SUSTAINABILITY WITHOUT SACRIFICING PERFORMANCE: WHERE BIO-BASED AND LOW-CARBON GREASES ACTUALLY WORK

Abstract

Interest in bio-based and low-carbon greases is growing as industries try to reduce environmental impact, but these products must still meet real equipment performance needs. This article provides a primarily qualitative review of the main types of sustainable base oils and the key performance requirements greases must meet, including resistance to heat, water, heavy loads, and long service intervals. While bio-based greases offer clear benefits such as biodegradability, low toxicity, and high lubricity, they can struggle with oxidation, extreme temperatures, and long-term durability unless they are carefully formulated. Presently, they work well in areas such as construction, marine, agriculture, and forestry, where spills are more likely and environmental regulations are stricter. In more demanding conditions, hybrid greases that blend renewable and traditional oils are often needed. Overall, sustainable greases are not yet a full replacement, especially in applications constrained by oxidation stability, extreme temperatures, and extended service intervals, but they are becoming practical, high-performance options for many real-world applications.

I. Introduction:

Sustainability is becoming a major focus in the lubrication and grease industry. Governments, companies, and customers are pushing for products that reduce environmental impact and lower dependence on petroleum. As a result, bio-based and low-carbon greases are receiving more attention. However, even with growing interest, these greases are not widely used across all industries. The main reason is that engineers need to make sure that sustainable greases can still deliver reliable performance in demanding equipment.

The environmental motivation for change is strong. About 2.5 billion gallons of lubricants (including oils and greases) are sold each year in North America, and studies suggest that roughly 60% eventually enter the environment through leaks, spills, and disposal losses [1]. Bio-based lubricants are attractive because they are renewable, less toxic, and biodegrade much faster than petroleum oils [28]. These benefits make them especially important for industries such as marine, agriculture, forestry, and construction, where lubricants are more likely to enter soil or waterways.

Despite these advantages, bio-based greases remain a small but growing segment, representing roughly 1-5% of total global grease consumption based on recent estimates [2, 3]. Their adoption has historically been driven more by environmental regulations and compliance than by performance advantages [3]. Although new technology has improved these products, many engineers still question whether they can handle extreme temperatures, heavy loads, water contamination, and long service intervals as well as traditional greases. This cautious skepticism is increasingly being met by market expansion. According to Figure 1, the global bio-lubricants market is forecast to nearly double its 2019 value by 2032, driven by an accelerating CAGR of 5.3%.This growth is particularly relevant for grease applications, where demand for biodegradable and environmentally safer formulations is increasing in industries such as manufacturing and transportation

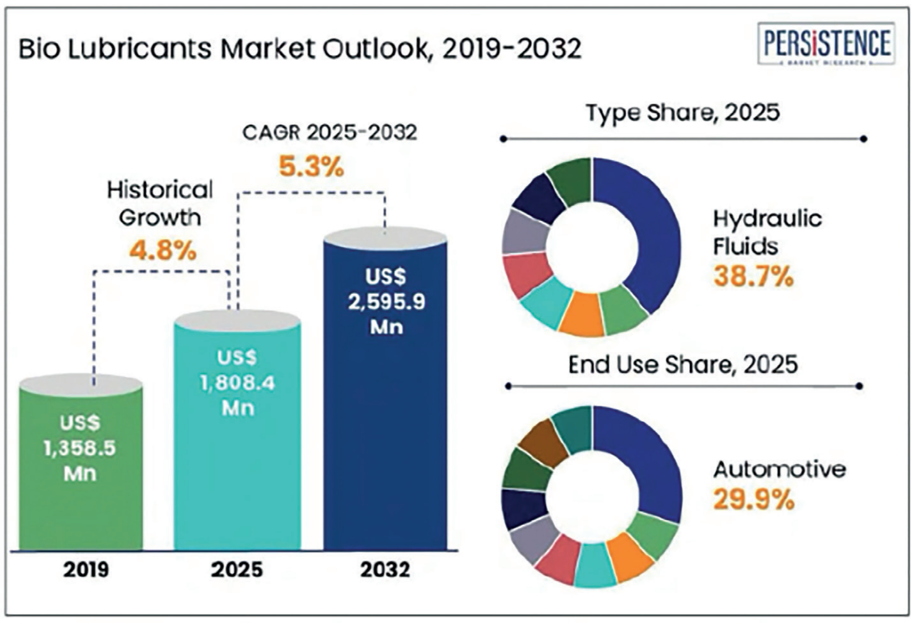


Figure 1. Bio-lubricants Market Outlook (2019–2032). Global market value is projected to grow from US$ 1,358.5 Mn to US$ 2,595.9 Mn. The CAGR is expected to rise from a historical 4.8% (2019–2025) to a projected 5.3% (2025–2032) [15].

