

Nanoparticle-Enhanced Biolubricants: Advancing Sustainable Lubrication Through Improved Tribological and Thermal Performance

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Abstract: This review examines recent advancements in biolubricant technology, emphasising their potential as sustainable alternatives to conventional mineral-based lubricants. Derived from renewable sources such as vegetable oils, animal fats, and microalgae, biolubricants are increasingly valued for their biodegradability, renewability, and reduced ecological impact. However, limitations such as low thermal stability, oxidative susceptibility, and variable feedstock quality challenge widespread commercial adoption. Recent innovations have focused on enhancing biolubricant performance by incorporating nanoparticles (NP), including copper, titanium dioxide (TiO₂), and silicon dioxide (SiO₂). These additives significantly improve tribological properties, reducing friction by up to 30% and enhancing wear resistance by forming protective films on contact surfaces. This review details the physical properties of bio-lubricants, such as viscosity, flash point, and oxidative stability. For instance, vegetable oils exhibit a range of viscosities at 40°C, with olive oil esters achieving up to 93.08 cSt. In comparison, flash points can reach 283°C in macadamia oil biolubricants modified with NPs, enhancing their suitability for high-temperature applications. Additionally, molecular modifications such as esterification and hydrogenation further optimize properties, enhancing thermal stability and oxidative resistance. This review provides a comprehensive evaluation of these physical enhancements and addresses the environmental and economic implications of nanoparticle-enhanced biolubricants. Insights into future research directions underscore biolubricants' potential to meet the dual objectives of environmental sustainability and industrial performance across diverse applications.

Keywords: Thermal Stability; Environmental Sustainability; Titanium Dioxide; Silicon Dioxide; Biolubricant Technology; Lubricant Life; Environmental Footprint; Greenhouse Gases; Carbon Dioxide.

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1. Introduction

Biolubricants have garnered substantial attention as sustainable alternatives to conventional mineral-based lubricants, characterised by their biodegradability, renewability, and diminished environmental footprint. [1]. Derived from renewable sources like vegetable oils, animal fats, and microalgae, biolubricants offer promising applications in various industries, including automotive, aerospace, and heavy machinery [2]. Environmental regulations and the global shift toward greener industrial lubrication practices drive demand for biolubricants [3]. However, despite their advantages, biolubricants face challenges such as low thermal stability, high oxidative susceptibility, and variability in feedstock quality, which impact their commercial viability [4]. Recent advancements in biolubricant formulation have focused on improving performance by incorporating nanoparticles (NPs) [5]. These metal-based NPs, such as copper and zinc oxide, are added to improve biolubricants' tribological properties, including wear resistance, load-carrying capacity, and thermal stability [6]. Studies show that nanoparticles' unique characteristics, including their high surface area-to-volume ratio and hardness, help reduce friction and wear by forming protective films on contact surfaces and acting as nano-ball bearings [7].

For instance, copper nanoparticles have significantly enhanced the anti-wear properties of vegetable oil-based lubricants, providing a stable, durable layer on metal surfaces under high-load conditions [8]. Additionally, research indicates that nanoparticle size, shape, and concentration play pivotal roles in determining the overall performance of biolubricants [9]. Nanoparticles can effectively fill micro-wear tracks, minimise asperity contact, and maintain fluid film thickness at the tribo-interface, thereby enhancing lubrication efficiency [10]. However, challenges arise in nanoparticle dispersion, stability, and potential environmental risks, necessitating careful consideration and further investigation [11]. This comprehensive review examines recent advancements in biolubricants, with a particular focus on nanoparticle-enhanced formulations. The review examines how nanoparticles enhance lubrication properties, addresses challenges related to nanoparticle stability in biolubricants, and explores potential environmental implications. The analysis provides valuable insights into the prospects of biolubricant applications, aiming to contribute to both environmental sustainability and industrial efficacy.

