Lube 2025

Digital Exclusive

THE EUROPEAN LUBRICANTS INDUSTRY MAGAZINE

March 2025

The official journal of UEIL

A path towards sustainability: Lubricants

Brajendra K. Sharma*, *Gobinda Karmakar*, *Raj Shah* and *William Chen

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***Brajendra K. Sharma**, US Department of Agriculture, Agricultural Research Service, Eastern Regional Research Center, Sustainable Biofuels and Coproducts Research,*
***Gobinda Karmakar**,*
Sri Narasingha Vidyapith,
*and **Raj Shah** & **William Chen**,*
Koehler Instrument Company

Introduction

The lubricants industry has grown significantly in recent years to the current value of 173.5 billion US dollars in 2024 from 169.1 billion USD in 2023 and expected to reach 198.4 billion USD by 2029 with a compound annual growth (CAGR) rate of 2.7%. As reported in 2023, the market shares of Asia, Europe, North America, the Middle East, and South America were 44.69 %, 23.81 %, 21.25 %, 5.5 %, and 4.76 % respectively [1,2]. Lubricants are widely used in a variety of industries due to their inherent properties that play a critical role in reducing friction in equipments, minimising wear, and enhancing operational efficiency. Mineral or synthetic lubricants, basically holding the lubricant market, being non-renewable petroleum originated, are less sustainable and create many environmental hazards throughout their entire life cycle.

The current environmental regulations like the EPA (Environmental Protection Agency), VIDA (Vessel Incidental Discharge Act), European Union's Ecolabel, UN Sustainable Development Goals [SDG, 2015] mainly focus on reduction of CO_2 emission which is increasing very rapidly due to use of these traditional lubricants. Therefore, sustainability within lubricants is of paramount importance to achieve the regulatory goals for sustainable movement. The use of bio-lubricants, prepared from renewable natural resources, is a perfect alternative to synthetic and mineral lubricants in this case. The application of bio-lubricants minimises all the hazards like increased carbon emissions, climate change, environmental toxicity etc. created by traditional lubricants during the entire life cycle [3, 4]. This has pushed the global bio-lubricants market upwards valued at USD 2 billion in 2023 and it is expected to reach USD 3.25 billion by 2033 as the industries seek alternatives to non-renewable traditional petroleum-based products.

In addition to the use of bio-lubricants, the utilisation of recycled and refined lubricating oils is a great step towards sustainability and carbon neutral environment. For example, Castrol's More Circular program aims to cut carbon emissions by 20-40% by promoting a circular economy where used oils are collected, purified, and re-used, reducing dependence on virgin resources [5]. Additionally, companies like Evonik are incorporating renewable energy sources at their production sites and targeting further emission reductions up to 30% by 2025 through efficiency improvements and green energy transitions [6].

While different regions, including the United States, Asia, and Europe, approach sustainability in unique ways, several key trends have emerged. These include the shift to bio-based lubricants derived from renewable sources, the integration of additives that enhance existing properties, the re-refining of lubricants to extend their lifecycle, the incorporation of nanotechnology, and the development of formulations with lower viscosity for improved energy efficiency. This paper will explore these emerging trends and analyse how they are driving the sustainability goals that are shaping the future of the lubricant industry.

Bio-based lubricant

Bio-based lubricants emerge as one of the most notable trends in creating sustainable lubricants. Bio-based lubricants, derived from renewable sources like vegetable oils or animal fats, offer an eco-friendly alternative to conventional petroleum-based lubricants [7]. The main advantages of bio-lubricants are that they are comparatively less toxic, readily biodegrade naturally over time helping to reduce environmental impacts of lubricant disposals and emit lesser CO_2 during application. The readily biodegradable character of biolubricants (60% or more degradation within days) makes them less harmful in the event of spills or leaks [8]. According to Koehler Instrument Company, bio-based lubricants derived from renewable resources, such as vegetable oils can result in a reduction of CO_2 emissions by up to 90% compared to traditional lubricants [9]. Furthermore, Shell emphasises that sustainable lubricants not only minimise environmental hazards but can also enhance equipment life and efficiency by reducing wear and energy consumption further reducing waste [7]. Many of the crops used, such as canola, soybeans, and palm, can be grown in ways that enhance soil health through practices like crop rotation and cover cropping, which improve nutrient cycling and prevent soil erosion. These crops also promote biodiversity by creating habitats for various organisms and supporting pollinators when intercropped or planted with flowering cover crops. Additionally, integrated pest management practices for these crops help reduce dependency on synthetic fertilisers and pesticides by encouraging natural pest control methods and utilising organic soil amendments [10]. This shift toward sustainable sourcing not only provides a renewable supply of lubricant base stocks but also supports local economies and reduces the environmental footprint associated with transporting petroleum products over long distances. Additionally, by replacing petroleum-derived lubricants with bio-based alternatives, industries can contribute to the reduction of reliance on fossil fuels, thus supporting the transition to a circular economy. This transition is vital as it aligns with global sustainability goals aimed at minimising the depletion of natural resources and reducing environmental degradation [11].

