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Optimising lubricant molecules at the genetic level

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Introduction

Lubricants are essential substances to industrial efficiency due to their mitigation of energy loss. Analysis done by a range of major sectors claim friction and wear account for about 23% of global energy consumption [1]. Moreover, lubricants are convenient for a variety of purposes including heat generation, forming protective coatings, and overall improving functionality. Considering the growing demand in production for automobiles and generally machine-produced goods, the global lubricant market is expected to continually increase. In 2021, the global lubricant market garnered a revenue of $132.44 billion and is at an estimated value of $150.25 billion in 2025 [1, 2]. This number is projected to reach $196.53 billion in seven years with an annual compound growth rate of nearly 4% [1]. Additionally, bio-lubricants, an ascendant sector in the tribology market, is garnering investments and attention. Bio-lubricants have a projected compound growth rate of 13.7. Figures 1 and 2, below, demonstrate the growth trends of both markets, with bio-lubricants expanding four times faster than the overall market and increasing their market share [2].

Bio-lubricants, a plant oil-based alternative, has been a speculative candidate for replacing petroleum-based lubricants. Bio-lubricants possess environmentally friendly traits such as extremely high biodegradability, low toxicity, and high availability due to plant oils being in large demand, exceeding traditional lubricants by up to 5.5 times [1].

Bio-lubricant market (USD, billions)

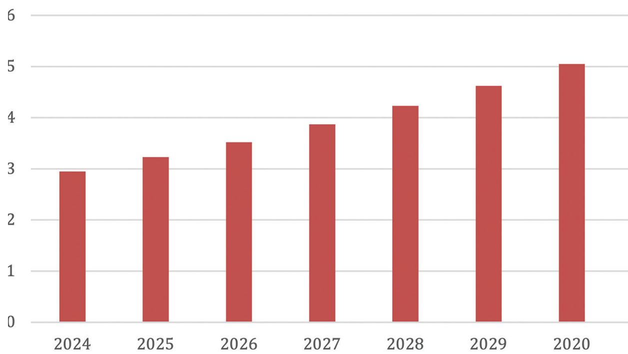
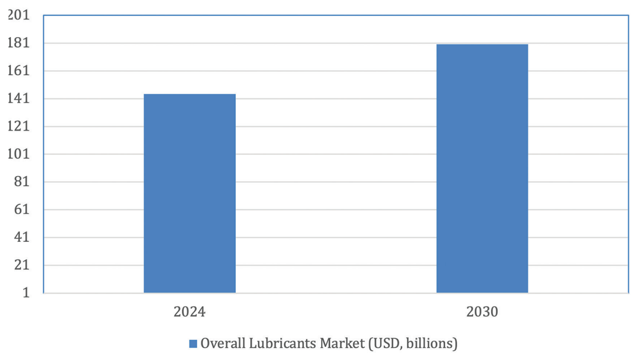


Figure 1: *Projection of the bio-lubricant market (USD, billions); estimated based on growth rate.*

Overall lubricants market (USD, billions)



Figures 2: *Projection of the total lubricant market (USD, billions); estimated based on growth rate.*

However, in 2021, the bio-based alternative made a relatively small share of $2.1 billion which pales in comparison to the overall market–approximately 2% of its entirety despite growing environmental pressures and regulation mandates [2]. The substantial difference in revenue is not because of a lack of interest, but from a gap in performance: the natural evolution of plant oils was optimised for energy storage in seeds, not for reducing friction in machinery. For many years, researchers have been trying to solve this problem by means of chemical modifications and additive packages. However, this approach is more of a 'band-aid' than a permanent solution, which is related to molecular structure.

Conventional plant oils face an inherent problem in their structure. The unsaturated fatty acids that keep oils liquid at low temperatures are due to structural features that make them weak to oxidative degradation at elevated temperatures. Saturated fatty acids, on the other hand, resist oxidation and are generally stable but tend to crystallise at room temperature, subsequently not being viable for most applications [3]. Traditional approaches including hydrogenation, transesterification, epoxidation, and synthetic additives can significantly increase manufacturing costs while possibly compromising biodegradability–the primary advantage of bio-based lubricants.

