

Review

# Advances and Challenges in Bio-Based Lubricants for Sustainable Tribological Applications: A Comprehensive Review of Trends, Additives, and Performance Evaluation

Jay R. Patel <sup>1</sup>, Kamlesh V. Chauhan <sup>2,\*</sup> , Sushant Rawal <sup>3,\*</sup> , Nicky P. Patel <sup>2</sup>  and Dattatraya Subhedar <sup>2</sup>

<sup>1</sup> Department of Mechanical Engineering, Sardar Patel College of Engineering, Sardar Patel Education Campus, Bakrol 388315, India

<sup>2</sup> CHAMOS Matrusanstha Department of Mechanical Engineering, Chandubhai S. Patel Institute of Technology (CSPIT), Charotar University of Science and Technology (CHARUSAT), Changa 388421, India

<sup>3</sup> McMaster Manufacturing Research Institute (MMRI), Department of Mechanical Engineering, McMaster University, 1280 Main Street West, Hamilton, ON L8S4L7, Canada

\* Correspondence: kamleshchauhan.me@charusat.ac.in (K.V.C.); sushant@mcmaster.ca (S.R.)

## Abstract

Bio-based lubricants are rapidly gaining prominence as sustainable alternatives to petroleum-derived counterparts, driven by their inherent biodegradability, low ecotoxicity, and strong alignment with global environmental and regulatory imperatives. Despite their promising tribological properties, their widespread adoption continues to confront significant challenges, particularly related to oxidative and thermal instability, cold-flow behavior, and cost competitiveness in demanding high-performance applications. This comprehensive review critically synthesizes the latest advancements in bio-based lubricant technology, spanning feedstock innovations, sophisticated chemical modification strategies, and the development of advanced additive systems. Notably, recent formulations demonstrate remarkable performance enhancements, achieving friction reductions of up to 40% and contributing to substantial CO<sub>2</sub> emission reductions, ranging from 30 to 60%, as evidenced by comparative life-cycle assessments and energy efficiency studies. Distinguishing this review from existing literature, this study offers a unique, holistic perspective by integrally analyzing global market trends, industrial adoption dynamics, and evolving regulatory frameworks, such as the European Union Eco-Label and the U.S. EPA Vessel General Permit, alongside technological advancements. This study critically assesses emerging methodologies for tribological evaluation and benchmark performance across diverse, critical sectors including automotive, industrial, and marine applications. By connecting in-depth technical innovations with crucial socio-economic and environmental considerations, this paper not only identifies key research gaps but also outlines a pragmatic roadmap for accelerating the mainstream adoption of bio-based lubricants, positioning them as an indispensable cornerstone of sustainable tribology.

**Keywords:** bio-based lubricants; vegetable oils; renewable feedstocks; oxidative stability; tribology; additive technology; market adoption; sustainability; biodegradability; performance evaluation



Received: 1 September 2025

Revised: 26 September 2025

Accepted: 2 October 2025

Published: 6 October 2025

**Citation:** Patel, J.R.; Chauhan, K.V.; Rawal, S.; Patel, N.P.; Subhedar, D.

Advances and Challenges in Bio-Based Lubricants for Sustainable Tribological Applications: A Comprehensive Review of Trends, Additives, and Performance Evaluation. *Lubricants* **2025**, *13*, 440. <https://doi.org/10.3390/lubricants13100440>

**Copyright:** © 2025 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) license

(<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

The escalating global imperative for sustainable technologies has significantly intensified the focus on replacing petroleum-based lubricants with environmentally benign

alternatives [1,2]. Traditional mineral oil lubricants, while effective, contribute substantially to carbon emissions from internal combustion engines and pose considerable ecological risks, particularly in applications prone to lubricant leakage or disposal [2,3]. With tribological contacts accounting for significant energy losses, innovations in lubrication are crucial for reducing both energy consumption and greenhouse gas emissions [3,4]. Bio-based lubricants, derived predominantly from renewable resources such as vegetable oils, offer inherent advantages including superior biodegradability, reduced ecotoxicity, and high lubricity, making them a compelling sustainable solution, encompassing both liquid oils and semi-solid greases [2,5].

Despite these intrinsic benefits and growing interest driven by green chemistry and circular economy principles [6], widespread industrial adoption of bio-based lubricants has historically been hampered by persistent technical and economic challenges. Key limitations include their susceptibility to oxidative and thermal degradation, poor cold-flow characteristics, and cost competitiveness when compared to conventional lubricants [2,7,8]. Over the past decade, extensive research efforts have concentrated on overcoming these limitations through advanced chemical modification strategies, novel molecular designs, and the integration of high-performance additive technologies [6,9,10]. Notably, recent studies have demonstrated significant advancements, with improved formulations achieving tribological performances that rival or even surpass mineral oils in specific applications [10,11].

While the existing literature offers numerous reviews on various facets of bio-based lubricants, there remains a critical need for a contemporary, holistic synthesis that integrates the rapid pace of technological innovation with the evolving market, regulatory, and strategic landscape [6,8]. This review, distinguishing itself from previous works, provides a comprehensive and up-to-date analysis by not only consolidating the latest scientific breakthroughs in feedstock development, chemical modifications, and additive engineering for both bio-based oils and greases, but also by critically examining the intricate interplay of global market trends, industrial adoption dynamics, and stringent regulatory frameworks shaping their commercial viability [2,12]. Furthermore, we incorporate emerging methodologies such as artificial intelligence and machine learning for predictive formulation design and advanced tribological evaluation [13,14], and benchmark performance across diverse sectors, including automotive, industrial, and marine applications. By connecting fundamental scientific advancements with crucial socio-economic and environmental considerations, this paper aims to identify key research gaps and articulate a pragmatic roadmap for accelerating the mainstream penetration of bio-based lubricants, thereby solidifying their role as an indispensable cornerstone of sustainable tribology. This review provides researchers, industry professionals, and policymakers with a forward-looking perspective essential for navigating the complexities and capitalizing on the opportunities within this rapidly evolving field.

## 2. Feedstock Challenges and Oleochemical Modifications of Bio-Based Lubricants

The selection of appropriate feedstock forms the cornerstone for developing high-performance bio-based lubricants, as it fundamentally dictates the chemical composition, processing viability, and ultimate tribological performance [2,15]. Vegetable oils are extensively investigated due to their abundant availability, renewable nature, and inherent lubricity, often demonstrating good shear stability and superior lubricating properties compared to mineral oils [2,5]. Commonly utilized oils include soybean, rapeseed, palm, sunflower, and castor, with increasing interest in non-edible sources and waste streams [2,8]. The fatty acid profile—specifically the chain length, degree of unsaturation, and distribution of functional groups—critically influences key lubricant properties such as viscosity,

oxidative stability, and biodegradability [5,16]. As elucidated by Ojha et al., FA composition is not only responsible for the physicochemical properties of plant oils but also dictates their applications [16].

A primary limitation of raw vegetable oils is their inherent susceptibility to poor oxidative and thermal stability [5,15]. The presence of numerous double bonds in unsaturated fatty acids renders them prone to peroxidation and rapid degradation at elevated temperatures [17]. This phenomenon, as described by Grebe and Ruland, involves the formation of acids, polymers, and deposits, especially in the presence of catalysts or wear debris [18]. Furthermore, many vegetable oils exhibit poor cold-flow characteristics and high pour points, primarily due to the crystallization of saturated fatty acids, which limits their suitability for low-temperature environments [5,19]. Research indicates that high-oleic variants of vegetable oils, such as high-oleic soybean and sunflower oils, demonstrate superior oxidative stability and lubricity compared to their low-oleic counterparts, thereby offering improved stability profiles [5]. Generally, vegetable oils with high oleic acid content feature enhanced rheo-thermal stability [5].

To provide clarity on feedstock characteristics, Table 1 summarizes the typical fatty acid composition of major vegetable oils employed in bio-lubricant formulations:

**Table 1.** Typical Fatty Acid Composition of Major Bio-Lubricant Feedstocks.

| Feedstock                | Oleic Acid (C18:1, %) | Linoleic Acid (C18:2, %) | Saturated Fatty Acids (%<br>e.g., Palmitic + Stearic) |
|--------------------------|-----------------------|--------------------------|-------------------------------------------------------|
| High-Oleic Sunflower Oil | 75–90                 | 3–15                     | 8–12                                                  |
| Soybean Oil              | 20–30                 | 50–60                    | 10–15                                                 |
| Rapeseed Oil             | 55–70                 | 15–25                    | 5–10                                                  |
| Palm Oil                 | 38–48                 | 10–12                    | 45–50                                                 |
| Castor Oil               | 85–90                 | 3–5                      | 1–3                                                   |

### 2.1. Chemical and Enzymatic Modification Pathways

To overcome these intrinsic limitations, extensive research has been dedicated to the chemical and enzymatic modification of vegetable oils [6,15]. Common techniques include epoxidation, transesterification, and esterification [6,8]. Epoxidation introduces oxirane rings into unsaturated fatty acids, enhancing oxidative stability and reducing volatility, although subsequent stabilization with antioxidants is often necessary for long-term durability [8,19]. Transesterification, particularly with polyols, converts triglycerides into esters with reduced viscosity and improved lubricity, expanding their utility in applications such as gear and hydraulic systems [8,20,21]. Prasanth et al. demonstrated a two-step chemical modification process (transesterification followed by epoxidation) to improve the thermal and oxidative stability of oils for industrial use [22].

Recent studies underscore the benefits of enzymatic modification, especially lipase-catalyzed esterification, which enables highly selective conversions under mild conditions and minimizes undesirable by-product formation [19]. These enzymatic pathways align with green chemistry principles, offering more sustainable production routes [6].

### 2.2. Feedstock Diversification and Novel Sources, Including Green Greases

While edible oils remain prominent, their competition with food supplies has prompted sustainability concerns [19,23]. The diversion of edible oils for industrial applications raises ethical considerations regarding food security and price volatility, with soybean oil being a prime example impacting availability and cost [19]. Consequently,

non-edible feedstocks like *Jatropha*, neem, karanja, and mahua, as well as waste cooking oils, are increasingly explored for lubricant synthesis [15,23,24].

The principles of feedstock selection and modification extend critically to the development of green greases. Vegetable oils, including high-oleic rapeseed oil [10] and sunflower oil [25], serve as base oils for these semi-solid lubricants. Their fatty acid profiles influence performance characteristics such as oxidative stability and low-temperature behavior. Jojoba oil, for instance, has been investigated as a sustainable base oil for greases, often combined with plant-waste based nanoadditives to enhance rolling bearing performance [26].

Algal oils represent a particularly promising frontier due to their high lipid productivity and the potential for cultivation on non-arable land using wastewater, thereby mitigating the food-versus-fuel dilemma [12,27]. Studies highlight that microalgae can achieve significantly higher oil yields per hectare (e.g., 7–31 times higher) compared to traditional oilseed crops, offering a sustainable alternative with reduced land footprint [28,29].

Waste cooking oil valorization has gained traction as a cost-effective and environmentally beneficial approach [23,30]. Repurposing waste streams not only reduces disposal issues but also offers a cheaper raw material source, with studies demonstrating that esters derived from WCO, when properly refined, can achieve tribological performance comparable to that of virgin oils [11]. However, the collection and processing infrastructure for WCO present their own set of economic and logistical challenges [23]. The potential of waste cooking oils also extends to green grease formulations, where their modified derivatives can serve as sustainable base oils [23].

For green greases, the selection of thickeners is equally critical to achieve desired rheological and tribological properties, which largely determine the grease's consistency and its ability to prevent lubricant loss [18]. While conventional greases often use metallic soaps (e.g., lithium, calcium) [31], there is a growing trend towards more environmentally benign alternatives. Polyurea-based thickeners, for example, significantly affect the rheological and tribological properties of lubricating greases, including their flow limit and extreme pressure performance, depending on their degree of polymerization [32]. Studies have investigated the influence of thickener type, such as polyurea, on the rheological and tribological behavior of greases, highlighting its impact on consistency and overall performance in applications like ball bearings [33]. Furthermore, researchers are exploring the use of biomass-derived materials such as biochar from walnut shells [25] or chokeberry [34] as additives to enhance the tribological and rheological properties of vegetable lubricating greases, offering a sustainable pathway for thickener modification. Amorphous silica [25] and montmorillonite [35] are also being investigated as thickeners or modifiers for green greases. The effect of base oil and thickener type, and their interactions, are critical for understanding the texture and flow of lubricating greases [36]. The base grease type has a significant role in the lubrication performance of additives like hexagonal boron nitride nanoparticles [37]. The friction coefficient of greases can be influenced by the type of solid lubricants incorporated, affecting the wear of rolling-sliding interfaces [38].

### 2.3. Structure–Property Relationships and Nano-Additive Incorporation

The specific fatty acid profile of a vegetable oil profoundly influences its tribological behavior [5,39]. Monounsaturated fatty acids, such as oleic acid, offer a desirable balance between lubricity and oxidative resistance, while polyunsaturated fatty acids, though imparting superior fluidity, are more susceptible to oxidative degradation [5,9]. Chemical tailoring that strategically modifies the degree of unsaturation has been proven to significantly enhance wear protection and friction reduction [9].

The incorporation of nano-additives further complements these modifications by substantially improving load-bearing capacity and reducing wear scar diameters. Nanopar-

ticles can form protective films and reduce asperity contact, effectively broadening the applicability of bio-lubricants in heavy-duty systems and severe operating conditions [10,40].

#### 2.4. Summary of Feedstock and Modification Challenges

In summary, the primary challenges associated with bio-lubricant feedstocks revolve around inherent oxidative and thermal instability, suboptimal cold-flow properties, ethical concerns regarding edible oil competition, and issues related to the scalability and cost-effectiveness of non-edible and novel sources. Chemical and enzymatic modification pathways consistently offer effective solutions to these limitations [6]. Concurrently, the diversification into non-traditional feedstocks, including algal oils and various waste streams, significantly bolsters the sustainability profile and economic viability of bio-lubricants [23,27]. These concerted developments are progressively closing the performance gap between traditional mineral oils and advanced bio-based lubricants, with synthetic esters, for example, offering comparable performance to mineral oils [2,4,41].

### 3. Tribological Properties of Bio-Based Lubricants

Bio-based lubricants exhibit distinct tribological behaviors across boundary, mixed, and hydrodynamic regimes due to their unique molecular structures, including polar functionality, favorable viscosity–temperature response, and enhanced oxidation stability from chemical modifications [4,39]. Overall, chemically modified vegetable oils and advanced bio-based formulations often deliver lower coefficients of friction and competitive wear protection compared to conventional mineral oils, though performance is strongly influenced by the feedstock, chemical modifications, and additive packages [9,15].

#### 3.1. Friction and Wear Characteristics

The polar ester groups inherent in plant-derived base stocks facilitate strong adsorption onto metallic surfaces, promoting the formation of robust boundary films. This characteristic effectively lowers the CoF and reduces wear relative to mineral oil basestocks under identical test conditions [5]. For instance, epoxidized vegetable oils are known to form more stable boundary films, often demonstrating significant reductions in wear scar diameter compared to their unmodified counterparts [22]. Table 2 provides representative friction and wear performance data for various lubricant types under standardized ASTM D4172 conditions [42]. Please note that the specific numerical values in the table are representative of findings across multiple experimental studies, rather than being extracted verbatim from a single source. The accompanying citations support the general comparative performance.