1.1. Lubrication and Properties

Lubrication is a fundamental process for minimizing friction and wear between contacting surfaces in mechanical systems, ensuring optimal operation, extended equipment lifespan, and enhanced performance. Traditionally, lubricants have been predominantly derived from petroleum-based sources, which provide reliable performance across a wide range of industrial applications. However, growing emphasis on environmental sustainability and the pursuit of renewable alternatives have increased focus on bio-based lubricants, commonly referred to as "biolubricants." These biolubricants not only offer desirable lubrication characteristics but also provide advantages in biodegradability and reduced toxicity [12]. Cerón et al. [2] describe lubrication as essential to minimising surface contact in machinery and note that choosing the correct lubricant and additive combination is crucial for ensuring specific performance parameters, such as load-bearing capacity and wear resistance [13]. Viscosity, defined as a fluid's resistance to flow, is one of the most crucial properties of lubricants. It determines the thickness of the lubricating film between surfaces and directly influences the lubricant's ability to prevent metal-to-metal contact. High-viscosity lubricants provide a thicker film that can support heavier loads but may increase energy consumption due to higher fluid resistance. In contrast, low-viscosity lubricants reduce drag and improve energy efficiency, making them suitable for high-speed applications [14]. Studies by Singh and Singh [5] indicate that viscosity plays a pivotal role in a lubricant's performance across varying temperatures, with biolubricants often showing more temperature-sensitive viscosity changes than synthetic counterparts. The structure of biolubricants, especially their fatty acid composition, can enhance their viscosity stability, making them effective in temperature-sensitive environments [15].

Thermal stability is a critical parameter for lubricants, particularly in high-temperature applications. Lubricants with poor thermal stability may degrade under heat, forming sludge and varnish that can impair machinery performance and increase maintenance costs. The thermal stability of biolubricants varies with molecular structure; for instance, the degree of unsaturation in vegetable oil-derived lubricants can reduce oxidative and thermal stability [16]. Studies by Ho et al. [7] highlight that vegetable oil-based biolubricants require modifications such as hydrogenation and epoxidation to improve thermal stability. These processes help biolubricants balance resistance to thermal breakdown with environmental sustainability, making them suitable for high-temperature applications while reducing carbon footprint [17]. Oxidative stability refers to a lubricant's resistance to oxidation, which is essential for long-term lubricant performance. Oxidation can increase acidity, cause sludge formation, and degrade the lubricant overall. Poor oxidative stability can accelerate lubricant aging and reduce its effectiveness in preventing wear and corrosion [18]. Durango-Giraldo et al. [34] emphasize that oxidative stability is particularly challenging in biolubricants because of their unsaturated molecular structure. To improve this property, researchers have tested antioxidants and chemical modifications that limit oxidative degradation of vegetable oils, making biolubricants more comparable to synthetic lubricants in longevity and performance [19]. Lubricants play a crucial role in reducing wear by forming a protective film on surfaces and preventing direct metal-to-metal contact. Anti-wear additives, such as zinc dialkyldithiophosphate (ZDDP), are commonly added to traditional lubricants to improve protection under high-pressure conditions. Recent studies on

biolubricants indicate that incorporating nanoparticles, such as copper and zinc oxide, can significantly enhance anti-wear and extreme-pressure performance [20].

Madhwesh et al. [8] report that nanoparticles act as miniature ball bearings within the lubricant, filling in micro-wear sites and preventing abrasion, thus improving the load-carrying capacity of biolubricants. This innovative approach is gaining traction in industries seeking sustainable lubricants without compromising performance [21]. One of the primary functions of lubricants is to reduce friction between moving parts. Effective friction reduction minimizes energy loss, heat generation, and wear, which extends the lifespan of mechanical components. The tribological behaviour of lubricants, how they interact with surfaces under relative motion, is influenced by factors such as viscosity, film thickness, and additive composition. For biolubricants, the molecular structure and fatty acid profile can affect their tribological performance. Studies by Syahir et al. [9] show that biolubricants derived from oleic acid-rich vegetable oils, such as sunflower and rapeseed oils, exhibit superior friction-reduction properties compared to mineral oils. These biolubricants' molecular structure supports smoother sliding, making them suitable for applications where minimising friction is essential [22]. In addition to their lubrication properties, biolubricants are valued for their low environmental impact and biodegradability. Traditional petroleum-based lubricants can pose serious environmental risks because they persist in ecosystems and contribute to pollution. By contrast, biolubricants break down more readily in the environment, reducing the risk of contamination in soil and water sources. Malik et al. [1] note that biolubricants derived from renewable resources contribute significantly to sustainability goals by reducing dependency on fossil fuels and decreasing greenhouse gas emissions. This makes biolubricants particularly valuable in sectors with strict environmental regulations, such as marine and forestry industries [23].

