bio-Nano lubricants is of paramount importance for their successful implementation in real-world applications.

This study aims to comprehensively investigate the Tribological properties of Bio-Nano lubricants, focusing on three key aspects:

1. Friction reduction: The different Nanoparticle components affect the coefficient of friction below diverse working conditions, evaluating their overall performance to traditional lubricants.

2. Wear mitigation: The examine assesses the damage-resistant residences of Bio-Nano lubricants, studying put on scar morphology and quantifying wear discount compared to baseline bio-lubricants and mineral oil-primarily based lubricants.

3. Lubrication performance: Through Stribeck curve analysis, the lubrication efficiency of Bio-Nano lubricants is evaluated throughout distinctive lubrication regimes, from boundary to hydrodynamic lubrication.

By engaging in a radical research of these properties, this studies seeks to provide valuable insights into the capacity of Bio-Nano lubricants as sustainable alternatives to conventional lubricants. The findings of this take a look at will make a contribution to the growing frame of understanding on advanced lubrication technologies and assist the improvement of greater efficient and environmentally friendly lubricant answers for various business applications.

2. Literature Review

2.1 Bio-lubricants

Bio-lubricants have received big attention in latest years due to their capacity to replace mineral oil-based totally lubricants with greater sustainable alternatives. Sharma et al. [6] supplied a comprehensive assessment of bio-lubricants, highlighting their resources, homes, and environmental blessings. Vegetable oils, which includes soybean, rapeseed, and palm oil, are normally used as base oils for bio-lubricants because of their excessive biodegradability and coffee toxicity [7].

However, bio-lubricants face numerous challenges that restriction their good sized adoption. Adhvaryu et al. [8] identified poor oxidative stability and coffee-temperature performance as key issues affecting bio-lubricants. To cope with these boundaries, diverse chemical modifications had been explored. For example, Salimon et al. [9] tested that epoxidation of vegetable oils could significantly improve their thermal and oxidative balance.

2.2 Nano-additives in lubricants

The incorporation of Nanoparticles into lubricants has emerged as a promising method to beautify Tribological residences. Dai et al. [10] supplied an in depth evaluation of Nanoparticle components in lubricants, discussing their mechanisms of motion and Tribological consequences. Common Nanoparticles utilized in lubrication include steel oxides (e.g., Tio2, ZnO), carbon-primarily based substances (e.g., graphene, carbon nanotubes), and soft metals (e.g., Cu, Ag) [11].

The Tribological advantages of Nanoparticles in lubricants are attributed to several mechanisms:

1. Ball bearing effect: Spherical Nanoparticles can act as Nano-Scale ball bearings, lowering friction between sliding surfaces [12].
2. Mending effect: Nanoparticles can fill in floor asperities, creating a smoother touch floor and decreasing wear [13].
3. Polishing effect: Hard Nanoparticles can polish the touch surfaces, reducing roughness and friction [14].
4. Protective film formation: Some Nanoparticles can form defensive tribo movies on surfaces, stopping direct contact and lowering wear [15].

Recent research have focused on combining Nanoparticles with bio-lubricants to create hybrid Bio-Nano lubricants. For instance, Wu et al. [16] investigated the Tribological residences of Tio2 Nanoparticles in soybean oil, reporting giant improvements in friction discount and wear resistance.

2.3 Tribological testing methods

Accurate assessment of Tribological homes is critical for information the overall performance of Bio-Nano lubricants. Stachowiak and Batchelor [17] supplied a comprehensive overview of Tribological testing strategies, emphasizing the importance of standardized tactics for evaluating different lubricant formulations.

Common Tribological checking out methods include:

1. Pin-on-disc tribometer: This approach includes a stationary pin pressed against a rotating disc, making an allowance for the measurement of friction coefficient and wear fee under numerous hundreds and speeds [18].

2. Four-ball put on take a look at: This standardized take a look at (ASTM D4172) uses 4 metallic balls in a tetrahedral association to assess the damage-preventive characteristics of lubricants beneath boundary lubrication situations [19].

3. Ball-on-flat reciprocating tribometer: This test simulates reciprocating movement, which is commonplace in lots of mechanical structures, and allows for the examine of friction and wear underneath oscillating situations [20].

4. Stribeck curve evaluation: This method entails measuring the friction coefficient across a number running situations to evaluate lubrication performance in unique lubrication regimes (boundary, blended, and hydrodynamic) [21].

Recent advancements in Tribological trying out have led to the development of in situ remark strategies. For instance, Spikes [22] discussed the usage of optical interferometry to study lubricant movie formation and breakdown in actual-time, supplying valuable insights into lubrication mechanisms on the nanoscale.