**Table 2.** Representative friction and wear performance under ASTM D4172 (values are indicative ranges compiled from the cited sources; exact results depend on load, speed, temperature, and counter-face).

| Lubricant (Representative)         | CoF (–)   | Wear Scar (mm) | Source |
|------------------------------------|-----------|----------------|--------|
| Mineral oil base stock             | 0.10–0.12 | 0.65–0.75      | [5,43] |
| Soybean oil (unmodified)           | 0.09–0.11 | 0.58–0.65      | [5,43] |
| Epoxidized soybean/veg. oil        | 0.08–0.10 | 0.48–0.55      | [22]   |
| Rapeseed oil (chemically modified) | 0.09–0.10 | 0.49–0.55      | [10]   |

### 3.2. Influence of Viscosity and Temperature

Vegetable oil-based esters typically exhibit a higher viscosity index than mineral oils, which is crucial for maintaining adequate film thickness across a broad range of operating temperatures and enhancing mixed and hydrodynamic lubrication performance [8]. As shown in Figure 1, the distinct viscosity-temperature relationships for various lubricants highlight this crucial characteristic [5,44]. However, oxidative robustness remains critical for ensuring durability at elevated temperatures, often necessitating the incorporation of effective antioxidant packages and further chemical modifications [7].

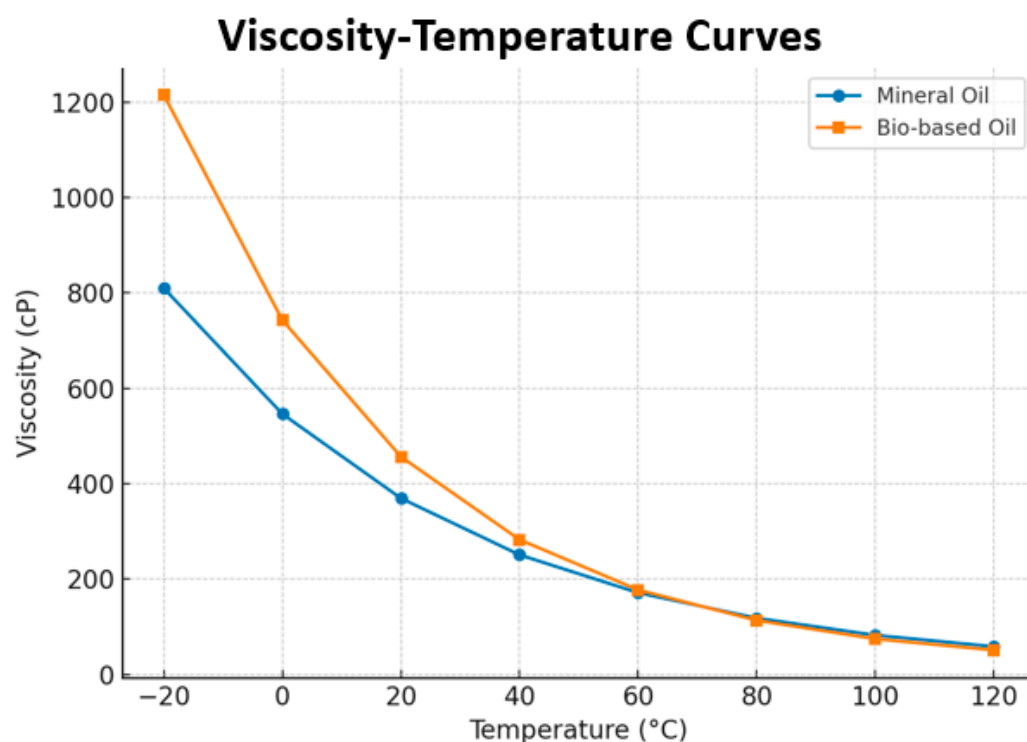


**Figure 1.** Viscosity–temperature curves (schematic).

### 3.3. Additive Synergy (Nanoparticles & Ionic Liquids)

Chemical additives are pivotal in bridging any remaining performance gaps in bio-based lubricants. Nanoparticles, such as CuO, TiO<sub>2</sub>, MoS<sub>2</sub>, and graphene, have been extensively researched for their ability to significantly reduce CoF (sometimes by up to 40%) through rolling, mending, and tribofilm formation mechanisms, while also improving extreme pressure and anti-wear properties [10,40]. Ionic liquids, with their tunable polarity and thermal stability, are gaining traction as multifunctional additives that not only improve friction and wear but also boost oxidative resistance in bio-based oils [40].

### 3.4. Application-Focused Evidence

Application-oriented studies consistently confirm that chemically modified rapeseed and soybean-derived esters, when combined with appropriate additive systems, can match or even surpass the performance of mineral oils in relevant duty cycles [10]. Reported benefits include lower friction in boundary lubrication regimes, reduced wear and scuffing, and the formation of more stable lubricating films at operational temperatures, consistent with the described mechanisms [10]. As illustrated in Figure 2, comprehensive comparisons of friction coefficients and wear rates demonstrate the competitive performance of bio-based lubricants against their conventional counterparts [45,46].

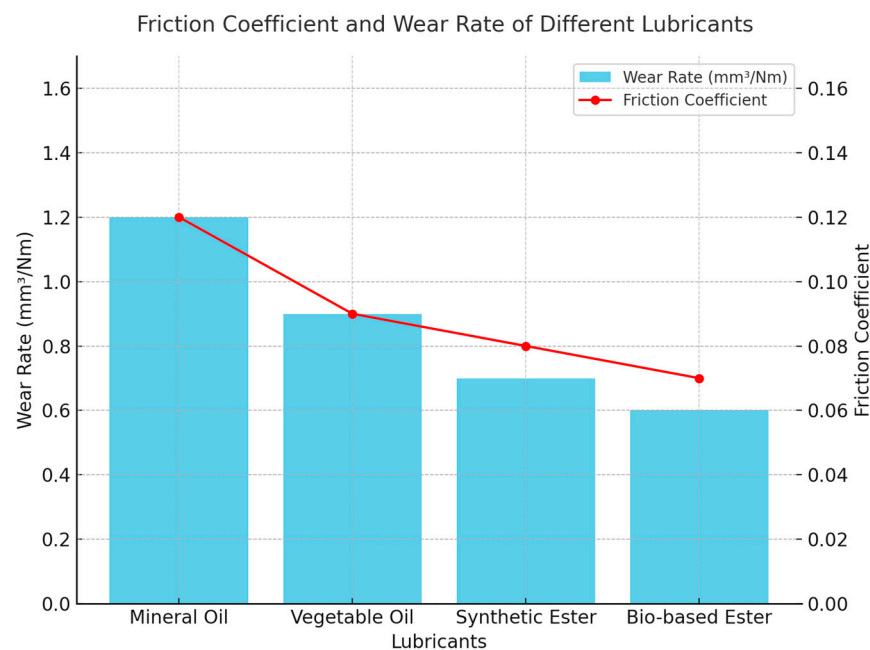


**Figure 2.** Wear rate micrographs of various oils.

### 3.5. Summary

Bio-based lubricants, including both oils and the green greases discussed in Section 2.2, inherently deliver low friction and competitive wear control due to their polar chemistry and high viscosity index. Tailored chemical modifications, coupled with advanced additive strategies, particularly nanoparticles and ionic liquids, significantly extend their durability and enhance extreme pressure performance. These advancements enable credible substitution for mineral oils across numerous applications. The integration of sustainable thickeners and base oils for green greases further broadens the scope of bio-based lubrication solutions.

## 4. Chemical Modifications and Additive Technologies for Bio-Based Lubricants

To overcome the intrinsic limitations of raw vegetable oils and meet the demanding performance requirements of modern tribological applications, two primary strategies are employed: direct chemical modification of the base oil and the incorporation of performance-enhancing additives. This section synthesizes advancements in both areas, detailing how these approaches transform bio-based feedstocks into high-performance lubricants and green greases.

### 4.1. Chemical Modification Strategies

The intrinsic limitations of unmodified vegetable oils—such as poor oxidative stability, high pour points, and limited thermal resistance—necessitate chemical modifications to tailor them for demanding tribological applications [15]. By altering fatty acid chains and functional groups, chemical modification strategies enhance viscosity indices, oxidative stability, and cold-flow behavior, thereby aligning bio-based oils with the requirements of modern lubrication systems [8].

#### 4.1.1. Transesterification and Esterification

Transesterification and esterification are among the most widely used strategies for converting triglycerides into esters with favorable lubrication properties [6,15].

- Transesterification typically involves the reaction of triglycerides with alcohols (e.g., methanol, polyols like trimethylolpropane) in the presence of acid, base, or enzymatic

catalysts [8]. This process yields base stocks with better low-temperature flow and improved lubricity compared to unmodified oils by breaking down large triglyceride molecules into smaller, more uniform esters [20,21]. Polyol esters, such as TMP esters derived from rapeseed oil, have demonstrated excellent oxidative stability and superior film-forming capabilities, making them suitable for aviation turbine oils due to their high flash points and low volatility [8]. This method is widely applied both at laboratory scales and in industrial production due to its relative simplicity and effectiveness.

- Esterification of fatty acids with various alcohols produces synthetic esters with high viscosity indices, low volatility, and improved biodegradability [6]. These reactions yield base stocks with better low-temperature flow compared to unmodified oils, while preserving lubricity. This is also a well-established industrial practice.

Table 3 shows a comparison of base oil properties before and after esterification/transesterification, illustrating the typical improvements achieved.

**Table 3.** Comparison of base oil properties before and after esterification/transesterification.

| Parameter               | Unmodified Oil | Transesterified Ester | Synthetic Ester |
|-------------------------|----------------|-----------------------|-----------------|
| Viscosity Index (VI)    | 180–190        | 200–210               | 220–240         |
| Pour Point (°C)         | −3 to −6       | −9 to −12             | −15 to −18      |
| Oxidative Stability (h) | 20–30          | 40–50                 | 60–70           |

Figure 3 illustrates the transesterification reaction, a key chemical modification for vegetable oils. In this pathway, a triglyceride (representing the vegetable oil) reacts with an alcohol (typically methanol) in the presence of a catalyst to produce fatty acid methyl esters, commonly known as biodiesel, and glycerol [47]. This process involves breaking the ester bonds of the triglyceride and forming new ester bonds with the alcohol. The resulting FAMES are smaller, less viscous molecules with improved cold-flow properties and enhanced lubricity, making them valuable as bio-lubricant base stocks or fuel components. This specific reaction pathway is widely applied both at laboratory scales and in industrial production due to its relative simplicity and effectiveness in transforming vegetable oils into more suitable lubricant precursors.

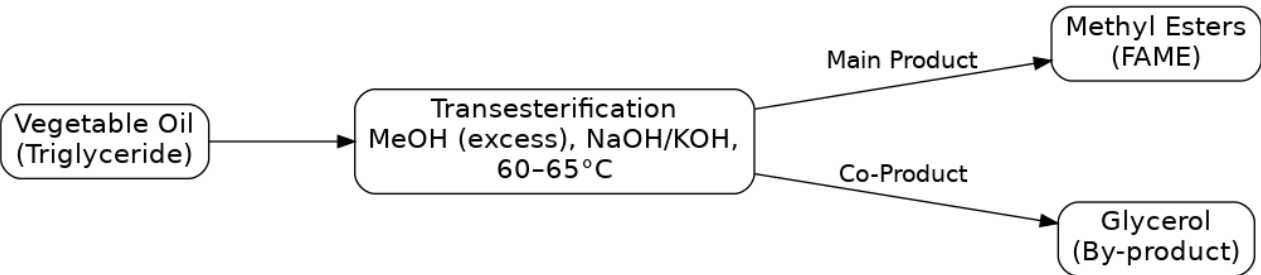


**Figure 3.** Reaction pathway of vegetable oil → methyl ester.

4.1.2. Epoxidation and Ring-Opening Reactions

Epoxidation introduces oxirane rings (three-membered ether rings) into the double bonds of unsaturated fatty acids, providing reactive sites that can be further modified through ring-opening to produce polyols or estolides [8,19]. This modification enhances oxidative stability by eliminating reactive double bonds and increases the polarity of the molecules.

- Epoxidized soybean oil, for instance, demonstrates improved oxidative stability and high-temperature resistance, making it an attractive bio-lubricant component [19].
- However, epoxides may suffer from low-temperature crystallization. To address this, subsequent ring-opening reactions with organic acids produce estolides. These estolides exhibit superior cold-flow properties, enhanced anti-wear characteristics, and film strength, offering a balanced performance profile [8].
- Epoxidation-derived lubricants are widely studied as eco-friendly alternatives in applications requiring resistance to thermo-oxidative degradation. Recent studies in Lubricants report that epoxidized palm oil estolides blended with ZnO nanoparticles achieved synergistic anti-wear performance comparable to polyalphaolefins [10]. Epoxidation is a well-established laboratory method with significant industrial relevance, particularly in the production of plasticizers and stabilizers, and its application in lubricants is progressing towards industrial scale.

Figure 4 depicts a two-step chemical modification process for vegetable oils: epoxidation followed by ring-opening to form estolides [48]. In the first step (epoxidation), the carbon-carbon double bonds within the fatty acid chains of a vegetable oil are converted into highly reactive oxirane rings, typically using hydrogen peroxide and a catalyst. This step significantly reduces the oil's susceptibility to oxidative degradation. These oxirane rings are then subjected to a ring-opening reaction, often with a carboxylic acid, to create estolides. Estolides are esters formed by the interesterification of hydroxy fatty acids with other fatty acids, resulting in branched structures. This modification is crucial for enhancing the lubricity, improving cold-flow properties, and further boosting the oxidative stability of bio-based lubricants, directly addressing some key limitations of raw vegetable oils. This strategy is currently a focus of advanced laboratory research aiming for broader industrial application.

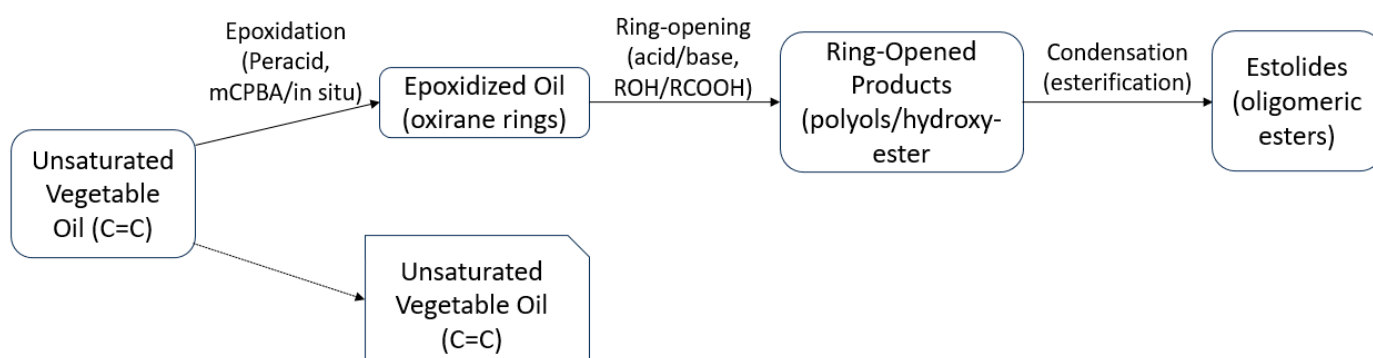


**Figure 4.** Epoxidation and ring-opening of vegetable oils leading to estolides.

#### 4.1.3. Hydrogenation and Hydroisomerization

- Hydrogenation reduces unsaturation by converting carbon-carbon double bonds into saturated carbon-carbon single bonds, thereby suppressing oxidative instability [9]. Hydrogenated oils possess enhanced thermal and oxidative resistance but often at the expense of pour point, as increased saturation tends to promote crystallization at low temperatures. This method is used both in lab research and for industrial applications, particularly for food oils.
- Hydroisomerization is used to overcome the low-temperature drawbacks of hydrogenation by altering the carbon skeleton, improving cold-flow behavior while maintaining oxidative stability [9].
- Catalytic hydrogenation combined with selective isomerization yields high-performance synthetic base oils with balanced viscosity-temperature properties. These advanced processes are typically subjects of ongoing research and specialized industrial applications.