In addition to their environmental benefits, bio-based lubricants often provide excellent lubricity and high viscosity indices. Specifically, these lubricants can exhibit viscosity indices (VI) ranging from around 180 to over 250, which is significantly higher than that of conventional mineral-based oils, which typically have a VI of 90 to 150 [12, 13]. This higher viscosity index indicates that bio-based lubricants maintain their performance across a broader temperature range making them suitable at varying conditions, from cold starts to high-temperature operations. Table 1 displays a list of bio-based lubricant and their correlating viscosity index. Moreover, bio-based lubricants are effective in reducing friction, with some formulations demonstrating comparable or superior lubricity to traditional lubricants. For example, estolides and other bio-derived esters have shown excellent lubricity, which contributes to reduced wear and tear on machinery, potentially extending equipment life [13]. These qualities, combined with their biodegradability and lower environmental impact, make bio-based lubricants an attractive option for industries looking to enhance sustainability while maintaining performance.

Bio-lubricants	Viscosity index
Palm	40
Sunflower	203
Chicken fat	191
Coconut	169
Cotton Seed oil	197
Corn	237
Soybean	159
Linseed	262
Rapeseed	218
Canola oil	204
Caster oil	88
Jatropha	204
Neem	212
Karanja	172
Algae	180

Table 1: *Bio-based lubricants and their viscosity index [14]*

The market for bio-lubricants is also growing, with projections suggesting an increase in demand between 3.5% and 5.6% annually, driven by the need for eco-friendly solutions across various sectors, including agriculture, construction, and marine [8]. Furthermore, there is potential to earn monetary CO_2 credits through reduced friction and energy consumption, which can help offset costs associated with implementing sustainable practices. In emissions trading systems, such as those in the European Union, companies can earn carbon credits by lowering their CO_2 emissions, either through direct reductions or by improving energy efficiency. By using bio-based lubricants, industries can decrease friction in machinery, leading to lower energy consumption.

This reduction in energy demand translates to fewer CO_2 emissions during equipment operation. These CO_2 savings can then be quantified into carbon credits, which companies can sell in carbon markets or use to meet regulatory compliance requirements. In this way, the transition to sustainable lubricants not only aligns with environmental goals but also provides financial incentives that can make these green practices more economically viable [9]. This economic incentive is crucial as companies seek to align with global sustainability goals while also managing their operational costs effectively. However, challenges such as oxidative stability and cost still limit their broader adoption [8]. Despite this, as sustainability becomes a global priority, industries are increasingly exploring bio-based options to meet regulatory requirements and enhance their environmental performance.

Additives and nanotechnology

Bio-based lubricants, while inherently biodegradable and non-toxic, sometimes lack certain performance characteristics, such as oxidative stability and thermal resistance. To address these challenges, researchers are incorporating various additives, including nanoparticles, estolides, wax esters, ionic liquids etc. that play a crucial role in enhancing the performance of bio-based lubricants, helping to overcome some of their inherent limitations while promoting sustainability. For instance, the addition of graphene and maghemite nanoparticles has been shown to significantly enhance oxidation stability and tribological performance. Through the use of these nanoparticles, the oxidation onset temperature was shown to increase by as much as 37.5°C, thus prolonging the lubricant's lifespan in high-temperature applications [15]. Nanolubricants also exhibit improved viscosity, reducing the coefficient of friction and wear scar diameter by notable percentages compared to conventional oils [15, 16]. Graphene-infused bio-lubricants have also been reported to achieve a reduction in the co-efficient of friction by approximately 10.4%, along with a decrease in wear scar diameter by 5.6% when compared to conventional oils [15, 16].

