RECENT ADVANCEMENTS IN BIO-LUBRICANTS WITHIN THE LAST 5 YEARS

Introduction

As concerns over climate change and environmental degradation intensify, industries and governments are adopting stricter regulations and sustainability initiatives to reduce carbon emissions and ecological harm. In this context, bio-lubricants have gained attention as a promising alternative to conventional petroleum-based lubricants, which are often non-biodegradable, derived from finite fossil resources, and liable to cause significant soil and water contamination when spilled. Bio-lubricants, or bio-based lubricants, are lubricating substances derived from renewable biological resources such as vegetable oils and animal fats. To be classified as biodegradable, they must degrade by more than 60% within 28 days, significantly faster than petroleum-based lubricants, which can take hundreds of years to break down and often persist in the environment. [1]. These lubricants are particularly valued for their biodegradability, low toxicity, and reduced environmental footprint, making them suitable for use in environmentally sensitive areas such as forests, agricultural fields, and waterways [2]. From a sustainability standpoint, their use reduces greenhouse gas emissions and dependence on fossil fuels within a myriad of industries that require lubricants. Moreover, life cycle assessments suggest that when bio-lubricants are produced using sustainably sourced raw materials, such as non-edible plant oils, and disposed of through proper collection and biodegradable waste treatment processes, they can offer a significantly lower ecological footprint [1]. For instance, studies have shown that bio-lubricants can reduce greenhouse gas emissions by up to 40–60% over their life cycle compared to conventional petroleum-based lubricants, primarily due to their renewable origin and higher biodegradability [3,4].