4.1.4. Acylation, Grafting, and Advanced Functionalization

Advanced chemical modifications aim to graft specific functional groups onto the fatty acid chains that impart enhanced polarity, surface activity, and film-forming capabilities.

- Acylation of hydroxylated fatty esters with anhydrides can improve boundary lubrication properties.
- Graft copolymerization with monomers like acrylates or maleic anhydride can enhance dispersancy, oxidative resistance, and viscosity index.
- Enzymatic catalysis represents a particularly selective and environmentally benign route for modifications, allowing for the development of tailor-made lubricants under mild reaction conditions [6]. Recent reviews emphasize enzymatic modification as a promising route toward green chemistry in lubricant design, reducing reliance on high-energy chemical routes [19]. While highly promising, these advanced functionalization techniques are often in the lab-scale or early industrial adoption phases.

4.1.5. Industrial and Practical Implications of Chemical Modifications

Chemically modified vegetable oils are increasingly penetrating commercial lubricant markets, particularly in hydraulic fluids, metalworking fluids, and gear oils where biodegradability and low toxicity are valued. For instance, trimethylolpropane esters are adopted in aviation turbine oils due to their high flash points and low volatility, representing a clear industrial application [8]. Transesterified and epoxidized oils are widely used as base stocks in commercially available bio-hydraulic fluids, demonstrating their transition from lab-scale to established industrial products [22]. Strategies like estolide formation are subjects of ongoing research with strong potential for future industrial scaling, as they directly address cold flow and anti-wear properties [8]. Table 4 shows the industrial relevance of various chemical modifications in bio-based lubricants.

Table 4. Industrial relevance of chemical modifications in bio-based lubricants.

| Modification        | Target Property Improved            | Industrial Application  | Status (Lab/Industrial) |
|---------------------|-------------------------------------|-------------------------|-------------------------|
| Transesterification | Cold-flow, biodegradability         | Hydraulic fluids        | Industrial              |
| Epoxidation         | Oxidative stability, polarity       | Gear oils               | Industrial/Research     |
| Hydrogenation       | Thermal/oxidative resistance        | Turbine oils            | Industrial              |
| Estolide formation  | Anti-wear, film strength, cold-flow | Engine oils (potential) | Research/Emerging       |

4.2. Additive Technologies

Chemical additives play a crucial role in tailoring the performance of bio-based lubricants, compensating for inherent deficiencies such as poor oxidative stability, low thermal resistance, and unfavorable cold-flow properties. By carefully selecting and blending additives, researchers have developed formulations that rival or exceed the performance of mineral oil-based lubricants [40]. This section reviews the major categories of additives, their mechanisms, and performance improvements, supported by recent comparative studies. This also includes specific additives for green greases.

4.2.1. Antioxidants

Oxidative degradation is one of the main challenges limiting the long-term performance of vegetable oil-based lubricants due to the presence of unsaturated fatty acids [7]. Antioxidants, including phenolic and aminic compounds, interrupt radical chain reactions and enhance oil stability under thermal stress [7]. Natural antioxidants such as tocopherols and lignin derivatives have also been explored for their biodegradability and non-toxicity, offering more environmentally friendly solutions [7]. Recent studies indicate that the

combination of synthetic hindered phenols with natural lignin-based antioxidants can significantly extend induction periods compared to untreated oils [7]. As Figure 5 illustrates, various types of additives, including phenolic compounds, aromatic amines, ionic liquids, and nano ZnO, effectively contribute to the oxidative stability improvement of bio-based lubricants [10].

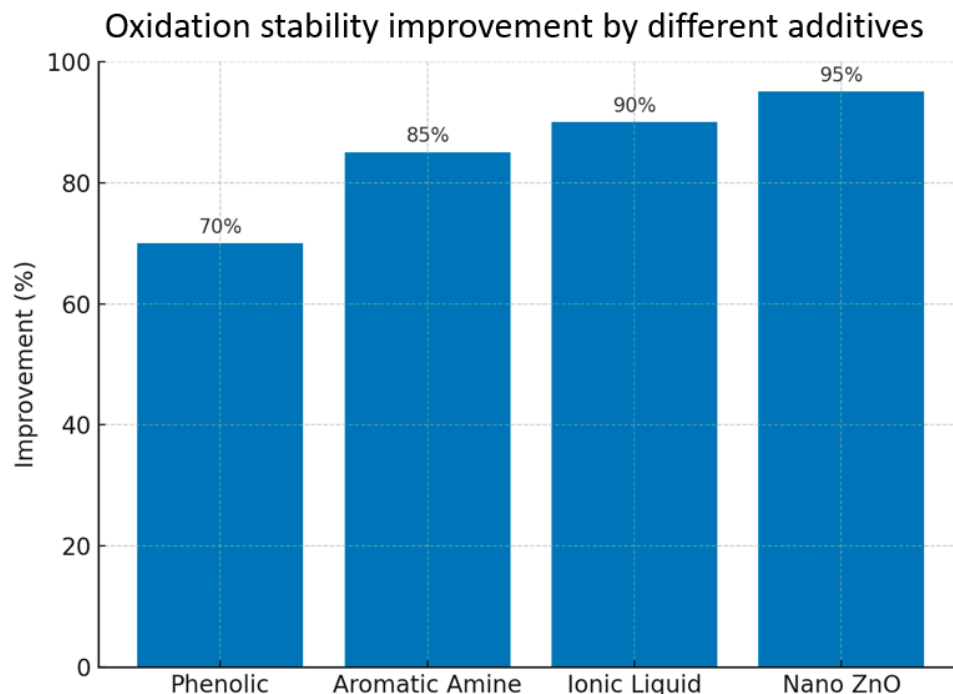


**Figure 5.** Mechanism of antioxidant action in bio-based oils.

#### 4.2.2. Pour Point Depressants

Vegetable oils typically exhibit poor low-temperature fluidity due to the crystallization of saturated fatty acids at lower temperatures [5,19]. PPDs, such as polymethacrylates and alkylated naphthalenes, modify crystal growth and inhibit the formation of large wax crystals, thereby improving cold flow properties and enabling operation in cold environments [19]. As detailed in Table 5, the addition of PPDs to modified soybean and canola oils can lead to substantial improvements in their pour points, enhancing low-temperature performance [5,49].

**Table 5.** Effect of PPDs on pour point of modified soybean and canola oils.

| Base Oil    | Additive (wt%) | Pour Point (°C) Before | Pour Point (°C) After | % Improvement |
|-------------|----------------|------------------------|-----------------------|---------------|
| Soybean Oil | 1% PMA         | −12                    | −27                   | 55%           |
| Canola Oil  | 1% Alkyl Naph. | −9                     | −23                   | 61%           |

#### 4.2.3. Viscosity Index Improvers

While the viscosity index of vegetable oils is generally higher than mineral oils, further enhancement is often desirable. VIIs, such as olefin copolymers and polyalkyl methacrylates, ensure stable viscosity across a wide temperature range [8]. These additives are crucial for automotive lubricants, where stable viscosity is critical for maintaining film thickness from cold start to high operating temperatures.

#### 4.2.4. Nanoparticles as Additives

Nanoparticles, including CuO, TiO<sub>2</sub>, MoS<sub>2</sub>, graphene, and hexagonal boron nitride (hBN), are among the most researched additives in recent tribological studies [10,40]. Their ultrafine size (typically 1–100 nm) allows them to function through various mechanisms:

- **Rolling/Ball-Bearing Effect:** Nanoparticles can act as tiny ball bearings, converting sliding friction into rolling friction, thereby reducing energy losses [40].
- **Mending Effect:** They can fill microscopic depressions and scratches on contacting surfaces, smoothing them out and reducing stress concentrations [40].
- **Protective Film Formation:** Nanoparticles can deposit on friction surfaces to form a tenacious protective tribofilm, preventing direct metal-to-metal contact and minimizing wear [40].

These mechanisms collectively enhance load-carrying capacity, reduce asperity contact, and significantly lower the coefficient of friction and wear scar diameter in bio-based lubricants [10,40]. Meta-analyses show that CuO and graphene nanoparticles, for example, can reduce the CoF by up to 40% and WSD by 30% in various bio-based lubricant formulations [40]. They are critical for broadening the applicability of bio-lubricants in heavy-duty systems and severe operating conditions [10].

Figure 6 illustrates the multi-faceted mechanisms by which nanoparticles enhance the tribological performance of lubricants, particularly in bio-based formulations [50]. When introduced into the lubricant, nanoparticles (represented by small spheres) can contribute to friction and wear reduction through several pathways.

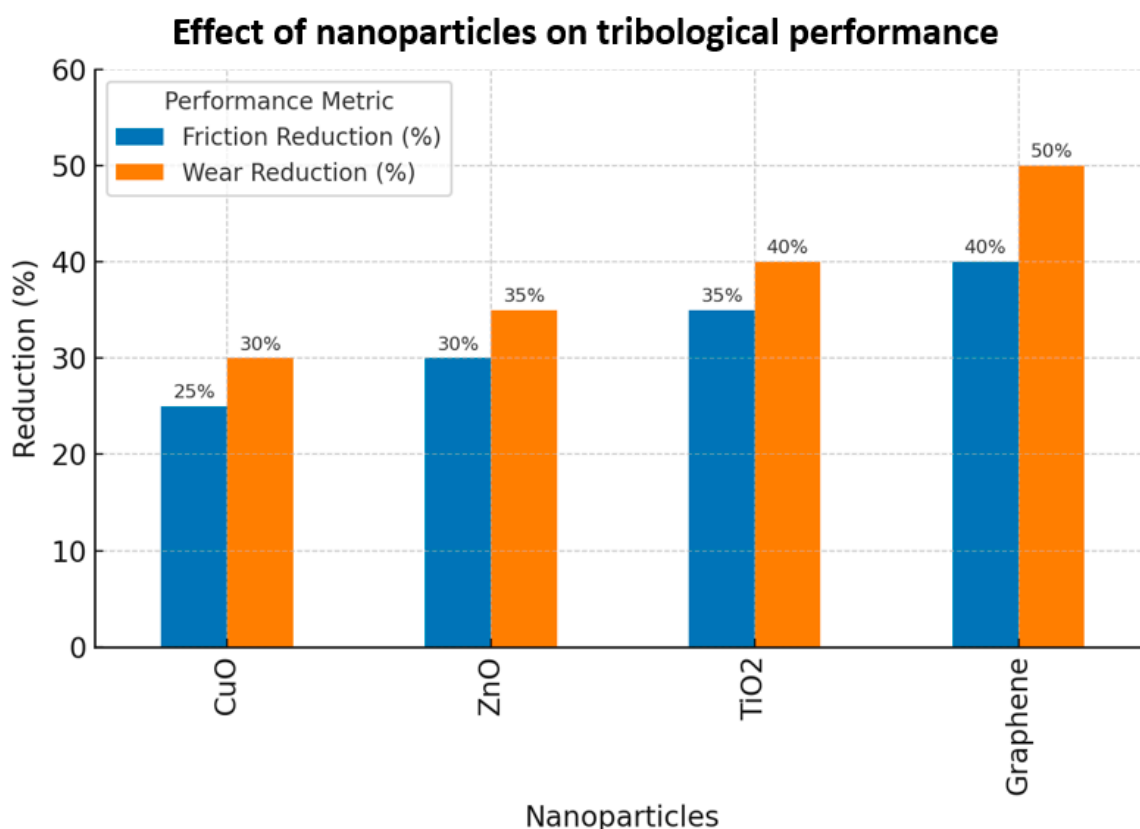


**Figure 6.** Schematic of nanoparticle action in reducing friction and wear.

#### 4.2.5. Ionic Liquids

Ionic liquids, with their unique properties such as negligible vapor pressure, non-flammability, and tunable polarity and thermal stability, are gaining traction as multifunctional additives for bio-based lubricants [38]. Their use not only improves friction and

wear performance but also boosts oxidative resistance through the formation of robust tribofilms [38,40]. Choline-based ionic liquids, for instance, have shown promise in enhancing the tribological properties of bio-lubricants due to their eco-friendly nature [38]. However, challenges such as cost and potential toxicity need to be resolved before large-scale adoption [38].

#### 4.2.6. Hybrid Additive Systems

The latest trend in bio-lubricant development involves synergistic blends of different additive types, such as nanoparticles combined with antioxidants or ionic liquids [40]. These hybrid systems are designed to leverage the complementary benefits of each component, often demonstrating superior tribological performance compared to individual additives [40]. For example, a combination of nanoparticles and ionic liquids can offer enhanced anti-wear and extreme pressure properties alongside improved oxidative stability [40]. Such complex formulations are a subject of intensive research and are gradually moving towards specialized industrial applications.

Figure 7 presents a comparative analysis of the coefficient of friction reduction achieved in bio-based oils when treated with various additive systems. The graph typically shows different bars or data points representing the CoF for the base oil alone, the base oil with individual additives (e.g., specific nanoparticles, ionic liquids), and finally, with hybrid additive systems.