Traditional lubricants often rely on synthetic additives to achieve desired properties, but the increasing demand for eco-friendly alternatives has led to innovative solutions using bio-derived materials. Moreover, bio-derived additives like estolides not only provide enhanced lubricating properties but also improve the biodegradability of the lubricant itself. These additives can increase the viscosity index, making the lubricant more effective across various temperatures[17], improve extreme pressure and shear stability of the composition.

Estolides are particularly effective additives for bio-based lubricants due to their unique molecular structure, which imparts several key performance benefits. Studies have shown that estolide-based lubricants can perform consistently in temperature ranges from -20°C to 150°C, making them suitable for applications in automotive engines, industrial machinery, and even aviation [18]. Another crucial benefit of estolides is their oxidative stability. Bio-based lubricants, particularly those derived from vegetable oils, are prone to oxidation, leading to the formation of sludge, varnish, and acids. Estolides resist this degradation due to their ester linkages, which remain stable under high-temperature conditions. Research has shown that estolide additives can significantly increase the oxidation induction time (OIT) of bio-based oils, prolonging their service life and enhancing reliability in long-term applications as shown in Figure 1.

Moreover, estolides improve the lubricity of bio-based lubricants by forming a thin, durable film on metal surfaces, thereby minimising friction and wear. This property is essential because bio-based oils may not naturally offer the same level of lubricity as synthetic oils. The addition of estolides has been observed to reduce the coefficient of friction by up to 25%, leading to lower energy consumption and less wear on mechanical parts [18]. These combined properties make estolides a versatile solution for enhancing the performance of bio-based lubricants, helping to bridge the gap between sustainability and high-performance requirements.

Effect of estolide additives on oxidation induction time (OIT)

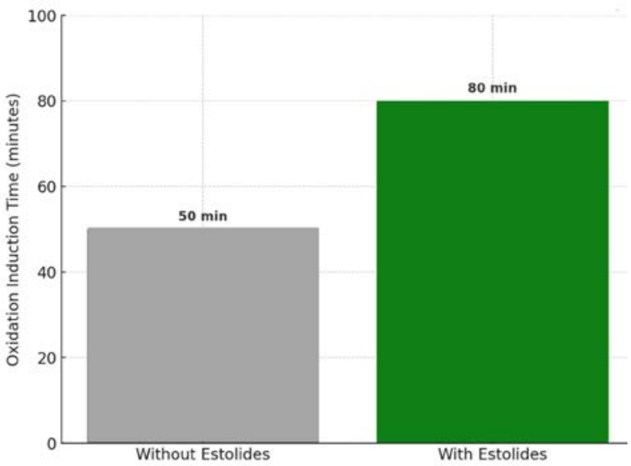

Figure 1: *Effect of estolide additives on oxidation induction time [19]*

Wax esters are another class of bio-derived additives that play a vital role in enhancing the performance of bio-based lubricants. These esters are composed of long-chain fatty acids and long-chain alcohols, which gives them unique properties suitable for lubrication. Naturally found in substances like jojoba oil, beeswax, and certain marine organisms, wax esters have been studied for their potential to improve various aspects of lubricant formulations [20]. One of the primary benefits of wax esters in bio-based lubricants is their excellent lubricity. The long-chain molecular structure allows them to form a smooth, continuous film on metal surfaces, significantly reducing friction and wear. This makes them ideal for applications where minimising mechanical friction is essential, such as in automotive engines, gears, and other machinery. Studies have shown that incorporating wax esters can lower the coefficient of friction by up to 15%, improving energy efficiency and reducing heat generation during operation [21]. Wax esters also contribute to the thermal stability of bio-based lubricants. They exhibit a relatively high melting point and thermal resistance, which helps maintain lubricant performance under elevated temperatures. High thermal stability ensures that the lubricants do not break down easily, even during prolonged exposure to heat, thus extending the lifespan of the lubricant and reducing the frequency of oil changes. For example, lubricants containing wax esters have been reported to maintain their structural integrity and viscosity even at temperatures exceeding 120°C, making them suitable for high-temperature industrial applications [20].

