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

Introduction

In recent years, the push towards sustainability has led manufacturing companies to seek and adopt environmentally conscious practices. The industrial push towards sustainable greases is largely driven by regulatory mandates, particularly those established by the U.S Environmental Protection Agency (EPA) and the federal requirements for Environmental Acceptable Lubricants. Adding to the regulatory pressures, Original Equipment Manufacturer expectations and increasing end-user demand for greener products have accelerated the adoption of sustainable oils and greases [1]. The global bio-lubricant market is projected to exceed $5 billion over the next decade, with steady growth each year [2]. Despite bio-lubricants accounting for 1 – 5% of the lubricant market, they remain more expensive in the US, compared with mineral-based greases [3]. Sustainable greases are primarily made from bio-based oils, which include vegetable-derived esters, renewable synthetic oils and re-refined or recycled base oils [4]. The majority of modern bio-greases are formulated with different biodegradable synthetic esters [5]. Bio-based and low-carbon lubricants have rapidly gained prominence as sustainable alternatives to petroleum-derived lubricants, due to their biodegradability, low ecotoxicity and strong alignment with global environmental and regulatory imperatives [6]. For greases to be classified as biodegradable, they are subjected to various tests such as ASTM D-5864, OECD 301B and EPA 560/6-82-003. The test needs to show that the substance degrades more than 60% during a 28-day incubation period [7]. ASTM D-5864 is a standard testing method for determining aerobic aquatic biodegradation of lubricants and their components [8]. OECD 301B testing methods measure the CO2 formation during the biodegradation process over 28 days, which directly reflects the biodegradation of the test substance [9]. EPA 560/6-82-003 is a shake flask test that measures the biodegradation of oils and lubricants in water by assessing how quickly they break down in CO2 and water [7]. These tests are essential for marine, forestry and agricultural applications as they ensure that oils and lubricants used are safe for the environment. Although the demand for sustainable alternatives continues to grow and has led to the development of bio-based and low-carbon greases, the question remains whether they can fully replace petroleum-based greases in demanding industrial applications.

Performance Boundaries of Bio-Based Greases

Polyalphaolefin (PAO) has been the gold standard lubricant used in automotive and high-performance industrial applications. Conventional PAOs lack ring structures, double bonds, sulfur, nitrogen components or waxy hydrocarbons [10]. Due to the lack of these structures, PAOs contain non-polar base oils with a high viscosity index, excellent thermal and oxidation stability, and low volatility [11]. These properties make them highly effective in demanding industrial applications. Recent research has led to the discovery of renewable PAOs, which are derived from bio-based feedstocks such as plant oils through linear alpha olefins [11], [12]. Figure 1 shows a schematic depicting a biorefinery process used to convert vegetable oils into functionalized and non-functionalized alpha olefins with renewable carbons. Girma et al [12] used this process to synthesize bio-based polyalphaolefin (BPAO) by first reacting vegetable oil with ethylene to produce a mixture of linear alpha olefins. The product is then distilled to separate 1-decane and another non-functionalized linear alpha olefin. The residue is then used in transesterification to produce 9-decenoic acid methyl ester and other functionalized linear alpha olefins. Then the functionalized and non-functionalized linear alpha olefins are used in the oligomerized reactions in the presence of a catalyst to produce BPAO. This process enables the manufacturing of bio-based PAOs that offer similar high-performance properties as PAO while having lower toxicity and better biodegradability [12].