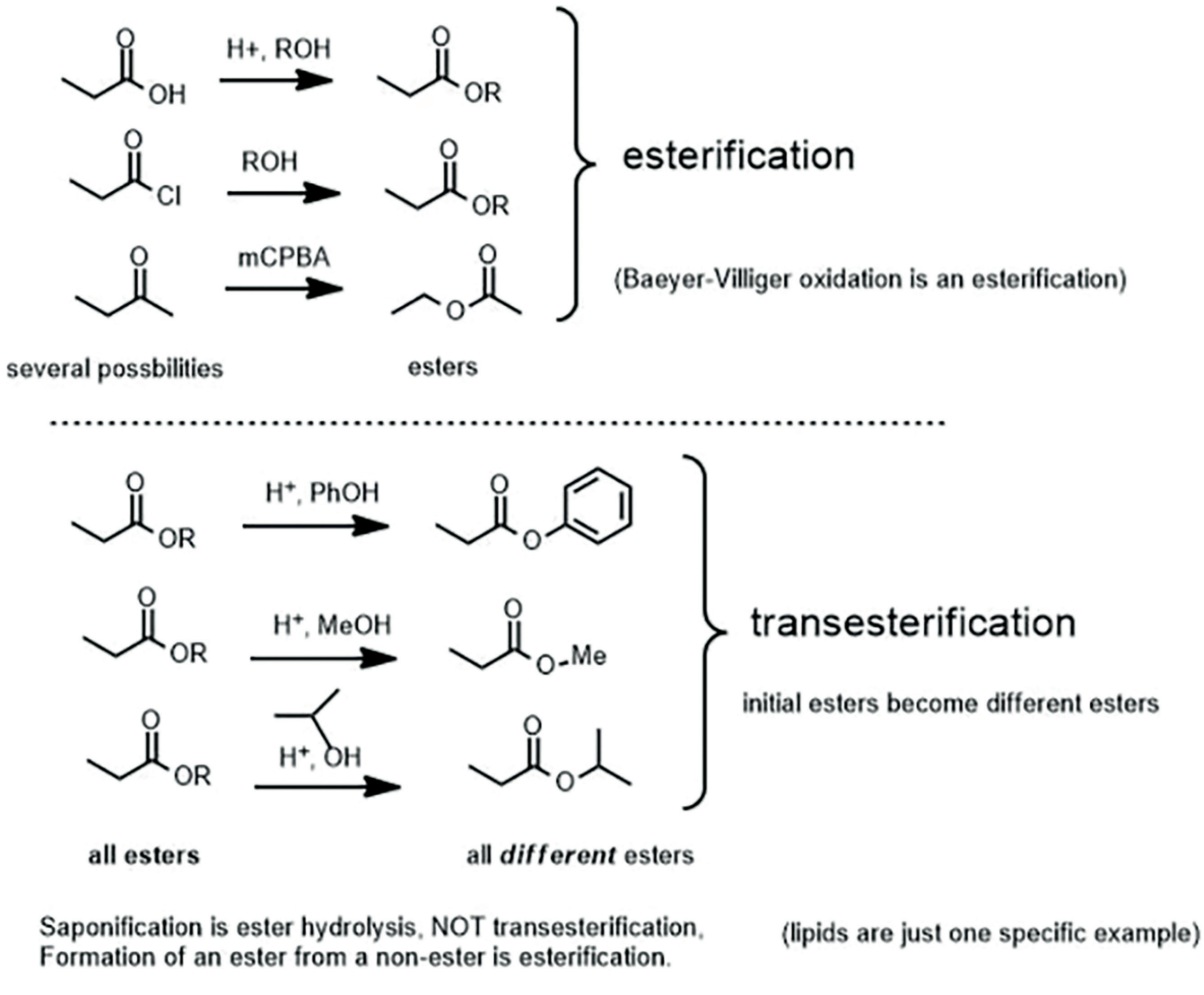

Figure 1: Esterification and transesterification chemical reaction pathways [20].

The primary feedstocks for bio-lubricants include soybean, rapeseed (canola), sunflower, coconut, and palm oil. These oils naturally offer excellent lubricity, high viscosity indices, and high flash points. However, in their raw form, they can suffer from low oxidative stability and poor performance in extreme temperatures, necessitating chemical modifications such as esterification or transesterification to enhance their thermal and oxidative stability [5,6]. To eliminate confusion, it is essential to distinguish between "bio-based" and "biodegradable" lubricants. A bio-based lubricant refers to its origin, constructed from renewable raw materials like vegetable oils. Biodegradability, however, pertains to how well a lubricant breaks down in the environment. Not all bio-based lubricants are biodegradable, especially when synthetic additives are introduced to enhance performance [5]. According to ASTM standards such as D6064 and D5864, lubricants are evaluated for their rate and extent of biodegradation using measurements like infrared spectroscopy and CO_2 evolution. For example, under ASTM D5864, a lubricant is classified as readily biodegradable if it achieves at least 60% degradation of its organic carbon content within 28 days.

The production process of bio-lubricants typically begins with agricultural cultivation, followed by oil extraction, refining, and chemical modification. These modifications are crucial for tailoring the physical and chemical properties of the lubricant to meet industrial performance standards. Research by Julien Crepier et al. has shown that the use of polyol esters derived from fatty acids and ricinoleic acids can match or exceed the oxidative stability of traditional petroleum-based oils [7]. Applications of bio-lubricants span a wide range of sectors, including automotive, marine, agriculture, construction, and industrial machinery. They are commonly used in hydraulic fluids, gear oils, greases, and metalworking fluids [2,8]. They are ideal for use in "total-loss systems," where lubricant leakage into the environment is unavoidable, such as in chainsaws or marine vessels [9].

While bio-lubricants are not yet as widespread as conventional lubricants due to higher production costs and technical limitations, such as oxidative stability and cold flow properties, ongoing advancements in base oil formulation and additive technology are steadily improving their viability [10]. Organizations such as the USDA and EU Ecolabel now certify bio-lubricants that meet environmental and performance criteria, further encouraging their adoption [6]. In this paper, recent advances within the last 5 years in bio-lubricants are explored, alongside the advantages and limitations of transitioning to bio-based lubricants.

Functionalization

One of the most significant advancements within this field is the functionalization of triglycerides to improve their oxidative and thermal stability. Techniques like epoxidation, hydrogenation,

Table 1: Properties comparisons between mineral oil and vegetable oil [27].

Property	Mineral Oil	Vegetable Oil
Density, kg.m^{-3} at 20 ^{0}C	880	940
Viscosity index	100	100-200
Shear stability	Good	Good
Pour point, ^{0}C	-15	-20 to +10
Cloud flow	Poor	Poor
Miscibility with mineral oils	NA	Good
Solubility in water	No	No
Oxidation stability	Good	Mediocre
Hydrolytic stability	Good	Poor
Sludge formation	Good	Poor
Seal swelling tendency	Slight	Slight

and transesterification are now widely implemented to modify the structure of base oils, reducing unsaturation and increasing resistance to degradation. Additionally, the incorporation of antioxidants, anti-wear agents, and viscosity index improvers, many of which are bio-based themselves, has enabled researchers to tailor bio-lubricants for high-performance demands. For example, in a study conducted by Ramírez et al. in 2024 in Future Generation Computer Systems explores data-driven optimization models for designing more efficient bio-lubricant blends, showcasing the integration of machine learning in lubricant formulation [11].

Bio-lubricants stand out not only for their biodegradable nature but also for their recyclability and sustainability throughout their lifecycle. Unlike conventional petroleum-based oils, many bio-lubricants can be re-refined and reused, contributing to a circular economy. For example, vegetable oil-based lubricants, such as those derived from soy, canola, and rapeseed, are biodegradable and have a much lower carbon footprint than mineral oils, significantly reducing pollutive qualities when disposed [12].