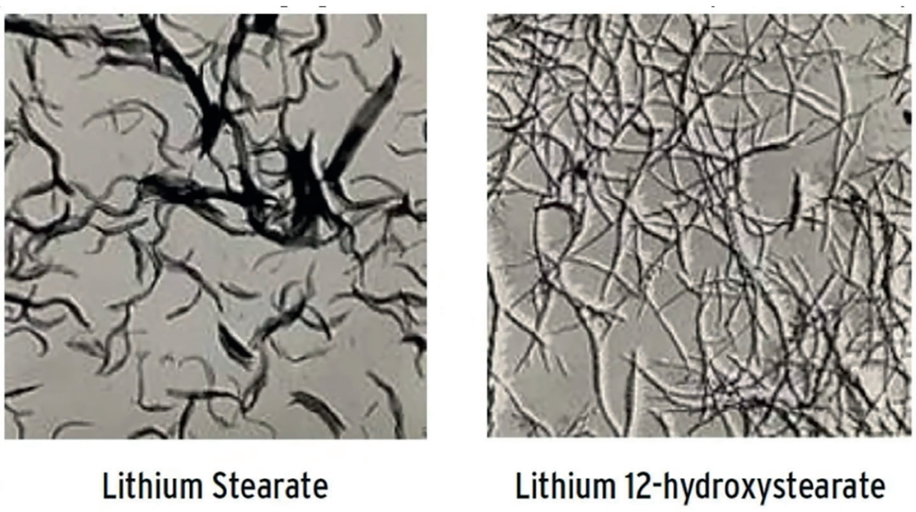
Vegetable oils often provide excellent lubricity and high viscosity index, meaning they maintain viscosity well across temperature changes [1]. However, they also have known limitations, especially lower oxidation stability and shorter service life unless modified or blended with additives or synthetic components [1, 3]. In addition, biodegradable products can degrade not only in the environment but also during storage and use, which can shorten shelf life and operating life [3].

Due to these tradeoffs, the shift toward sustainable greases is not a simple replacement of mineral oils. Instead, it is a gradual process of identifying where bio-based greases already perform well, where hybrid formulations are needed, and where traditional products still dominate. Understanding this balance between environmental benefits and real-world performance is essential for making informed decisions about the future of industrial lubrication.

II. Types of Sustainable Grease Base Oils

Sustainable grease formulations rely heavily on the selection of environmentally responsible base oils that can reduce toxicity, improve biodegradability, and decrease dependence on petroleum resources. The most widely used sustainable base oil categories include vegetable oils, synthetic esters, polyalkylene glycols (PAGs), and other renewable or biodegradable fluids. Each class offers distinct advantages and limitations in performance, cost, and environmental impact.

Vegetable-based oils are among the most common sustainable base stocks used in greases. Derived from renewable agricultural sources such as soybean, grapeseed (canola), sunflower, and palm oil, these oils are attractive because of their high biodegradability and low toxicity. Their molecular structure provides excellent lubricity and high viscosity index, which helps maintain consistent lubrication across temperature ranges. However, unmodified vegetable oils can suffer from poor oxidative stability and limited performance at very high (>100–120 °C) or very low (<–10 to –20 °C) temperatures, which may require chemical modification or additive packages to enhance durability and shelf life [3]. Despite these performance trade-offs, the fundamental appeal of these base stocks lies in their sustainable origins and end-of-life profile. However, overall grease performance is not determined by the base oil alone, but also by its internal structure. To better understand how grease structure influences performance, Figure 2 shows the microstructure of common lithium-based thickeners, illustrating the fiber networks that trap base oil and determine properties such as mechanical stability and consistency.


Lithium Stearate

Lithium 12-hydroxystearate

Figure 2: Microstructural comparison of lithium-based grease thickeners. The fibrous network formed by lithium stearate (left) and lithium 12-hydroxystearate (right) illustrates how thickener morphology influences grease structure. These interconnected fiber networks trap and retain base oil, directly affecting mechanical stability, oil retention, and resistance to shear under operating conditions [16].

Synthetic esters represent another major class of sustainable base oils. These fluids are often produced from renewable fatty acids or alcohols and can be engineered to achieve tailored performance characteristics. Compared with natural vegetable oils, synthetic esters generally offer improved oxidation resistance, wider operating temperature ranges, and enhanced thermal stability. They also maintain strong biodegradability and low toxicity, making them suitable for environmentally sensitive applications such as agriculture, marine systems, and forestry equipment [4, 24].

PAGs are increasingly used in sustainable grease formulations due to their inherent biodegradability and excellent lubricating properties. PAGs exhibit strong film strength, low friction characteristics, and tunable water solubility. For example, PAGs with higher ethylene oxide (EO) content are typically water-soluble, whereas those with higher propylene oxide (PO) content are generally water-insoluble. This distinction is critical in grease applications, as water solubility influences washout resistance, moisture interaction, and compatibility with operating environments. These features make them particularly valuable in applications where contamination with water is likely or where reduced energy consumption is a priority. Their performance benefits often include improved efficiency and reduced wear, although compatibility with certain materials and higher cost can be challenges [4].

In addition to these primary categories, other biodegradable and renewable fluids are being explored to expand the range of sustainable grease options. Advances in biotechnology and green chemistry have enabled the development of bio-derived synthetic oils and improved additive systems that enhance oxidation resistance and extend service life. These innovations are helping close the performance gap between traditional petroleum-based greases and environmentally friendly alternatives while supporting regulatory and sustainability goals [4].

Sustainable grease base oils are evolving toward formulations that balance environmental responsibility with high performance. By combining renewable feedstocks, advanced synthetic chemistry, and improved additive technologies, modern sustainable greases can meet demanding lubrication requirements while reducing environmental impact [3, 4].

III. Performance Needs in Industrial Grease Applications

Industrial greases are expected to perform reliably under a wide range of operating conditions, including high or low temperatures, heavy loads, varying speeds, and exposure to moisture, dust, or other contaminants, often for extended periods and with limited maintenance. Regardless of sustainability goals, greases must meet strict functional requirements to protect equipment, reduce wear, and prevent failure. These requirements include mechanical stability, load-carrying capability, resistance to oxidation and water contamination, and consistent performance across temperature extremes [28, 2]. As illustrated in Figure 3, while the demand for high-performance industrial greases remains a medium-to-high-impact driver, the emergence of bio-based, environment-friendly alternatives presents a significant market opportunity that must still overcome technical hurdles. One of the most critical performance needs is oxidation stability. Greases exposed to heat, air, and metal surfaces can oxidize over time, leading to thickening, sludge formation, and loss of lubricating effectiveness.

