MAKING LUBRICATION SUSTAINABLE THE RECENT ADVANCEMENTS OF BIOLUBRICANTS

Abstract

Increasing environmental regulations and incentives for sustainability has led to an increase in research into biologically based lubricants as an alternative to traditional methods. While widely used mineral-based lubricants can be efficient, they are non-renewable and can cause pollution with improper disposal and by virtue of the means in which they are produced. This review discusses methods for improving biolubricant capabilities so they can become commercially relevant. This article discusses recent research of additives in biolubricants. Specifically, incorporations of nanoparticles such as Titanium Dioxide and graphene showed improvements in frictional stability and thermal efficiency. Chemical modifications are also being researched with focus being placed on recent studies on the influence of esterification and epoxidation. Ultimately, these techniques offer performance enhancements and improve attributes such as friction stability and wearability. The article also discusses where biolubricants are commercially as well as the promotion of their uses. The wide range of biolubricants opens up pathways to this more sustainable alternative.

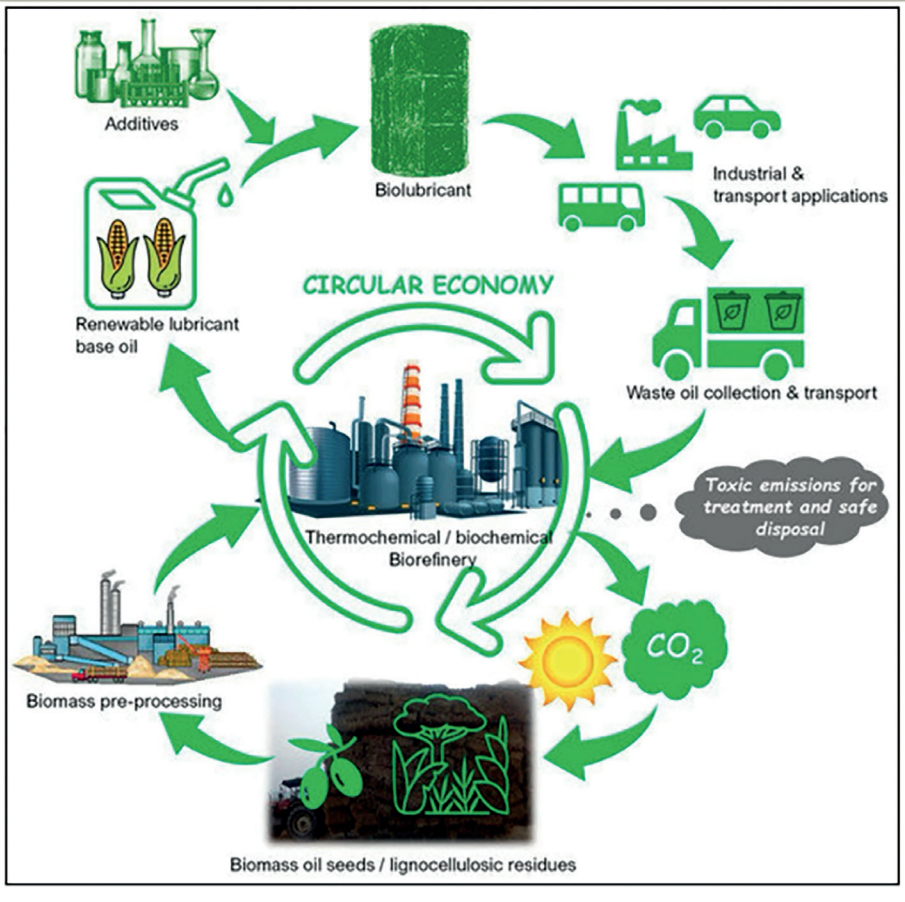

Figure 1: Ideal cycle of biolubricant application [2].

Introduction

Lubricants are critical in many aspects of modern society. They help reduce friction and wear rates, ultimately improving a system's efficiency. While the most common lubricants are either mineral or petroleum-based, these traditional lubricant formulations are unsustainable [1]. They can have harsh influences on the environment, from air pollution, to infiltrating ground water. These sources are also becoming limited, while there is still a high demand for them. A more sustainable approach is being considered: bio-lubricants. These are lubricants sourced from renewable resources, primarily plant oils, and can be used in a sustainable manner as shown in Figure 1 [2]. However, despite their environmentally friendly attributes, they also need to perform just as well as their non-renewable competitors in tribological settings [3].