Researchers at Oak Ridge National Laboratory (ORNL) have developed nontoxic, biodegradable lubricant additives derived from renewable resources, specifically designed to protect turbine equipment while minimising ecological impact [22]. These additives, effective across a temperature range of -40°F to 300°F, enhance the performance of turbine lubricants by providing superior protection against friction and wear. Furthermore, the integration of ionic liquids in lubricant formulations represents a significant leap forward, as these salts remain liquid at room temperature and exhibit low volatility, reducing emissions and potential harm to the environment. Notably, studies have shown that ionic liquids can be tailored to be non-toxic to aquatic life, including tiny plankton, which are vital to aquatic ecosystems [22]. By incorporating nanotechnology, these additives improve the lubricants' viscosity and stability, reducing the frequency of oil changes and minimising waste. This progress exemplifies the potential for integrating cutting-edge technologies to create high-performance, environmentally responsible lubricant formulations that meet the demands of modern machinery while protecting essential marine life.

Emerging biobased additives, such as plant-based fatty acids like oleic, linoleic, and stearic acids, are gaining attention for their lubricating properties. Research indicates that the incorporation of these fatty acids can enhance lubricating properties while simultaneously reducing environmental impact. For example, bio-lubricants containing 20% plant-based fatty acids exhibited improved viscosity stability and a flash point increase of 25°C, making them more effective for high-temperature applications [23]. This improvement in flash point means that the bio-lubricant can withstand higher temperatures before reaching its ignition point, which is crucial for applications in engines or machinery operating under extreme heat. Additionally, enhanced viscosity stability implies a consistent thickness under varying temperatures, reducing wear and tear on machine components and improving overall efficiency and lifespan [23]. In addition, it is crucial to ensure that bio-based lubricants and additives are compatible with existing lubrication systems. This compatibility is essential for facilitating their adoption in industrial settings, particularly in sectors where downtime is costly. Regulatory compliance adds another layer of significance to the development of these formulations.

Adhering to environmental regulations, such as the EPA's definition of environmentally acceptable lubricants, ensures that new products meet the ecological standards required for various industries [24]. Furthermore, lifecycle analysis is increasingly being employed to enhance the sustainability credentials of bio-based lubricants, assessing their environmental impact from production to disposal [11].

Lower viscosity lubricants

Nanolubricants also exhibit improved viscosity, reducing the coefficient of friction and wear scar diameter by notable percentages compared to conventional oils [15, 16]. The push for lower-viscosity oils has gained momentum in regions like the USA and Europe, where regulations demand lower emissions. In Asia, the trend is also gaining traction as manufacturers look to optimise engine performance and efficiency. Lower viscosity in lubricants is increasingly important for enhancing fuel efficiency and reducing emissions. Lubricants with lower viscosity reduce internal friction in engines and machinery, leading to less energy loss and improved performance. This shift is particularly important in automotive applications, where thinner oils, such as SAE 0W-20 or 0W-16, have become popular for enabling engines to operate more smoothly, especially at lower temperatures [25]. The new ILSAC GF-7 standard emphasises maintaining CO_2 performance across a vehicle's lifespan, driving the adoption of these low-viscosity oils [25]. On average, switching from higher viscosity oils (like 15W-40) to lower viscosity options (such as 5W-30) can yield fuel savings of approximately 0.5% to 1.5% [26].

Viscosity and VI are critical physicochemical properties influencing lubricant performance. Bio-lubricants, often having higher viscosity due to longer hydrocarbon chains in ester formulations, demonstrate significant variation in viscosity with temperature. A higher viscosity index indicates smaller viscosity changes across a broader temperature range, which is beneficial for maintaining lubricant efficiency. Malik et al. noted an improvement in the viscosity index of lubricant oil from 171 to 214 when vacuum pressure was reduced during the transesterification of palm oil methyl esters [27]. By utilising high-quality lubricants and implementing best practices, manufacturers can achieve energy savings, waste reduction, and enhanced operational efficiency [28]. These advancements are crucial for not only meeting regulatory requirements but also improving the overall environmental footprint of manufacturing processes. However, achieving lower viscosity without compromising wear protection and film strength remains a challenge due to the inherent trade-offs between viscosity and the oil's ability to form a stable lubricating film. While lower viscosity oils can reduce friction and improve fuel efficiency, they often struggle to provide adequate protection against wear under high-pressure and high-temperature conditions. Thinner oils are more likely to experience breakdown under stress, leading to reduced film strength and potential metal-to-metal contact, which can cause engine damage. Additionally, the formulation of lower viscosity oils often requires the addition of anti-wear agents and friction modifiers to maintain performance, but these additives may not be as effective in oils with reduced viscosity. Achieving the right balance between viscosity reduction for fuel economy and maintaining sufficient protective film strength is a complex challenge in lubricant formulation. Furthermore, oils with lower viscosity can be more prone to oxidation, which may compromise their longevity and protective properties over time. Advances in additives and synthetic base oils have played a key role in this development. Modern additives can improve oil's film-forming properties and enhance anti-wear performance, even when the oil is thinner. These innovations ensure that lower-viscosity lubricants can still provide sufficient lubrication under varying temperatures and loads, which is crucial for maintaining engine durability and reliability.