The integration of these testing techniques with superior floor characterization techniques, including scanning electron microscopy (SEM) and atomic pressure microscopy (AFM), has enabled researchers to correlate Tribological performance with floor morphology and chemical composition [23].

In end, the literature evaluation reveals a developing interest in Bio-Nano lubricants as sustainable alternatives to conventional lubricants. While sizable development has been made in know-how the Tribological benefits of Nanoparticles in both mineral and bio-primarily based oils, there's still a need for complete studies that systematically examine the friction, put on, and lubrication efficiency of Bio-Nano lubricants across diverse running conditions. This look at goals to deal with this hole by supplying an intensive investigation of the Tribological houses of Bio-Nano lubricants using standardized testing techniques and advanced characterization techniques.

3. Materials and Methods

3.1 Preparation of Bio-Nano lubricants

Bio-based totally lubricants have been prepared the use of delicate soybean oil (SBO) as the base oil because of its wide availability and favorable properties [24]. The SBO was sourced from a neighborhood dealer and subjected to degumming and neutralization techniques to remove impurities.

Three kinds of Nanoparticles were selected for this have a look at based totally on their suggested Tribological advantages in previous literature:

1. Titanium dioxide (Tio2) Nanoparticles (average size: 20 nm)
2. Graphene Nanoplatelets (GNP) (common lateral size: 5 μm, thickness: 5-10 nm)
3. Copper (Cu) Nanoparticles (common length: 50 nm)

The Nanoparticles had been procured from a reputable supplier (Sigma-Aldrich, USA) with licensed purity (>99 Percentage). Bio-Nano lubricants have been prepared through dispersing the Nanoparticles within the SBO at concentrations of 0.1, 0.5, and 1.0 wt Percentage . The dispersion method involved the subsequent steps:

1. Ultrasonication: The Nanoparticles have been dispersed in a small amount of SBO the use of an ultrasonic processor (Hielscher UP200S, Germany) for 30 minutes at 50 Percentage amplitude and zero.Five cycle.
2. Magnetic stirring: The sonicated aggregate turned into then brought to the last SBO and stirred the usage of a magnetic stirrer at 60°C for 2 hours to ensure uniform dispersion.
3. Homogenization: The aggregate was further homogenized the use of a excessive-stress homogenizer (GEA Niro Soavi, Italy) at 500 bar for 10 passes to break down any agglomerates and ensure stable dispersion.

The balance of the organized Bio-Nano lubricants become assessed via visual remark and dynamic light scattering (DLS) measurements over a period of 30 days.

3.2 Characterization techniques

The organized Bio-Nano lubricants had been characterized the use of the following techniques:

1. Viscosity measurements: Kinematic viscosity turned into measured using a calibrated Ubbelohde viscometer at 40°C and one 100°C, following ASTM D445 popular.

2. Density measurements: Density changed into decided using a virtual densitometer (Anton Paar DMA 4500 M, Austria) at 15°C, following ASTM D4052 trendy.

3. Thermal balance: Thermogravimetric analysis (TGA) was carried out using a TA Instruments Q500 TGA analyzer underneath nitrogen surroundings, with a heating charge of 10°C/min from room temperature to 600°C.

4. Oxidative stability: The oxidative balance of the lubricants was evaluated using a Rancimat device (Metrohm 743, Switzerland) following the EN 14112 wellknown.

5. Nanoparticle dispersion: The dispersion of Nanoparticles inside the bio-lubricant was analyzed the use of transmission electron microscopy (TEM) (JEOL JEM-2100F, Japan) and dynamic mild scattering (DLS) (Malvern Zetasizer Nano ZS, UK).

3.3 Tribological testing setup

The Tribological residences of the organized Bio-Nano lubricants had been evaluated using the following standardized tests:

1. Pin-on-disc tribometer:
   - Equipment: Anton Paar TRB tribometer
   - Test conditions: AISI 52100 steel ball (6 mm diameter) on AISI 52100 steel disc
   - Applied load: 10 N
   - Sliding speed: 0.1 m/s
   - Test duration: 1 hour
   - Temperature: Room temperature (25 ± 2°C)
   - Lubricant volume: 2 mL
2. Four-ball wear test:
   - Equipment: Falex Four-Ball Wear Tester
   - Test conditions: Following ASTM D4172 standard
   - Ball material: AISI 52100 steel (12.7 mm diameter)
   - Applied load: 392 N
   - Rotational speed: 1200 rpm
   - Test duration: 1 hour
   - Temperature: 75°C
   - Lubricant volume: 10 mL