A new approach applies a nature-based, genomics to tribology method to offer a more efficient and effective solution. Genetic engineering can alter the molecular composition of seed oils before biosynthesis in the plant [5]. This framework starts with the tribological requirements of determining the specific molecular structures known to reduce friction wear, and oxidative degradation, or influence lubricant properties. Then, the process traces back to the genes regulating fatty acids and lipid pathways [5]. Through the modification of elongation pathways, plants can accumulate long chain fatty acids (C20-C22) that form more durable, lubricative coatings and boost oxidation stability [6, 7]. Additionally, engineering biosynthetic routes toward branched lipids such as estolides or wax esters can directly create molecules that resist oxidation and crystallisation, overcoming key limitations of seed oils [5, 7, 8]. Ultimately, the theoretical outcome is a superior bio-lubricant that is capable of industrial performance, compared to a retrofitted energy-storage molecule.

The concept of genomics to tribology

The framework of the genomics to tribology approach, termed as "nature-guided synthesis" by Romsdahl et al. (2019), represents an ideological shift from post-oil extraction manipulation to a more direct path of altering molecular design [5]. Traditional bio-lubricant development follows a linear path: cultivate oilseed crops, extract oils, analyse their properties, then attempt to address deficiencies through chemical modifications or additives. Moreover, this process is inherently flawed due to the plant composition itself–whatever fatty acid composition the plant naturally possesses. The application of genomics inverts this sequence.

Researchers initially identify the molecular structures that tribological testing shows will contribute to the reduction of friction and wear, then engineers biosynthesise those structures during seed development [5, 6]. Instead of retrofitting oils with expensive and inefficient post-harvest practices, this method aims to optimise lubricant molecules at the genetic level to leverage the plant's own biosynthetic properties to assemble complex lipid structures [5]. For instance, in the case of Orychophragmus violaceus seed oil, researchers discovered the naturally occurring presence of TAG (triacylglycerol) with great tribological properties; this suggests the oil naturally builds toward overcoming lubrication challenges through its molecular architectures [5]. Moreover, these natural structures serve as templates for synthetic chemistry and genetic engineering approaches. This directly opens the door for synthetic chemistry and genetic engineering approaches.

The biological foundation of this method lies in how plants synthesise fatty acids and lipids. In plant seeds, fatty acid biosynthesis happens through enzymatic pathways where each step is controlled by specific genes [6]. Fatty acid synthase complexes build initial 16 and 18 carbon chains, which then serve as a substrate for elongase enzymes that extend chain length, desaturase enzymes that introduce double bonds, and specialised enzymes that add functional groups such as hydroxyl branches [6]. Further, each enzyme corresponds to a gene's code–the FAE1 (Fatty Acid Elongase 1) gene produces an elongase enzyme that extends 18 carbon oleic acid (C18:1) to 20 and 22 carbon chains [6]. By overexpressing or introducing specific elongase genes such as FAE1 into oilseed crops, researchers can shift the fatty acid identity from mainly C18 chains to possess longer-chain fatty acids (VCLFAs) like erucic acid (C22:1) and eicosenoic acid (C20:1) [6, 7]. This sequence of introducing or altering genes then enzymes can translate to predictable oil composition changes. Particular requirements for optimal tribology include longer chains for film strength, branched structures for cold-flow properties, and hydroxyl groups for polarity. These specifications can be engineered into the crop's genetic makeup to significantly improve their viability.

The genomics to tribology framework operates on iterative, repetitive design compared to a single linear process. Tribologists identify performance requirements, such as a desired viscosity, oxidative stability, or wear protection level, and test oil candidates to determine which molecular features correlate to desired properties [5, 7]. The findings inform plant molecular biologists about which genes to modify or introduce; after engineering the crop and extracting the modified oil, tribological testing validates whether the genetic changes led to improvements or the intended level of performance [6, 7]. For instance, studies have shown that oils with higher VLCFA content, especially erucic acid, demonstrate improved friction reduction and wear protection at elevated temperatures compared to oils that are predominantly composed of shorter-chain fatty acids [7]. If results do not meet expectations, genetic modifications can simply be refined in the next crop generation. This establishes a feedback loop by continuously gathering empirical data to optimise, instead of a trial and error formulation. Additionally, this research requires close collaboration between relatively distant disciplines–tribology, plant genomics/biology, and metabolic engineering. Partnerships are crucial to advance this field [5, 6, 7].