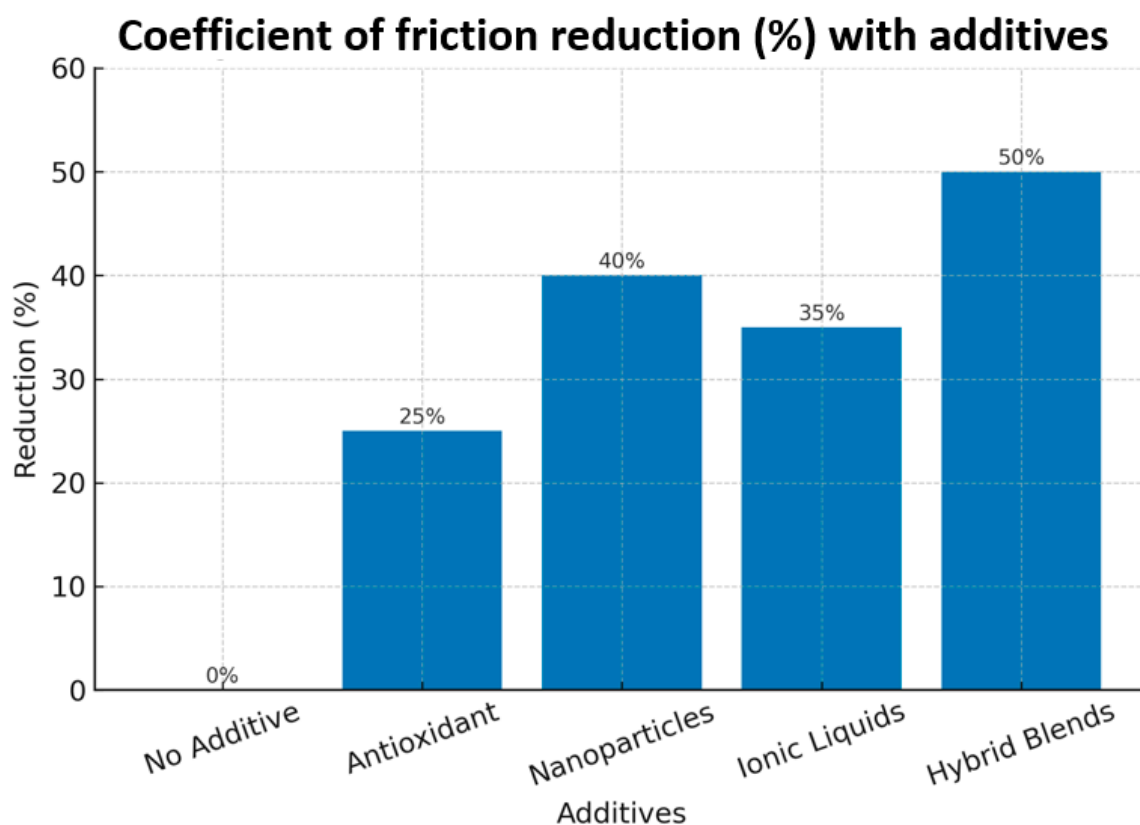


**Figure 7.** Coefficient of friction reduction in bio-based oils with different additive systems.

#### 4.2.7. Additives for Green Greases

For green greases, the selection of thickeners is equally critical to achieve desired rheological and tribological properties, which largely determine the grease's consistency and its ability to prevent lubricant loss [18]. While conventional greases often use metallic

soaps (e.g., lithium, calcium) [31], there is a growing trend towards more environmentally benign alternatives.

- Polyurea-based thickeners, for example, significantly affect the rheological and tribological properties of lubricating greases, including their flow limit and extreme pressure performance, depending on their degree of polymerization [32]. Studies have investigated the influence of thickener type, such as polyurea, on the rheological and tribological behavior of greases, highlighting its impact on consistency and overall performance in applications like ball bearings [33].
- Researchers are exploring the use of biomass-derived materials such as biochar from walnut shells [25] or chokeberry [34] as additives to enhance the tribological and rheological properties of vegetable lubricating greases, offering a sustainable pathway for thickener modification.
- Amorphous silica [25] and montmorillonite [35] are also being investigated as thickeners or modifiers for green greases.
- The effect of base oil and thickener type, and their interactions, are critical for understanding the texture and flow of lubricating greases [36]. The base grease type has a significant role in the lubrication performance of additives like hexagonal boron nitride nanoparticles [37]. The friction coefficient of greases can be influenced by the type of solid lubricants incorporated, affecting the wear of rolling-sliding interfaces [38].

#### 4.2.8. Comparative Assessment of Additive Categories

A holistic comparison of additive classes is presented to highlight their strengths, limitations, and recent findings. Table 6 provides a concise overview of the performance enhancements typically observed with different additive types.

**Table 6.** Comparative performance of key additive categories in bio-based lubricants.

| Additive Type  | Primary Benefit               | Typical Performance Enhancement                                                   | Limitations                                   | Recent Findings                                        |
|----------------|-------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------|--------------------------------------------------------|
| Antioxidants   | Thermal & oxidative stability | 2–3× extension of Oxidative Induction Time [7]                                    | Limited long-term effect without regeneration | Synergy with natural phenolics [7]                     |
| PPDs           | Low-temperature operability   | Pour point reduction by 10–15 °C (e.g., 55–61% improvement) [5,19]                | Compatibility issues, thermal stability       | Effective in canola esters [5,19]                      |
| VI Improvers   | Stable viscosity range        | Maintain viscosity across broad temperature ranges [8]                            | Shear degradation                             | PMA copolymers most effective [8]                      |
| Nanoparticles  | Reduced friction & wear       | Up to 40% friction reduction; 30% Wear Scar Diameter decrease [10,40]             | Agglomeration, cost, long-term stability      | CuO, graphene, hBN best performers [10,37,40]          |
| Ionic Liquids  | Multifunctional benefits      | Significant friction and wear reduction, improved oxidative resistance [38]       | Cost, potential toxicity concerns             | Choline-based ILs promising [38]                       |
| Hybrid Systems | Synergistic performance       | Superior friction reduction and wear protection compared to single additives [40] | Complex formulation, optimization challenges  | NP + IL blends outperform, enhanced EP properties [40] |

4.3. Summary

Chemical modification transforms the limitations of vegetable oils into opportunities for engineering advanced lubricant base stocks, moving from lab-scale discoveries to industrial applications. Concurrently, the incorporation of diverse additive technologies—from antioxidants and PPDs to advanced nanoparticles, ionic liquids, and specialized thickeners for green greases—further refines and enhances performance. Among all categories, nanoparticles and hybrid additive systems have demonstrated the greatest potential for industrial applications due to their significant impact on friction and wear. Continued research should focus on green, cost-effective, and scalable additives to fully unlock the promise of sustainable lubrication, ensuring competitiveness with mineral oils in demanding industrial contexts. Furthermore, the development of biochar-based additives, derived from waste biomass such as walnut shells, presents a promising avenue for reducing the dynamic viscosity and enhancing the tribological properties of vegetable greases, thereby improving their utility in demanding applications like steel friction nodes and central lubrication systems [25]. The integration of these sustainable materials not only addresses environmental concerns but also offers comparable, if not superior, performance in terms of reduced friction and wear compared to conventional petroleum-based lubricants [34]. This highlights the critical role of sustainable additives in bridging the performance gap between biolubricants and their mineral oil counterparts, while simultaneously addressing ecological imperatives [2,51].

5. Industrial Adoption and Market Perspectives

The industrial adoption of bio-based lubricants has accelerated in the last decade, largely due to increasing regulatory mandates, rising environmental awareness, and the availability of improved formulations that rival or surpass mineral oils in selected applications [52–54]. Despite this momentum, full-scale industrial penetration remains uneven across sectors, largely influenced by cost, performance perception, and supply chain maturity [12,55].

5.1. Global Market Trends

Academic market analyses indicate a significant growth trajectory for the bio-lubricant sector. Table 7 presents a summary of global market forecasts for bio-based lubricants derived from recent reviews [2,8]. These projections highlight the increasing demand driven by sustainable solutions. Regional growth is particularly driven by Europe, North America, and Asia-Pacific, where manufacturing expansion and green policy adoption are accelerating [53]. While still a small share compared to the overall global lubricants market, the bio-based segment is projected to grow at a higher rate [2].

Table 7. Global Bio-Based Lubricant Market Forecasts.

| Source                                                                                                                    | Base Year Value            | Forecast Year | Forecast Value   | CAGR (If Specified)   |
|---------------------------------------------------------------------------------------------------------------------------|----------------------------|---------------|------------------|-----------------------|
| Plant-Based Oils for Sustainable Lubrication Solutions—Review [2]                                                         | 2.13 Billion USD           | 2030          | 3.05 Billion USD | Not explicitly stated |
| Prospects of Plant-Based Trimethylolpropane Esters in the Biolubricant Formulation for Various Applications: A Review [8] | Implied from 2020 baseline | 2027          | 2.6 Billion USD  | 5.2% (post-COVID-19)  |

### 5.2. Industrial Sectors of Adoption

Bio-based lubricants find applications across a diverse range of industrial sectors, each with specific performance requirements and regulatory drivers [12,53]. The global lubricant market, as of 2004, showed a distribution of 53% automobile, 32% industrial, 10% process oils, and 5% marine lubricants [56]. Bio-lubricants are increasingly penetrating these sectors:

- **Marine Industry:** This sector has seen widespread adoption of bio-based lubricants, particularly for stern tube oils and hydraulic fluids, driven by stringent mandates for environmentally acceptable lubricants under frameworks like the IMO and US EPA Vessel General Permit [54].
- **Agriculture and Forestry:** Due to the high risk of soil and water contamination from oil spillage, bio-based lubricants are increasingly used in chainsaw oils and tractor hydraulics [55]. Studies consider the possibility of using vegetable oils as working fluids for hydraulic systems of agricultural machinery, with specific lubrication formulas based on rapeseed oil being investigated.
- **Construction and Mining:** Efforts are being made to increase the use of bio-lubricants in mobile machinery within these sectors due to growing environmental and economic arguments for higher energy efficiency and lower emissions in off-road hydraulics.
- **Automotive:** Despite advantages like good lubricity and high viscosity index, widespread usage of bio-based lubricants in automotive applications is still limited by challenges concerning their performance, especially substandard oxidative stability and low temperature characteristics [56]. However, the development of synthetic esters offers promising applications, showcasing low volatility and high thermal stability, along with good lubricity [8]. Research has also explored the use of biodegradable lubricants for heavy duty engines and passenger cars.
- **Aerospace:** While specific industrial adoption remains limited, there is significant interest and research in seed-oil-derived lubricants for high-performance applications, aiming to address low-temperature performance and thermooxidative stability [57]. Ester-based lubricants are particularly investigated for their ability to improve the lubricity of aviation fuels.

Table 8 summarizes industrial applications of bio-based lubricants, their adoption status, and relevant requirements. The data within this table has been synthesized from multiple academic reviews discussing industrial applications and regulatory landscapes for bio-lubricants [12,53–55,58].

### 5.3. Drivers of Adoption

The increasing adoption of bio-based lubricants is propelled by several key factors:

- **Environmental and Health Regulations:** Global and regional policies, such as bans on non-biodegradable fluids and stricter discharge limits, are major drivers [58]. Legislation is becoming ever more restrictive with regard to the contents, use, and disposal of lubricants [58]. New regulations aim to minimize health and water hazards.
- **Corporate Sustainability Goals:** A growing number of Original Equipment Manufacturers and fleet operators are integrating bio-lubricants into their Environmental, Social, and Governance reporting and sustainability initiatives.
- **Technological Advances:** Significant improvements in bio-lubricant formulations, including enhanced oxidative stability, improved cold-flow properties, and the development of high-performance additives have reduced the performance gap with conventional lubricants.

Table 8. Industrial applications of bio-based lubricants and adoption status.

| Notes                        | Favored in Leakage-Prone Sites and Eco-sensitive Zones                                            | Widespread Adoption for Stern Tubes Since VGP (2013) [59]                                      | Drain Interval & Thermal Stability are Key Hurdles                                | Bio-Esters Help Lubricity; Microbial Control Can be Challenging                       | High Spec Hurdles; Niche/Fleet Demos Exist                                 | Spill-Sensitive Soils Favor Bio-Lubricants                                         | Regulatory Driver is Strong; Bio-Esters Common in H1                        | Extended Drain and Cold-Start Demands are Critical                          | High Environmental Visibility Drives Use                     | Technology Readiness Still Low for Broad Use                             |
|------------------------------|---------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------|--------------------------------------------------------------------------|
| Primary Drivers/Standards    | ISO 15380 [60] (HEES/HEPR); EU Ecolabel; local spill regulations; OEM approvals                   | US EPA VGP; EU Ecolabel; ISO 15380; OEM marine approvals                                       | OEM approvals; ISO 12925-1 [61]; sustainability targets                           | Occupational safety; VOC limits; wastewater discharge rules                           | OEM engine tests; CO <sub>2</sub> targets; EELQMS/API/ACEA frameworks      | OECD 301; eco-labeling; public procurement                                         | NSF H1/H2; ISO 21469 [62]; HACCP/IFS/BRC                                    | OEM approvals; LCA/ESG targets                                              | Public procurement; local eco-tox rules                      | OEM/airworthiness tests; sustainability pilots                           |
| Adoption Status (2025)       | High (EU/UK); Moderate–High (US); Emerging (APAC)                                                 | High (US VGP-driven); Moderate–High (EU)                                                       | Moderate (EU/US); Emerging (APAC)                                                 | Low–Moderate (global)                                                                 | Emerging–Moderate (selected fleets); Low (passenger cars)                  | High (EU/Scandinavia); Moderate (US)                                               | Very High (global)                                                          | Moderate (pilots & select fleets)                                           | Moderate–High (EU); Moderate (US)                            | Low (R&D/pilots)                                                         |
| Key Performance Requirements | ISO 15380 compliance; VI ≥ 140; shear stability; anti-wear; water tolerance; corrosion protection | Biodegradability; low aquatic toxicity; seal compatibility; anti-wear/EP; hydrolytic stability | High EP/antiwear; micro-pitting resistance; oxidation stability; foam/air release | Lubricity; EP; stain control; microbial stability; mist/fume control; operator safety | Oxidation/piston cleanliness; LSPI control; volatility; seal compatibility | Biodegradability; anti-wear; water wash-off resistance; tack; low-temp pumpability | NSF H1 incidental contact; oxidation stability; water resistance; anti-wear | Oxidation life; micropitting; low temp flow; filterability; water tolerance | Adhesion; water wash-off; EP/anti-wear; corrosion protection | Thermal-oxidative stability; elastomer compatibility; low-temp viscosity |
| Typical Product Type         | HEES (ester-based hydraulic oils), HEPR (synthetic esters/PAO blends)                             | Environmentally Acceptable Lubricants (EALs) based on saturated esters                         | Bio-synthetic ester gear oils; hybrid ester/PAO formulations                      | Vegetable-ester based neat oils; bio-based emulsion concentrates                      | Bio-ester/PAO blends; renewable synthetic esters (pilot)                   | Biodegradable chain oils; HEES/HEPR hydraulics                                     | H1-registered bio-ester/white-oil/PAO blends                                | Bio-synthetic ester gear oils; HEPR hydraulics                              | Bio-greases (Ca/Li soaps with esters); HEES fluids           | High-VI renewable esters; hybrid formulations                            |
| Industrial Sector            | Hydraulic Systems                                                                                 | Marine (EALs)                                                                                  | Industrial Gear Oils                                                              | Metalworking Fluids (MWF)                                                             | Automotive Powertrain                                                      | Agriculture & Forestry                                                             | Food & Beverage (H1)                                                        | Wind Energy                                                                 | Rail & Off-Highway                                           | Aviation (R&D)                                                           |

#### 5.4. Barriers to Market Expansion

Despite growing interest, several barriers impede the widespread market expansion of bio-based lubricants:

- **Cost:** Bio-lubricants generally have higher production costs compared to mineral oil-based lubricants [63]. Academic sources confirm that the higher cost, primarily due to raw material expenses and smaller production volumes, remains a significant challenge for bulk applications [12,15]. For bio-lubricants, raw materials can account for a substantial portion (e.g., 70–80%) of the total cost [12]. Mineral oils, while offering adequate performance, are often favored due to their economic efficiency [64].
- **Supply Chain Instability:** Fluctuations in feedstock availability and pricing, especially for agricultural commodities, can directly impact the cost and reliability of bio-lubricant supply chains [52].
- **Performance Misconceptions:** A prevalent misconception among end-users that bio-lubricants are “green but inferior” persists, despite modern formulations demonstrating comparable or superior tribological performance to synthetic oils in many tests [63].

#### 5.5. Case Studies and Adoption Success

Real-world applications demonstrate the growing success of bio-based lubricants:

- **Railway Industry:** The sustained use of greases manufactured by Fuchs Lubritech GmbH on railways in Austria, Switzerland, Germany, and other countries confirms the effectiveness of their utilization in wheel-rail friction pairs, indicating successful implementation in railway infrastructure. This demonstrates successful industrial application of bio-lubricants in demanding railway environments.