Moreover, modern re-refining processes enable used bio-lubricants to be treated and reintroduced into the market, with re-refined base oils meeting the specifications necessary for a wide range of applications, including automotive and industrial uses. This approach of resuing bio-lubricants offers significant environmental and economic advantages. For instance, re-refined base oils can reduce greenhouse gas emissions by up to 77% compared to traditional virgin base oils, as demonstrated by Crystal Clean's HCC 150 product, while also offering substantial cost savings, often 30–50% cheaper per unit volume, compared to traditional processing [13]. Additionally, the re-refining process consumes approximately 50% less energy than producing base oils from crude oil, further compounding the substantial cost savings. In contrast, producing new petroleum-based lubricants involves energy-intensive extraction and refining processes, resulting in higher CO_2 emissions and greater production costs. Therefore, re-refining not only conserves resources and reduces environmental impact but also offers a more cost-effective solution for lubricant production [13, 14, 15]. In Ontario alone, approximately 245 million liters of used oil are collected annually, much of which is eligible for re-refining [16].

Lubricants From Waste

A key advancement in sustainability is the potential to create bio-lubricants from domestic and agricultural waste. This includes transforming home organic waste and used cooking oil into valuable bio-oils and lubricants. Innovations in anaerobic digestion and pyrolysis enable the conversion of home trash and agricultural byproducts like wood chips and crop residues into renewable feedstock for lubricants [17,18]. Research has shown that biolubricants derived from food waste, such as used cooking oil (UCO) and meat processing residues, can match or exceed the performance of conventional plant-based bio-lubricants [18]. For example, in a study conducted by the Dutch startup ChainCraft, UCO-derived esters have demonstrated superior oxidative stability and anti-wear performance in bench tests like the Four-Ball Wear Test and Pressure Differential Scanning Calorimetry (PDSC), as highlighted by Boris Kamchev [14]. These properties are critical in applications requiring high thermal resistance and lubricity, such as engine oils and hydraulic fluids. The chemical backbone of these transformations relies heavily on esterification and transesterification reactions, as seen in Figure 1, wherein triglycerides, fats, and oils, are reacted with alcohols, typically methanol or ethanol, in the presence of a catalyst to produce fatty acid methyl esters (FAMEs), a core component of biodiesel and many biodegradable lubricants [19].

The chemical reactions driving these transformations are equally innovative and sustainable. One key process is epoxidation, where waste cooking oil is chemically altered to improve its oxidative stability and viscosity, essential traits for high-performance lubricants [19]. This process typically involves converting triglycerides into epoxides and then opening their rings using alcohols, enhancing the ester's lubricating and thermal properties.

Despite its environmental benefits, sourcing UCO for applications like biolubricant production presents significant challenges. According to Beyond Oil, a company specializing in the filtration and purification of used cooking oil, the quality of waste cooking oil can vary widely, especially when collected from multiple sources. Their expertise in oil recycling technologies lends credibility to their observations. This inconsistency arises from differences in how oils are used, the types of food cooked, and how long the oil is exposed to heat, leading to degradation and contamination. Beyond Oil also notes that UCO often contains food residues, water, and other impurities, which complicate the recycling process and require additional treatment steps to purify. Furthermore, the site highlights logistical difficulties in collecting and transporting UCO efficiently, particularly from smaller or decentralized sources. These complicate the scalability of UCO-based solutions, despite their potential to reduce waste and create circular economy opportunities [21].

Nanomodification

A major area of recent advancement in bio-lubricants involves their enhancement with nanomaterials and ionic liquids, significantly boosting tribological performance. In a bibliometric review published in Cleaner Engineering and Technology, Nugroho et al., a multidisciplinary team led by Agus Nugroho from Indonesia's National Research and Innovation Agency (BRIN), alongside co authors from reputable institutions including Universiti Malaysia Pahang and Ningxia University, highlight the integration of nanoparticles like graphene, titanium dioxide (TiO_2), and iron oxide (Fe_3O_4) to enhance wear resistance, oxidative stability, and thermal durability in bio-lubricants. These nanomaterials form protective boundary films that reduce friction and wear under extreme mechanical stress and heat [22]. Furthermore, ionic liquids, which are thermally stable and non-volatile, are being used as additives to increase oxidation resistance and maintain lubricant integrity under high-temperature industrial conditions. Such molecular-level innovations address longstanding challenges in bio-lubricant formulation, including low-temperature fluidity and rapid oxidative degradation, pushing their performance closer to and sometimes beyond that of synthetic petroleum-based counterparts [22].