Observably, this genetic design strategy offers several advantages over the traditional chemical modification approach. Once the iterative process determines a stable and effective genetically-enhanced line of plant species, producing the optimised oil only requires conventional gathering and extracting methods–no additional chemical additions are required, substantially increasing efficiency by cutting reoccurring costs and complexity [6]. The resulting products are inherently bio-based oils without synthetic additives, preserving its core feature of biodegradability while achieving better performance [5, 7]. Furthermore, three molecular targets have emerged as promising for genetically engineered lubricants. Succinctly, the three are very long chain fatty acids for coating strength, estolides for oxidative stability and crystallisation mitigation, and wax esters for extreme-pressure applications. Figure 3 details a diagram of this framework.

Very Long Chain Fatty Acids (VLCFAs)

VLCFAs, especially C22:1 and C20:1, form more durable and robust lubricating films than C16 and C18 fatty acids that are predominantly in most conventional vegetable oils [7]. VLCFAs, by extending carbon chain length, substantially

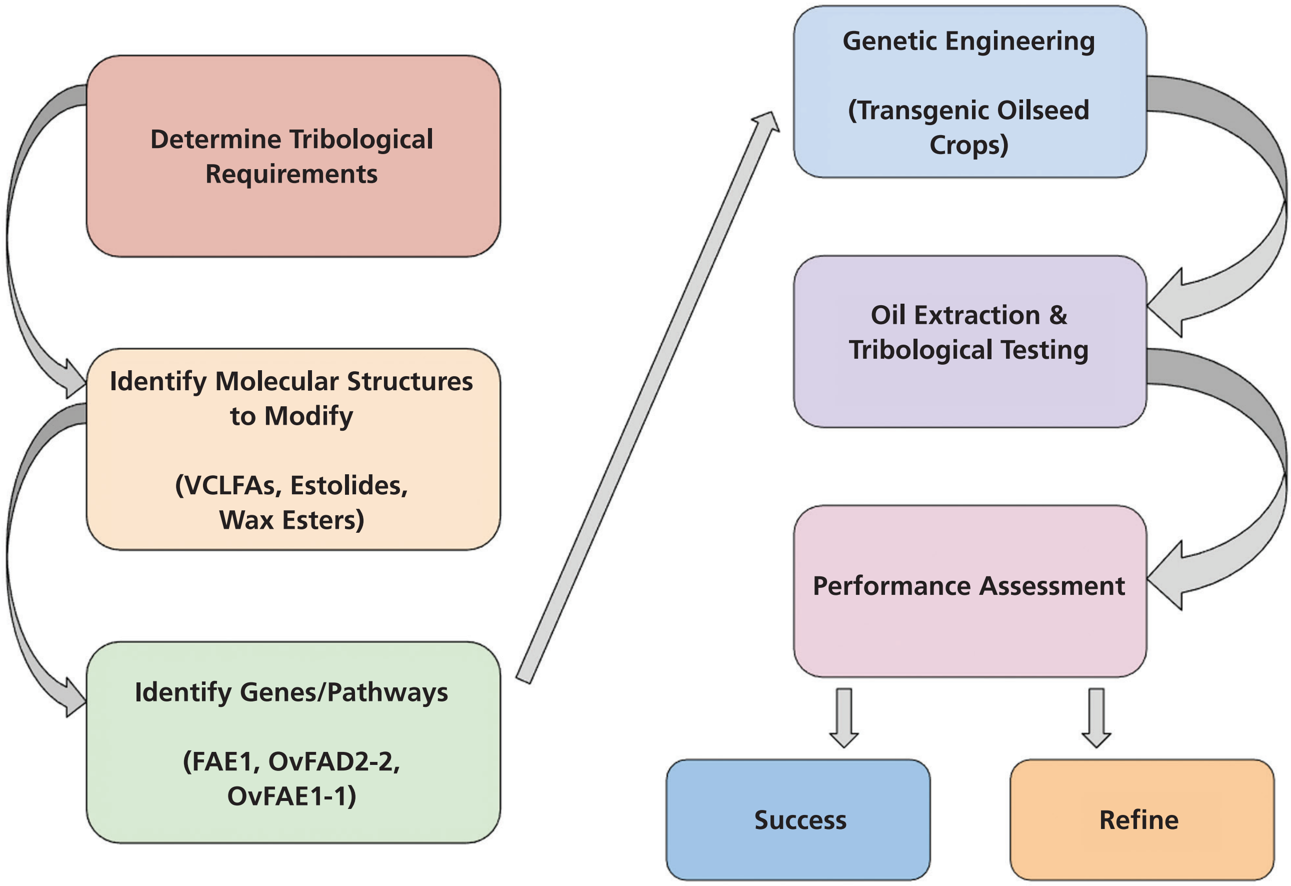


Figure 3: *A workflow chart of the genomics to tribology framework [5,6, 7].*

increases molecular weight and viscosity, leading to these fatty acids maintaining a stable boundary layer between metal surfaces under high contact pressures [7]. Again, this is a valuable trait for tribological applications. Also, previously mentioned, the FAE1 elongase gene catalyses the addition of two-carbon units to existing fatty acid chains [6]. In Brassicaceae oilseed crops like crambe and rapeseed, naturally high FAE1 activity causes seed oils to contain 40-60% erucic acid [6]. On the other hand, mutations in the FAE1 gene, shown by canola and pennycress varieties with low-erucic activity, reduce VLCFA content to less than 5% of total fatty acids [7]. Specifically, for example, rapeseed oil has a higher erucic acid of 49.5% compared to 1.6% of canola oil. Canola oil also has a higher polyunsaturated FA content of 27.8% versus 20.9% in rapeseed oil [7]. Tribological data shows oils with elevated erucic acid possess coefficient of friction values 20-30% lower than lower erucic alternatives at temperatures from 100°C to 200°C, or realistic industrial settings [7]. Also, high-VLCFA oils show superior oxidative stability and reduced wear rates on steel surfaces at elevated temperatures [7].