Many bio-lubricants tend to have challenges with thermal stability and oxidative stability [4]. Because of this, pathways are being investigated to enhance these potentially influential lubricants. Methods such as additives and chemical modifications are being researched to ultimately enhance the performance of these renewable lubricants. Their fast degradation and little to no carbon emissions are a redeeming quality that can help make the industry environmentally friendly [3].

Nanoparticles

Nanoparticles appear to be an opportunity to greatly improve these lubricants. Specifically, the nanoparticles titanium dioxide (TiO_2) and graphene are gaining attention in recent years. This is due to their abilities to enhance the tribological performances of lubricants. Nanoparticles can penetrate and disperse through a lubricant's surface, filling microscopic defects. This can reduce the coefficient of friction through effects such as rolling effects or formation of a protective film which are shown in Figure 2 [5].

Nanoparticles can also be used to improve thermal stability. The nanoparticle graphene, for example, has high thermal conductivity and stability. Its proficiency in dispersing heat has gained attention in various industries including lubrication [6,7].

In a study done by Madwesh et al. in association with the Manipal Institute of Technology, TiO_2 was used as nanoparticles incorporated into a jojoba bio-oil lubricant [3]. Jojoba oil is commonly used in many skincare and fragrance products; their renewable and biodegradable capabilities offer potential to gain traction in bio-lubricants. With particle sizes ranging between 20-50 nanometers, titanium dioxide was added to jojoba bio-lubricants which was then compared to a performance of a jojoba-bio-lubricant without titanium dioxide in which a biodiesel from jojoba oil was utilized. Another comparison was used which had a mineral based lubricant, from which one was used with jojoba bio-diesel while the other used neat diesel. The lubricants and their associated fuels were then used in a computerized Kirloskar TV1 single-cylinder, 4-stroke compression ignition, which was then measured through engine performance indicators, shown in Figure 3 [3].

Attributes such as frictional power were tested which had the best performance when jojoba components were used. The jojoba-based samples fell below 2 kilowatts with the TiO_2 having the lowest value falling just below 1.5 kilowatts. These lower values correlate to more efficient systems as well as thermal stability. The neat diesel had the highest frictional power value, measuring just above 2 kilowatts. Brake thermal efficiency (BTE) was also evaluated. The results were quite promising, with the jojoba bio-lubricant added titanium dioxide having 33.6% efficiency. In comparison, the standard diesel and mineral oil (MO) lubricant had an efficiency of 30.3%. The results of the titanium dioxide added lubricant were further compared with other studies, which exceeded values when similar tests were done on other bio-lubricants and nanoparticles [3]. The performance shown in this study presents a promising pathway in the utilization of bio-lubricants, offering environmentally advantageous solutions as well as higher efficiencies.

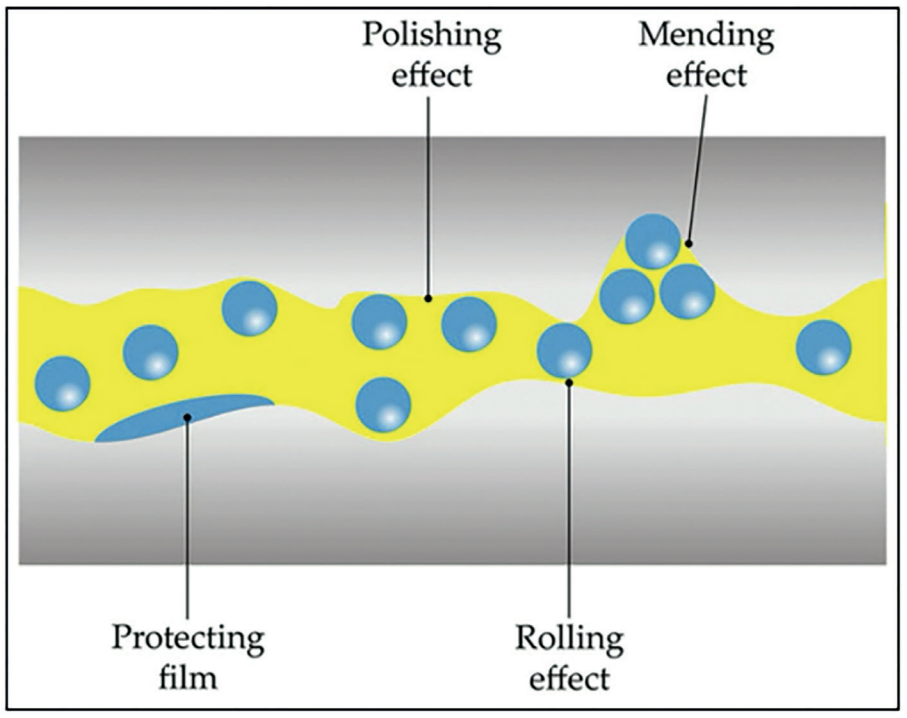

Figure 2: Effects of nanoparticles on a lubricant's surface [5]