1.2. Conventional Lubricants: Advantages and Limitations

Conventional lubricants, derived predominantly from petroleum-based sources, have formed the foundation of lubrication technology for decades. Their widespread use stems from their excellent performance, cost-effectiveness, and the availability of well-established processing and application infrastructure. These lubricants include mineral oils, synthetic oils, and semi-synthetic blends, each tailored for specific industrial needs. Despite their performance benefits, the environmental impact of conventional lubricants has driven the search for greener alternatives [24]. Conventional lubricants are formulated to withstand the harsh operating conditions of modern machinery. Mineral oils, derived from crude oil, are among the most common and have a diverse hydrocarbon composition that enables high lubricity and stable viscosity [25]. However, their poor biodegradability and environmental persistence pose substantial risks if improperly disposed of, as they contribute to ecological contamination [26]. Synthetic oils, by contrast, are manufactured through chemical synthesis, allowing precise control over molecular structure. This structure provides superior thermal and oxidative stability, making synthetic oils suitable for high-stress applications like aerospace and automotive engines. Because synthetic oils resist breakdown at extreme temperatures, they tend to last longer and are often more efficient than mineral oils. However, they are also more costly, which restricts their use to applications where performance requirements justify the additional expense [27].

To maximise performance, conventional lubricants incorporate additives that enhance properties such as viscosity, thermal stability, and anti-wear capabilities. Additives like viscosity index (VI) improvers help maintain viscosity across temperature changes, which is essential for lubricants used in engines and industrial machinery where temperature fluctuations are common [28]. For example, Negi et al. [17] highlight the role of VI improvers in enabling mineral oils to perform reliably in both high- and low-temperature conditions, thereby extending equipment life and efficiency [29]. Antioxidants are commonly added to delay oxidation, reducing sludge formation and extending lubricant life. Anti-wear agents, such as zinc dialkyldithiophosphate (ZDDP), are essential for preventing metal-to-metal contact under high load and protecting equipment from wear [30]. These additives enhance the lubricant's ability to withstand the demands of industrial environments where high pressures and high temperatures are prevalent. Recent advancements have also explored nano-additives, such as molybdenum disulfide, which form protective layers on metal surfaces, thereby enhancing wear resistance and reducing friction [31]. Despite their benefits, conventional lubricants have significant environmental and health drawbacks. Petroleum-based lubricants degrade slowly, leading to persistent environmental contamination if they leak into soil or water sources. The improper disposal of used mineral oils has been linked to water pollution and soil toxicity, with harmful effects on aquatic life and ecosystems.

Furthermore, producing these lubricants is energy-intensive, contributing to greenhouse gas emissions and reducing their overall sustainability profile [32]. Research by Tung and McMillan [18] underscores the toxicological risks posed by heavy metal additives and phosphorus compounds in conventional lubricants, which can accumulate in the environment and threaten both human health and ecosystems [33]. These issues have led to stricter regulations in several industries and increased interest in biolubricants as more environmentally friendly alternatives [34]. As sustainability becomes a central focus in lubricant technology, the future of conventional lubricants is evolving. While they remain essential for specific high-performance applications, the shift toward greener options is accelerating. Companies are investing in research to improve the environmental footprint of conventional lubricants by blending them with bio-based components or developing synthetic lubricants with reduced toxicity [35]. Nanotechnology is also being explored to enhance the properties of conventional lubricants, such as

thermal stability, wear resistance, and service life, while minimising environmental impact. Researchers are optimistic that nanotechnology can reduce lubricant volume and extend oil-change intervals, reducing waste and pollution [36]. Despite these advances, the long-term goal remains to shift the industry toward fully sustainable alternatives, with conventional lubricants supplemented or replaced by biolubricants that provide similar performance benefits without the environmental drawbacks.

1.3. Biolubricants: Advantages and Limitations

Biolubricants, derived from renewable biological resources, have gained traction in various industries as sustainable alternatives to conventional petroleum-based lubricants. Their applications are extensive and diverse. In the automotive and industrial sectors, biolubricants provide effective lubrication for engines and machinery, reducing environmental impact while maintaining performance. In metalworking, biolubricants are used as cutting fluids, significantly reducing friction and wear during machining processes and improving tool life and overall efficiency. Additionally, biolubricants are found in greases and chain lubricants, particularly in bicycles and other machinery, ensuring smooth operation and prolonged equipment life. The agricultural sector also benefits from biolubricants, as their use in farming equipment helps minimise soil contamination, aligning with the growing emphasis on sustainable agricultural practices [31]. Moreover, certain biolubricants meet food safety standards, allowing their use in food processing and handling environments where health and safety are paramount. The advantages of biolubricants extend beyond their applications. One of the most significant benefits is their environmental impact. Because they are biodegradable and derived from renewable resources, biolubricants help reduce pollution and ecological footprints, making them an attractive choice for environmentally conscious industries. Additionally, biolubricants often offer superior lubricating properties, such as improved viscosity stability and thermal resistance, and can outperform conventional lubricants in various applications. They also have lower toxicity levels, reducing health risks for users and workers in industrial settings and promoting safer working conditions.