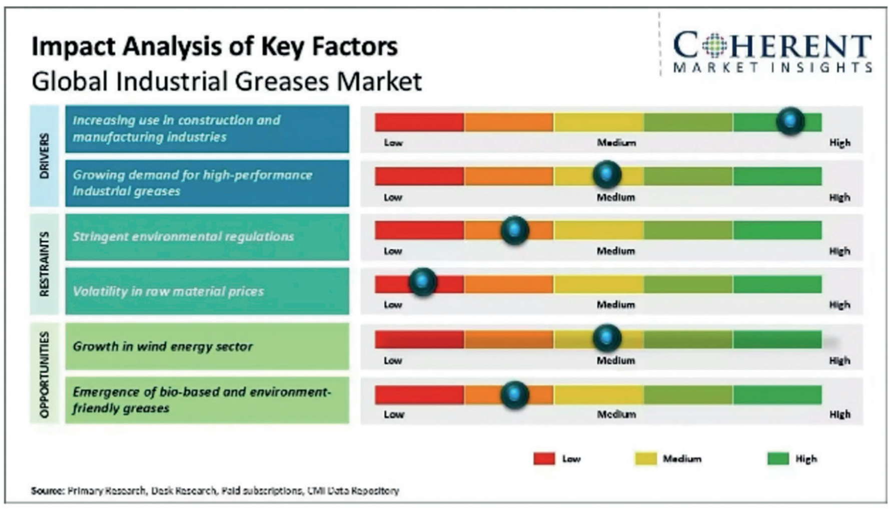


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Figure 3: Impact analysis of industrial grease market drivers. Construction and manufacturing are high-impact drivers wind energy is a key opportunity [17].

In industrial environments such as steel mills, paper machines, and electric motors, poor oxidation stability can significantly shorten grease life and increase maintenance frequency [2, 3]. Sustainable base oils, particularly vegetable oils, may require enhanced additive systems or blending with synthetic components to meet these performance demands, including improved oxidative and thermal stability, anti-wear performance, and resistance to moisture and corrosion [1, 24].

Water resistance is another key requirement, especially in applications such as food processing, marine equipment, agriculture, and mining. Water contamination can wash grease out of bearings, reduce film strength, and promote corrosion. Greases must maintain structure and lubricity even when exposed to moisture or direct water spray. While some bio-based and PAG-based greases perform well in wet environments, others may experience softening or emulsification depending on formulation and thickener selection. For example, formulations containing more hydrophilic base oils, such as certain water-soluble PAGs, may absorb water more readily, promoting emulsification. Similarly, some thickener systems, including lithium or calcium soap-based thickeners, can lose structural integrity in the presence of water, leading to grease softening, whereas more water-resistant thickeners such as calcium sulfonate or polyurea generally provide improved water stability [3, 4].

> *Interest in bio-based and low-carbon greases is growing as industries try to reduce environmental impact*

Temperature performance also strongly influences grease selection. Industrial equipment often operates in both high-temperature (>120 °C) and low-temperature (<−20 °C) conditions, requiring greases to maintain appropriate consistency and flow across this temperature range. At low temperatures, excessive stiffness can prevent grease from reaching lubricated surfaces, while at high temperatures, softening or oil separation can occur. Sustainable greases can offer advantages such as high viscosity index, but may also face limitations at temperature extremes without formulation adjustments [3, 5].

Load-carrying capacity and wear protection are equally important, particularly in heavily loaded bearings, gears, and slow-speed applications. Greases must form a stable lubricating film and protect metal surfaces under boundary and mixed lubrication conditions. While many bio-based oils provide excellent natural lubricity, extreme-pressure and anti-wear performance often depends on additive chemistry, which can influence both performance and environmental compatibility [2, 4].

Finally, service life and storage stability are practical concerns for industrial users. Greases must remain stable during storage and deliver predictable performance over long relubrication intervals. Biodegradable products may be more sensitive to degradation during storage or prolonged use, which can limit their suitability in certain applications unless carefully formulated [3, 5].

Industrial grease performance requirements place clear constraints on the adoption of sustainable alternatives. While environmental benefits are increasingly important, greases must first satisfy fundamental mechanical and chemical performance needs. Understanding these requirements provides the foundation for evaluating where bio-based and low-carbon greases can be successfully applied and where additional formulation strategies are necessary [4, 5].

IV. Oxidation and Temperature Limits

Oxidation stability and operating temperature range are two of the most important factors that determine whether a grease can perform reliably in industrial applications. Exposure to heat, oxygen, and mechanical stress can cause chemical degradation of the base oil and additives, leading to sludge formation, increased viscosity, and eventual loss of lubrication performance. The relationship between thermal stress and chemical stability is quantitatively illustrated in Figure 4. While the reaction reaches an optimal oxirane yield of 89.9% at 120°C, prolonged exposure to high temperatures triggers significant oxidative degradation. This is evidenced by the steady increase in Acid Number (A.N.) over time and the visual darkening of the oil as temperatures approach 150°C.