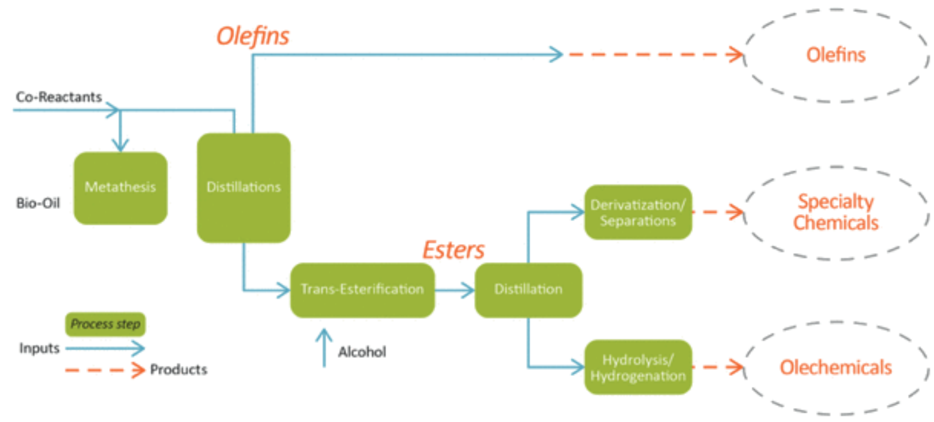

Figure 1: Biorefinery process for synthesis of functionalized and non-functionalized linear alpha olefins from vegetable oils [12].

In addition to renewable PAOs, there are other bio-based alternatives, such as bio-esters, that have gained traction due to their favorable properties. Bio-esters offer superior lubrication, biodegradability, and high viscosity indices. However, bio-esters have several disadvantages in comparison to synthetic esters and need alterations so that they can be used in industries. Molecules from bio-esters often contain unsaturated carbon-carbon double bonds, and when combined with oxygen, they form peroxides and acidic byproducts. This leads to increased viscosity, sludge formation, and deposit build-up that ruins machinery [13], [14]. Despite their high viscosity index, they are not suitable for extremely low temperatures below - 40°C due to crystallization of saturated fatty acids at lower temperatures [15]. The fatty acid composition of bio-esters affects their oxidation stability. Bio-esters exhibit poor oxidation stability due to unsaturated fatty acid structure [16]. To overcome these limitations, bio-esters are often combined with polyalphaolefin (PAO) and commercial additives to enhance performance and stability and reduce friction.

Applications of Bio-based and Low-carbon Greases.

Bio-based greases are preferred where environmental protection is crucial. These areas include forest machinery, construction equipment, railway systems, and marine operations [17]. This is mainly because if an accidental leakage or spill occurs, their biodegradability characteristics ensure that they break down naturally over time. One major application where bio-based greases are used is in the agriculture and forestry industry. Hydraulic bio-based oils are used in operating equipment such as tractors, harvesters, excavators and chainsaws that are used in farms, parks, waterways, and golf courses. In particular, they are used in tractor wheel bearings, harvester components, irrigation system bearings, and plow and tillage equipment joints.

High-performance bio-based oils provide advanced lubrication and stability while reducing the risks of environmental contamination [18]. Studies have shown that advanced bio-based greases can achieve low wear scar diameters and reduced coefficients of friction, indicating strong anti-wear performance [19]. Figure 2 shows the comparison of wear scar diameter between commercial mineral oil and sunflower oil. In different loads, the sunflower oil's wear scar diameters were smaller compared to the wear diameters measured from mineral oil. This is because sunflower oil contains unsaturated fatty acids that combine with the bare metallic surfaces to create a protective biofilm on the metal surface. In Figure 3, sunflower oil had a lower coefficient of friction than mineral oil. This is because bio-lubricants act as bio-friction-reducing agents, which in this case is due to long fatty acid chains present in sunflower oil [19].

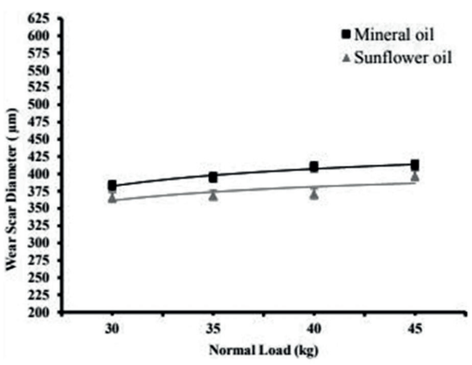

Figure 2: Wear scar diameters for mineral oil and sunflower oil [18].

