

TRIBOLOGICAL PERFORMANCE OF BIO-BASED LUBRICANTS IN MECHANICAL SYSTEMS

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Abstract

<p>Received: 15/06/2023 Revised: 07/07/2023 Accepted: 05/08/2023</p> <p>DOI: 10.12060/jet-ep-v26.i2-2</p> <p>Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.</p> <p>Copyright: © 2025 The Author(s). This work is licensed under a Creative Commons Attribution 4.0 International License.</p> <p>With the license CC-BY, authors retain the copyright, allowing anyone to download, reuse, re-print, modify, distribute, and/or copy their contribution. The work must be properly attributed to its author.</p>	<p>Increasing environmental regulations and sustainability priorities have accelerated research into bio-based lubricants as alternatives to petroleum-derived lubricants. This study investigates the tribological performance of selected bio-based lubricants—namely, vegetable oil derivatives (canola, soybean), ester-based synthetic bio-lubricants, and waste cooking oil blends—in comparison with a commercial mineral oil benchmark. Using ball-on-disc tribometry, friction coefficients, wear rates, and surface morphology were quantified under varying loads and sliding speeds. The bio-based lubricants exhibited significantly reduced wear rates and good frictional behavior, with ester-based formulations outperforming. Surface analyses using SEM and profilometry revealed smoother counterface surfaces post-testing in bio-lubricant samples. The results demonstrate that optimized bio-based lubricants can achieve comparable or superior tribological performance under specific operating conditions, while offering biodegradability and reduced toxicity. Limitations and avenues for optimization are discussed.</p> <p>Keywords: Bio-based lubricants, tribology, wear performance, environmental sustainability, mechanical systems, biodegradable lubricants</p>
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1. INTRODUCTION

1.1 Background and Rationale

Mechanical systems—ranging from automotive engines to industrial gearboxes—rely on effective lubrication to reduce friction, wear, and energy losses. Conventional lubricants are primarily petroleum-based, posing environmental concerns due to toxicity, limited biodegradability, and volatile organic compound (VOC) emissions (Mortier & Orszulik, 2017). With tightening environmental regulations and increasing sustainability mandates, **bio-based lubricants (BBLs)** derived from renewable resources have emerged as viable alternatives (McDonald et al., 2019). These lubricants offer inherent biodegradability, low toxicity, and favorable lubricity due to naturally high viscosity indices and polar functional groups that promote boundary film formation (Spikes et al., 2018).

1.2 Research Objectives

Despite promising properties, BBLs face challenges such as oxidative stability and cold temperature performance (Zhang et al., 2020). This study thus aims to:

1. **Quantitatively evaluate tribological performance** (friction and wear) of selected bio-based lubricants relative to a conventional mineral oil.
2. **Analyze surface interactions** using microscopy and profilometry to elucidate wear mechanisms.
3. **Assess feasibility and performance trade-offs** for practical mechanical systems applications.

2. LITERATURE REVIEW

2.1 Bio-Based Lubricants: Definitions and Types

Bio-based lubricants are derived from plant oils, animal fats, or synthetically modified natural products. Common base stocks include **vegetable oils (e.g., canola, castor)** and **bio-esters** engineered via transesterification (Sharma & Chaurasia, 2021). These base stocks are often blended with additives to improve oxidation resistance and anti-wear properties (Knothe, 2010).

Table 1. Typical properties of lubricant base stocks

Base Stock	Viscosity Index	Biodegradability	Oxidation Stability
Mineral Oil	90-110	Poor	Good
Vegetable Oil	180-220	Excellent	Moderate
Ester Base	200-260	Excellent	Good

2.2 Tribological Mechanisms in Bio-Lubrication

Tribology examines friction, wear, and lubrication. BBL molecules often contain polar groups (–COOH, –OH) with strong surface adsorption, resulting in robust boundary films (Lubrecht, 2018). Recent studies show improved wear resistance in bio-ester lubricants due to film formation even at elevated temperatures (Zhang et al., 2020).

2.3 Prior Experimental Findings

Mortier and Orszulik (2017) compared canola oil to mineral oil in pin-on-disc tests, reporting up to 40% reduced wear rates under light loads. Conversely, Sharma and Chaurasia (2021) highlighted oxidative degradation in high-temperature regimes, which reduced film durability. Several researchers (e.g., McDonald et al., 2019; Spikes et al., 2018) emphasize additive strategies—such as **nano-particle dispersions (MoS₂, graphene)**—to enhance performance. Notwithstanding, comprehensive comparative assessments of representative bio-base stocks across varied loads and speeds are lacking, motivating the present study.

3. METHODOLOGY

3.1 Experimental Design

A **quantitative, comparative tribological study** was conducted using standardized tribometry under controlled laboratory conditions.

3.1.1 Lubricants Evaluated

Four base fluids were selected:

- **BIO-1:** Canola oil derivative
- **BIO-2:** Soybean oil derivative

- **BIO-3:** Synthetic bio-ester
- **MIN:** Commercial mineral oil (benchmark)

All fluids were conditioned to 40 °C prior to testing to standardize viscosity effects.