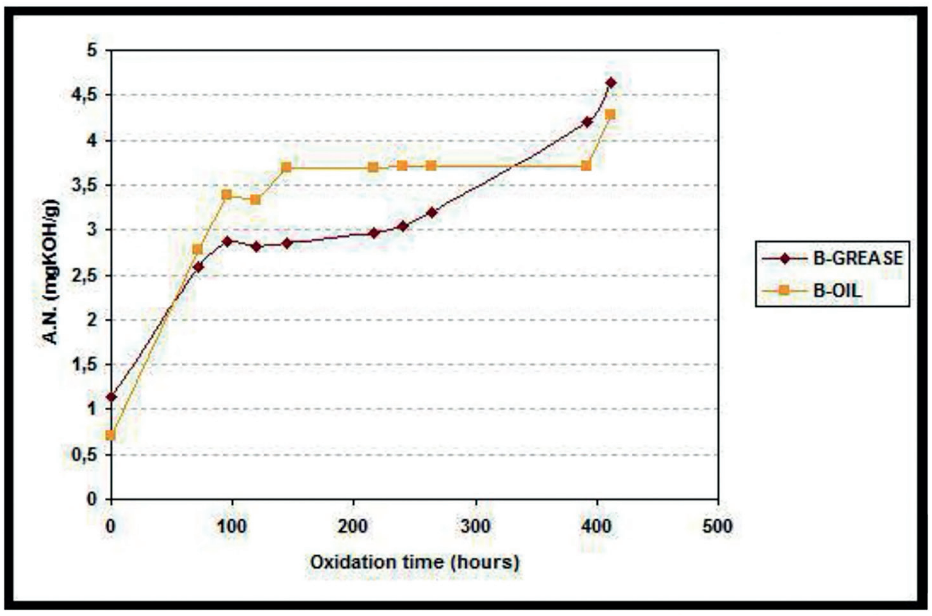

Figure 4: Effect of thermal stress on the oxidative stability (A.N.) of bio-lubricants over a 500-hour period. Optimal oxirane conversion is achieved at 120°C [18].

As oxidation progresses, grease may harden, lose its oil-bleeding ability, and shorten service life, which can increase wear and maintenance frequency in machinery [6].

Temperature further accelerates these degradation processes. Greases must function within defined low-temperature and high-temperature performance limits to ensure proper lubrication. At low temperatures (typically below −20 °C), grease can become too stiff to flow or release sufficient oil to lubricated surfaces, resulting in higher friction and possible startup damage. At high temperatures, excessive softening, oxidation, or thermal breakdown can occur, reducing structural integrity and lubrication effectiveness [22]. Because oxidation reactions increase rapidly with temperature, thermal stability and oxidation resistance are closely linked performance requirements.

Bio-based and biodegradable greases often face additional challenges in this area. Vegetable-oil-derived base stocks can provide good lubricity and biodegradability, but they may also show lower oxidative stability, faster aging, limited viscosity range, and poor low-temperature fluidity compared with conventional mineral oils. These limitations can restrict their use in demanding temperature conditions unless chemical modification, synthetic ester blending, or stabilizing additives are applied [7]. Modern biogreases increasingly rely on biodegradable synthetic esters to improve thermal and oxidative resistance, although these materials can significantly increase formulation cost and influence market adoption [27].

Despite these challenges, regulatory pressure and sustainability goals continue to drive development of bio-lubricants capable of meeting both environmental and performance requirements. Industry market analysis indicates that adoption is increasingly tied not only to environmental benefits but also to the ability of products to meet operational temperature limits and durability requirements in real applications [8]. As a result, improving oxidation resistance and expanding usable temperature ranges remain central research priorities for sustainable grease technology.

Oxidation behavior and temperature tolerance define the practical boundaries of both conventional and sustainable greases. Understanding these limits is essential for determining where bio-based formulations can successfully replace petroleum-derived products and where further formulation improvements are still required [6, 8].

V. Water Resistance and Hydrolytic Stability

Water contamination is a common challenge in many industrial grease applications, particularly in environments such as marine systems, mining operations, agriculture, and food processing. When grease is exposed to moisture, its structure and lubricating ability can be significantly affected. Water can wash grease away from contact surfaces, reduce film strength, promote corrosion, and accelerate chemical degradation, ultimately shortening component life and increasing maintenance requirements [6]. As shown in Figure 5, the severity of this contamination is highly temperature-dependent. The saturation curve illustrates that as temperatures drop, the fluid's capacity to hold dissolved water decreases, leading to the formation of "free water" which is most damaging to the lubricant's performance and the system design point.

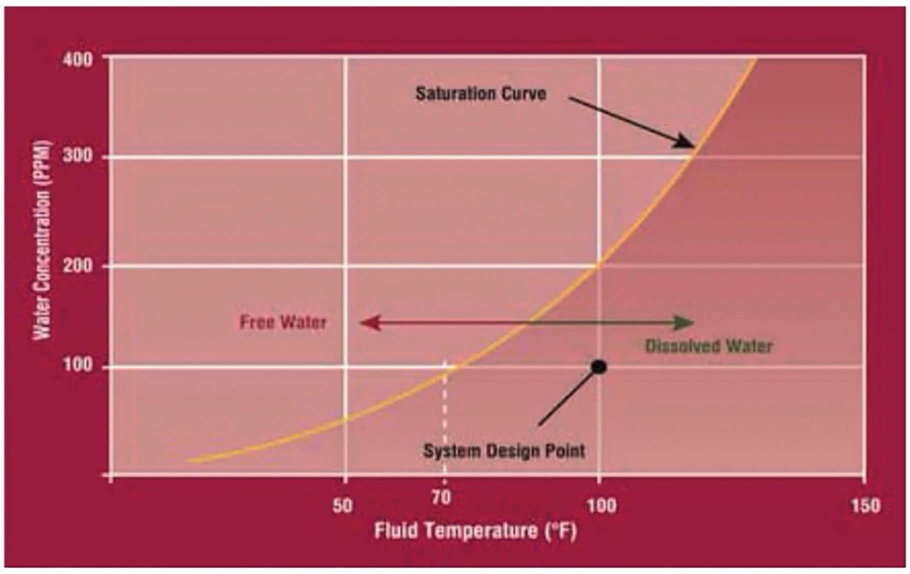

Figure 5: Water saturation curve in hydraulic fluid. Relationships between temperature, water concentration, and the transition from dissolved to free water [19].