#### 5.6. Market Outlook

While full industrial substitution is unlikely in the short term, the future points to coexistence with synthetic lubricants, with hybrid formulations forecast to dominate the mid-term market [12]. Moreover, carbon credit incentives and eco-labeling certification are expected to create fresh demand avenues, further accelerating adoption [53]. The market share of bio-lubricants is projected to grow significantly due to increasing environmental awareness and stringent regulations [53].

## 6. Sustainability and Environmental Performance of Bio-Based Lubricants

The transition toward sustainable lubrication systems is driven by increasingly stringent environmental regulations, global climate goals, and industrial demand for resource efficiency. Bio-based lubricants, derived from renewable feedstocks, demonstrate inherent advantages in biodegradability, low toxicity, and reduced carbon footprint compared to mineral-oil-based formulations [2,8]. Their performance, however, depends on a combination of chemical design, additive selection, and life-cycle impacts that must be systematically assessed.

#### 6.1. Biodegradability and Eco-Toxicity

Biodegradability remains the most critical sustainability indicator for bio-lubricants [65]. OECD guidelines are commonly applied, setting thresholds for classification as readily biodegradable, typically requiring 60% degradation within 28 days [15,66]. Comparative standards, as summarized in Table 9, highlight differences in methodologies such as dissolved organic carbon removal and CO<sub>2</sub> evolution, but generally confirm the superior biodegradability of bio-based alternatives over mineral oils [54,58]. Figure 8 illustrates typical biodegradation curves of vegetable oil esters versus mineral oils, confirming superior

biodegradability for bio-based alternatives [67]. Moreover, eco-toxicity studies demonstrate that esterified vegetable oils generally present lower aquatic toxicity than conventional lubricants, making them favorable for applications in marine and agricultural machinery.

Table 9. Comparative biodegradability standards for lubricants.

| Test Standard                              | Principle                                                | Test Duration | Pass Criteria                                       | Typical Bio-Based Lubricant Result | Typical Mineral Oil Result    |
|--------------------------------------------|----------------------------------------------------------|---------------|-----------------------------------------------------|------------------------------------|-------------------------------|
| OECD 301B (CO <sub>2</sub> Evolution Test) | Measures CO <sub>2</sub> evolution during biodegradation | 28 days       | ≥60% CO <sub>2</sub> evolution (ThCO <sub>2</sub> ) | High biodegradability (70–95%)     | Low biodegradability (15–25%) |
| OECD 301F (Manometric Respirometry Test)   | Monitors oxygen uptake in a closed system                | 28 days       | ≥60% O <sub>2</sub> consumption (ThOD)              | High biodegradability (65–90%)     | Low biodegradability (10–20%) |

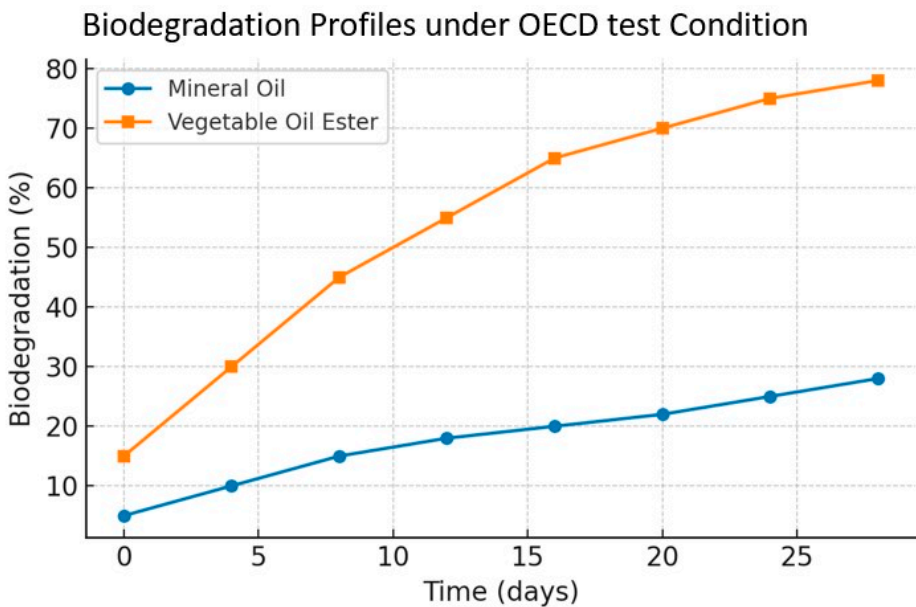


Figure 8. Biodegradation profiles of vegetable oil esters compared to conventional mineral oils under OECD test conditions.

6.2. Energy Efficiency and Friction Reduction

The tribological efficiency of lubricants significantly influences system-wide energy use [65]. As shown in Table 10, bio-based lubricants often exhibit lower friction coefficients compared to mineral oils, contributing to energy savings in controlled test environments [46,68–70].

Table 10. Average friction coefficients of mineral oils vs. selected bio-based lubricants in standardized tribological tests.

| Lubricant Type | Test Conditions                   | Average Friction Coefficient (μ) |
|----------------|-----------------------------------|----------------------------------|
| Mineral Oil    | Steel-on-steel, 40 °C, ASTM D4172 | 0.13                             |
| Soybean oil    | Steel-on-steel, 40 °C, ASTM D4172 | 0.11                             |

Figure 9 compares friction coefficients across lubricant categories, underlining the superior energy efficiency of ionic liquid blends and synthetic esters. These improvements not only reduce greenhouse gas emissions but also extend equipment life, strengthening the sustainability case for bio-based alternatives [65].

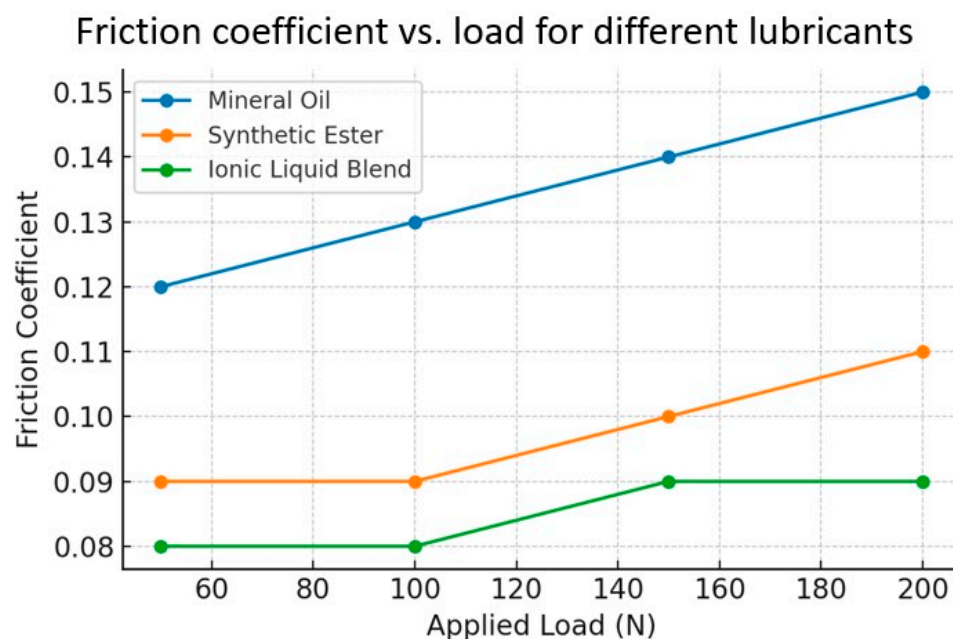


**Figure 9.** Friction coefficient comparison of mineral oils, synthetic esters, and ionic liquid blends across varying loads.

### 6.3. Life-Cycle Assessment and Carbon Footprint

A comprehensive sustainability assessment requires life-cycle analysis, encompassing feedstock cultivation, processing, use-phase, and end-of-life disposal. Figure 10 summarizes comparative LCA findings for mineral oils and bio-lubricants, showing reductions in carbon emissions when bio-based systems are adopted [7].

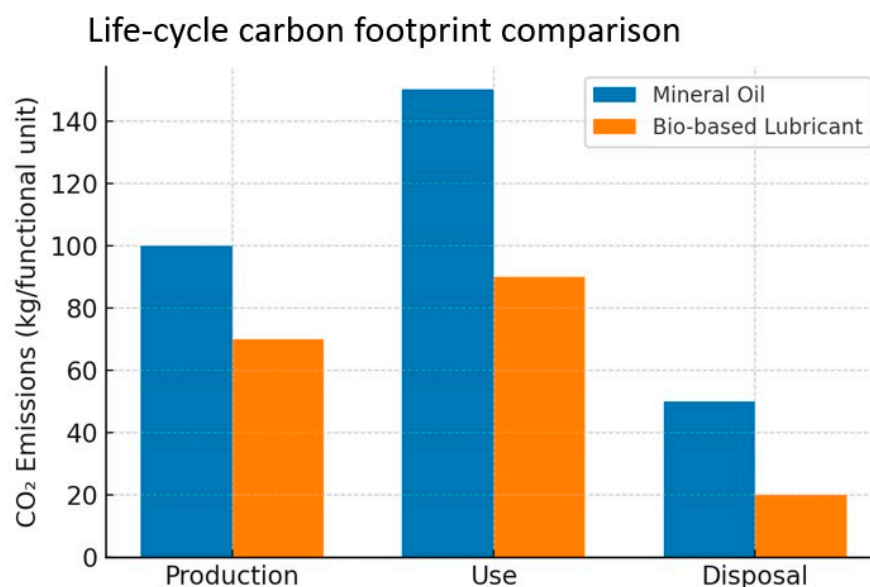


**Figure 10.** Life-cycle carbon footprint of mineral oils vs. bio-based lubricants, showing relative reductions in CO<sub>2</sub> emissions across production, use, and disposal phases.

Notably, LCA results are sensitive to agricultural practices: intensive pesticide or fertilizer use in oilseed production may offset environmental benefits [71]. Recent studies recommend integrating circular economy strategies, such as recycling used cooking oils and valorizing agro-residues, to further enhance the carbon savings potential.

## Methodological Uncertainties in LCA

While Life Cycle Assessment is a powerful tool for quantifying environmental impacts, its results, especially for bio-based products like lubricants, are often subject to significant methodological uncertainties [71,72]. These uncertainties can lead to varying conclusions across different studies comparing mineral oil-based and bio-based lubricants, highlighting the need for transparent reporting and robust analysis [71]. Understanding these methodological nuances is crucial for accurate interpretation and transparent reporting [73].

- **System Boundaries:** Defining the scope of an LCA (i.e., its “system boundaries”) profoundly impacts the outcome [73,74]. For lubricants, this involves deciding which stages of the product’s life cycle to include, such as “cradle-to-gate” (from raw material extraction to the factory gate) or “cradle-to-grave” (extending to the use phase and end-of-life treatment) [75]. The exclusion or inclusion of specific upstream processes (e.g., land-use change associated with agricultural feedstock production, which can have significant negative environmental consequences) or downstream processes (e.g., environmental impacts of lubricant disposal or biodegradation in nature) can shift the perceived environmental burden between bio-based and conventional lubricants [73]. For bio-based lubricants, negative impacts mainly stem from their agricultural production and performance in the use phase [71], and these impacts are critical but can be underestimated if not fully included in the system boundary [71]. Studies often lack detail on decisions taken regarding system boundaries, omitting key parts of the value chain [73].
- **Allocation Procedures:** The challenge of “allocation” arises in multi-product systems, particularly in biorefineries that produce lubricants alongside other co-products (e.g., animal feed from oilseed crush, glycerol from transesterification) [76]. Environmental burdens (e.g., emissions from oilseed cultivation, energy used in processing) must be distributed among these co-products [76]. Common allocation methods include:
  - Mass allocation: Distributes burdens based on the mass of each co-product.
  - Economic allocation: Distributes burdens based on the economic value of each co-product.
  - Energy allocation: Distributes burdens based on the energy content of each co-product.

Different allocation choices can drastically alter the environmental profile assigned to the bio-lubricant, making comparisons between studies difficult if these choices are not transparently reported and justified [76]. The choice of allocation method can considerably influence the results of LCAs and thus decision-making based on those results [77].

- **Data Quality and Uncertainty Analysis:** LCA models often rely on a mix of primary and generic inventory data, which can introduce parameter uncertainty [72]. Furthermore, model uncertainties arise from simplifications and assumptions made in the LCA methodology itself [72]. Many LCA studies, especially for emerging technologies, do not undertake comprehensive uncertainty or sensitivity analysis, despite these being crucial for understanding the reliability of LCA outcomes [72,73]. Without such analysis, the deterministic results presented in LCAs may mask significant variability stemming from methodological choices, spatial and temporal variability, and data gaps [73]. Increased transparency regarding methodological decisions and comprehensive uncertainty analyses are recommended to improve the credibility and comparability of LCA studies in the biorefinery sector [73]. A critical review of LCA studies on bioenergy technologies also identified methodological issues in terms of system boundaries, functional unit, and multifunctionality [74].

#### 6.4. Policy and Regulatory Drivers

Sustainability adoption is accelerated by global regulations. The European Union's Ecolabel program and U.S. EPA Vessel General Permit mandate the use of environmentally acceptable lubricants in marine and offshore applications [54,78]. Such policies create market incentives, pushing industries toward bio-based alternatives [58]. However, harmonization of global sustainability standards remains a challenge, necessitating coordinated international policy frameworks.

### 7. Future Perspectives, Policy Implications, and Emerging Technologies

The trajectory of bio-based lubricants is strongly shaped by both technological innovation and evolving regulatory landscapes [52,54]. While advances in oleochemistry, tribological testing, and additive technologies have positioned bio-lubricants as sustainable alternatives, several systemic barriers remain to be addressed in the coming decade [12,63].

#### 7.1. Policy and Standardization Outlook

Global adoption of bio-based lubricants depends heavily on the establishment of internationally harmonized standards for biodegradability, toxicity testing, and carbon footprint reporting [54,58]. Regulatory bodies such as the EU and U.S. EPA are moving toward stricter limits on polyaromatic hydrocarbons and sulfur in lubricants, indirectly favoring renewable formulations [58]. However, a lack of standardized test protocols across regions often impedes scalability and market competitiveness [52]. The introduction of ISO standards for eco-lubricants, such as ISO 15380 for environmentally acceptable lubricants, and economic incentives like carbon credits are expected to accelerate adoption [54,58].

Figure 11 illustrates the increasing global regulatory stringency for lubricants over time, emphasizing the policy-driven shift towards more environmentally friendly formulations [79]. This trend is characterized by evolving legislation that aims to minimize environmental impact and promote sustainability in industrial and automotive applications [58,80]. Such regulatory frameworks, including restrictions on hazardous substances and mandates for biodegradability, directly incentivize the development and adoption of bio-based lubricants, thereby influencing their market penetration and technological advancements.