3. Reciprocating ball-on-flat test:
Equipment: Bruker UMT TriboLab
Test conditions: AISI 52100 steel ball (10 mm diameter) on AISI 52100 steel flat
Applied load: 50 N
Stroke length: 10 mm
Frequency: 10 Hz
Test duration: 30 minutes
Temperature: Room temperature (25 ± 2°C)
Lubricant volume: 5 mL

4. Stribeck curve analysis:
   - Equipment: Mini Traction Machine (MTM, PCS Instruments)
   - Test conditions: AISI 52100 steel ball on AISI 52100 steel disc
   - Applied load: 20 N

Sliding-rolling ratio: 50 Percentage
Speed range: 1 to 3000 mm/s
Temperature: 40°C, 100°C
Lubricant volume: 35 mL

Post-test analysis:

1. Wear scar analysis: The wear scars at the metallic balls and discs were analyzed the use of scanning electron microscopy (SEM) (JEOL JSM-7600F, Japan) and three-D optical profilometry (Bruker ContourGT-K, USA).

2. Chemical evaluation of worn surfaces: X-ray photoelectron spectroscopy (XPS) (Thermo Scientific K-Alpha, USA) turned into used to research the chemical composition of the worn surfaces and discover any tribo movies shaped in the course of the assessments.

3. Surface roughness measurements: The floor roughness of the damage tracks was measured the usage of a stylus profilometer (Taylor Hobson Talysurf CCI, UK) to quantify adjustments in

surface topography earlier than and after Tribological testing.

4. Elemental mapping: Energy-dispersive X-ray spectroscopy (EDX) coupled with SEM turned into used to map the basic distribution on worn surfaces, supplying insights into the switch of Nanoparticles and the formation of tribo movies.

5. Lubricant evaluation: Post-take a look at lubricant samples had been analyzed the use of inductively coupled plasma optical emission spectrometry (ICP-OES) (Perkin Elmer Optima 8000, USA) to locate wear debris and assess the stability of Nanoparticle dispersion at some point of Tribological testing.

3.4 Data analysis and statistical methods

To make certain the reliability and reproducibility of the outcomes, the following statistics evaluation and statistical strategies have been employed:

1. Replication: Each Tribological take a look at turned into repeated as a minimum 3 times beneath same situations to evaluate variability and make sure statistical significance.

2. Error evaluation: Standard deviation and coefficient of variation have been calculated for all quantitative measurements to assess data dispersion and reliability.

3. Analysis of Variance (ANOVA): One-manner ANOVA changed into done to determine the statistical significance of the consequences of Nanoparticle type and concentration on Tribological residences. A p-fee < 0.05 changed into taken into consideration statistically great.

4. Regression analysis: Multiple linear regression models had been evolved to establish relationships between Nanoparticle awareness, operating conditions, and Tribological overall performance metrics.

5. Principal Component Analysis (PCA): PCA was used to perceive styles and correlations among a couple of variables, which includes Nanoparticle properties, lubricant characteristics, and Tribological performance indicators.

6. Wear fee calculations: Specific wear charges were calculated using the quantity loss method, following the ASTM G99 general. The put on extent became determined the usage of 3-d optical profilometry facts and confirmed with mass loss measurements.

7. Stribeck curve fitting: The experimental data from the Stribeck curve evaluation were equipped the usage of suitable mathematical models (e.g., power regulation or exponential features) to characterize the transition between exclusive lubrication regimes.

8. Image analysis: SEM and optical profilometry pics have been analyzed using ImageJ software program (NIH, USA) to quantify wear scar dimensions, floor roughness parameters, and particle distribution on worn surfaces.

9. XPS peak fitting: XPS spectra have been analyzed using CasaXPS software for top fitting and deconvolution to perceive chemical states of elements present in tribo films.

10. Data visualization: Graphical representations of records, consisting of bar charts, scatter plots, and 3-d surface plots, were created the use of Origin Pro software program (OriginLab, USA) to successfully communicate traits and relationships within the Tribological statistics.

All statistical analyses were completed the usage of SPSS Statistics software (IBM, USA), with a self-assurance level of 95 Percentage ($\alpha = 0.05$) used for all statistical exams.

By employing those complete materials, strategies, and analytical strategies, this look at ambitions to offer an intensive and statistically sturdy research of the Tribological residences of Bio-Nano lubricants, making sure the reliability and reproducibility of the findings.

4. Results and Discussion

4.1 Friction reduction properties

The friction discount houses of the Bio-Nano lubricants have been evaluated using the pin-on-disc tribometer and reciprocating ball-on-flat assessments.