Hydrolytic stability is closely related to water resistance and refers to a grease's ability to resist chemical breakdown in the presence of water. Poor hydrolytic stability can lead to base-oil degradation, additive depletion, and changes in grease consistency, all of which reduce lubrication effectiveness. These effects are especially important for biodegradable or bio-based formulations, since some natural and ester-based oils are more sensitive to hydrolysis than conventional mineral oils if not properly stabilized [7].

Modern sustainable greases attempt to address these limitations through improved base-oil chemistry, thickener selection, and additive technology. Synthetic esters and other engineered biodegradable fluids can provide better resistance to water-induced degradation while still maintaining environmental compatibility, although performance and cost tradeoffs may remain [27]. At the same time, industry development is being shaped by regulatory expectations that require lubricants to demonstrate both environmental safety and reliable operation in wet or contaminated conditions [8].

Standardized testing and performance guidance emphasize that grease used in water-exposed environments must maintain consistency, resist washout, and continue protecting metal surfaces from wear and corrosion. Evaluations of water spray-off, water washout, and structural stability after water exposure are therefore critical for determining suitability in real operating conditions. These measures help define whether a grease can sustain lubrication performance when subjected to moisture or immersion during service [9].

Overall, water resistance and hydrolytic stability represent key performance boundaries for sustainable grease technology. While environmentally acceptable formulations continue to improve, ensuring reliable operation in wet and contaminated environments remains essential for broader industrial adoption [7, 9].

VI. Low-Temperature Performance

Low-temperature behavior is a critical requirement for greases used in outdoor equipment, transportation systems, wind turbines, and machinery operating in cold climates. As temperature decreases, grease viscosity increases and the product becomes stiffer, reducing its ability to flow and release oil to lubricated surfaces. Poor flow at startup can lead to increased friction, higher energy consumption, and accelerated wear due to metal-to-metal contact. For this reason, cold-temperature pumpability, torque performance, and oil mobility are essential parameters when evaluating grease performance [1, 22].

Base-oil chemistry strongly influences low-temperature performance. Vegetable oils typically offer a high viscosity index (often 180–220) and excellent lubricity, which helps maintain film strength across temperature changes. However, unmodified vegetable oils can suffer from limited low-temperature fluidity and may become too stiff in cold environments, restricting grease mobility and oil release [3, 7]. These limitations have historically restricted the use of bio-based greases in applications requiring reliable cold-start performance, such as outdoor machinery and high-speed equipment.

Modern formulation strategies, including chemical modification, additive incorporation, and blending with synthetic components, are increasingly used to enhance the oxidative stability, thermal resistance, and low-temperature performance of vegetable-oil-based lubricants [5]. Chemical modification of vegetable oils, blending with synthetic esters, and the use of advanced additive packages can significantly improve pour point, pumpability, and low-temperature torque performance. Synthetic esters, in particular, offer wider operating temperature ranges and improved thermal behavior while maintaining biodegradability and low toxicity [3, 4, 7].

The impact of chemical modification and nano-additives on base-oil rheology is quantified in Figure 6. These data show that the viscosity-temperature relationship of Jatropha oil (JO) is significantly enhanced by epoxidation (EJO) and subsequent inclusion of TiO_2 and MWCNT. Specifically, these modifications result in more stable, elevated viscosity profiles across the 20-80°C range. While these trends focus on base-oil modification, they demonstrate the potential for engineered biolubricants to narrow the performance gap between renewable sources and conventional grease technologies. While these measurements focus on base-oil behavior, the enhanced viscosity and thermal stability of these modified fluids are critical precursors for formulating high-performance greases, as the base oil remains the primary component governing the lubricant's functional limits. These developments demonstrate how hybrid and engineered base oils can close the performance gap between renewable and conventional grease technologies.

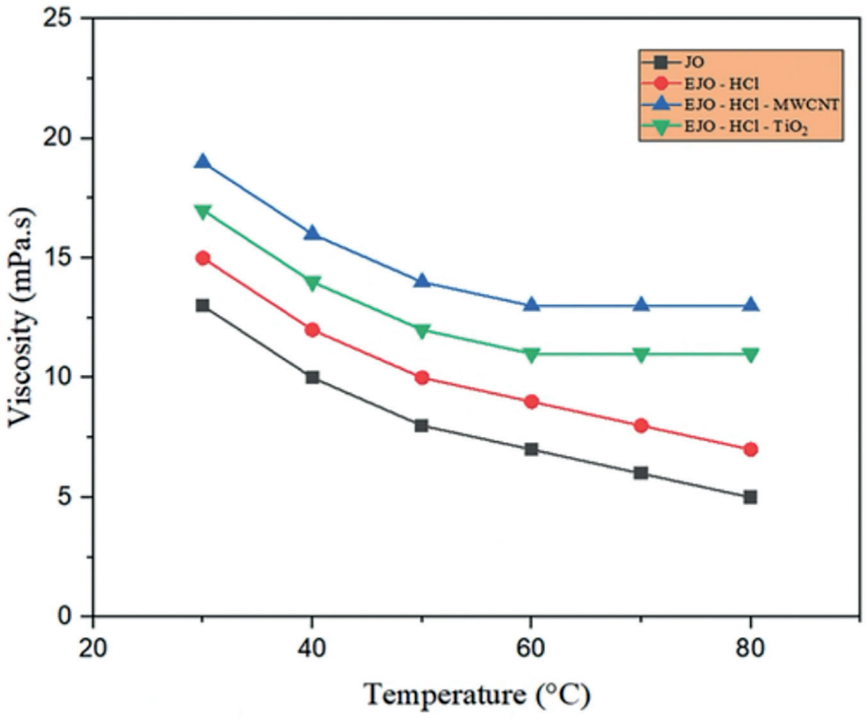

Figure 6: Viscosity-temperature profiles for Jatropha oil (JO) and epoxidized derivatives (EJO) with various nano-additives. Data reflects base-oil level performance, showing how modification trends enhance viscosity stability across a thermal range of 20-80°C [20].