Furthermore, these nano-enhanced formulations use materials such as graphene, MoS2, or metal oxides to significantly boost anti-friction and anti-wear characteristics while reducing energy losses in mechanical systems. These properties are crucial for industries like automotive and aerospace, where even minor improvements in friction reduction can yield substantial energy savings. Studies indicate that these nanomaterials not only improve performance but may also extend the lifecycle of both the lubricant and the machinery, contributing to circular economy goals [26]. The integration of nanomaterials also addresses traditional performance limitations like oxidative instability, poor thermal resistance, and limited pressure tolerance. Additionally, nanoparticles such as graphene oxide (GO), titanium dioxide (TiO_2), zinc oxide (ZnO), molybdenum disulfide (MoS_2), and boron nitride (BN) are being incorporated into vegetable oil-based lubricants. These nanoparticles act as nano-additive tribofilms, forming a protective boundary layer on metal surfaces under load. The tribological effects occur through mechanisms such as rolling, where spherical particles reduce friction by acting like miniature ball bearings; mending, where particles fill in microscopic surface cracks; and polishing, which smooths out rough surfaces. These processes work together to reduce the coefficient of friction (COF) and minimize surface wear. For example, the use of TiO_2 nanoparticles in canola-based lubricants has demonstrated COF reductions of up to 35%, significantly enhancing performance in high-load applications. These nano-enhanced bio-lubricants also improve thermal conductivity, enabling better heat dissipation during operation, a critical feature for engines and industrial gearboxes [26].

Additionally, nanoparticles can be integrated directly into bio-lubricants to improve tribological performance, such as wear resistance, load-carrying capacity, and thermal stability. Unlike traditional mineral-based lubricants, which often rely on bulk additives and can degrade quickly under high loads, nano-enhanced biolubricants leverage their small particle size and high surface area to fill microscopic surface defects and form durable protective films. This reduces friction and wear more effectively while extending service life and reduces maintenance costs, factors that make them increasingly competitive in both performance and overall cost-efficiency [16]. This innovation further supports the recyclability of lubricants, as nanoparticle-enhanced bio-lubricants can last longer and require less frequent replacement, cutting down on waste generation and oil disposal. Building on this, recent peer-reviewed research by Latos et al., published in Catalysis Today, demonstrated that a novel catalyst formed by incorporating zinc oxide into the protic ionic liquid [Hmim][OTf], yielding a ([Hmim][OTf])3Zn adduct, can efficiently catalyze esterification reactions under mild conditions [25]. The study was conducted by chemists from the Silesian University of Technology in Poland, highlighting their contribution to the development of greener catalytic processes [25]. These esters, closely related to those used as base oils in bio-lubricants, were synthesized with high conversion rates, minimal zinc leaching, and excellent catalyst recyclability. Such advances could streamline the sustainable production of high-performance bio-lubricants, reducing environmental impact while improving industrial viability. These processes also help reduce the demand for virgin fossil-based raw materials by sourcing feedstocks from renewable waste streams. For example, food and household waste can be converted into base oils through biochemical or thermochemical pathways, offering a second life to discarded biomass. This alleviates landfill pressure but also supports circular economy principles. By diverting organic waste from incineration or decomposition, both of which emit greenhouse gases, bio-lubricant production aligns with national carbon neutrality targets and fosters more sustainable resource management. Therefore, the integration of sustainable feedstocks, home waste streams, and cutting-edge nanochemistry illustrates the holistic recyclability and sustainability potential of bio-lubricants. These developments mitigate the environmental impact of lubrication and open the door to decentralized, small-scale production systems, empowering communities to contribute directly to sustainable industry practices.

A critical breakthrough in this area is the use of nano-catalysts, such as cobalt ferrite ($CoFe_2O_4$) nanoparticles, which have been shown to significantly enhance transesterification efficiency for biodiesel production. In a peer-reviewed study published in Bioresource Technology, Sarno and Iuliano, researchers from the University of Salerno in Italy, demonstrated that these nanoparticles achieved over 95% conversion yield under mild reaction conditions (60 °C, atmospheric pressure), highlighting their potential for more eco-friendly, energy-efficient biodiesel production processes. For context, many conventional catalysts, such as sulfuric acid in homogeneous acid-catalyzed reactions, typically reach around 90–99% yield but often require much harsher conditions, including elevated temperatures (≥95 °C) and longer reaction times [23, 24]. These catalysts not only enhance the transformation of raw waste oils but also reduce the need for harsh chemicals, contributing to greener manufacturing protocols.