Re-refining of waste lubricants

Re-refining of waste lubricating oils (WLO) is another crucial process in sustainability and resource management. The release of used lubricants to the environment pollutes water and soil while also impacting sewage networks. The contamination of toxic substances like heavy metals, chlorine, sulfur etc. from WLO with water harms aquatic life severely. The disposal of waste oil in the ground pollutes soil and underground water also by which the plant kingdom and human lives are affected. Their uncontrolled burning creates severe air pollution due to release of toxic gases. Therefore, proper handling and storage of WLO by the generators is of utmost importance for the proper management of the hazardous waste. The re-refining process begins with the collection and storage of used lubricants from various sources, including automotive service centers and industrial facilities. Proper storage prevents contamination of the different waste lubricants before the pre-treatment and also stops to mix the common contaminants such as water, dirt, and metal particles. Filtration and centrifugation is carried out to remove these types of contaminations if any [29]. Next, the used oil is subjected to distillation, which separates it into fractions based on boiling points, effectively removing volatile impurities and allowing for the collection of useful fractions. Following distillation, hydrotreating occurs, where hydrogen is added under high pressure and temperature to eliminate sulphur, nitrogen, and oxygen compounds, improving the oil's stability and performance. The process concludes with a finishing phase, incorporating additional treatments like adsorption and filtration to ensure the final product meets industry specifications.

Safety-Kleen, the largest re-refiner in North America, processes over 200 million gallons of used oil annually, demonstrating the scale of this operation. Their comprehensive approach includes rigorous testing of collected oils for contaminants, dehydration to remove water, and vacuum distillation to separate heavy impurities [30]. Re-refining can reclaim approximately 75 to 80 percent of the original base stock from used oils, with some re-refined oils matching or exceeding the performance of virgin base oils [29]. Furthermore, advances in technologies like vacuum distillation and hydrotreating have improved the quality of re-refined base oils (RRBOs), enabling them to reduce carbon emissions by 20% to 40% without compromising performance [31].

According to CalRecycle, re-refined lubricants undergo rigorous testing and must meet the same specifications as virgin oils, ensuring that they perform reliably in various applications. Additionally, re-refined oils typically generate less waste, promoting a more sustainable lifecycle and reducing the overall environmental footprint associated with lubricant use as shown in Figure 2 [32-34]. Re-refining lubricants offers significant benefits, including reducing the volume of waste oil entering landfills and minimising environmental contamination. It also conserves resources by reclaiming base oils, thus reducing the demand for new crude oil extraction.

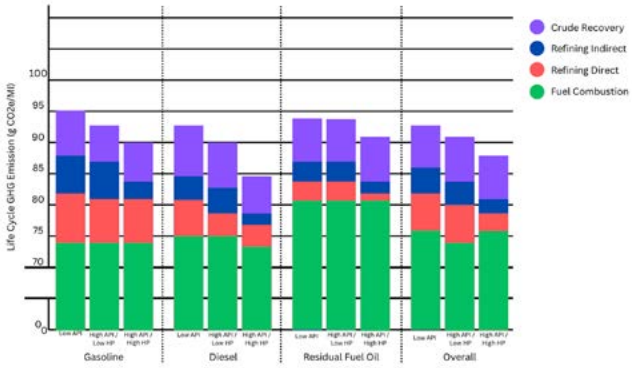

Figure 2: *Life Cycle CO_2 Emission [34]*

Despite its advantages, re-refining faces challenges, including regulatory hurdles and competition from virgin oil suppliers. Ongoing research aims to enhance re-refining processes through advanced technologies, such as nanotechnology and biorefining methods, which could improve the quality of re-refined lubricants. Moreover, as global regulations increasingly mandate the use of recycled materials, the re-refining industry must adapt to meet these standards. Collaboration with regulatory bodies and the development of certifications for quality assurance can also help build consumer trust and acceptance of re-refined products.