Industry adoption data indicates growing confidence in bio-based lubricants. Market analyses report that approximately 40–60% of industrial sectors are incorporating bio-lubricants, driven by environmental regulations and sustainability initiatives, with increasing use in applications such as hydraulic systems, automotive lubricants, and heavy machinery [14]. Industry experience suggests that soy-based lubricants can deliver comparable performance to petroleum-based products in many applications, and in some cases have demonstrated improved equipment cleanliness, reduced gumming, and longer component life [10]. At the same time, adoption still depends on proving reliable performance across temperature extremes and demonstrating sufficient service life to offset higher material costs [3, 10].

Low-temperature performance also affects grease service life and storage stability. Biodegradable products can be more sensitive to degradation over time, which may influence long-term reliability if not properly stabilized with antioxidants and performance additives [3, 5]. As research continues, improving low-temperature mobility while maintaining oxidation resistance and long service intervals remains a central engineering goal for sustainable grease technology [2, 9].

VII. Real Performance Limits of Bio-Based Greases

Although bio-based lubricants offer clear environmental advantages and strong lubricity, their real-world adoption continues to be shaped by several performance limitations. Understanding these constraints is essential for determining where bio-based greases can realistically replace petroleum-derived products and where further development is still required.

One of the most frequently cited limitations is oxidative stability and temperature sensitivity. Crude vegetable oils, which form the basis of many bio-based lubricants, can degrade more rapidly than mineral oils when exposed to heat, oxygen, and mechanical stress. This degradation can lead to viscosity changes, sludge formation, and shortened lubricant life if the formulation is not properly stabilized with additives or synthetic components [1, 3]. As a result, many applications require chemical modification of natural oils or blending with engineered base stocks to achieve acceptable durability and service intervals.

Low-temperature performance also remains a significant constraint. Research shows that some vegetable oils can become cloudy, form crystalline structures, and eventually solidify at temperatures near −10 °C, preventing proper flow and limiting cold-weather operation [11]. This behavior reinforces the need for advanced formulation strategies and highlights why unmodified bio-based greases are not suitable for all environments.

Another real-world limitation involves production scale, supply chains, and economic considerations. Despite growing demand, bio-based lubricants still represent a relatively small share of the overall lubricant market, partly due to higher raw-material costs and the long-standing dominance of petroleum-based infrastructure [2, 23]. Manufacturers must demonstrate longer service life, added functionality, or improved equipment protection to justify higher initial costs and encourage widespread adoption. To overcome the current economic and technical barriers of biolubricants, a holistic, lifecycle-based strategy is required. Figure 7 presents a comprehensive framework that integrates advanced material pretreatment, controlled molecular modification, and rigorous performance evaluation. By streamlining these interconnected phases, from raw material extraction to environmental impact assessment, this approach ensures that bio-based greases can achieve both technical parity with conventional products and long-term economic viability through optimized production processes.

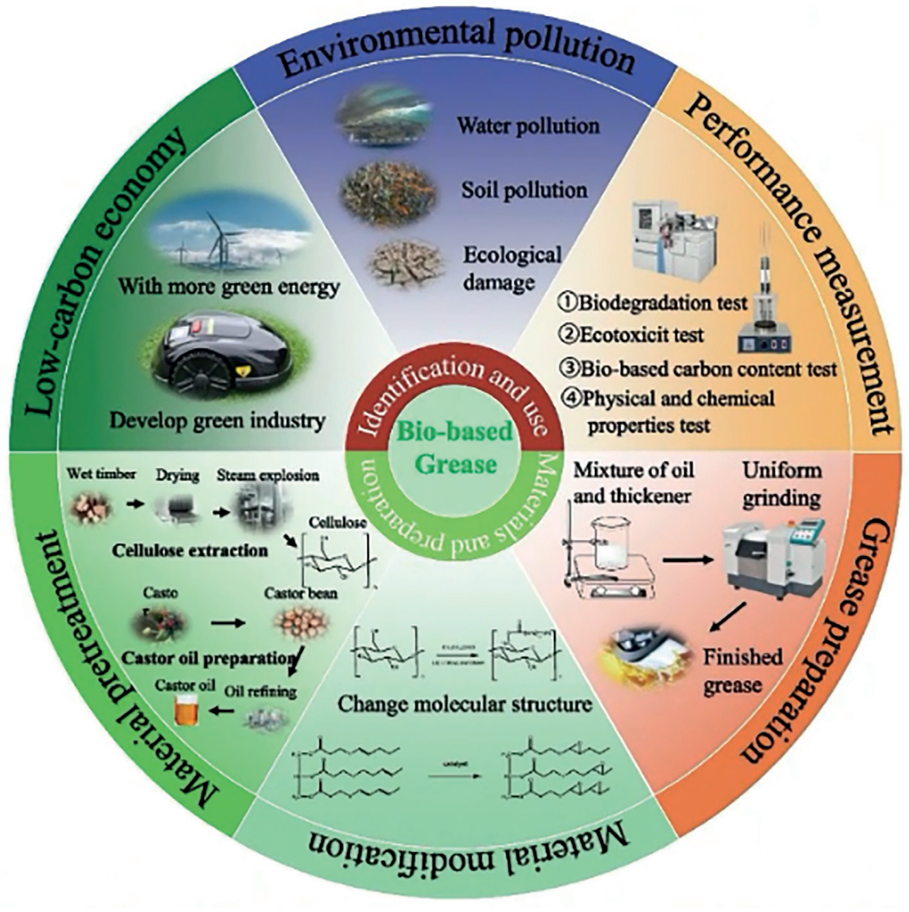

Figure 7: Comprehensive framework for bio-based grease: from material pretreatment and chemical modification to performance measurement and environmental impact [21].