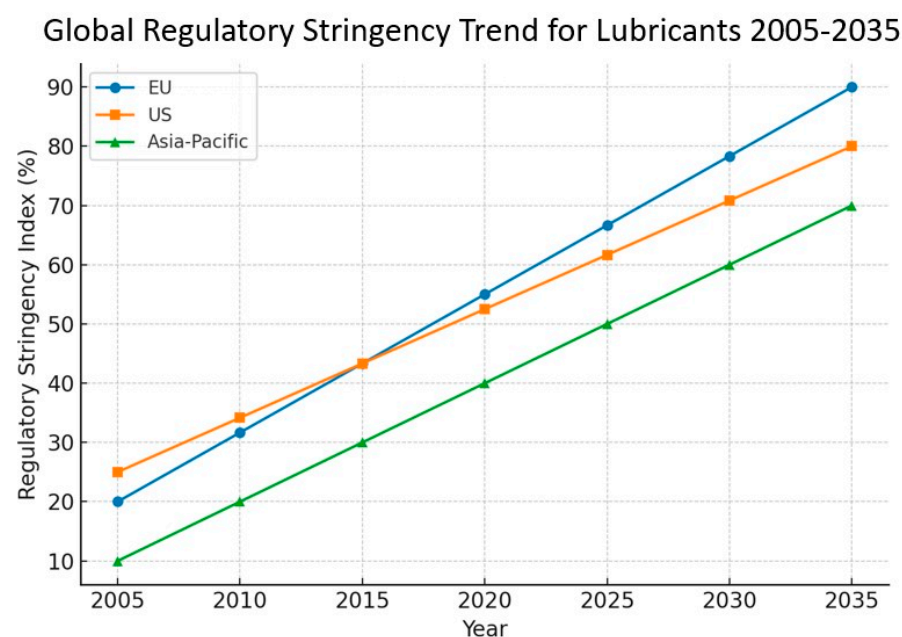


**Figure 11.** Global regulatory stringency trend for lubricants, highlighting policy push toward bio-based formulations.

7.2. Emerging Technologies in Bio-Lubricant Development

Recent years have witnessed the integration of nanotechnology, ionic liquids, and enzyme-catalyzed esterification to tailor lubricant performance [54,81]. Hybrid nanoparticle systems, combining different nanomaterials like MoS<sub>2</sub>–hBN, have demonstrated synergistic effects in enhancing tribological properties (friction and wear reduction), thermal stability, and oxidative properties of lubricants [10,82]. Such nanomaterials represent an emerging tribological approach for sustainable lubrication [3]. Parallel advances in artificial intelligence and machine learning have enabled predictive formulation design, reducing trial-and-error cycles and improving resource efficiency in lubricant development [73]. The development status and future trends in lubricant additives technology indicate a strong focus on multifunctional composite additives and more environmentally friendly, economically degradable additives [81].

Table 11 synthesizes the major research challenges, technological opportunities, and corresponding policy levers that are critical for advancing bio-lubricant development and widespread adoption. This mapping reflects a consensus derived from the current academic literature and market analysis regarding the strategic direction of the field [52,54,58,63,81].

**Table 11.** Mapping of Research Challenges, Technological Opportunities, and Policy Levers in Bio-Lubricants.

| Challenge                     | Technology Response                                    | Policy Lever                    |
|-------------------------------|--------------------------------------------------------|---------------------------------|
| Poor oxidative stability      | Enzyme-catalyzed esterification, advanced antioxidants | Incentives for biorefineries    |
| High production cost          | AI-driven process optimization, waste valorization     | Carbon credits, subsidies       |
| Cold-flow limitations         | Hybrid nanoparticle additives, molecular design        | Regional cold-weather standards |
| Lack of global test standards | ISO biodegradability protocols, standardized LCA       | WTO harmonization policies      |

7.3. Future Market and Environmental Impacts

Market adoption of bio-lubricants is projected to grow significantly. The global market for biolubricants was valued at USD 2.13 billion in 2021 and is projected to grow to USD 3.05 billion by 2030 [2]. Another report estimated the market to reach USD 2.6 billion with a post-COVID-19 CAGR of 5.2% over the analysis period of 2020–2027 [8]. These projections highlight the increasing demand driven by sustainable solutions. The market outlook for biolubricants is influenced by many factors, including political, economic, demographic, environmental, and regulatory aspects [53].

Figure 12 illustrates the projected adoption rates of bio-based lubricants under various market and policy scenarios (e.g., Conservative, Baseline, and Optimistic) [83]. These scenarios are typically developed based on a combination of historical trends, anticipated technological advancements, and varying levels of regulatory support and economic incentives, as broadly discussed in market analyses [53,56]. The figure highlights how favorable policy environments and continued innovation could significantly accelerate the market penetration of bio-lubricants, leading to a larger market share compared to more conservative growth projections.

Life Cycle Assessment studies compare the environmental impacts of mineral oil-based and bio-based lubricants, reporting varying conclusions [71]. These studies utilize LCA to evaluate energy and material flows throughout the product life, from raw material extraction to manufacturing, usage, and disposal or reuse [71]. Bio-lubricants can offer reductions in overall CO<sub>2</sub> emissions and environmental benefits compared to mineral oil-based counterparts [27,75,84]. The negative impacts of bio-lubricants primarily stem from their agricultural production and performance during the use phase [71]. This assessment of environmental impact, coupled with biodegradability and lower eco-toxicity, positions bio-lubricants as a key component of sustainable industrial development [63].

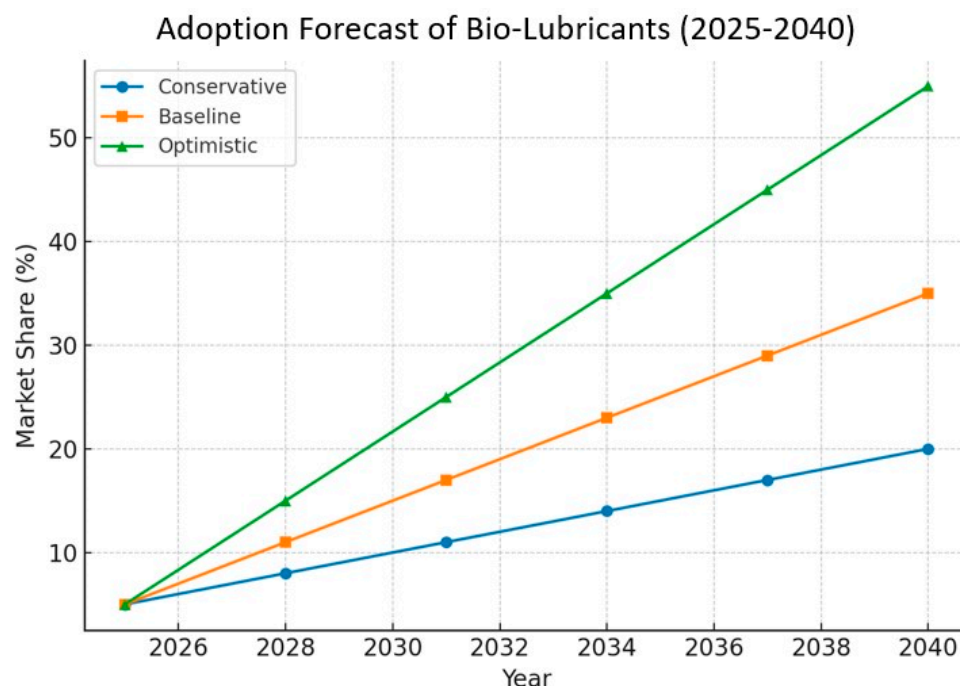


**Figure 12.** Adoption forecast of bio-lubricants under three scenarios: Conservative, Baseline, Optimistic.

#### 7.4. Concluding Perspectives

The future success of bio-based lubricants will depend on bridging the technology-policy-market nexus. Advances in catalysis, hybrid additive systems, and digital formulation tools must be matched with robust policy frameworks and industry-wide collaboration. Establishing eco-label certifications, providing economic incentives, and expanding global R&D networks are critical steps to ensure that bio-lubricants not only remain competitive but also central to sustainable tribology [53,54].

#### 7.5. Roadmap for Technological Advancement

The R&D roadmap for bio-based lubricants, as synthesized from current challenges, technological opportunities, and market and policy drivers discussed throughout this review, outlines a strategic progression [52,54,81]. Near-term priorities focus on incremental performance enhancements and cost reduction. Mid-term efforts target large-scale industrial demonstrations and the development of versatile hybrid additive systems. Long-term goals envision full integration into Industry 5.0 smart manufacturing, with advanced digital formulation tools and a robust circular economy for lubricants. This phased approach, supported by ongoing research and policy, is crucial for widespread adoption.

#### 7.6. Adoption Potential Across Sectors

The adoption of bio-lubricants varies across industries, influenced by regulatory pressures, performance requirements, and economic factors [12,53]. The extent of their current usage is limited by challenges concerning their performance, production scale, and lack of comprehensive support from authorities [55]. While high-performance seed-oil-derived lubricants are being developed, meeting the demanding low-temperature and thermooxidative stability requirements for sectors like aerospace remains a key area of focus [57].

Figure 13 presents a technology adoption matrix for bio-based lubricants, mapping readiness levels and market penetration across various industrial sectors [85]. This matrix is a conceptual representation based on the overall discussion of challenges, applications, and market factors within this review [12,53,55]. It visually represents that some sectors,

like agriculture and marine, may have higher readiness due to regulatory drivers and suitability of existing formulations, while others, like aerospace, might be in earlier stages of adoption due to stringent performance and safety requirements. Understanding this matrix is crucial for identifying target markets and tailoring development efforts to specific sectoral needs.

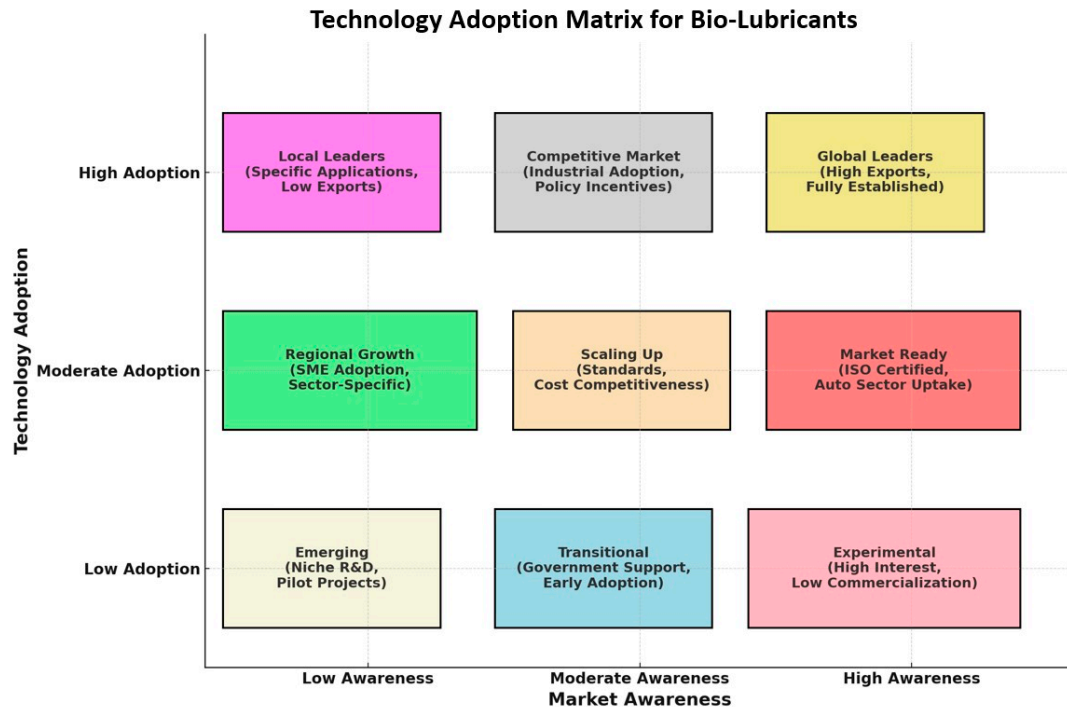


**Figure 13.** Technology Adoption Matrix for Bio-Lubricants.

### 7.7. Opportunities and Challenges

Key opportunities for bio-based lubricants include their potential for reduced carbon emissions, biodegradability, and compatibility with renewable energy systems [54,63]. On the other hand, major challenges include achieving cost competitiveness, ensuring feedstock supply stability, and conducting extensive long-term durability testing to meet the rigorous demands of modern machinery [12,15,52].

## 8. Conclusions and Future Outlook

This comprehensive review has synthesized the rapid advancements and persistent challenges in the field of bio-based lubricants, moving beyond a mere summary of existing literature.

### 8.1. Novelty and Distinguishing Features

Distinguishing itself from prior works that often focus on specific aspects of bio-lubricants such as feedstock types or individual additive classes [8,12,39], this review provides a contemporary and holistic analysis. Our unique contribution lies in integrating the rapid pace of technological innovation—including advanced chemical modifications and novel additive engineering for both bio-based oils and greases—with a critical examination of the intricate interplay of global market trends, industrial adoption dynamics, and stringent regulatory frameworks [54]. Furthermore, we incorporate emerging methodologies such as artificial intelligence and machine learning for predictive formulation design [73] and advanced tribological evaluation, benchmarking performance across diverse sectors, including automotive, industrial, and marine applications [2]. By connecting fundamental scientific advancements with crucial socio-economic and environmental considerations,

this paper identifies key research gaps and articulates a pragmatic roadmap for accelerating the mainstream penetration of bio-based lubricants, including their semi-solid counterparts, green greases, which are increasingly crucial for environmental protection [86,87].

### 8.2. Key Bottlenecks for Industrial Adoption

Despite the inherent advantages and significant advancements, several key bottlenecks continue to impede the widespread industrial adoption of bio-based lubricants, including green greases. Foremost among these is cost competitiveness relative to conventional mineral oil-based lubricants, primarily due to higher raw material expenses and economies of scale enjoyed by the established petroleum industry [2]. Secondly, supply chain instability and fluctuations in feedstock availability and pricing, particularly for agricultural commodities, pose significant challenges [52]. For green greases, specifically, finding and developing effective and affordable bio-based thickeners that can replicate the rheological and mechanical stability of traditional metallic soaps remains a notable hurdle [88–90]. While some bio-based thickeners show comparable rheological and thermal properties, their physical and mechanical stabilities have often been seriously compromised [90]. Thirdly, a persistent performance misconception among end-users, viewing bio-lubricants as “green but inferior” despite modern formulations demonstrating comparable or superior tribological performance in many tests, remains a barrier [63]. Finally, the lack of globally harmonized test standards and regulatory frameworks across regions often impedes scalability and market entry, contributing to perceived risk and higher development costs [52,58].

### 8.3. Priority Research Directions

To overcome these bottlenecks and accelerate the transition towards sustainable lubrication, priority research directions must focus on:

**Hybrid Additive Systems:** Further development and optimization of multifunctional hybrid additive packages that synergistically combine nanoparticles (e.g., CuO, graphene) with ionic liquids, polymers, or natural antioxidants are crucial [10,81,82,91]. These systems aim to simultaneously address oxidative stability, cold-flow limitations, and tribological performance, ensuring high performance across demanding applications for both bio-oils and green greases. The requirement for biodegradable additives in environmentally friendly greases also limits the range of suitable products [92].

**Circular Economy Strategies:** Research should emphasize integrating bio-lubricant production and consumption within circular economy frameworks. This includes advanced valorization techniques for waste cooking oils and other agro-residues as feedstocks, and developing efficient closed-loop recycling and regeneration processes for used bio-lubricants and greases to minimize waste and maximize resource efficiency [54,63,93].