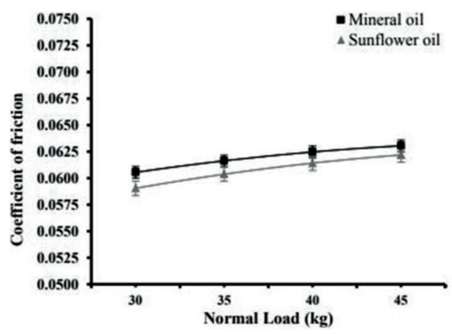

Figure 3: Coefficient of friction of mineral oil and sunflower oil [18].

Another major application for bio-based oils is in marine and waterway equipment, where environmental consequences of oil leakage are severe. Conventional petroleum-based greases form thin surface layers that block oxygen transfer and sunlight, suffocating aquatic plants and animals. Additionally, long-lasting harmful chemicals disrupt food chains and threaten human health [20]. Bio-based greases are preferred in marine and waterway environments because they break down more quickly and have lower aquatic toxicity [6]. For example, the Deepwater Horizon oil spill is estimated to have leaked 4.9 million barrels of oil. The water contained 40 times more polycyclic aromatic hydrocarbons (PAH) than before the spill, which is linked to various health risks to human and marine life, including cardiac arrests [21]. Because of this, bio-based greases are preferred as they are biodegradable and essentially dissipate, unlike conventional greases, which if spilled, will remain in the environment over a long period of time.

Where Hybrid or Conventional Greases Are More Preferred

Conventional greases remain superior to bio-greases in applications that demand extreme performance, long service intervals, or operations in extreme temperature conditions. Additionally, due to the high manufacturing costs related to bio-oils, conventional greases are still favored for their cost-effectiveness and general all-purpose applications. While bio-greases have improved significantly over the years, they still exhibit lower oxidative stability and poor low and high-temperature performance compared to petroleum-based greases [22]. Although their biodegradability makes disposal easier, it also decreases the grease's shelf-life. Synthetic greases provide superior mechanical stability and are less likely to soften and lose viscosity, causing leakage at high temperatures.

In rail and transportation systems, bio-greases are used as lubrication to reduce environmental impacts along railway corridors. They are used in rail curve lubrication systems, train wheel flange and switch plate lubrication. Baiko et al, research studies showed that while pure and modified glycerin-based oil performed similarly under low loads, the borax-containing additive exhibited lower wear and improved friction performance at higher loads, as seen in Figure 4 [23]. The experiments used three pins arranged over 45 mm diameter circle with a 120° interval against a rotating counter body which was fully lubricated with 3-5 mm thick of liquid. These strategies of incorporating additives represent a promising pathway to improve the performance of bio-greases in high-load and highly demanding environments.

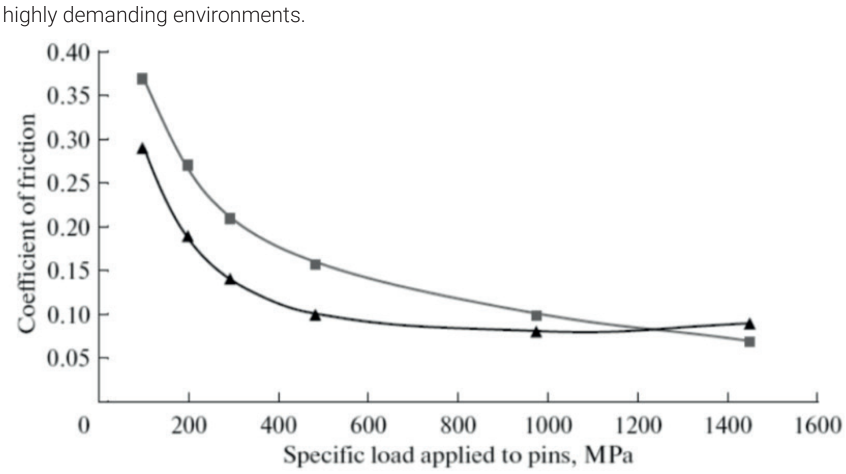

Figure 4: Relation between the coefficient of friction and applied specific load for (triangles) glycerin and (squares) 5% solution of borax in glycerin [23].