Performance variability is also influenced by feedstock selection and formulation complexity. Unlike petroleum oils, which have relatively uniform chemistry, bio-based lubricants are derived from diverse biological sources such as vegetable oils and animal fats. Their molecular structures directly influence viscosity, oxidation resistance, and tribological performance, meaning that no single bio-based lubricant can be treated as universally interchangeable across applications [11]. This variability requires careful engineering, testing, and application-specific design.

Despite these limitations, research consistently shows that bio-based lubricants can provide excellent lubricity, high viscosity index, and strong wear protection, and in some cases can outperform conventional lubricants when properly formulated [11]. These mixed results highlight an important reality: bio-based greases are not a universal replacement, but they already perform successfully in a growing number of specific applications where their strengths align with operating requirements. An important consideration is where bio-based greases are already being used successfully in real-world applications.

VIII. Where Bio-Greases Work Today

While bio-based greases are not yet universal replacements for petroleum products, they are already widely used in several industries where their environmental and operational advantages align with real-world requirements. Many of these applications involve high risk of lubricant loss to the environment, making biodegradability and low toxicity especially valuable.

One of the most important current application areas is construction and heavy equipment operating in environmentally sensitive locations. Modern biodegradable lubricants are now used in hydraulic systems, engines, pivot points, gears, transmission fluids, and final drives of machinery such as excavators, bulldozers, and loaders [12]. These applications are particularly suited to bio-based lubricants because heavy equipment frequently operates near soil, waterways, forests, and shorelines where lubricant leaks or spills can create environmental and regulatory consequences.

Advances in formulation have enabled synthetic-ester-based biodegradable lubricants to meet the performance demands of these machines. Compared with early generations of biodegradable products, newer formulations provide improved oxidation stability, thermal stability, and shear protection, allowing longer oil-drain intervals and reduced system deposits [12]. These improvements reduce maintenance frequency, lower downtime risk, and extend equipment life, which can offset higher upfront lubricant costs.

Bio-based lubricants are especially valuable in applications where spills are difficult to prevent or fully contain. When conventional mineral-oil lubricants enter the environment, they degrade slowly and can contaminate groundwater, soil, or marine ecosystems. In contrast, readily biodegradable lubricants can achieve greater than 60% degradation within 28 days in standardized laboratory biodegradability tests (e.g., OECD 301 series) and exhibit low ecotoxicity, reducing environmental impact if accidental release occurs [12]. This property makes them particularly attractive for forestry, construction near waterways, marine equipment, and infrastructure projects. This property makes them particularly attractive for forestry, construction near waterways, marine equipment, and infrastructure projects, as illustrated in Figure 8.

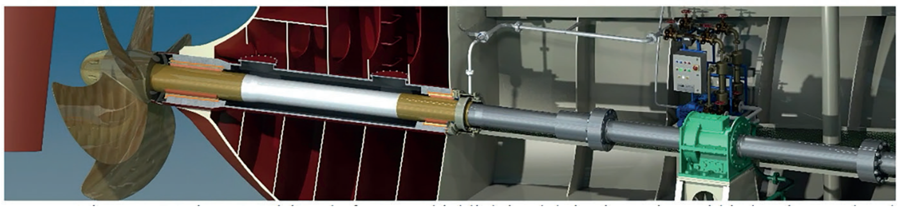

Figure 8: Marine propulsion shaft system highlighting lubrication points within bearings and seals. Such systems operate in environmentally sensitive conditions where grease leakage can occur, making biodegradable and low-toxicity formulations particularly important for reducing environmental impact while maintaining reliable lubrication performance [29].

Regulatory and contractual pressures are also accelerating adoption. Government contracts and projects in sensitive environments increasingly require the use of Environmentally Acceptable Lubricants (EALs), which must be biodegradable, non-bioaccumulative, and low in toxicity [12]. Companies are therefore adopting bio-based lubricants not only to reduce environmental risk but also to qualify for contracts and meet sustainability and ESG goals.

In addition to environmental benefits, companies are recognizing the operational advantages of modern biodegradable lubricants. Longer oil-drain intervals reduce lubricant consumption and disposal, lower maintenance costs, and help reduce CO_2 emissions associated with operations [12]. By minimizing unplanned downtime and extending equipment life, these lubricants can contribute to a lower total cost of ownership over the equipment lifecycle.

Growing interest in electrified construction equipment is further expanding the role of bio-based lubricants. As machinery transitions toward electrification, biodegradable lubricants are increasingly used for hydraulic systems and cooling applications, supporting broader sustainability initiatives within the industry [12].

However, despite these successful applications, there remain operating conditions where fully bio-based formulations alone cannot yet meet every performance requirement. This limitation has led to blended, partially bio-based products that aim to balance sustainability and performance, especially when fully bio-based options don't perform as well.

IX. When Hybrid Formulations Are Needed

While bio-based greases provide clear environmental advantages, fully renewable formulations do not yet meet all industrial performance requirements. Applications involving high operating temperatures, long relubrication intervals, high loads, or exposure to oxidative and mechanical stress often exceed the durability limits of unmodified vegetable-oil-based greases. In these situations, hybrid formulations that combine renewable base oils with synthetic esters or selected petroleum-derived components are commonly required to achieve acceptable performance and reliability, particularly improving oxidation stability and extending service life in high-temperature or long-relubrication-interval applications [3, 13].