Furthermore, growing regulatory emphasis on sustainability drives demand for biolubricants, helping companies not only comply with environmental regulations but also bolster their corporate image as responsible stewards of the environment. The growing market for biolubricants encourages innovation and competition, leading to more economically viable options as production processes evolve and scale. However, despite these advantages, biolubricants face several limitations that can hinder their widespread adoption. Cost remains a major barrier; producing biolubricants can be more expensive than traditional lubricants because of raw material and processing costs. Additionally, some biolubricants may not perform as effectively under extreme conditions, such as high temperatures or heavy loads, which can limit their applicability in certain industrial settings. Stability is another concern, as biolubricants can be more susceptible to oxidation and degradation over time, potentially impacting their shelf life and usability compared to petroleum-based alternatives. Market acceptance is crucial for biolubricant growth; educating manufacturers and consumers about their benefits and performance is essential to overcome skepticism and foster wider adoption. Lastly, regulatory approval processes for new biolubricant formulations can be complex and time-consuming, posing challenges for new market entrants. Biolubricants offer a promising alternative to conventional lubricants, combining environmental benefits with effective performance across a range of applications. Addressing their limitations, particularly those related to cost, performance under extreme conditions, and market acceptance, is critical for enhancing their adoption in various industries [32]. As bio-lubricant development continues, their role in promoting sustainability and reducing environmental impact is likely to grow, making them a vital component of the future lubricant market.

2. Bio-Lubrication: Source, Synthesis and Nanoparticle Additives

2.1. Source of Bio-Lubricants

2.1.1. Fossil Fuels and Fossil-Derived Lubricants

In contemporary industrial practices, fossil-derived resources, including petroleum, coal, and natural gas, play a pivotal role in powering economic growth and development. These resources serve as primary raw materials for various industrial products, including lubricants, due to their long-established efficiency and infrastructure compatibility. However, the finite nature of these non-renewable resources, coupled with escalating greenhouse gas (GHG) and carbon dioxide (CO₂) emissions, has raised critical sustainability concerns. Rahmani et al. [3] emphasise the environmental footprint of fossil fuels, highlighting the impact of CO₂ emissions on climate change and the urgent need to adopt sustainable alternatives [37]. As fossil-derived lubricants contribute to the depletion of these finite resources, Nguyen et al. [4] argue that transitioning to renewable lubricants is essential to mitigate adverse environmental impacts and promote long-term ecological balance [38].

2.1.2. Biodiesel

Biodiesel has emerged as a viable, eco-friendly substitute for conventional fossil fuels, offering benefits like biodegradability, low sulfur content, and high heat content. Synthesised from vegetable oils such as soybean, palm, sunflower, and rapeseed,

biodiesel shows promising properties that make it suitable as a lubricant base oil. Singh and Singh [5] identify these oils as favorable sources because of their renewability and lower emissions than fossil-based counterparts, emphasizing that using plant-based oils aligns with global sustainability goals [32]. Moreover, studies by Santos et al. [12] and Ceron et al. [2] support the shift toward biolubricants, presenting biodiesel as an avenue to reduce reliance on non-renewable resources and address concerns about environmental degradation caused by conventional lubricants [27].

2.1.3. Chicken Source for Biodiesel and Biolubricant

With growing interest in waste valorisation, poultry waste, specifically chicken fat, has gained attention as a promising raw material for biodiesel and biolubricant production. Chicken fat, a non-food, renewable byproduct, offers an environmentally friendly alternative that helps reduce waste on poultry farms. Converting chicken fat to biodiesel through processes like transesterification enables the production of biolubricants with properties comparable to traditional options [4]. Nguyen et al. [4] highlight chicken fat's potential in biolubricant applications, underscoring its role in reducing environmental waste while providing a sustainable feedstock for the lubricant industry.

2.1.4. Vegetable Oil-Derived Biolubricants

The demand for eco-friendly lubricants has driven innovation in biolubricants derived from vegetable oils. Triglyceride esters in vegetable oils such as soybean, sunflower, and rapeseed oils offer distinct advantages in renewability, biodegradability, and reduced greenhouse gas emissions [3]. Hamnas and Unnikrishnan [13] discuss how vegetable oils serve as a sustainable alternative to mineral-based lubricants, significantly reducing the environmental footprint associated with traditional options. Furthermore, Gemsprim et al. [14] explore how vegetable oil-derived biolubricants reduce wear and enhance lubrication performance, positioning them as suitable candidates for industrial applications that require high-performance, environmentally friendly lubricants.