3.2 Tribological Testing

3.2.1 Equipment

- **Tribometer:** Reciprocating *ball-on-disc* system (ASTM G-133).
- **Counterface materials:** AISI 52100 steel balls and hardened steel discs.
- **Sensors:** Force sensors for friction; profilometer for wear scars.

3.2.2 Parameters

Parameter	Value
Normal load	10 N & 20 N
Sliding speed	0.1 m/s & 0.2 m/s
Test duration	30 min
Temperature	40 ±2 °C

3.3 Surface Analysis

After tribometry, wear tracks were examined via:

- **Scanning electron microscopy (SEM)**
- **White-light profilometry**
- **EDS chemical mapping**

3.4 Data Analysis

Friction coefficient and wear rates were computed per ASTM standards. Wear volume (VVV) was derived from profilometry measurements (Archard's wear equation), and average values across three replicates were used. Statistical significance was evaluated using one-way ANOVA ($\alpha = 0.05$).

4. RESULTS

4.1 Friction Coefficient Trends

Lubricant	10 N	20 N
BIO-1	0.065	0.078
BIO-2	0.072	0.085
BIO-3	0.059	0.072
MIN	0.081	0.094

Key Observations:

- BIO-3 (bio-ester) consistently maintained the **lowest friction**.
- All BBLs outperformed mineral oil (MIN) at both loads.
- Increased load moderately raised friction across all fluids.

4.2 Wear Rate Analysis

Table 2. *Wear rates ($\times 10^{-6} \text{mm}^3/\text{N} \cdot \text{m} \times 10^{-6}$)*

$$\frac{\text{mm}^3}{\text{N}\cdot\text{m}} \times 10^{-6} \text{mm}^3/\text{N}\cdot\text{dotpm}$$

Lubricant 10 N 20 N

BIO-1	1.54	2.41
BIO-2	1.73	2.80
BIO-3	1.32	2.11
MIN	2.14	3.25

Findings:

- BIO-3 yielded the *lowest wear rates*, significantly better than MIN ($p < .01$).
- Canola-based BIO-1 performed better than BIO-2 (soybean).
- High load increased wear rates, but BBLs remained superior.

4.3 Surface Morphology

SEM analyses revealed:

- **MIN:** Deep grooves and abrasive wear patterns.
- **BIO-1 & BIO-2:** Mild adhesive wear, smooth tracks.
- **BIO-3:** Least surface disturbance; evidence of robust tribofilm.

EDS mapping identified trace iron oxides on MIN surfaces, suggesting oxidative wear, whereas BBL samples showed carbonaceous boundary layers.

5. DISCUSSION

5.1 Comparative Performance

The data indicate **bio-based lubricants can surpass mineral oil** in friction and wear performance under controlled conditions. Particularly, **bio-esters (BIO-3)** exhibit lowest friction and wear, likely due to:

- Strong adsorption affinity of ester groups on metal surfaces, forming a protective boundary film.
- High viscosity index, maintaining lubrication across pressure regimes.

These findings align with Zhang et al.'s (2020) results showing bio-esters' superior tribological performance due to molecular polarity and film formation.

5.2 Mechanistic Insights

The SEM and profilometry analyses support the conclusion that **tribofilm formation** is critical to performance differences:

- BBL molecules with polar functional groups strongly adhere to asperities.
- Mineral oils primarily rely on additives for boundary protection, which may degrade faster under load.

BIO-1 and BIO-2 showed slightly higher wear rates than BIO-3, possibly due to **unsaturated fatty acid composition**, which can oxidize or break down under stress (Sharma & Chaurasia, 2021).

5.3 Operational Implications

From an engineering perspective:

- **BBLs** are promising for systems where environmental impact and biodegradability are priorities (e.g., wind turbines, marine applications).
- For high-temperature or severe service, **bio-esters with antioxidant additives** could mitigate oxidation.

However, cold temperature viscosity and long-term thermal stability are areas needing optimization.

5.4 Limitations

- **Lab conditions** may not perfectly mimic real mechanical environments with contaminants and variable temperatures.
- Only base fluids were tested; commercial formulations include additive packages that may change performance profiles.
- Long-duration fatigue testing was outside the scope.

6. CONCLUSION

This study demonstrates that **bio-based lubricants**, particularly **bio-ester-based formulations**, can outperform a conventional mineral oil in tribological performance under moderate loads and sliding speeds. Key takeaways:

1. Bio-esters delivered the **lowest friction coefficients and wear rates**.
2. Surface analyses confirmed improved tribofilm formation with BBLs.
3. Environmental benefits are compounded by competitive mechanical performance.

Future research should investigate:

- Long-term durability under variable thermal and contamination conditions.
- Effects of **additives (nanoparticles, antioxidants)** in bio-lubricants.
- Field implementation studies in industrial mechanical systems.

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