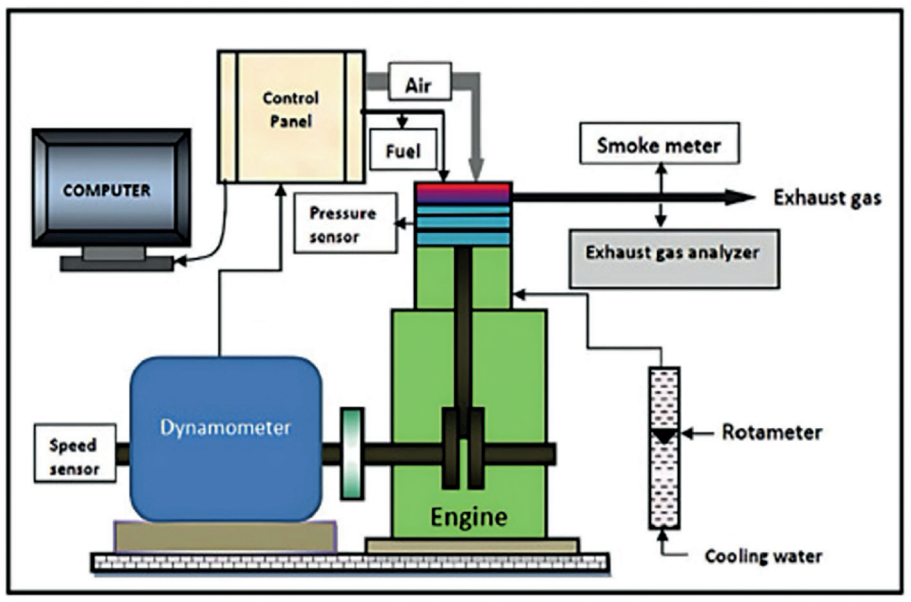

Figure 3: Apparatus used for Madwesh et al. [3]

TiO_2 is not the only nanoparticle showing promising results for biofuels. In a study done by the School of Mechanical Engineering at University Technology Malaysia, Suhaimi et al. used a coconut oil as the lubricant and had graphene and maghemite nanoparticles incorporated at 0.1% volume concentration [4]. The study compared a base line lubricant (CCO), the same lubricant doped with graphene (XGCO), and another group enhanced with maghemite (MGCO). To test the thermal stability, a thermogravimetric analysis (TGA) was performed from which differential thermogravimetric (DTG) graphs were used to determine thermal stability. This was done by taking roughly 15 mg of each sample and subjecting it to a nitrogen atmosphere in which the temperature increased from 20°C to 900°C, increasing at a rate of 10°C /min, along with an air flow rate of 50 mL/min. The results showed oxidative onset temperatures which correlate with thermal stability as it indicates the temperature a material can handle before being susceptible to exothermic decomposition [4]. The onset temperature was measured with MGCO and XGCO having the highest values of 343.75 and 362.5°C, respectively. CCO had the lowest at 325°C. These values illustrate the influence nanoparticles can have on the characteristics of lubricants.

Additives can have an influence on the performance of biolubricants. Although there is a variation in results, incorporating additives can enhance a lubricant's attributes to improve performance. Table 1 shown below offers a summary of some lubricants and their additives along with their respective attributes [3,4].