2.1.5. Tilapia Oil as a Renewable Source

The utilisation of fish waste, particularly Tilapia oil, has emerged as an innovative approach to biolubricant production. By modifying Tilapia oil through processes like transesterification, epoxidation, and ring-opening reactions, researchers have developed biolubricants that leverage renewable resources and reduce waste. Do Valle et al. [15] show that Tilapia oil offers a viable alternative in the biolubricant market, supporting both waste management and sustainable lubricant production. The novel use of fish waste for biolubricant synthesis provides a circular approach to waste management, reducing the reliance on non-renewable sources.

2.1.6. Microalgae as a Source

Microalgae have attracted attention as a potential source of biofuel and biolubricants because of their rapid biomass productivity, short growth cycles, high oil content, and adaptability to diverse environmental conditions [5]. Malik et al. [1] discuss the advantages of microalgae for biofuel production, particularly their ability to convert CO₂ into biomass efficiently. This characteristic aligns well with the growing need for sustainable fuel and lubricant sources that can mitigate carbon emissions and address climate change challenges. Moreover, research by Sanjurjo et al. and Zhu et al. [16] reinforces the potential of microalgae as a lubricant base, highlighting their renewable nature and ability to thrive in non-arable environments, reducing competition with food production.

2.2. Bio-Lubricants Molecular Structure

The molecular structure of biolubricants is fundamentally derived from vegetable oils, primarily composed of triacylglycerols. These triacylglycerols consist of three fatty acid molecules linked to a glycerol molecule through ester bonds, which play a crucial role in defining biolubricants' properties and performance. Fatty acid carbon chain lengths typically range from C12 to C24 and significantly influence the lubricating characteristics of these biolubricants. Fatty acid composition is a critical determinant of various properties in biolubricants. Specifically, higher fatty-acid unsaturation yields biolubricants with lower viscosity, melting point, and thermo-oxidative stability. To address unsaturation, several strategies are used, including hydrogenation and epoxidation followed by oxirane ring-opening. Hydrogenation is effective but complicates production, whereas epoxidation offers a viable alternative that mitigates unsaturation-related issues. Vegetable oils rich in monounsaturated fatty acids, such as oleic acid and ricinoleic acid, are considered optimal feedstocks for biolubricant production. The moderate unsaturation in these fatty acids provides a balance that enhances oxidation resistance while minimising molecular stacking and crystallisation issues.

Moreover, the saturation levels of fatty acids in vegetable oils influence essential properties such as cloud and pour points. Achieving the right degree of saturation is critical to enhancing oxidative stability while maintaining favorable low-temperature performance. Molecular branching at oxirane ring-opening sites during processes like epoxidation can further affect the biolubricant's overall molecular structure. While this process increases melting point, viscosity, and thermal oxidative stability, excessive molecular branching may introduce steric hindrance that could negatively affect tribological properties. Additionally, biodiesel, which derives its carbon from atmospheric sources, poses fewer environmental threats than fossil fuels, leading to a 78% reduction in overall carbon dioxide emissions. Acid catalysts, including sulfate metals, zeolites, and mixed metal oxides, have been used successfully to synthesise biolubricants, while enzymes offer a more expensive but effective alternative. The positive environmental impact of biodiesel also includes reduced harmful emissions, particularly carbon monoxide and carbon dioxide, thereby promoting a cleaner ecological footprint (Table 1).

Table 1: Comparison of viscosity of processed esters at 40°C and 100°C

Processed Ester	Viscosity 40°C	Viscosity 100°C
Castor Oil TMP	20.94	4.47
Jatropha Oil TMP	43.9	8.71
Palm Oil TMP	47.9	9
Olive Oil PE	93.08	12
Rapeseed Oil Alcohols	7.8-38.2	2.7-8.4
Soybean Oil Alcohols	10.3-432.7	3-34.4
Sunflower Oil Octanol	7.93	2.74

The viscosity of each processed ester correlates with the feedstock's fatty acid composition and molecular structure. For instance, olive oil polyol esters exhibit the highest viscosity at 40°C (93.08 cSt), attributable to their higher content of long-chain saturated fatty acids, which enhances film thickness and lubricating performance. In contrast, sunflower oil and rapeseed oil alcohols demonstrate lower viscosity values, suggesting their suitability for applications requiring reduced friction.

2.3. Synthesis of Bio-Lubricant

Bio-lubricant synthesis uses various methods to modify raw materials and enhance lubricating properties and performance. Key chemical processes such as transesterification and esterification are commonly employed alongside physical extraction techniques like cold pressing and solvent extraction. Each method offers distinct advantages and significantly impacts the final properties of the biolubricants.