There have been various new formulation strategies being researched to make bio-based greases more competitive and economically feasible with conventional greases. The integration of nanoparticles into biodiesel has been widely investigated to improve the combustion efficiency of engine performance and fuel stability. Nanoparticles have a positive effect in lubricants such as increasing antiwear and anti-scuffing properties. Spherical nanoparticles slide between frictional surfaces and separate them acting as bearings. They can tribochemically react with materials on friction surfaces and form a protective chemisorption film on them. If microcracks and micronods are formed on surfaces, nanoparticles can fill the spaces, forming a flat surface, therefore reducing friction [24]. N et al. [25] found that adding 2% titanium dioxide nanoparticles to jojoba oil bio lubricant improved engine performance and emissions compared to pure jojoba oil. In this study, the tests were conducted using varying fuel-lubricant combinations. The baseline experiments used diesel with SAE 40 mineral oil, followed by 20% jojoba oil blend with mineral oil, then with epoxidized jojoba oil as bio-lubricant and finally the same bio-lubricant enhanced with 2% TiO2 nanoparticles. Adding TiO2 improved thermal efficiency by 33.6% in comparison with standard diesel operation and lowered the frictional power loss by 36%. Figure 5 shows the decreasing trend in frictional power in the fuel-lubricant combination, with the TiO2 additive fuel showing the least frictional power.

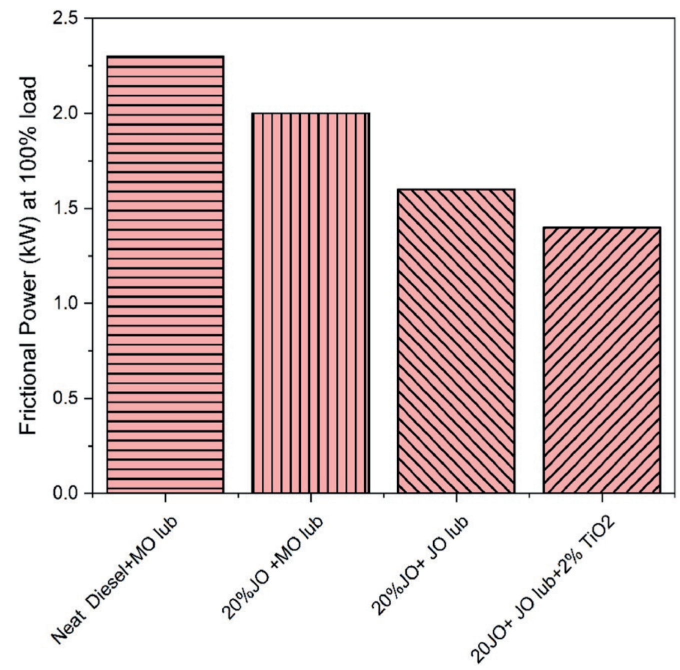

Figure 5: Friction power at full load for different fuel-lubricant combinations [25].

Figure 6 shows that the nanoparticle-enhanced bio-lubricant lowered key emissions, such as unburned hydrocarbons indicating better combustion. While this example cited focuses mainly on biodiesel, the principles are applicable in bio-based grease formulations. Al_2O_3, TiO_2, and CuO can similarly improve heat transfer, reduce wear and lower the coefficient of friction.