The challenge in engineering VLCFA-rich oils for industrial application rests on balancing chain length with cold-flow properties, because excessive VLCFA content can contribute to crystallisation at room temperature. Still, metabolic engineering methods that overexpress FAE1 genes in desired crops for oils are a pathway to optimising high temperature bio-lubricant applications.

Estolides

Estolides are naturally occurring branched lipid structures formed by esterifying secondary fatty acids are esterified to hydroxyl groups of a primary fatty acid [5]. This provides estolides with a unique set of characteristics: the derived hydroxyl ester linkages lead to an increased polarity and metal surface adhesion, while the branched structure disrupts 'molecular packing' to maintain fluidity at lower temperatures [5]. The estolides identified in Orychophragmus violaceus seed oil truly shows this molecular design, consisting of TAG molecules where a single glycerol bound fatty acid carries additional fatty acids esterified to hydroxyl groups at the C7 and C18 places [5, 6].

Tribological testing of Orychophragmus violaceus oil exemplified a significant tribological improvement: the coefficient of friction demonstrated a value about three times lower than castor oil at 100°C, alongside reduced wear rates and better resistance to metal surface oxidation [5]. The biosynthesis of estolides needs enzymatic activities such as the hydroxylation of fatty acids (typically catalysed with FAD2 enzymes like OvFAD2-2) and the esterification of additional fatty acids to these hydroxyl groups [6]. In the elongation pathway, OvFAE1-1 extends three hydroxy intermediates without finishing the steps of normal dehydration and reduction steps, leading to fatty acids with hydroxyl groups that can serve as sites for the formation of estolides [6]. Further, when the genes were expressed together with Arabidopsis seeds, the produced oils showed presence of dihydroxy acids, or molecules that act as sites for estolides. Evidently, engineering this pathway into crop plants is possible [6]. Also, the ester linkages are less susceptible to autoxidation compared to the isolated double bonds in polyunsaturated fatty acids, while the branching structure limits oxidative reactions [5]. All these characteristics make estolides a very promising candidate for the applications of biolubricants, specifically the aspects of biodegradability and durability under heat stress.