2.3.1. Transesterification and Esterification

Transesterification is a widely used chemical reaction in biolubricant production, in which triglycerides from vegetable oils react with an alcohol (commonly methanol or ethanol) to form fatty acid esters. This process breaks the ester bonds in triglycerides and forms new ester bonds, resulting in lower viscosity and improved low-temperature fluidity. The choice of catalyst, acid or base, can influence reaction efficiency and yield. Base catalysts are typically preferred because they react faster; however, acid catalysts are necessary for oils with high levels of free fatty acids. Esterification involves the direct reaction of fatty acids with alcohols to form esters. This method can produce biolubricants with specific properties by controlling the degree of saturation and molecular weight of the resulting esters. Both transesterification and esterification produce biolubricants with enhanced oxidative stability and lubricating performance compared with their original vegetable oil counterparts (Table 2).

Table 2: Methods of extraction and their descriptions

Method of Extraction	Description
Transesterification/Esterification	Triglycerides (fats and oils) react with an alcohol to produce biolubricant and glycerol.
Cold Pressing/ Solvent Extraction	Mechanically pressing oilseeds to extract oil without heat. Solvents like hexane can be used to extract oil from seeds
Hydrogenation	Reaction of vegetable oils with hydrogen gas in the presence of a catalyst. This process can improve the stability and viscosity of the oil
Epoxidation	The addition of an oxygen atom to an unsaturated compound (oil), forming an epoxy group
Esterolide	Esterifying fatty acids, usually from natural oils, to create complex esters with multiple linkages.

2.3.2. Cold Pressing and Solvent Extraction

Cold pressing is a physical extraction method that obtains oil from seeds and nuts without applying heat. This technique preserves the oil's natural properties, resulting in a product that retains its original flavor and nutritional qualities. Cold pressing is particularly advantageous for producing high-quality biolubricants because the lack of heat minimizes degradation of sensitive compounds. Oils extracted through this method typically have lower viscosities and higher levels of unsaturation, enhancing their lubricating capabilities. Conversely, solvent extraction uses organic solvents to dissolve the oil, then separates it from the solid residue. This method is often more efficient than cold pressing, yielding more oil from the same quantity of raw material. However, the choice of solvent and subsequent purification steps are critical to ensure the final product is free of residual solvents that could affect performance. Oils extracted through this method may require further processing, such as refining or transesterification, to enhance their properties for lubrication applications.

2.3.3. Epoxidation and Estolide Formation

Epoxidation introduces an epoxide group into the fatty acid chains of vegetable oils. This process involves treating unsaturated fatty acids or vegetable oils with an oxidising agent, such as peracetic acid or performic acid. The formation of epoxide groups significantly alters the molecular structure of the biolubricants, improving their thermal stability and oxidative resistance. Epoxidized oils can also undergo subsequent ring-opening reactions, increasing viscosity and improving the oil's ability to form protective films under high-shear conditions. Estolides are linear or branched fatty acid polymers formed through the condensation of fatty acids or their esters. This process can create biolubricants with enhanced viscosity and oxidative stability. Estolide formation typically requires specific reaction conditions, including elevated temperatures and water. The resultant products exhibit unique performance characteristics that can be tailored to meet the requirements of various lubrication applications.

2.3.4. Lipase-Mediated Reactions

Lipase-mediated processes represent an enzymatic approach to synthesising biolubricants. Lipases catalyse triglyceride hydrolysis and transesterification, producing fatty acid esters under mild conditions. This enzymatic method offers several advantages, including high specificity, reduced energy consumption, and the ability to operate under solvent-free conditions. The mild reaction conditions of enzymatic processes help preserve sensitive functional groups within fatty acid chains, resulting in biolubricants that retain their natural characteristics while exhibiting enhanced performance. Overall, the choice of synthesis method significantly impacts the molecular structure, viscosity, and overall performance of biolubricants. By exploring these techniques, researchers can continue to innovate and improve biolubricant performance sustainably.

2.4. Impact of Copper Nanocatalyst and Additives on Tribological Properties

The use of nanoparticles (NPs) as lubricant additives to enhance friction and wear properties has emerged as a promising avenue in tribology, the study of friction, wear, and lubrication. NPs have unique characteristics that make them highly effective in lubrication applications, particularly because of their size, shape, and chemical composition. As the particle size decreases, several beneficial changes occur in the mechanical properties of these nanoparticles. For instance, smaller particles tend to exhibit increased hardness and elastic modulus, enhancing their effectiveness as lubricants by better accommodating operational stresses (Table 3).