Vegetable Oil-Based Bio-lubricants

Vegetable oil-based bio-lubricants offer a sustainable and environmentally-friendly alternative to conventional mineral oil lubricants. Derived from plant seeds, vegetable oils primarily consist of triacylglycerols (91–96%), along with polar lipids, mono- and diacylglycerols, and minor free fatty acids. Their intrinsic molecular structure, rich in unsaturated fatty acids, contributes to high lubricity, a high viscosity index (VI ≈ 200–220), and superior film-forming capabilities, especially at elevated temperatures [26]. Compared to mineral oils (VI ≈ 90–100), vegetable oils exhibit a higher flash point and lower volatility, making them safer under thermal stress. Their high viscosity index ensures consistent performance across wide temperature ranges, and their flash and fire points make them less flammable, enhancing

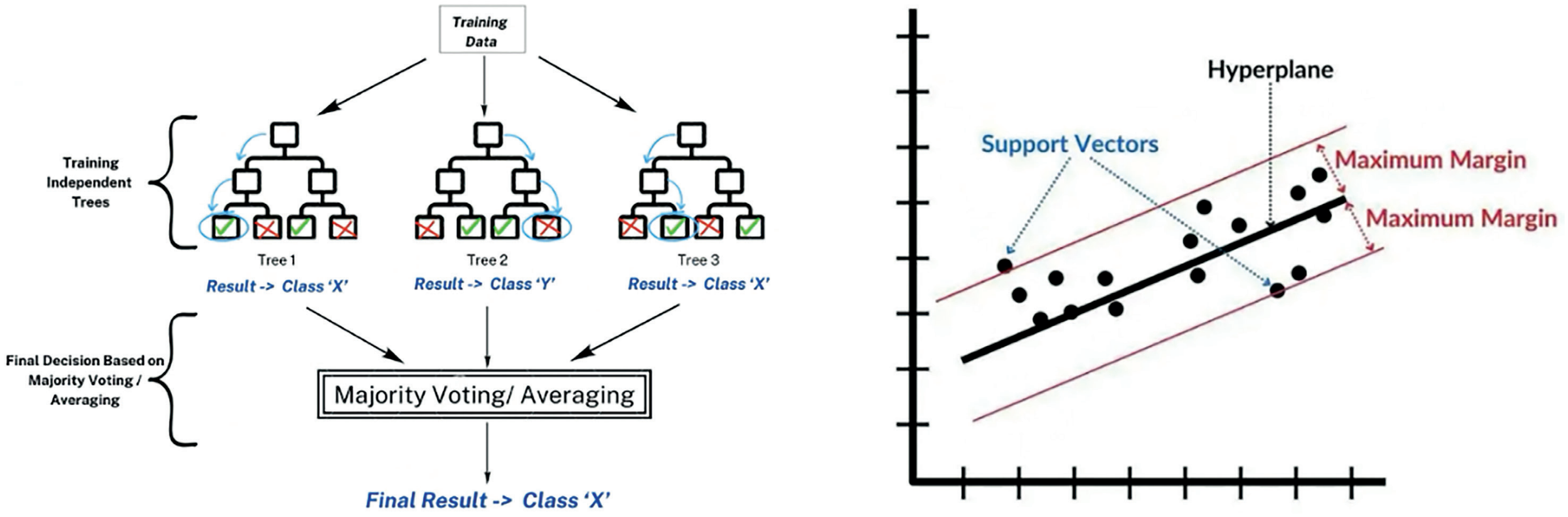

Figure 2: (a) random forest algorithm, (b) support vector regression [30, 31].

workplace safety. For example, canola oil-based lubricants exhibit flash points up to 288 °C and excellent pour points when chemically modified, making them significantly safer in high-temperature applications [26]. This high flash point reduces fire risk in heavy machinery and confined industrial environments where conventional lubricants might pose combustion hazards. Additionally, vegetable oils are inherently biodegradable, with some achieving >80% degradation in 28 days, meeting OECD standards for environmentally safe lubricants. Table 1 shows other properties in addition to the viscosity index that display the difference in mineral oil compared to vegetable oil.