**AI-Driven Formulations and Digital Twins:** Leveraging artificial intelligence, machine learning, and digital twin technologies is paramount for accelerating lubricant design and optimization [14,73,94]. AI-driven molecular design and predictive tribology simulations can significantly reduce trial-and-error experimentation, optimize formulations for specific applications, and forecast long-term performance under diverse operating conditions, thereby improving resource efficiency and reducing development costs [95,96]. This approach is equally critical for the complex formulation of green greases, optimizing base oil-thickener-additive interactions and addressing issues like stability against mechanical degradation [89].

**Sustainable Feedstock Diversification:** Continued exploration of non-edible and waste biomass sources, such as algal oils and lignocellulosic materials, coupled with advanced chemical and enzymatic modification pathways, is essential to mitigate food-versus-fuel concerns and ensure stable, cost-effective feedstock supply [97]. This extends to sustain-

able base oils and alternative bio-based thickeners for green greases, utilizing renewable resource-based ingredients to replace traditional synthetic materials in conventional greases [31,87,98,99].

**Performance and Stability of Green Greases:** Dedicated research is needed to overcome the performance challenges of green greases, particularly regarding their physical and mechanical stability, and their rheological behaviors, to match or exceed conventional greases in demanding applications [89,90]. Developing robust, biodegradable thickeners from renewable resources that offer comparable thermal and load-bearing capabilities to metallic soaps is a critical area for innovation [87,89]. While substituting mineral base oils with vegetable oils is common, the substitution of traditional metallic soaps with biodegradable and renewable thickeners is less considered but essential [99].

In conclusion, the next decade will define whether bio-based lubricants, including both liquid oils and semi-solid green greases, transition from promising alternatives to mainstream global lubricants. The successful integration of high-performance hybrid additives, the adoption of robust circular economy strategies, and the widespread application of AI-driven design tools will be pivotal in this transformation. If these pathways align, bio-lubricants can significantly reduce dependence on fossil-based oils, lower carbon emissions, and redefine the future of sustainable tribology [1]. Green greases, specifically, will play an increasingly vital role in various industrial and consumer applications, protecting the environment from the negative effects of conventional lubricants and contributing significantly to the overall sustainability goals of the tribology sector [63,86,87,98].

**Author Contributions:** J.R.P.: Formal analysis, writing—original draft preparation. K.V.C.: Formal analysis, writing—original draft preparation. S.R.: Conceptualization, methodology, software, validation, supervision N.P.P.: Resources, writing—review and editing, data curation. D.S.: Formal analysis, resources, writing—review. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

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

## References

1. Freschi, M.; Paniz, A.; Cerqueni, E.; Colella, G.; Dotelli, G. The Twelve Principles of Green Tribology: Studies, Research, and Case Studies—A Brief Anthology. *Lubricants* **2022**, *10*, 129. [\[CrossRef\]](#)
2. Berman, D. Plant-Based Oils for Sustainable Lubrication Solutions—Review. *Lubricants* **2024**, *12*, 300. [\[CrossRef\]](#)
3. Huynh, K.K.; Pham, S.T.; Tieu, A.K.; Wan, S. Tribocatalysis Induced Carbon-Based Tribofilms—An Emerging Tribological Approach for Sustainable Lubrications. *Lubricants* **2023**, *11*, 327. [\[CrossRef\]](#)
4. Cañellas, G.; Emeric, A.; Combarros, M.; Navarro, Á.Y.R.; Beltran, L.; Vilaseca, M.; Vives, J. Tribological Performance of Esters, Friction Modifier and Antiwear Additives for Electric Vehicle Applications. *Lubricants* **2023**, *11*, 109. [\[CrossRef\]](#)
5. Saka, A.; Abor, T.K.; Okafor, A.C.; Okoronkwo, M.U. Thermo-Rheological and Tribological Properties of Low- and High-Oleic Vegetable Oils as Sustainable Bio-Based Lubricants. *RSC Sustain.* **2024**, *3*, 1461–1476. [\[CrossRef\]](#)
6. Nogales-Delgado, S.; Encinar, J.M.; González, J.F. A Review on Biolubricants Based on Vegetable Oils through Transesterification and the Role of Catalysts: Current Status and Future Trends. *Catalysts* **2023**, *13*, 1299. [\[CrossRef\]](#)
7. Amran, N.A.; Bello, U.; Ruslan, M.S.H. The role of antioxidants in improving biodiesel's oxidative stability, poor cold flow properties, and the effects of the duo on engine performance: A review. *Heliyon* **2022**, *8*, e09846. [\[CrossRef\]](#)
8. Raof, N.A.; Hamid, H.A.; Aziz, N.A.M.; Yunus, R. Prospects of Plant-Based Trimethylolpropane Esters in the Biolubricant Formulation for Various Applications: A Review. *Front. Mech. Eng.* **2022**, *8*, 833438. [\[CrossRef\]](#)

9. Filho, P.R.C.F.R.; Santos, L.d.S.e. The Influence of Unsaturation Modifications on the Tribological Characteristics of Bio-Based Lubricants Obtained from Vegetable Oils: A Review. *J. Braz. Soc. Mech. Sci. Eng.* **2025**, *47*, 216. [\[CrossRef\]](#)
10. Nassef, B.G.; Pape, F.; Poll, G. Enhancing the Performance of Rapeseed Oil Lubricant for Machinery Component Applications through Hybrid Blends of Nanoadditives. *Lubricants* **2023**, *11*, 479. [\[CrossRef\]](#)
11. Sikdar, S.; Menezes, P.L. Enhancing Lubrication Performance of Plastic Oil Lubricant with Oleic Acid-Functionalized Graphene Nanoplatelets and Hexagonal Boron Nitride Solid Lubricant Additives. *Lubricants* **2024**, *12*, 251. [\[CrossRef\]](#)
12. Hamnas, A.; Unnikrishnan, G. Bio-Lubricants from Vegetable Oils: Characterization, Modifications, Applications and Challenges—Review. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113413. [\[CrossRef\]](#)
13. Zhu, X.; Pan, Y.; Lan, B.; He, W.; Huang, H. Remaining Useful Life Prediction Based on Wear Monitoring with Multi-Attribute GAN Augmentation. *Lubricants* **2025**, *13*, 145. [\[CrossRef\]](#)
14. Li, X.; Guo, F. Prediction of Lubrication Performance of Hyaluronic Acid Aqueous Solutions Using a Bayesian-Optimized BP Network. *Lubricants* **2025**, *13*, 215. [\[CrossRef\]](#)
15. Uppar, R.; Dinesha, P.; Kumar, S. A Critical Review on Vegetable Oil-Based Bio-Lubricants: Preparation, Characterization, and Challenges. *Environ. Dev. Sustain.* **2022**, *25*, 9011. [\[CrossRef\]](#)
16. Ojha, P.K.; Poudel, D.K.; Rokaya, A.; Maharjan, S.; Timsina, S.; Poudel, A.; Satyal, R.; Satyal, P.; Setzer, W.N. Chemical Compositions and Essential Fatty Acid Analysis of Selected Vegetable Oils and Fats. *Compounds* **2024**, *4*, 37–70. [\[CrossRef\]](#)
17. Ugolini, L.; Matteo, R.; Lazzeri, L.; Malaguti, L.; Folegatti, L.; Bondioli, P.; Pochi, D.; Grilli, R.; Fornaciari, L.; Benigni, S.; et al. Technical Performance and Chemical–Physical Property Assessment of Safflower Oil Tested in an Experimental Hydraulic Test Rig. *Lubricants* **2023**, *11*, 39. [\[CrossRef\]](#)
18. Grebe, M.; Ruland, M. Influence of Mechanical, Thermal, Oxidative and Catalytic Processes on Thickener Structure and Thus on the Service Life of Rolling Bearings. *Lubricants* **2022**, *10*, 77. [\[CrossRef\]](#)
19. Silva, R.A.; Vieira, A.C.; Giordano, R.C.; Fernández-Lafuente, R.; Tardioli, P.W. Enzymatic Synthesis of Fatty Acid Isoamyl Monoesters from Soybean Oil Deodorizer Distillate: A Renewable and Ecofriendly Base Stock for Lubricant Industries. *Molecules* **2022**, *27*, 2692. [\[CrossRef\]](#)
20. Ifeanyi-Nze, F.O.; Akhiehiro, E.T. Optimization of the Process Variables on Biodegradable Industrial Lubricant Basestock Synthesis from Jatropha Curcas Seed Oil via Response Surface Methodology. *Front. Energy Res.* **2023**, *11*, 1169565. [\[CrossRef\]](#)
21. Filon, D.; Anastopoulos, G.; Karonis, D. Synthesis and Evaluation of Bio-Lubricants from Renewable Raw Materials. *Lubricants* **2024**, *12*, 446. [\[CrossRef\]](#)
22. Prasanth, M.A.; Rani, S.; Singh, S.P.; Raja, D.E.; Barmavatu, P. Formulation and Evaluation of Bio-Grease from the Blend of Chemically Modified Rice Bran Oil and Calophyllum Inophyllum Oil. *J. Eng. Appl. Sci.* **2024**, *71*, 80. [\[CrossRef\]](#)
23. Dykha, O.; Hetman, M.V.; Staryi, A.; Kałaczyński, T. Review of Aspects of Processing and Use of Waste Cooking Oils as Effective Lubricants. *Probl. Tribol.* **2023**, *28*, 62. [\[CrossRef\]](#)
24. Singh, Y.; Negi, P.; Yadav, A.; Tripathi, R. Euphorbia Lathyris: A Novel Feedstock for Bio Based Lubricant Application with Titanium Dioxide Nanoparticles as Additives. *Mater. Today Proc.* **2021**, *46*, 10518. [\[CrossRef\]](#)
25. Kozdrach, R.; Radulski, P. Influence of a Walnut Shell Biochar Additive on the Tribological and Rheological Properties of Vegetable Lubricating Grease. *Lubricants* **2025**, *13*, 213. [\[CrossRef\]](#)
26. Dube, N.N.; Elkady, M.; Noby, H.; Nassef, M.G.A. Developing a Sustainable Grease from Jojoba Oil with Plant Waste Based Nanoadditives for Enhancement of Rolling Bearing Performance. *Sci. Rep.* **2024**, *14*, 539. [\[CrossRef\]](#)
27. Farfan-Cabrera, L.I.; Franco-Morgado, M.; González-Sánchez, A.; Pérez-González, J.; Marín-Santibáñez, B.M. Microalgae Biomass as a New Potential Source of Sustainable Green Lubricants. *Molecules* **2022**, *27*, 1205. [\[CrossRef\]](#)
28. Adewuyi, A. Production of Biodiesel from Underutilized Algae Oil: Prospects and Current Challenges Encountered in Developing Countries. *Biology* **2022**, *11*, 1418. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Udayan, A.; Pandey, A.K.; Sirohi, R.; Sreekumar, N.; Sang, B.; Sim, S.J.; Kim, S.; Pandey, A. Production of Microalgae with High Lipid Content and Their Potential as Sources of Nutraceuticals. *Phytochem. Rev.* **2022**, *22*, 833. [\[CrossRef\]](#)
30. Singh, N.; Agarwal, P.; Porwal, S.K. Natural Antioxidant Extracted Waste Cooking Oil as Sustainable Biolubricant Formulation in Tribological and Rheological Applications. *Waste Biomass Valorization* **2022**, *13*, 3127. [\[CrossRef\]](#)
31. Tian, C.; Xu, H.; Dong, J. Development of Environmentally Friendly Lubricant Using Natural Resources: Layered Double Hydroxide Gels. *Ind. Crops Prod.* **2023**, *208*, 117879. [\[CrossRef\]](#)
32. Jopen, M.; Degen, P.; Henzler, S.; Grabe, B.; Hiller, W.; Weberskirch, R. Polyurea Thickened Lubricating Grease—The Effect of Degree of Polymerization on Rheological and Tribological Properties. *Polymers* **2022**, *14*, 795. [\[CrossRef\]](#)
33. Wang, Y.; Zhang, P.; Lin, J.; Gao, X. Rheological and Tribological Properties of Lithium Grease and Polyurea Grease with Different Consistencies. *Coatings* **2022**, *12*, 527. [\[CrossRef\]](#)
34. Kozdrach, R.; Radulski, P. Application of Chokeberry Biochar as a Modified Additive to the Vegetable Lubricants: The Tribological and Rheological Properties. *Sci. Rep.* **2025**, *15*, 3964. [\[CrossRef\]](#)