Table 3: Comparative physicochemical properties of vegetable oils and modified oil blends

Name of the Oil	Viscosity @ 40(cSt)	Viscosity @ 100	Flash Point	Pour Point	Fire point
Macadamia oil	243.14	18.12	272	-	259
Macadamia oil+0.1%	245.12	18.23	272.1	-	262
Macadamia oil +0.2%	246.29	18.34	272.5	-	269
Macadamia oil +0.3%	246.48	19.45	272.6	-	273
Macadamia oil +0.4%	247.62	19.775	271.8	-	279
Macadamia oil +0.5%	247.89	20.15	272.9	-	283
Balanites Aegyptiaca	18.84	4.21	247	-	-
Balanites Aegyptiaca + 0.3%	17.42	4.47	219.38	-	-
Balanites Aegyptiaca + 0.6%	17.68	4.58	219.57	-	-
Balanites Aegyptiaca + 1.3%	17.75	4.67	219.66	-	-
Balanites Aegyptiaca + 1.6%	17.89	4.76	219.89	-	-

Paraffinic mineral oil	107.54	17.7	-	-	-
Paraffinic mineral oil + 0.3%	107.1	11.87	-	-	-
Paraffinic mineral oil +3.0%	107.98	11.87		-	-
Rapeseed Oil	-	8	320	-11	-
Chemically modified Rapeseed Oil	-	16.5	265	-15	-
Chemically modified Rapeseed Oil + Nano 1.0%	-	15.4	242	-15	-
Soya bean + 0.5 %	144.72	144.72			
Sun Flower + 0.5 %	149.04	151.2			

Among various nanoparticle types, copper nanoparticles have garnered significant attention for their remarkable tribological properties. Their nanoscale dimensions enable them to form protective films on the surfaces of tribo-pairs, two surfaces that interact during motion, thereby minimising wear and significantly reducing friction during operation. This film formation is crucial for improving the longevity and efficiency of mechanical systems. NP-associated lubrication mechanisms are multifaceted and include the formation of adsorbed films on contacting surfaces, the rolling effect between sliding surfaces, and the filling of wear tracks through processes like sintering. These mechanisms work synergistically to enhance the overall lubrication performance and to mitigate the negative effects of friction. Extensive research has examined integrating copper nanoparticles into lubricant matrices such as mineral oils, paraffinic oils, polyalphaolefins, and biolubricants. Studies have shown that interactions between copper nanoparticles and the base lubricant can significantly improve friction reduction and anti-wear (AW) performance. Notably, several factors influence the efficacy of copper nanoparticles as lubricant additives, including their size, shape, and aspect ratio. These attributes affect their ability to penetrate the tribo-pair interface, promoting chemical interactions that further enhance their friction-reducing capabilities (Table 4).

Table 4: Tribological performance and properties of different biolubricant oils

Biolubricant Type	Wear Reduction (%)	Friction Coefficient	Other Properties
Rapeseed Oil	30%	0.08	Enhanced thermal stability
Sunflower Oil	25%	0.07	Improved viscosity index
Castor Oil	28%	0.09	Better oxidative stability
Jatropha Oil	32%	0.06	Enhanced film strength

Recent investigations, including a notable study by Xu et al. [37], have highlighted the effectiveness of copper nanoparticles in minimising surface wear when incorporated into various lubricant formulations. The findings showed a substantial reduction in wear rates compared to conventional lubricant additives, underscoring the unique rolling effects and chemical resilience of copper nanoparticles. These properties not only reduce friction but also help form a more stable lubricating film under operational stresses, improving overall lubrication system performance. Furthermore, the controlled size and composition of copper nanoparticles are critical determinants of their performance as lubrication additives. By tailoring these properties, researchers can optimise the nanoparticles for specific applications, enhancing the overall performance of biolubricants and other lubricant formulations. This optimisation is essential to advancing environmentally friendly lubricants that provide superior tribological performance while minimizing environmental impact.

2.5. Impact of TiO₂ and SiO₂ Nanoparticles in Biolubricants

In recent years, nanoparticles such as titanium dioxide (TiO₂) and silicon dioxide (SiO₂) in biolubricants have gained considerable attention for their potential to enhance tribological properties. TiO₂ and SiO₂ nanoparticles, known for their high thermal stability and wear resistance, can significantly improve biolubricant performance when used as additives (Table 5).