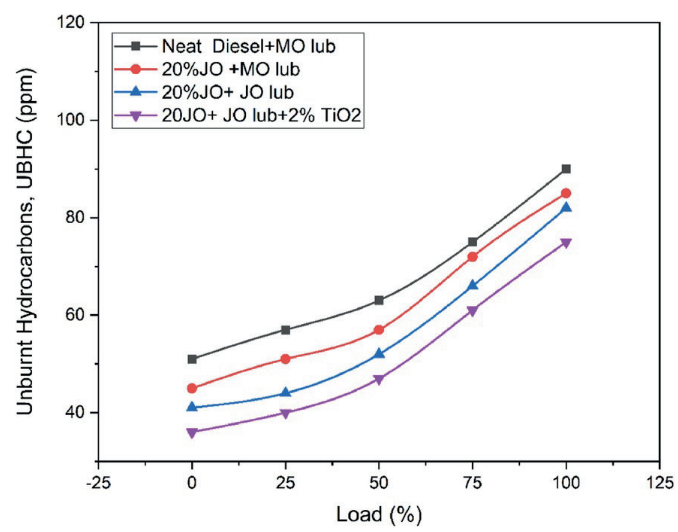

Figure 6: Unburnt Hydrocarbons, UBHC, emissions variation for different bio-lubricant combinations [25].

Regulatory Pressure vs True Life Cycle Impact.

Sustainability in the manufacturing industry has led to the adoption of bio-based and low-carbon greases in an effort to reduce carbon footprints. This is due to regulatory mandates, corporate sustainability goals and consumers' expectations. To protect the environment, the laws governing grease disposal are becoming tougher and the market share of environmentally friendly lubricants is expected to increase 15% in the next 15-20 years [26]. Government mandates have led companies to adapt bio-lubricants and label their greases biodegradable simply by conducting biodegradable tests. However, relying solely on biodegradability is insufficient because it only measures how fast a material breaks down naturally by organisms when disposed but ignores the production process and the impact of additives [27]. Life Cycle Assessment (LCA) and Carbon Footprint of Products (CFP) methods need to be conducted. These methodologies are used to quantify the environmental performance of products, processes, and services [28].

An assessment of bio-oil derived from southern pine demonstrates significantly improved environmental performance compared to fuel oil when evaluated on a functional unit of 1 MJ of energy. The study done by Steele et al, reported near carbon neutrality and a reduction of 0.075 kg CO2 per MJ of fuel consumption, nearly 70% decrease in emissions [29]. Additionally, 92% of energy consumption occurred during the production phase while the rest of the contribution came from feedstock collection, preparation and transportation. This study shows the importance of evaluating full life cycle impacts rather than single indicators of biodegradability.

While bio-based greases are biodegradable, the additives such as antioxidants, anti-wear agents and corrosion inhibitors that are added to improve their performance are not and are harmful to the environment [30]. Additionally, due to their low-oxidative stability and age-hardening, they require frequent replacement compared to synthetic greases. Companies that produce bio-greases should ensure that the products are validated through LCA and CFP methods. This is to ensure that true sustainability is achieved rather than stating environmental claims by relying on biodegradation tests alone.

Conclusions

Despite the growing interest in adapting bio-based and low-carbon greases, there are several barriers that limit their expansion in the market. They present a viable alternative, particularly in environmentally sensitive applications such as agriculture, forestry, railway systems and marine systems, where the risks of contamination when leaks occur are high. Their biodegradability and lower ecotoxicity characteristics provide clear advantages in the environment, unlike conventional greases.

Bio-based greases showcase competitive properties in moderate operating conditions such as reduced wear scar diameters and lower coefficient of friction. However, due to poor performance in demanding applications, they are yet to be fully adapted. Research in advancing their formulation has been studied to address challenges such as lower oxidative stability and poor extreme temperature performance. Advancements include the use of nanoparticles, using hybrid additive systems and blending with synthetic base oils, which have significantly improved their performance.

Life Cycle Assessment and Carbon Footprint of Products analysis should be made to account for the processes' impact on the environment. For bio-greases and low-carbon oils to be adapted in high-performance applications, continued research is needed on oxidation stability, temperature adaptability, additive chemistry, and advancements of renewable synthetic base stocks. Large-scale adoption of bio-oils poses a significant disadvantage due to the high cost of operation. Future research should focus on optimizing formulations to narrow the gap between bio-based and conventional greases. In conclusion, bio-greases and low-carbon greases are great alternatives; however, sustainability requires not only observing environmental impact but also operational reliability, costs and overall total life cycle performance.

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