Wax esters

Wax esters, made of long chain fatty alcohols esterified to long chain fatty acids, represent the third primary molecular target. Unlike the TAG structure of most plant seed oils, wax esters lack a 'glycerol backbone,' leading to higher molecular weight that ranges between 600 and 900 Da, alongside higher viscosities [8]. Jojoba oil, which naturally consists of about 98% of wax esters, has been renowned to have great lubricant properties, particularly the highly sought properties of oxidative stability and low temperature fluidity [7]. The main wax ester species in jojoba oil contains C20 and C22 monounsaturated fatty acids and fatty alcohols, creating molecular structures like C40:2 and C4:2 [7].

Recent efforts in genetic engineering have aimed to transfer wax ester biosynthesis similar to that found in jojoba oil into viable oilseed crops [8]. This requires the coordination of genes responsible for encoding fatty acyl-CoA reductases, which convert fatty acyl-CoA to fatty alcohols, and wax synthases, which drives the esterification of fatty alcohols with fatty acyl-CoA substrates [8]. Wax ester-containing oils from genetically modified oilseed crops have shown promising tribological performance, even exceeding those of conventional mineral-based lubricants under the same extreme-pressure conditions [8].

Stemming from earlier, the basis for this performance lies in the combination of high molecular weight, which enhances film strength and viscosity, and the absence of polyunsaturated acids, which effectively eliminates the main site of oxidative degradation [7, 8]. Further, the linear structure of wax esters leads to more ordered molecular packing that contributes to the formation of robust boundary films on metal surfaces [8]. Although current wax ester production levels in transgenic oilseeds remain lower than the almost complete wax ester content of jojoba oil, improvements through metabolic engineering and optimal gene expression continue to forge the path towards the viability of wax ester-based biolubricants from crop plants [8]. Figure 4, below, is a performance comparison of the molecular targets.

Molecular Target	Key Property	Performance Improvement	Testing Conditions
VLCFAs (Erucic Acid)	Film strength, oxidative stability	20-30% lower coefficient of friction	100-200°C, steel surfaces
Estolides	Low-temperature flow, thermal stability	3x lower coefficient of friction compared to castor oil	100°C, 1.5 GPa pressure
Wax Esters	Extreme pressure application, thermal stability	55% reduction in wear	100°C, 15% blend

Figure 4: *A table synthesising the key properties, performance improvements, and test conditions of the molecular targets mentioned above [5, 6, 7, 8].*

Market dynamics

Although currently small compared to the entirety of lubricants, the global bio-lubricants market has entered rapid expansion and significantly outpaces growth in the sector. The bio-lubricant market was valued at $2.95 billion in 2024 and is projected to reach $5.04B by 2030, following a compound annual growth rate of 13.7% [2]. This growth rate surpasses the approximately 4% compound annual growth rate for conventional petroleum-based lubricants, suggesting alternatives are capturing interest [2]. This is due to technological improvements, such as the genetic optimisation strategies mentioned previously, and external pressures from environmental regulations being put forth by many organisations.

In terms of regional adoption, North America is the current market leader; the continent accounts for the largest share of global bio-lubricant consumption in 2024 [2]. This is mostly because of the United States' dominant 76.5% share of regional demand, driven by regulatory requirements for renewable practices, a resurgence of domestic automotive production, and strong biodiesel production infrastructure that provides feedstock availability [2]. Further, the European market, which is smaller, demonstrates high regulatory policies for lubricants as well. They are keen on promoting bio-based products and encouraging an atmosphere of environmentally favorable lubricants. Lastly, the Asian-Pacific region represents the fastest-growing region, with China and India serving as hubs for automotive production that increasingly incorporate bio-lubricants to meet export market requirements and environmental standards [2]. Observably, automotive purposes are driving current demand, representing 62.4% of the total bio-lubricant consumption [2]. Specifically, engine oils and transmission fluids take account for most of the demand, with bio-based lubricants offering higher biodegradation rates, lower aquatic toxicity, and reduced bio accumulation compared to mineral oil products [2].