From a life cycle perspective, these oils offer substantial ecological benefits. Their low sulfur and aromatic content results in fewer emissions of NO_x, CO, and particulate matter when used in internal combustion engines or when spilled into the environment. Peer-reviewed studies by Uppar et al., published in Environment, Development and Sustainability, show that using methyl esters of rapeseed oil in engines can reduce CO emissions by 14%, smoke opacity by 12%, and CO_2 by 10% compared to mineral oil-based lubricants [26]. The research team, affiliated with institutions such as the National Institute of Technology Karnataka in India, contributes to growing evidence on the environmental benefits of bio-lubricants. Moreover, utilizing non-edible vegetable oils such as jatropha, neem, and karanja helps avoid the food-versus-fuel dilemma because these oils are inherently unsuitable for human consumption due to their toxicity and anti-nutritional factors. As a result, their cultivation does not divert resources from food production. Additionally, these plants thrive on marginal or degraded lands that are not fit for traditional agriculture, further ensuring they do not compete with food crops for fertile soil. For instance, Jatropha curcas, a non-edible oilseed crop, can produce up to 1,600 liters of oil per hectare annually under favorable conditions, making it a viable option for sustainable bio-lubricant production without displacing food agriculture [40]. These oils are currently underutilized, primarily used in soap and cosmetic industries, but they hold tremendous potential for bio-lubricant applications. For instance, Jatropha-based TMP triesters have demonstrated high oxidative stability and excellent viscosity indices, making them suitable for industrial lubrication. As a result, adopting these non-edible, renewable oils could reduce reliance on petroleum-based lubricants, lower lifecycle emissions, and promote the circular use of marginal lands, potentially accelerating the shift toward a more sustainable and food-secure bioeconomy.

Advanced Chemical Modification

In the context of growing environmental concerns and stricter regulations, such as the EU Ecolabel and U.S. EPA's Vessel General Permit (VGP), which mandate reduced toxicity, biodegradability, and minimal bioaccumulation for lubricants used in sensitive environments, bio-lubricants have emerged as promising alternatives. Derived from renewable sources, they naturally degrade more quickly and produce fewer harmful byproducts, allowing them to meet these regulatory requirements while minimizing ecological harm. However, their early limitations, such as oxidative instability, poor low-temperature flow properties, and limited thermal resistance, restricted their application. Recent research, including work published in the Journal of Cleaner Production [28], has focused on enhancing the physicochemical properties of bio-lubricants through chemical modification and additive technology.

Simultaneously, advanced chemical modification techniques are emerging to increase the oxidative and thermal stability of natural oils. Methods like transesterification, reaction of triglycerides with alcohols to form esters, and epoxidation, conversion of unsaturated C=C bonds to oxirane rings, are being optimized to tailor fatty acid chains. These reactions reduce autoxidation caused by β-hydrogens adjacent to double bonds, increase molecular branching, and improve cold-flow properties. Additionally, sulfur- and phosphorus-free anti-wear additives are being developed to maintain eco-safety while enhancing extreme pressure (EP) resistance. Researchers are also exploring multi-stage catalytic pathways to enhance the efficiency of bio-lubricant production. For instance, a 2016 peer-reviewed study by Chumuang and Punsuvon, published in Key Engineering Materials, investigated the application of calcium methoxide as a solid base catalyst for biodiesel production from waste cooking oil [29]. The study demonstrated that using calcium methoxide under optimized conditions, specifically, a 3 wt% catalyst concentration, a 12:1 methanol-to-oil molar ratio, and a reaction temperature of 65°C, achieved a fatty acid methyl ester conversion rate of 99.06% within 3 hours. This high yield was consistently observed across multiple feedstocks, including waste cooking oil and soybean oil, indicating the catalyst's versatility and robustness. These findings indicate that such catalytic systems can significantly improve ester yields and reduce reaction times. Advancements like these are critical in extending the viability of vegetable oil-based lubricants for commercial use, particularly under harsh mechanical and thermal conditions where conventional plant oils typically degrade.

Machine Learning Applications

Another key innovation involves data-driven modeling and machine learning techniques to predict and optimize bio-lubricant formulations. Using input data such as fatty acid composition, molecular descriptors, and tribological parameters, machine learning algorithms like Random Forest and Support Vector Regression are increasingly applied to screen and optimize bio-lubricant candidates. Compared to traditional trial-and-error formulation, these data-driven approaches can reduce development time by up to 50–70% and significantly lower experimental costs by minimizing the number of physical tests required. Figure 2 illustrates how these algorithms, random forest, and support vector regression, process large databases to identify molecular structures with desirable lubrication properties, improving the efficiency of bio-lubricant development [30, 31]. This significantly accelerates the identification of optimal feedstock blends and additive concentrations for target performance metrics such as viscosity index (VI), pour point, and thermal decomposition onset temperature. These AI-driven approaches are reducing experimental time and resource consumption, supporting more rapid and sustainable development cycles [22]. Finally, bibliometric analysis shows a marked rise in research activity from India, China, Malaysia, and Brazil, correlating with regional agriculturalgoutput and governmental investment in green technologies [22].