35. Martín-Alfonso, J.E.; Martín-Alfonso, M.J.; Valencia, C.; Cuberes, M.T. Rheological and Tribological Approaches as a Tool for the Development of Sustainable Lubricating Greases Based on Nano-Montmorillonite and Castor Oil. *Friction* **2020**, *9*, 415. [\[CrossRef\]](#)
36. Hodapp, A.; Conrad, A.; Hochstein, B.; Jacob, K.; Willenbacher, N. Effect of Base Oil and Thickener on Texture and Flow of Lubricating Greases: Insights from Bulk Rheometry, Optical Microrheology and Electron Microscopy. *Lubricants* **2022**, *10*, 55. [\[CrossRef\]](#)
37. Senyk, S.; Gocman, K.; Wachowski, M.; Kałdoński, T. Role of Base Grease Type on the Lubrication Performance of Hexagonal Boron Nitride Nanoparticles and Microparticles. *Materials* **2025**, *18*, 2196. [\[CrossRef\]](#)
38. Cebulska, W.; Bąkowski, H.; Hadryś, D. The Influence of Selected Solid Lubricants on the Wear of the Rolling–Sliding Interface in the Wheel–Rail System According to the Standard PN-EN 15427-2-1:2022. *Materials* **2025**, *18*, 1672. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Soodoo, N.; Bouzidi, L.; Narine, S.S. Fundamental Structure–Function Relationships in Vegetable Oil-Based Lubricants: A Critical Review. *Lubricants* **2023**, *11*, 284. [\[CrossRef\]](#)
40. Liu, W.; Qiao, X.; Liu, S.; Chen, P. A Review of Nanomaterials with Different Dimensions as Lubricant Additives. *Nanomaterials* **2022**, *12*, 3780. [\[CrossRef\]](#)
41. Shazly, R.I.E.; El-Sheshtawy, H.S.; Ahmed, N.S.; Nassar, A.M. Synthesis and Biodegradation Testing of Some Synthetic Oils Based on Ester. *Sci. Rep.* **2024**, *14*, 3416. [\[CrossRef\]](#)
42. ASTM D4172-21; Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method). ASTM: Conshohocken, PA, USA, 2021.
43. Sadiq, M.I.; Ghopa, W.A.W.; Nuawi, M.Z.; Rasani, M.R.; Ibrahim, S. An Experimental Investigation of Static Properties of Bio-Oils and SAE40 Oil in Journal Bearing Applications. *Materials* **2022**, *15*, 2247. [\[CrossRef\]](#)
44. Du, C.Q.; Sheng, C.; Liang, X.; Rao, X.; Guo, Z. Effects of Temperature on the Tribological Properties of Cylinder-Liner Piston Ring Lubricated with Different Oils. *Lubricants* **2023**, *11*, 115. [\[CrossRef\]](#)
45. Bhowmik, P.; Sharma, B.K.; Sarker, M.I.; Mainali, K.; Wang, Y.; Tang, C.; Roy, S. Exploring the Additive Compatibility and Tribological Behavior of Regular and High Oleic Soybean Oil. *Front. Mech. Eng.* **2024**, *10*, 1488407. [\[CrossRef\]](#)
46. Biresaw, G.; Bantchev, G.B.; Murray, R.E. Investigation of Biobased and Petroleum Base Oils in the Entire Spectrum of Lubrication Regimes. *J. Am. Oil Chem. Soc.* **2017**, *94*, 1197. [\[CrossRef\]](#)
47. Elgharabawy, A.S.; Sadik, W.A.; Sadek, O.M.; Kasaby, M.A. Transesterification Reaction Conditions and Low-Quality Feedstock Treatment Processes for Biodiesel Production—A Review. *J. Pet. Min. Eng.* **2021**, *98*, 89–94. [\[CrossRef\]](#)
48. Abdullah, B.M.; Zubairi, S.I.; Huri, H.Z.; Hairunisa, N.; Yousif, E.; Basu, R.C. Polyesters Based on Linoleic Acid for Biolubricant Basestocks: Low-Temperature, Tribological and Rheological Properties. *PLoS ONE* **2016**, *11*, e0151603. [\[CrossRef\]](#) [\[PubMed\]](#)
49. Keramat, M.; Ehsandoost, E.; Golmakani, M.-T. Recent Trends in Improving the Oxidative Stability of Oil-Based Food Products by Inhibiting Oxidation at the Interfacial Region. *Foods* **2023**, *12*, 1191. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Castellanos-Leal, E.L.; Osuna-Zatarain, A.; García-García, A. Frictional Properties of Two-Dimensional Nanomaterials as an Additive in Liquid Lubricants: Current Challenges and Potential Research Topics. *Lubricants* **2023**, *11*, 137. [\[CrossRef\]](#)
51. Karmakar, G.; Ghosh, P.; Sharma, B.K. Chemically Modifying Vegetable Oils to Prepare Green Lubricants. *Lubricants* **2017**, *5*, 44. [\[CrossRef\]](#)
52. Cecilia, J.A.; Ballesteros-Plata, D.; Saboya, R.M.A.; Luna, F.M.T.; Cavalcante, C.L.; Rodríguez-Castellón, E. An Overview of the Biolubricant Production Process: Challenges and Future Perspectives. *Processes* **2020**, *8*, 257. [\[CrossRef\]](#)
53. Bart, J.C.J.; Gucciardi, E.; Cavallaro, S. Markets for Biolubricants. In *Elsevier eBooks*; Elsevier BV: Amsterdam, The Netherlands, 2012; p. 712. [\[CrossRef\]](#)
54. Pichler, J.; Eder, R.M.; Besser, C.; Pisarova, L.; Dörr, N.; Marchetti-Deschmann, M.; Frauscher, M. A Comprehensive Review of Sustainable Approaches for Synthetic Lubricant Components. *Green Chem. Lett. Rev.* **2023**, *16*, 2185547. [\[CrossRef\]](#)
55. Syahir, A.Z.; Zulkifli, N.W.M.; Masjuki, H.H.; Kalam, M.A.; Alabdulkarem, A.; Gulzar, M.; Khuong, L.S.; Harith, M.H. A Review on Bio-Based Lubricants and Their Applications. *J. Clean. Prod.* **2017**, *168*, 997. [\[CrossRef\]](#)
56. Mobarak, H.M.; Mohamad, E.N.; Masjuki, H.H.; Kalam, M.A.; Mahmud, K.A.H.A.; Habibullah, M.; Ashraful, A.M. The Prospects of Biolubricants as Alternatives in Automotive Applications. *Renew. Sustain. Energy Rev.* **2014**, *33*, 34. [\[CrossRef\]](#)
57. Sonnenschein, M.F.; Greaves, M.R.; Bell, B.M.; Wendt, B.L. Design, Polymerization, and Properties of High-Performance Seed-Oil-Derived Lubricants. *Ind. Eng. Chem. Res.* **2012**, *51*, 8386. [\[CrossRef\]](#)
58. Bart, J.C.J.; Gucciardi, E.; Cavallaro, S. Legislation of Relevance to Lubricants. In *Elsevier eBooks*; Elsevier BV: Amsterdam, The Netherlands, 2012; p. 451. [\[CrossRef\]](#)
59. U.S. Environmental Protection Agency (EPA). *Vessel General Permit for Discharges Incidental to the Normal Operation of Vessels (VGP)*; EPA-833-F-13-001; U.S. Environmental Protection Agency: Washington, DC, USA, 2013. Available online: <https://www.epa.gov/sites/default/files/2015-11/documents/vgp2013.pdf> (accessed on 29 August 2025).
60. ISO 15380:2023; Lubricants, industrial oils and related products (class L)—Family H (Hydraulic systems)—Specifications for hydraulic fluids in categories HETG, HEPG, HEES and HEPR. ISO: Basel, Switzerland, 2023.
61. ISO 12925-1:2024; Lubricants, industrial oils and related products (class L)—Family C (gears). ISO: Basel, Switzerland, 2024.

62. ISO 21469:2006; Safety of machinery—Lubricants with incidental product contact—Hygiene requirements. ISO: Basel, Switzerland, 2006.
63. Shah, R.; Woydt, M.; Zhang, S. The Economic and Environmental Significance of Sustainable Lubricants. *Lubricants* **2021**, *9*, 21. [CrossRef]
64. Sazzad, M.R.I.; Rahman, M.M.; Hassan, T.; Rifat, A.A.; Mamun, A.A.; Adib, A.R.; Meraz, R.M.; Ahmed, M.F. Advancing Sustainable Lubricating Oil Management: Re-Refining Techniques, Market Insights, Innovative Enhancements, and Conversion to Fuel. *Heliyon* **2024**, *10*, e39248. [CrossRef] [PubMed]
65. Salimon, J.; Salih, N.; Yousif, E. Biolubricants: Raw Materials, Chemical Modifications and Environmental Benefits. *Eur. J. Lipid Sci. Technol.* **2010**, *112*, 519. [CrossRef]
66. Nowak, P.; Kucharska, K.; Kamiński, M. Ecological and Health Effects of Lubricant Oils Emitted into the Environment. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3002. [CrossRef]
67. Luther, R. Lubricants in the Environment. In *Lubricants and Lubrication*, 3rd ed.; Mang, T., Dresel, W., Eds.; Wiley-VCH: Weinheim, Germany, 2017; Chapter 7; pp. 153–236. [CrossRef]
68. Sanjeev, K.; Adhikari, S.; Jackson, R.L. An investigation of the friction and wear properties of high oleic vegetable-based and mineral oils. *Int. J. Agric. Environ. Biores.* **2021**, *6*, 1. [CrossRef]
69. Siniawski, M.T.; Saniei, N.; Adhikari, B.; Doezeema, L.A. Influence of Fatty Acid Composition on the Tribological Performance of Two Vegetable-based Lubricants. *Lubr. Sci.* **2007**, *24*, 101. [CrossRef]
70. Jabal, M.H.; Khlefia, M.Z.; Ahmed, I.S.; Salman, H.D. Performance features of the sunflower seeds oil as a hydraulic bio fluid under various normal loads. *J. Teknol.* **2020**, *82*, 13354. [CrossRef]
71. Bart, J.C.J.; Gucciardi, E.; Cavallaro, S. Environmental Life-Cycle Assessment (LCA) of Lubricants. In *Elsevier eBooks*; Elsevier BV: Amsterdam, The Netherlands, 2012; p. 527. [CrossRef]
72. Barahmand, Z.; Eikeland, M.S. Life Cycle Assessment under Uncertainty: A Scoping Review. *World* **2022**, *3*, 692–717. [CrossRef]
73. Gaffey, J.; Collins, M.N.; Styles, D. Review of Methodological Decisions in Life Cycle Assessment (LCA) of Biorefinery Systems across Feedstock Categories. *J. Environ. Manag.* **2024**, *358*, 120813. [CrossRef]
74. Wang, K.; Tong, R.; Zhai, Q.; Lyu, G.; Li, Y. A Critical Review of Life Cycle Assessments on Bioenergy Technologies: Methodological Choices, Limitations, and Suggestions for Future Studies. *Sustainability* **2025**, *17*, 3415. [CrossRef]
75. Våg, C.; Marby, A.; Kopp, M.; Furberg, L.; Norrby, T. A Comparative Life Cycle Assessment of the Manufacture of Base Fluids for Lubricants. *Lubr. Sci.* **2002**, *19*, 39. [CrossRef]
76. Obydenkova, S.V.; Kouris, P.D.; Smeulders, D.; Boot, M.D.; van der Meer, Y. Modeling Life-cycle Inventory for Multi-product Biorefinery: Tracking Environmental Burdens and Evaluation of Uncertainty Caused by Allocation Procedure. *Biofuels Bioprod. Biorefin.* **2021**, *15*, 1281. [CrossRef]
77. Sandin, G.; Røyne, F.; Berlin, J.; Peters, G.; Svanström, M. Allocation in LCAs of Biorefinery Products: Implications for Results and Decision-Making. *J. Clean. Prod.* **2015**, *93*, 213. [CrossRef]
78. Ademi, K.; Wijanarko, W.; Espallargas, N. Toward Cost-Effective Environmentally Acceptable Lubricants: Influence of Synthetic Ester and Low-Viscosity Polyalphaolefin Blend Type on Additive Performance. *Tribol. Lett.* **2025**, *73*, 61. [CrossRef]
79. Future Market Insights. *Lubricants Market Forecast and Outlook 2025–2035*; Future Market Insights: New York, NY, USA, 2025; pp. 1–328. Available online: <https://www.futuremarketinsights.com/> (accessed on 8 August 2025).
80. Bartz, W.J. Lubricants and the Environment. *Tribol. Int.* **1998**, *31*, 35. [CrossRef]
81. Wang, M.; He, H.; Fang, X.; Li, H.P. The Development Status and Future Trends of Lubricant Additives Technology: Based on Patents Analysis. *PLoS ONE* **2024**, *19*, e0304888. [CrossRef]
82. Nagarajan, T.; Sridewi, N.; Wong, W.P.; Walvekar, R.; Khanna, V.; Khalid, M. Synergistic Performance Evaluation of MoS<sub>2</sub>–hBN Hybrid Nanoparticles as a Tribological Additive in Diesel-Based Engine Oil. *Sci. Rep.* **2023**, *13*, 12559. [CrossRef]
83. Grand View Research. *Lubricants Industry Data Book: Automotive Lubricants, Industrial Lubricants, Marine Lubricants and Aerospace Lubricants Market Size, Share, Trends Analysis, and Segment Forecasts 2023–2030*; Grand View Research: San Francisco, CA, USA, 2023; pp. 1–250. Available online: <https://www.Grandviewresearch.Com/Sector-Report/Lubricants-Industry-Data-Book> (accessed on 8 August 2025).
84. Ekman, A.; Börjesson, P. Life Cycle Assessment of Mineral Oil-Based and Vegetable Oil-Based Hydraulic Fluids Including Comparison of Biocatalytic and Conventional Production Methods. *Int. J. Life Cycle Assess.* **2011**, *16*, 297. [CrossRef]
85. Ho, C.; McAuley, K.B.; Peppley, B.A. Biolubricants through Renewable Hydrocarbons: A Perspective for New Opportunities. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109261. [CrossRef]
86. Fiedler, M.; Sánchez, R.; Valencia, C.; Leopold, C.S.; Kuhn, E.; Franco, J.M. Influence of Base Oil Polarity on the Transient Shear Flow of Biodegradable Lubricating Greases. *Lubricants* **2015**, *3*, 611. [CrossRef]
87. Abdulbari, H.A.; Akindoyo, E.O.; Mahmood, W.K. Renewable Resource-Based Lubricating Greases from Natural and Synthetic Sources: Insights and Future Challenges. *ChemBioEng Rev.* **2015**, *2*, 406. [CrossRef]

88. Vafaei, S.; Fischer, D.; Jopen, M.; Jacobs, G.; König, F.; Weberskirch, R. Investigation of Tribological Behavior of Lubricating Greases Composed of Different Bio-Based Polymer Thickeners. *Lubricants* **2021**, *9*, 80. [\[CrossRef\]](#)
89. Martín-Alfonso, J.E.; Núñez, N.G.; Valencia, C.; Franco, J.M.; Díaz, M.J. Formulation of New Biodegradable Lubricating Greases Using Ethylated Cellulose Pulp as Thickener Agent. *J. Ind. Eng. Chem.* **2011**, *17*, 818. [\[CrossRef\]](#)
90. Borrero-López, A.M.; Martín-Sampedro, R.; Ibarra, D.; Valencia, C.; Eugenio, M.E.; Franco, J.M. Evaluation of Lignin-Enriched Side-Streams from Different Biomass Conversion Processes as Thickeners in Bio-Lubricant Formulations. *Int. J. Biol. Macromol.* **2020**, *162*, 1398. [\[CrossRef\]](#) [\[PubMed\]](#)
91. Karmakar, G.; Dey, K.; Ghosh, P.; Sharma, B.K.; Erhan, S.Z. A Short Review on Polymeric Biomaterials as Additives for Lubricants. *Polymers* **2021**, *13*, 1333. [\[CrossRef\]](#)
92. Florea, O.; Luca, M.; Constantinescu, A.; Florescu, D. The Influence of Lubricating Fluid Type on the Properties of Biodegradable Greases. *Lubr. Sci.* **2003**, *19*, 303. [\[CrossRef\]](#)
93. Pinheiro, C.T.; Quina, M.J.; Gando-Ferreira, L.M. Management of Waste Lubricant Oil in Europe: A Circular Economy Approach. *Crit. Rev. Environ. Sci. Technol.* **2020**, *1*, 2015–2050. [\[CrossRef\]](#)
94. Gokcekuyu, Y.; Ekinici, F.; Guzel, M.S.; Acici, K.; Aydin, S.; Asuroglu, T. Artificial Intelligence in Biomaterials: A Comprehensive Review. *Appl. Sci.* **2024**, *14*, 6590. [\[CrossRef\]](#)
95. Yu, T.; Yin, P.; Zhang, W.; Song, Y.; Zhang, X. A Compounding-Model Comprising Back Propagation Neural Network and Genetic Algorithm for Performance Prediction of Bio-Based Lubricant Blending with Functional Additives. *Ind. Lubr. Tribol.* **2020**, *73*, 246. [\[CrossRef\]](#)
96. Rosenkranz, A.; Marian, M.; Profito, F.J.; Aragon, N.; Shah, R. The Use of Artificial Intelligence in Tribology—A Perspective. *Lubricants* **2020**, *9*, 2. [\[CrossRef\]](#)
97. Nogales-Delgado, S.; Cabanillas, A.G.; Romero, Á.G.; Encinar, J.M. Monitoring Tert-Butylhydroquinone Content and Its Effect on a Biolubricant during Oxidation. *Molecules* **2022**, *27*, 8931. [\[CrossRef\]](#)
98. Nagendramma, P.; Kumar, P. Eco-Friendly Multipurpose Lubricating Greases from Vegetable Residual Oils. *Lubricants* **2015**, *3*, 628. [\[CrossRef\]](#)
99. Sánchez, R.; Franco, J.M.; Delgado, M.Á.; Valencia, C.; Gallegos, C. Development of New Green Lubricating Grease Formulations Based on Cellulosic Derivatives and Castor Oil. *Green Chem.* **2009**, *11*, 686. [\[CrossRef\]](#)

**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.