Conclusions

The lubricant industry is increasingly focused on sustainability and innovation. Bio-based lubricants, offer a biodegradable and non-toxic alternative to petroleum-based products, are at the forefront of this shift. These lubricants, enhanced with performance-boosting additives and nanotechnology, help reduce environmental impact while ensuring high operational efficiency. Additionally, the industry's move toward lower-viscosity oils responds to regulatory pressures and consumer demand for fuel efficiency and reduced emissions, contributing to both engine performance and sustainability goals. Re-refining used lubricants plays a crucial role in resource conservation, waste reduction, and mitigating environmental impact. Companies embracing these innovations not only contribute to a more sustainable industry but also position themselves as leaders in responsible manufacturing. Looking ahead, further research into the scalability, performance, and long-term environmental impact of bio-based lubricants will be essential for their broader adoption. With the global lubricant market expected to grow due to factors such as rising industrialisation and vehicle production, ongoing advancements in nanotechnology and eco-friendly formulations will continue to drive the industry's transformation toward more sustainable solutions.

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Authors

Brajendra K. Sharma *is a Research Chemist at ERRC, USDA/ARS/NEA, a fellow of the Royal Society of Chemistry and the Society of Tribology & Lubrication Engineers, and conducts research on bio-lubricants, bio-fuels, alternative fuels, biobased asphalt binders, additives, and chemicals.*

Dr Gobinda Karmakar *is conducting research on lubricants as a senior post-doctoral researcher under Prof. Pranab Ghosh, University of North Bengal, India. He is presently working as a post-graduate teacher of chemistry at Sri Narasingha Vidyapith, Darjeeling. His special interests on research are synthesis of environmentally sustainable lubricants from different oils of biological origin, synthesis of bio-additives and different analytical studies related to characterisation and performance evaluation of the formulated bio-lubricants. During his fifteen years tenure of research career, he has 24 publications including four book chapters in different international journals of repute. He reviewed several manuscripts of different journals of Springer, MDPI, Taylor & Francis etc. He is a member of Topical Advisory Panel, Lubricants, MDPI.*

Dr Raj Shah *has dedicated over 30 years to advancing innovation in greases, fuels, lubricants, and materials science. As a Director at Koehler Instrument Company in New York, he has played a key role in developing testing technologies that support industry standards worldwide. Recently honored with the ASTM Award of Merit (its highest honour), his contributions span tribology, petroleum engineering, and chemical analysis.*

Recognised by his peers for his expertise, Dr Shah has been elected a Fellow of a dozen distinguished professional organisations, including the Society of Tribologists and Lubrication Engineers (STLE), the Institute of Chemical Engineers (IChemE), the American Oil Chemists Society (AOCS), the Energy Institute (EI), the Royal Society of Chemistry (RSC), the Institute of Physics (IOP), the American Institute of Chemists (AIC), the Institute of Measurement and Control (InstMC), the Chartered Management Institute (CMI), the National Lubricating Grease Institute (NLGI), and ASTM International.

Dr Shah holds a Ph.D. in Chemical Engineering from The Pennsylvania State University and is a Chartered Engineer (Engineering Council, UK), Chartered Petroleum Engineer (Energy Institute), and Chartered Scientist (Science Council). He has also been recognised as an Eminent Engineer by Tau Beta Pi, the oldest engineering honour society in the United States.

Beyond his industry work, Dr Shah remains committed to education and mentorship. He serves on advisory boards of Auburn University, Stony Brook University, SUNY Farmingdale, and Penn State University, supporting programs in engineering and tribology. As an Adjunct Professor for the last decade at State University of New York, Stony Brook, Department of Materials Science and Chemical Engineering, he shares his knowledge with students and future professionals. Dr Shah is the recipient of numerous ASTM, STLE and NLGI awards and served on NLGI board of directors for over a decade.

With over 700 publications and decades of experience, Dr Shah continues to contribute to industry standards and technological advancements. He remains currently actively involved on advisory boards at professional societies, collaborating with colleagues to drive progress in science and engineering.

Mr. William Chen *is a student of chemical engineering at State University of New York, Stony Brook,, at which Drs Sharma and Shah are on the external advisory board of directors.*