Beyond the laboratory, real-world deployment of biodegradable, biobased lubricants is accelerating. According to Machinery Lubrication, industries such as forestry, agriculture, and marine operations are increasingly adopting these lubricants due to environmental restrictions and a desire to improve safety and sustainability [32]. These sectors benefit from the low toxicity and biodegradability of bio-lubricants, especially in environmentally sensitive areas where spills can have serious ecological consequences. Further supporting this transition, a comprehensive review in the journal Lubricants highlights the ongoing efforts to standardize bio-lubricant formulations and performance metrics [33]. The review emphasizes the importance of international standards, such as ASTM D6751 and ISO 15380, to ensure that new bio-lubricant products meet consistent quality and performance benchmarks. It also discusses policy incentives and government mandates, particularly in the EU and U.S., that are accelerating research funding and commercial adoption. Together, these scientific and industrial advancements reflect a maturing field that is transitioning from innovation to implementation. As material science, data analytics, and environmental policy continue to converge, bio-lubricants are likely to become a mainstream component in sustainable engineering practices worldwide.

Simultaneously, industry-driven developments have introduced smart lubrication systems and self-healing bio-lubricants, aligning with the push for predictive maintenance and sustainability. According to Santie Oil Company, as reported in a 2012 article published by Machinery Lubrication, a leading industry journal specializing in lubrication technology, modern smart lubricants now incorporate IoT-enabled sensors that provide real-time feedback on lubricant conditions, such as viscosity, contamination, and temperature fluctuations [35]. This enables precise monitoring, reducing unnecessary lubricant replacement and equipment downtime. In addition, emerging self-healing lubricants contain microcapsules that release restorative agents when mechanical stress ruptures the lubricant matrix, extending service life and performance under heavy-duty applications [35]. These advances, while still developing, point toward a future where bio-lubricants are not just environmentally superior but intelligently responsive and self-maintaining, reducing total lifecycle costs and further cementing their industrial viability.

Limitations and Regulations

Despite growing environmental support for bio-lubricants, several technical disadvantages continue to limit their widespread industrial adoption. One major concern is their susceptibility to microbial degradation, particularly during storage or use in high-moisture environments. The natural triglyceride structure of vegetable oils provides a nutrient-rich environment for microbial growth, leading to rancidity, unpleasant odors, and reduced lubricating efficiency over time [35]. This microbial instability can be partially mitigated with biocidal additives, but these introduce new concerns around toxicity and environmental safety.

Another drawback is the shorter shelf life of bio-lubricants when compared to mineral-based oils. Due to their high degree of unsaturation and hygroscopic nature, vegetable oil-based lubricants are prone to oxidative polymerization and hydrolysis, particularly under exposure to air and water. These chemical degradations result in thickening, acid formation, and performance loss during long-term storage, especially without antioxidant stabilization [34]. Even when chemically modified through epoxidation or esterification, bio-lubricants may still lag behind fully synthetic or petroleum-based lubricants in durability under demanding operating conditions. Additive compatibility also presents a critical limitation. Many commercial additives, such as zinc dialkyl dithiophosphate (ZDDP), detergents, and dispersants, are optimized for petroleum oils and may not function correctly in polar bio-based matrices. However, some progress has been made, for example, boron-containing esters and ashless antiwear additives have been successfully formulated to enhance performance in bio-lubricant systems without compromising biodegradability. This leads to reduced efficacy in anti-wear, corrosion inhibition, and viscosity control unless formulations are re-engineered with bio-compatible additive systems [33]. Such reformulation can be costly and may reduce the overall sustainability profile if petrochemical additives are reintroduced. To offset these drawbacks and incentivize the adoption of bio-lubricants over more cost-effective and higher-performing petroleum-based options, governments and industry stakeholders can implement policy tools such as tax credits, green procurement mandates, and stricter environmental compliance standards. Additionally, investment in R&D and scaling production technologies can gradually reduce costs and improve performance metrics, making bio-lubricants more competitive in the long term.

From an economic standpoint, bio-lubricants still face significant cost barriers. The raw materials for high-quality vegetable oils can be up to 50% more expensive than refined mineral oil, and bio-lubricant production often requires more complex chemical processing such as multi-stage esterification, transesterification, or blending with synthetic esters. The absence of global economies of scale further inflates costs, limiting their competitiveness in price-sensitive markets [37]. Moreover, supply variability due to climate, crop yields, and regional infrastructure impacts the consistency and pricing of feedstocks. Regulatory frameworks have made progress in promoting bio-lubricants, but fragmentation and inconsistency across regions remain significant hurdles. For example, the EPA's Vessel General Permit (VGP) mandates the use of Environmentally Acceptable Lubricants (EALs) in marine applications, setting strict benchmarks for biodegradability, non-toxicity, and non-bioaccumulation [38]. In the European Union, the EU Ecolabel and CEN/TC 19 bio-based standards offer similar guidelines, but they vary in bio-based content thresholds and testing methods, making compliance burdensome for global producers [39]. The lack of universal certification criteria complicates international trade and increases costs for lubricant manufacturers, who must conduct multiple product tests to meet region-specific standards. For example, the EU's Ecolabel imposes strict biodegradability and toxicity thresholds, while the U.S. EPA's Environmental Preferable Purchasing (EPP) program emphasizes biobased content under the USDA BioPreferred label [39]. In contrast, China's certification framework remains less harmonized, often requiring separate approvals depending on industrial application. These disparities create barriers to global market entry for bio-lubricant producers [39].