Oxidation stability remains one of the most significant drivers for hybrid grease development. Natural vegetable oils are more susceptible to oxidation than mineral oils, which can lead to increased viscosity, sludge formation, and shortened grease life at elevated temperatures [1, 7]. Blending with synthetic esters or chemically modifying the base oil improves resistance to thermal degradation and allows grease formulations to maintain performance over longer service intervals [7, 26]. Low-temperature performance also necessitates hybrid approaches in many applications. As illustrated by the diverse industrial applications for conductive lubricants in Figure 9, the use of hybrid and bio-based formulations is critical for protecting high-precision components. This ensures that the shift toward sustainable, electrically functional lubricants does not compromise mechanical reliability under heavy-duty operating conditions.

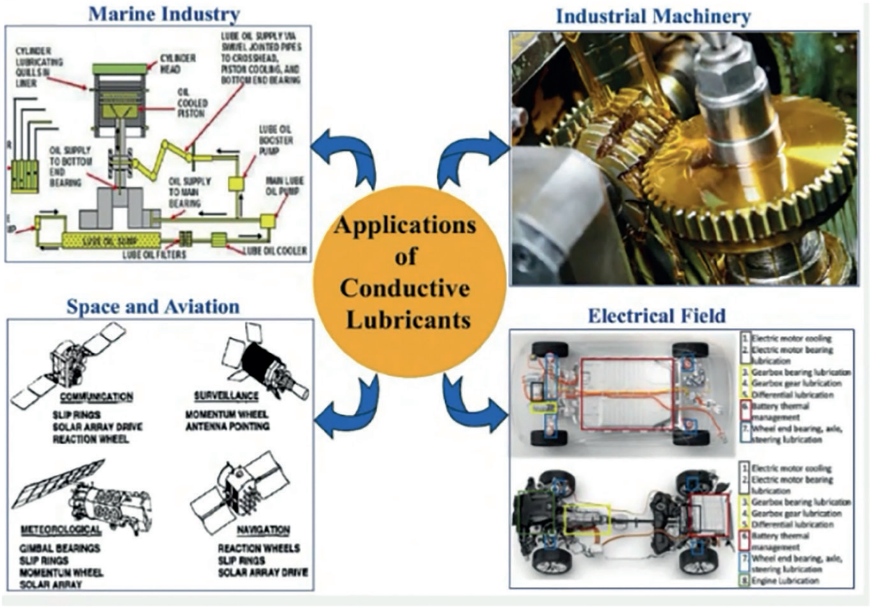

Figure 9. Applications of conductive lubricants across marine, industrial, aerospace, and electrical sectors [25].

Unmodified bio-based greases may exhibit poor pumpability and high startup torque in cold environments due to crystallization and increased stiffness [7, 23]. Hybrid formulations using synthetic esters or tailored additive systems can improve pour point, cold-flow behavior, and torque performance while retaining a significant portion of renewable content [3, 10].

Additive chemistry further influences the need for hybrid greases. Extreme pressure, anti-wear, and antioxidant additives are often required to meet industrial load and durability requirements, but not all additive systems are fully biodegradable or environmentally benign. As a result, many environmentally acceptable lubricants rely on optimized combinations of base oils and additives to balance performance, environmental compliance, and regulatory requirements [2, 13].

Regulatory frameworks also support the use of hybrid products. Environmentally acceptable lubricants are often defined by biodegradability, low toxicity, and non-bioaccumulative behavior rather than by 100% renewable content. This allows products with partial bio-based composition to qualify for use in sensitive environments while delivering the performance required for industrial machinery [12, 25]. Consequently, hybrid greases currently serve as a practical bridge between sustainability objectives and real-world engineering constraints.

X. Conclusion

The environmental impact of industrial greases is driven primarily by their behavior during use rather than at end-of-life disposal. A significant portion of lubricants are lost to the environment through leakage, spills, and total-loss applications, particularly in construction, agriculture, marine, and forestry equipment [25, 28]. In these situations, biodegradability and low toxicity are more critical than recyclability alone in reducing environmental harm.

Lifecycle assessments indicate that bio-based and biodegradable greases generally degrade more rapidly than conventional petroleum-based products. They also tend to exhibit lower ecotoxicity in soil and aquatic environments. However, these results depend on the specific feedstock used and the system boundaries defined in the assessment, meaning that performance can vary across different formulations and evaluation methods [5, 25]. Even partially bio-based formulations can meaningfully reduce environmental persistence when accidental release occurs. When combined with longer relubrication intervals and improved oxidation stability, these greases can also lower overall lubricant consumption and reduce waste generation over the equipment lifecycle [2, 8].

From an engineering standpoint, continued development is focused on improving durability while maintaining environmental performance. Key priorities include increasing oxidation resistance, expanding usable temperature ranges, improving hydrolytic stability, and extending grease service life under high loads and severe operating conditions [3, 11]. Advances in synthetic ester chemistry, chemical modification of renewable base oils, and additive technologies are steadily narrowing the performance gap between sustainable and conventional greases.

Greater standardization in testing methods and clearer performance benchmarks are further supporting adoption. Improved evaluation of oxidation behavior, water resistance, low-temperature torque, and long-term mechanical stability is increasing confidence in bio-based and hybrid greases across industrial sectors [9, 22]. As testing data and field experience continue to expand, engineers are increasingly able to match sustainable grease formulations to specific operating conditions, reinforcing their role as practical, performance-capable solutions within modern lubrication systems.

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