The industrial sector, which involves hydraulic systems, metalworking substances, and processing oils, makes up 46.1% of bio-lubricant use. Hydraulic fluids, for instance, tend to leak into the environment due to system leakage, prompting a more environmentally friendly alternative in bio-lubricants [2, 10]. Additionally, it is estimated that about 61 million litres of lubricating oil are leaked into marine environments annually, underscoring the importance of biodegradable alternatives [10].

Based on revenue market share, analysis shows vegetable oil serves as the primary feedstock, accounting for 89.6% of bio-lubricant formulations in 2024 [2]. This dominant trend exemplifies the favorability of vegetable oils due to the traits they pass onto their product (biodegradability, low aquatic toxicity, and lubricity) but their recent usage in agricultural biotechnology, increasing oilseed yields and altering genetics. Further, synthetic esters, while making a smaller size of the market, currently offer superior oxidative stability and performance across wide temperature ranges. Although a more 'premium' option, they are more suitable for demanding applications like aviation hydraulics and marine stern tube lubrication while genetic optimisation is being developed [10]. Lastly, polyalkylene glycols represent a niche segment that is valued for applications requiring water tolerance or extreme temperature functionality [10]

Investments and commercial development

The viability of genomic optimisation research has led to significant commercial investment in bio-lubricant production, storage, and development. In April 2023, ExxonMobil, a U.S.-based oil and gas company, announced a $110 million investment to create a lubricants production facility in India, with a predicted annual capacity of 159 million litres. The project is nearing its completion as it aims to be operational by the end of 2025 [2]. Although the facility is not exclusively dedicated to bio-lubricants, it is positioned to serve growing domestic demand from steel, mining, power, construction, and automotive sectors increasingly wanting environmentally preferable lubricants [2]. This also reflects recognition in Asian markets for wanting sustainable industrial production as regulations are increasingly put in place.

In February 2024, Kraton Corporation introduced SylvaSolve, a new line of bio-based oils from renewable sources. Their purpose of design applies to industrial products (adhesives, coatings) and personal care products. Likewise, this line exemplifies the common motive of petroleum-based product companies seeking eco-friendly alternatives for their products [2]. Moreover, it shows how companies are using bio-based feedstocks across different products to diversify. By making platform technologies that can be used for a variety of applications, production can be scaled and lower costs. So, bio-based chemicals can be competitive like petroleum chemicals [2].

Ultimately, the landscape of bio-lubricants includes many major energy companies. Familiar companies such as Shell plc, Chevron Corporation, and ExxonMobil are described to be "key bio-lubricant companies" because of their large market shares within the field. Specialised manufacturers such as CASTROL Limited, FUCHS, and Kluber Lubrication are also included; these companies have been reportedly expanding their portfolios of bio-based products over the past few years which is a step toward the wider usage of bio-lubricants [2]. Moreover, many of the companies mentioned have an identity as a manufacturer for petroleum products, suggesting an increasing preference for buyers to go eco-friendly.

Regulatory frameworks driving adoption

Government regulatory policies have been strong influences on biolubricant adoption, creating performance standards and market access requirements that prefer eco-friendly products. For instance, in the European Union, the Ecolabel for Lubricants established criteria on lubricant qualities like ready biodegradability (the rapid and complete breakdown), aquatic toxicity, bioaccumulation potential, and renewability [9].