Although regulatory interest is increasing, incentives and enforcement mechanisms are unevenly applied. According to a 2025 market analysis published by Kline & Company, a leading global market research firm specializing in the energy sector, future bio-lubricant market expansion will depend heavily on supportive policies such as green procurement mandates, carbon pricing, and R&D subsidies to level the playing field with established petroleum-based products [37]. Without coordinated global policy and investment, many bio-lubricant manufacturers will continue to face technical, regulatory, and economic obstacles that limit the technology's mainstream industrial deployment.

Conclusion

Bio-lubricants have evolved from niche alternatives to serious contenders in the global effort to create sustainable industrial systems. Derived from renewable sources such as vegetable oils, animal fats, and increasingly from waste biomass, they offer compelling environmental advantages like biodegradability, lower toxicity, and reduced greenhouse gas emissions. Advances in feedstock optimization, chemical modification techniques like epoxidation and transesterification, and the integration of nanotechnology have significantly improved the thermal, oxidative, and tribological performance of bio-lubricants, enabling them to meet or exceed the specifications of traditional petroleum-based oils in many applications.

At the same time, real-world implementation has expanded, with applications spanning numerous sectors and systems where environmental exposure is a concern. Bio-lubricants also support circular economy goals through their recyclability, low emission profiles, and the emerging ability to use household and agricultural waste as raw materials. However, despite these strides, several challenges remain. Issues such as oxidative instability, limited shelf life, higher production costs, and inconsistent additive compatibility continue to hinder their mainstream adoption. Additionally, regulatory fragmentation across countries complicates certification, while a lack of harmonized testing protocols creates market entry barriers for global manufacturers.

Looking forward, the future of bio-lubricants appears promising. Continued investment in R&D, particularly in green chemistry, catalysis, and AI-assisted formulation, will be essential for addressing technical barriers and lowering costs. Moreover, the development of standardized international policies and stronger economic incentives will be key in accelerating market penetration. As environmental regulations tighten and the demand for sustainable alternatives grows, bio-lubricants are poised to transition from specialized eco-friendly options to industry standards. By bridging innovation in materials science with responsible policy frameworks, bio-lubricants can play a pivotal role in the decarbonization and ecological modernization of industrial lubrication systems.

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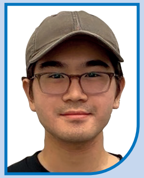
About the Authors

Dr. Raj Shah is a Director at Koehler Instrument Company in New York, Holtsville, NY. He is an elected Fellow by his peers at ASTM, IChemE, CMI, STLE, AIC, NLGI, INSTMC, AOCS, Institute of Physics, The Energy Institute and The Royal Society of Chemistry. An ASTM Eagle award recipient, Dr. Shah recently coedited the bestseller, "Fuels and Lubricants handbook", details of which are available at ASTM's Long-Awaited Fuels and Lubricants Handbook 2nd Edition Now Available (https://bit.ly/3u2e6GY).He earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow from The Chartered Management Institute, London. Dr. Shah is also a Chartered Scientist with the Science Council, a Chartered Petroleum Engineer with the Energy Institute and a Chartered Engineer with the Engineering council, UK. Dr. Shah was recently granted the honourific of "Eminent engineer" with Tau beta Pi, the largest engineering society in the USA. He is on the Advisory board of directors at Farmingdale university (Mechanical Technology) , Auburn Univ (Tribology), SUNY, Farmingdale, (Engineering Management) and State university of NY, Stony Brook (Chemical engineering/ Material Science and engineering). An Adjunct Professor at the State University of New York, Stony Brook, in the Department of Material Science and Chemical engineering, Raj also has approximately 700 publications and has been active in the energy industry for over 3 decades. More information on Raj can be found at https://bit.ly/3QvfaLX

Contact: rshah@koehlerinstrument.com

William Chen is an engineering Intern at Koehler Instrument company.in Holtsville Ny.



William Chen

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY11742 USA
• Email: rshah@koehlerinstrument.com • Web: www.koehlerinstrument.com