Table 1: Lubricants with nanoparticle additives and their attributes [3,4]

Lubricant	Nanoparticle additive	Frictional Power (kW)	Coefficient of Friction	Brake Thermal Efficiency (%)	
Jojoba Oil	--	--	--		[3]
Jojoba Oil	TiO_2	1.50	--	33.6%	[3]
Coconut Oil	CeO_2	--	--	32.1%	[3]
MO	--	2.35		30.3%	[3]
Coconut Oil	--	--	0.0961	--	[4]
Coconut Oil	Graphene	--	0.086	--	[4]
Coconut Oil	Maghemite	--	0.0920	--	[4]

Chemical Modification

Chemical modification can improve the performance of biolubricants. While the addition of nanoparticles can enhance a lubricant through physical, surface alterations, chemical modification alters the lubricant on a molecular level [8]. There are a variety of pathways that can be taken when considering chemical modifications. One approach is esterification which ultimately combines carboxylic acid and alcohol to form esters as a product [9,10]. Epoxidation is another technique and is already commercialized for soybean oils which has a global value market of 0.3 billion USD [11]. The process takes fatty acids of oils and converts them into epoxides also referred to as oxirane rings. The conversion alters the physiochemical structures of oils that allow them to withstand higher temperatures as well as improve tribological properties [12].

Esters are crucial in lubrication as they support oxidation and thermal stability [13]. In a study done by Monteiro et al., esterification of the free fatty acids (FFAs) from castor oil and the fatty alcohol 2-ethyl-1-hexanol, was observed [14]. The goal of the study was to optimize enzyme production without the use of an acid catalyst or the incorporation of solvents. Acid catalysts are commonly used in FFA esterification; however, it often influences equipment degradation and uses high amounts of energy due to necessary high temperatures [15]. Monteiro et al. uses an enzyme that was genetically engineered from Thermomyces lanuginosus (TLL), referred to as lipase Eversa Transform 2.0 (ETL). With its original purpose of increasing FFA content for biodiesel production, ETL was tested to see if the catalyst will have a similar success when used in esterification. To observe the performance capabilities, the ETL was compared to catalysts that are commercially used: RML, TLL, CALA and CALB. As shown in Figure 4 below, TLL had the highest conversions rates, followed by ETL [14].

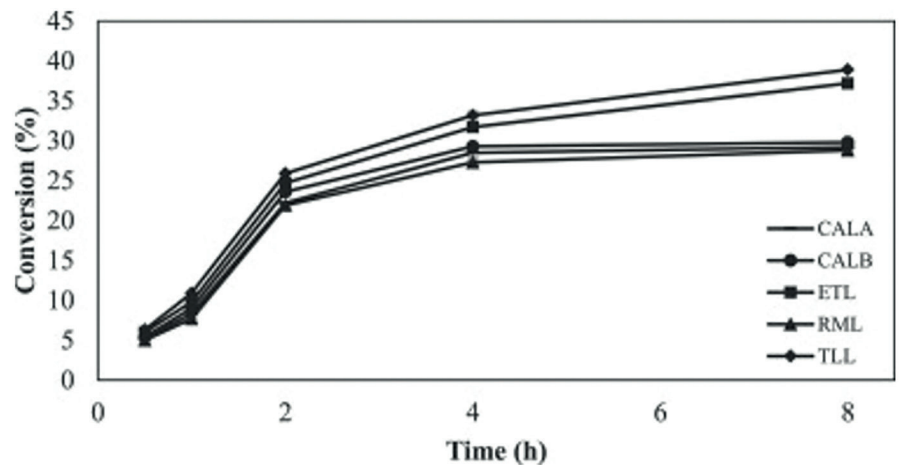

Figure 4: Conversion percentages of Monteiro et al. samples [14].

According to Monteiro et al., although ETL did not exceed the values of TLL, they both increased in a similar manner, while the other three enzymes show little to no change after the four-hour mark. After this conclusion was drawn, the ETL was then optimized through the testing of five independent parameters: temperature, stirring rate, substrate molar ratio (acid/alcohol), biocatalysts content, and time (hours). The optimal ETL was found at a biocatalyst content of 15% at 30°C, 180 rpms, and a 1:4 molar ratio. Ultimately, the conversion rate reached a value of 95.70% [14].

ETL was also compared to the commercial mineral lubricant 20 W-50. From this, tribological tests were performed. Out of the two lubricants, the bio lubricant had a better-performing friction coefficient which was 0.052 ± 0.07, while the mineral lubricant had a coefficient of 0.078 ± 0.04. However, for the wear scan diameter (WSD), a different conclusion was made. The diameters were measured at 209.72 ± 3.01μm and 140.36 ± 1.36μm for the biolubricant and mineral lubricant, respectively. From these values along with the images from the Four-ball wear test shown in Figure 5, the biolubricant showed signs of higher oxidation wear [14]. According to Monteiro et al., while the biolubricant did show a higher wear scan diameter, its value is lower compared to commercial biolubricants. Further study of enzymes in biolubricant production can be greatly influential on the future of lubricants [14].