Manufacturers who want their products to be Ecolabel certified have to demonstrate that at least 25% of their composition consists of bio-based carbon content to be sold as "bio-based" or a "biolubricant" [9]. Although a decently modest threshold, a clear baseline has been established, pushing for renewability and preventing misleading environmental marketing with minimal bio-based content that declare to be "bio-based." Beyond renewable content, the EU Ecolabel mandates stricter biodegradability for applications with higher stakes or greater environmental risk. For example, hydraulic oils, classified as "Accidental Loss Lubricants," must contain over 90% of ready biodegradable content; two-stroke oils and stern tube oils, labeled as "Partial Loss Lubricants," require over 75%; and greases require over 80% [9]. Including environmental toxicity, the EU Ecolabel requires compliance with certification schemes for sustainable palm oil production to prevent deforestation and ecosystem degradation, which is associated with feedstock cultivation [9]. Additional requirements include a minimum 25% post-consumer recycled plastic content in lubricant packaging, alongside mandatory consumer instructions for correct disposal and container design to minimise spillage [9]. This elaborate and multifaceted criterion reflects the environmental approach that considers not only lubricant performance, but also feedstock production and waste management.

In the United States, the Environmental Protection Agency's (EPA) regulations for marine lubricants establish stringent laws for vessels present in U.S. waters. The Vessel General Permit program mandates the use of "Environmentally Acceptable Lubricants (EALs) for all applications where lubricants are likely to have contact with the water, including stern tube bearings, hydraulic systems, thrusters, and stabilisers [10]. In terms of EPA standards, lubricants must possess three properties: ready biodegradability, defined as greater than 60% biodegradation within 28 days using OECD 301 test methods; low aquatic toxicity, established through LC50 testing on algae, daphnia, and fishing using OECD 201-203 methods; and non-bioaccumulative characteristics, which is demonstrated through log Kow values less than 3 or bioconcentration factors lower than 100 L/kg [10].

The environmental significance of these marine lubricant regulations becomes more apparent when considering the magnitude of operational mishaps dealing with lubricants. The EPA estimates that commercial vessels make over 1.7 million port visits annually worldwide, during which stern tube leakage alone releases 4.6 to 28.6 million liters of lubricating oil [10]. Combined with additional discharges from deck machinery and equipment underwater, total annual inputs of lubricating oil to marine port waters reach 36.9 to 61 million liters [10]. The estimated annual damage and response costs associated with this statistic amounts to about $322 million globally, with $31 million attributable to U.S. waters alone [10]. By mandating these applications, these policies directly attempt to address oil and lubricant aquatic damages.

Conclusion

The genomics to tribology framework marks a fundamental shift in biolubricant development, aiming to replace post-farm chemical modification with molecular design at the genetic level. By determining the lipid architectures that lead to superior tribological behavior (very long chain fatty acids, estolides, and wax esters) and engineering oilseed crops for direct production, this approach can overcome performance limitations that have been restricting bio-based lubricants.

In examination of the three molecular targets that cause improved tribology, the engineered oils show clear advantages. Lines with high-erucic lines demonstrate 20-30% less while improving oxidative stability and wear protection [7]. Revamped estolide pathways produce oils with three times less friction and better metal-to-surface oxidation resistance compared to castor oil [5, 6]. Lastly, wax ester-rich oils from modified crambe, for example, cut wear volume by 55% and maintain high thermal stability even at modest blends like 15% [8]. This remarkable scientific progress aligns with strong market and regulatory drivers. The bio-lubricants market is growing at 13.7% annually, outcompeting the 3.9% growth rate of petroleum lubricants, with North America paving the way with regulatory mandates and large market shares [2]. Following this are the other major regions, like Europe's Ecolabel mandates, for renewable and environmentally acceptable lubricants [9, 10].

Ultimately, the genomics to tribology approach provides more than improved bio-lubricants. It establishes a theoretical framework for designing renewable substitutes to greenify industry operations which will immensely benefit the environment. As biological and tribological research progresses, most bio-based products might have more incentive for usage compared to the conventional but reliable petroleum-based materials.

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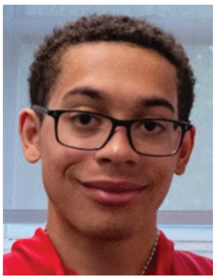

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