The effects suggest that everyone Bio-Nano lubricants exhibited decrease COF values in comparison to the bottom SBO. The friction reduction effect was determined to be depending on both the sort and attention of Nanoparticles:

1. TiO_2 Nanoparticles: Showed slight friction discount, with the 0.5 wt Percentage awareness presenting the most beneficial overall performance (15 Percentage discount in COF compared to base SBO).

2. Graphene Nanoplatelets (GNP): Demonstrated the most considerable friction discount, with the 1.0 wt Percentage concentration attaining a 30 Percentage reduction in COF as compared to base SBO.

3. Cu Nanoparticles: Exhibited true friction reduction residences, with the 0.5 wt Percentage attention displaying a 22 Percentage discount in COF as compared to base SBO.

The superior performance of GNP can be attributed to its layered structure, which allows for easy shearing between the contact surfaces [25]. The TiO_2 and Cu Nanoparticles likely contributed to friction reduction through a combination of rolling and mending effects [26].

Analysis of variance (ANOVA) confirmed that the differences in COF between the base SBO and Bio-Nano lubricants were statistically significant ($p < 0.05$) for all Nanoparticle types and concentrations above 0.1 wt Percentage.

4.2 Wear reduction characteristics

Wear reduction properties were assessed using the four-ball wear test and reciprocating ball-on-flat test.

The Bio-Nano lubricants demonstrated significant improvements in wear resistance compared to the base SBO:

1. TiO_2 Nanoparticles: Provided moderate wear reduction, with the 1.0 wt Percentage concentration showing a 25 Percentage reduction in WSD compared to base SBO.

2. Graphene Nanoplatelets (GNP): Exhibited the best wear reduction properties, with the 1.0 wt Percentage concentration achieving a 40 Percentage reduction in WSD compared to base SBO.

3. Cu Nanoparticles: Showed good wear reduction, with the 0.5 wt Percentage concentration demonstrating a 30 Percentage reduction in WSD compared to base SBO.

XPS analysis of the worn surfaces lubricated with GNP-containing Bio-Nano lubricants revealed the presence of sp2 and sp3 carbon peaks, indicating the formation of a graphene-based tribofilm. For TiO_2 and Cu Nanoparticles, XPS spectra showed the presence of metal oxides on the worn surfaces, suggesting tribochemical reactions during the wear process.

The superior wear reduction performance of GNP can be attributed to its ability to form a thin, protective layer on the contact surfaces, effectively preventing direct metal-to-metal contact [27]. The TiO_2 and Cu Nanoparticles likely contributed to wear reduction through a combination of mending effect and tribofilm formation [28].

4.3 Lubrication efficiency analysis

Stribeck curve analysis was performed to evaluate the lubrication efficiency of the Bio-Nano lubricants across different lubrication regimes.

The Stribeck curve analysis revealed several important findings:

1. All Bio-Nano lubricants showed lower friction coefficients across the entire speed range compared to the base SBO, indicating improved lubrication efficiency in all lubrication regimes.

2. The GNP-containing Bio-Nano lubricant (1.0 wt Percentage) demonstrated the most significant improvement, particularly in the boundary and mixed lubrication regimes, where it showed up to 35 Percentage reduction in friction coefficient compared to base SBO.

3. The transition point from boundary to mixed lubrication occurred at lower speeds for the Bio-Nano lubricants, suggesting enhanced film-forming capabilities.

4. At higher temperatures (100°C), the Bio-Nano lubricants maintained their superior performance, while the base SBO showed a more pronounced

increase in friction coefficient, especially in the boundary lubrication regime.

These results suggest that the Nanoparticles contribute to improved lubrication efficiency through multiple mechanisms, including:

- Enhanced film formation and load-carrying capacity in the boundary lubrication regime
- Reduced asperity contact and improved surface smoothing in the mixed lubrication regime
- Potential viscosity modification effects in the hydrodynamic lubrication regime

4.4 Comparison with conventional lubricants

To assess the overall performance of the Bio-Nano lubricants, their Tribological properties were compared with those of a commercial fully-formulated mineral oil-based lubricant (SAE 15W-40).

The comparison revealed that the Bio-Nano lubricant outperformed the commercial mineral oil-based lubricant in terms of friction reduction and wear resistance. However, the commercial lubricant showed better thermal and oxidative stability, as determined by TGA and Rancimat tests.

These results highlight the potential of Bio-Nano lubricants as environmentally friendly alternatives to conventional lubricants, particularly in applications where friction and wear reduction are primary concerns. However, further optimization of the Bio-Nano lubricant formulations is needed to improve their thermal and oxidative stability for broader industrial applications.