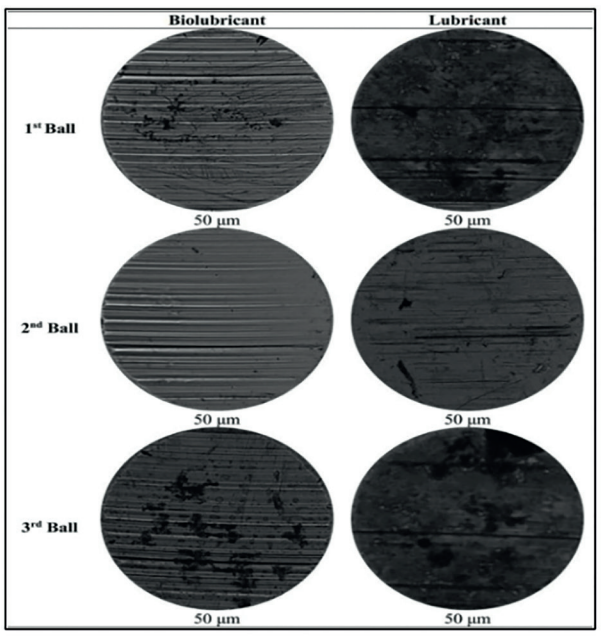

Figure 5: Results of Four-Ball Test [14]

Another study done by Neta et al. compared the performances of castor oil fatty acids (COFA) with ones when modified with esterification (BL1), or with esterification and epoxidation (BL2) [15]. The study recorded a wide variety of parameters including viscosity and pour points, along with tribological properties. For oxidative stability, an instrument used to measure oxidation levels of oils referred to as a Rancimat, was used in which samples were subjected to 110°C. The stability was measured in the time it took for conductivity to reach a value of 200μS/cm. The epoxidated lubricant performed the best at a value of 14.29 ± 0.16 hours, in comparison to the non-epoxidated lubricant which had a value of 12.89 ± 0.57 hours [16]. All three samples had a thermal stability of roughly 200°C. Similar to the study done by Monteiro et al., both biolubricants were then tested in comparison to a commercially used mineral

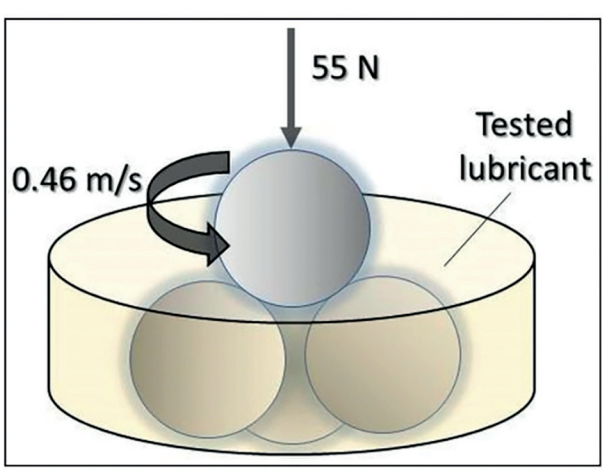

Figure 6: Four-ball Tribological Test [16].

lubricant. Referring to Figure 6, the test performed was a Four-ball tribological test [16].

The biolubricants had the lower of the friction coefficients with values of 0.037, 0.044 and 0.051 for BL2, COFA and BL1, respectively. The mineral lubricant, however, had a higher friction coefficient value recorded at 0.065. The WSD also provided insightful results. The commercial mineral lubricant along with BL1 had close values, measured at 264.75 µm and 251.06 µm, respectively. BL1 and COFA also had similar values; however, they were much lower. This result represents that the additional step of epoxidation can ultimately help preserve the anti-wear capabilities that are seen in the COFA sample. This can be due to the oxirane rings which can help protect chemical and physical properties [16].

Chemical modifications can help improve the characteristics and overall performance of biolubricants. Although results can vary between the type of biomass used as well as the kind of modifications, it is critical to continue research in this sector. Studies have already shown how modification can enhance the already redeemable qualities of certain biolubricants. Table 2 shown below offers a summary of various biolubricants in comparison to some commercially used mineral lubricants [14,16].

Table 2: Chemically Modified Biolubricants [14,16].

Lubricant	Thermal Stability	Friction Coefficient	Wear Surface Diameter	
20 W-50	---	0.078 ± 0.04	140.36 ± 1.36	[14]
ETL	---	0.052 ± 0.07	209.72 ± 3.01	[14]
COFA	236.14 °C			
(at 5% wt loss)	0.044	140.68	[16]	
BL1	223.72 °C			
(at 5% wt loss)	0.051	251.06	[16]	
BL2	187.62 °C			
(at 5% wt loss)	0.037	157.87	[16]	

Prospects of Biolubricants

Although biolubricants are not the primary kind of lubricant used commercially, they do have current niche applications. The market value of biolubricants is at 2.72 billion USD in 2025 and is predicted to rise to 4.14 billion USD by 2032 but is already seeing some commercial use [17]. For example, these lubricants are already seen in transportation. Larger vehicles such as trucks and buses are starting to use animal oils as a lubricant. While the initial costs may be higher for these biolubricants, their longer lifespans can ultimately become cost-effective [17]. Biolubricants also have potential in gear applications. Their corrosion and friction reduction capabilities can help increase productivity on some machinery by 20% [18]. Government initiatives are also being taken across the globe. The leader of biolubricants is currently Europe. This is due to certain policies being enforced in countries including France and Germany. Certain regulations such as the European Green Deal help promote the use of biolubricants to be used in sectors like automotive and industrial [18]. There is a vast variety of biolubricants all ranging in purpose and attributes which contributes to the potential of seeing these types of lubricants in industry.

Conclusion

Biolubricants have an array of advantageous qualities. They are an environmentally friendly alternative to the mainly used lubricants seen today. While biolubricants have their drawbacks, there is an abundance of pathways being taken to further biolubricants' capabilities. Physical additives of nanoparticles are one technique that is gaining traction. Additives including titanium dioxide, graphene, and maghemite have been studied resulting in enhancements of certain renewable lubricants [3,4]. Chemical modifications are another area being explored. Techniques such as esterification and epoxidations help promote ester production in lubricants [12,13]. They can be seen enhancing the performances of biolubricants by improving thermal stability, WSD, and frictional stability. Ultimately, biolubricants have yet to be as dependently used compared to mineral-based lubricants. However, they are gaining traction and are even being promoted through governments [18]. Biolubricants truly have a promising future. Their performance capabilities can greatly influence the shift to more sustainable lubricants.

References

[1] Uniyal, P., Gaur, P., Yadav, J., Khan, T., & Ahmed, O. S. (2024). A Review on the Effect of Metal Oxide Nanoparticles on Tribological Properties of Biolubricants. ACS Omega. https://doi.org/10.1021/acsomega.3c08279

[2] Narayana Sarma, R., & Vinu, R. (2022). Current Status and Future Prospects of Biolubricants: Properties and Applications. Lubricants, 10(4), 70. https://doi.org/10.3390/lubricants10040070

[3] N, M., Karanth, K. V., & Kumar, S. (2025). Nanoparticle-enhanced bio-lubricants for cleaner and more efficient diesel engine performance. International Journal of Thermofluids, 29, 101398. https://doi.org/10.1016/j.ijft.2025.101398

[4] Ibrahim Ogu Sadiq, Mohd Azlan Suhaimi, Sharif, S., Noordin Mohd Yusof, & Muhammad Juzaili Hisam. (2022b). Enhanced performance of bio-lubricant properties with nano-additives for sustainable lubrication. Industrial Lubrication and Tribology, 74(9), 995–1006. https://doi.org/10.1108/ilt-08-2021-0348

[5] Milton Garcia Tobar, Wilmer, R., Bryan Jimenez Cordero, & Julio Guillen Matute. (2024). Nanotechnology in Lubricants: A Systematic Review of the Use of Nanoparticles to Reduce the Friction Coefficient. Lubricants, 12(5), 166–166. https://doi.org/10.3390/lubricants12050166

[6] Erdi Korkmaz, M., & Kumar Gupta, M. (2024). Nano lubricants in machining and tribology applications: A state of the art review on challenges and future trend. Journal of Molecular Liquids, 407, 125261. https://doi.org/10.1016/j.molliq.2024.125261

[7] Zhu, P., Yan, Y., Zhou, Y., Qi, Z., Li, Y., & Chen, C.-M. (2024). Thermal Properties of Graphene and Graphene-Based Nanocomposites: A Review. ACS Applied Nano Materials, 7(8), 8445–8463. https://doi.org/10.1021/acsanm.4c00411