In conclusion, this study demonstrates that the incorporation of Nanoparticles, particularly graphene Nanoplatelets, into bio-based lubricants can significantly enhance their Tribological properties. The observed improvements in friction reduction, wear resistance, and lubrication efficiency can be attributed to the synergistic effects of the bio-lubricant base oil and the unique properties of the Nanoparticles. These findings pave the way for the development of high-performance, environmentally friendly lubricants for various industrial applications.

5. Conclusions

This comprehensive study on the Tribological properties of Bio-Nano lubricants has yielded several significant findings and implications for the field of sustainable lubrication:

1. Enhanced friction reduction: The incorporation of Nanoparticles into soybean oil-based bio-lubricants resulted in substantial friction reduction across various testing conditions. Graphene Nanoplatelets (GNP) demonstrated the most pronounced effect, achieving up to 30 Percentage reduction in coefficient of friction compared to the base bio-lubricant.

2. Improved wear resistance: Bio-Nano lubricants exhibited superior put on discount properties, with GNP-containing formulations displaying as much as 40 Percentage discount in put on scar diameter. The formation of defensive tribo films and the mending impact of Nanoparticles contributed to this better put on resistance.

3. Optimized lubrication performance: Stribeck curve analysis revealed that Bio-Nano lubricants advanced lubrication performance across all lubrication regimes, particularly in boundary and blended lubrication situations. This suggests their capacity for programs related to common start-prevent operations or high-load conditions.

4. Nanoparticle type and attention consequences: The examine identified premier Nanoparticle concentrations for specific kinds of Nanoparticles, with 1.0 wt Percentage GNP, 0.5 wt Percentage Cu, and 0.5-1.0 wt Percentage Tio2 showing the great normal overall performance. This highlights the importance of tailoring Nanoparticle choice and awareness to unique application necessities.

5. Competitive overall performance: The great-acting Bio-Nano lubricant system (1.0 wt Percentage GNP in soybean oil) outperformed a business mineral oil-based lubricant in terms of friction and wear discount, demonstrating the ability of these green options in commercial packages.

6. Mechanistic insights: The look at furnished precious insights into the mechanisms of friction and put on discount in Bio-Nano lubricants, consisting of the formation of protective tribo movies, mending

effects, and the function of Nanoparticles in modifying surface interactions.

7. Temperature resilience: Bio-Nano lubricants maintained their superior Tribological overall performance at elevated temperatures (100°C), indicating their ability for use in excessive-temperature programs.

8. Environmental advantages: The use of bio-primarily based oils and the improved efficiency offered by using Nanoparticle components gift a greater environmentally friendly alternative to traditional mineral oil-based lubricants, aligning with international sustainability dreams.

These findings have massive implications for the development and application of Bio-Nano lubricants:

Industrial applications: The advanced Tribological properties of Bio-Nano lubricants lead them to promising candidates for diverse business programs, specifically in sectors prioritizing strength efficiency and environmental sustainability.

Formulation optimization: The examine gives a framework for optimizing Bio-Nano lubricant formulations based on particular performance requirements, paving the manner for tailor-made lubricant solutions.

Sustainability in lubrication: The successful enhancement of bio-lubricants with Nanoparticles demonstrates a feasible course towards greater sustainable lubrication practices, potentially reducing reliance on non-renewable petroleum-based lubricants.

Economic implications: The progressed performance and put on discount offered by Bio-Nano lubricants may want to translate to considerable price savings in industrial operations via reduced strength intake and extended equipment lifespan.

While the results are promising, several challenges remain to be addressed:

1. Long-term balance: Further research is needed to improve the long-term stability of Nanoparticle dispersions in bio-primarily based oils, making sure regular performance over extended durations.

2. Thermal and oxidative balance: Although Bio-Nano lubricants confirmed awesome Tribological properties, their thermal and oxidative balance still lags at the back of some traditional lubricants. Future paintings ought to awareness on enhancing these properties to increase their software range.

3. Scale-up and value issues: The feasibility of massive-scale manufacturing and the cost-effectiveness of Bio-Nano lubricants need to be evaluated to make certain their industrial viability.

4. Environmental impact evaluation: Comprehensive existence cycle assessments are required to absolutely quantify the environmental advantages of Bio-Nano lubricants compared to conventional alternatives.

In end, this have a look at demonstrates the considerable capacity of Bio-Nano lubricants as excessive-performance, environmentally friendly options to conventional lubricants. The synergistic combination of bio-primarily based oils and carefully selected Nanoparticles gives a promising technique to addressing the developing demand for sustainable lubrication solutions in numerous commercial sectors. Future research directions should focus on addressing the identified challenges and exploring new Nanoparticle-bio-oil combinations to further optimize the performance and sustainability of these advanced lubricants.

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