[8] Nugroho, A., Kozin, M., Bo, Z., Mamat, R., Ghazali, M. F., Kamil, M. P., Puranto, P., Fitriani, D. A., Azahra, S. A., Suwondo, K. P., & Ashfiya, P. S. (2024). Recent advances in harnessing biolubricants to enhance tribological performance and environmental responsibility – Bibliometric review (2015–2024). Cleaner Engineering and Technology, 23, 100821. https://doi.org/10.1016/j.clet.2024.100821

[9] Akanksha, M. S., Sumanth, P., Akhil, U. V., Radhika, N., & Ravichandran, M. (2024). The modification and adoption of biolubricants as alternatives in the automotive industry. Environmental Science and Pollution Research, 32(3), 1043–1072. https://doi.org/10.1007/s11356-024-35670-z

[10] BioSolvents. (2024, June 25). What Are Esters? Properties, Structures, and Uses | Vertec. Www.vertecbiosolvents.com. https://www.vertecbiosolvents.com/what-are-esters-properties-structures-and-uses

[11] BALDE, I. , KANE, C. , DIME, A. K. , BALDE, S. , & NDIAYE, K. (2022). Vegetable Oils Epoxidation Mechanisms. World Journal of Analytical Chemistry, 7(1), 1-6.

[12] Cogliano, T., Turco, R., Martino Di Serio, Salmi, T., Tesser, R., & Russo, V. (2024). Epoxidation of Vegetable Oils via the Prilezhaev Reaction Method: A Review of the Transition from Batch to Continuous Processes. Industrial & Engineering Chemistry Research. https://doi.org/10.1021/acs.iecr.3c04211

[13] Housel, T. (n.d.). Synthetic Esters: Engineered to Perform. Www.machinerylubrication.com. https://www.machinerylubrication.com/Read/29703/synthetic-esters-perform

[14] Monteiro, R. R. C., de Melo Neta, M. M. F., Rocha, W. S., Soares, J. B., de Luna, F. M. T., Fernandez-Lafuente, R., & Vieira, R. S. (2024). Optimizing the enzymatic production of biolubricants by the Taguchi method: Esterification of the free fatty acids from castor oil with 2-ethyl-1-hexanol catalyzed by Eversa Transform 2.0. Enzyme and Microbial Technology, 175, 110409. https://doi.org/10.1016/j.enzmictec.2024.110409

[15] Pirahanchi, Y., & Sharma, S. (2023, June 26). Biochemistry, lipase. National Library of Medicine; StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK537346/

[16] Marliete, M., Gustavo, de, P., de, I., da, W., Paulo, Cavalcante, C. L., & Murilo, F. (2023). Thermo-Oxidative Stability and Tribological Properties of Biolubricants Obtained from Castor Oil Fatty Acids and Isoamyl Alcohol. Lubricants, 11(11), 490–490. https://doi.org/10.3390/lubricants11110490

[17] S&S Insider. (2025). SNS Insider | Strategy and Stats. Snsinsider.com. https://www.snsinsider.com/reports/biolubricants-market-4419

[18] Jain, A. K., & Amit Suhane. (2013). Capability of Biolubricants as Alternative Lubricant in Industrial and Maintenance Applications.

About the Authors

Dr. Raj Shah, is a Director at Koehler Instrument Company in New York, where he has worked for the last 25 plus years. He is an elected Fellow by his peers at ASTM, IChemE, ASTM, AOCS, CMI, STLE, AIC, NLGI, INSTMC, 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 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 honorific 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 over 725 publications and has been active in the energy industry for over 3 decades. More information on Raj can be found at https://shorturl.at/JDPZN

Miss Madeline Chiappone is part of the thriving internship program at Koehler Instrument Company and is studying towards a degree in Civil Engineering at Stony Brook University in Stony Brook, New York.

Madeline Chiappone

William Chen

Mister William Chen is a member of a thriving internship program at Koehler Instrument company in Holtsville, and is a student of Chemical Engineering at State University of New York, Stony Brook, NY.

Mister Gavin Thomas is part of the thriving internship program at Koehler Instrument Company and has graduated with a degree in Chemical Engineering at Stony Brook University in Stony Brook, New York. He also is a process engineer at Mill-Max where he optimizes performance with sustainability and efficiency.

Gavin Thomas

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company

- **Holtsvile, NY11742 USA**
- **Email: rshah@koehlerinstrument.com**
- **Web: www.koehlerinstrument.com**