Table 5: Comparison between Tio2 and Sio2 nanoparticle incorporation in biolubricants

Parameter	TiO ₂ Nanoparticles	SiO ₂ Nanoparticles
Particle Size Range (nm)	10 - 100	10 - 50
Thermal Stability	High thermal stability, resists degradation at elevated temperatures	Moderate thermal stability, enhances base oil performance
Oxidative Stability	Improves oxidative resistance by 15-20% in biolubricant	Enhances oxidative stability, particularly in vegetable oils
Friction Reduction	Reduces coefficient of friction by up to 30%	Reduces friction by 25%, adds a "rolling" lubrication effect
Wear Resistance	Forms a durable tribofilm, decreasing wear rate by 20-25%	Provides an anti-wear layer, reducing wear by 15-20%

Surface Hardness Impact	Increases hardness of surfaces by up to 10%	Minor impact on surface hardness
Protective Tribofilm Formation	Creates a ceramic-like tribofilm on metal surfaces	Forms a silica-based protective film
Application Temperature Range	Effective from -10°C to 300°C	Effective from -10°C to 200°C
Environmental Impact	Low toxicity, relatively eco-friendly	Low toxicity, biodegradable
Cost Considerations	Moderate	Low to moderate
Primary Applications	Engine oils, hydraulic fluids, high-temperature applications	Hydraulic fluids, metalworking oils, general lubrication

Their unique properties, such as high hardness, chemical inertness, and the ability to form protective tribofilms on surfaces, make them valuable for minimizing friction, reducing wear, and enhancing the overall stability of biolubricants under severe operating conditions.

2.5.1. Enhanced Friction and Wear Reduction

Adding TiO₂ and SiO₂ nanoparticles to biolubricants has been shown to improve friction and anti-wear performance. TiO₂ nanoparticles, with their high surface area-to-volume ratio, form a smooth protective layer on metal surfaces, effectively reducing direct metal-to-metal contact during operation. This thin, adherent layer minimizes wear and promotes smoother movement between interacting surfaces.

Similarly, SiO₂ nanoparticles reduce friction through their rolling effect, acting as nanoscale “ball bearings” that facilitate movement and reduce resistance between surfaces. Studies have shown that incorporating TiO₂ and SiO₂ nanoparticles into biolubricants can reduce the coefficient of friction by up to 30% and decrease wear rates by 25% compared with base biolubricants without nanoparticle additives.

2.5.2. Improved Thermal and Oxidative Stability

A critical limitation of biolubricants is their relatively low oxidative stability, which can lead to degradation at elevated temperatures. TiO₂ and SiO₂ nanoparticles address this issue by enhancing the oxidative resilience of biolubricants. TiO₂, in particular, exhibits high resistance to thermal decomposition and oxidation, which helps maintain the lubricant’s integrity at high operating temperatures. Additionally, both TiO₂ and SiO₂ nanoparticles can absorb and dissipate heat more effectively than traditional biolubricant formulations, thereby reducing the risk of thermal degradation. This enhanced stability ensures consistent performance and prolongs biolubricant lifespan, especially in high-temperature applications such as automotive engines and industrial machinery.

2.5.3. Formation of Protective Tribofilms

The unique mechanisms by which TiO₂ and SiO₂ nanoparticles interact with biolubricants enable the formation of protective tribofilms on sliding surfaces. Under shear stress, these nanoparticles can adhere to contact surfaces, creating a physical barrier that reduces wear and prevents surface damage. TiO₂ nanoparticles, for example, have been observed to form a ceramic-like film on metal surfaces, providing a hard, durable layer that resists scratching and scoring under load. SiO₂ nanoparticles, while softer, form a silica-based film that also helps mitigate wear by filling surface asperities. These tribofilms act as self-replenishing protective layers, continually regenerating as nanoparticles migrate to the areas experiencing the most frictional contact. This property extends the lifespan of both the biolubricant and the machinery components, reducing maintenance needs and enhancing operational efficiency.

2.5.4. Environmental and Economic Implications

From an environmental perspective, using TiO₂ and SiO₂ nanoparticles aligns with the sustainable objectives of biolubricants. These nanoparticles are relatively non-toxic and can be synthesised in environmentally friendly ways. Additionally, the enhanced performance and durability imparted by TiO₂ and SiO₂ nanoparticles reduce the frequency of lubricant changes, minimising waste and decreasing the environmental impact of lubricant disposal. Economically, the extended life of biolubricants containing these nanoparticles can lower costs by reducing the need for frequent lubricant replacement and machine maintenance, offering a cost-effective option for industries committed to sustainable practices. By integrating these nanoparticles into biolubricants, researchers can improve friction and wear reduction, thermal stability, and protective film formation. This improves biolubricant performance and longevity, supporting environmental and economic sustainability. As research progresses, TiO₂ and SiO₂ nanoparticles are poised to play a pivotal role in developing next-generation high-performance biolubricants.

2.6. Impact of Other Nanoparticles in Biolubricants

ZnO nanoparticles are widely recognised for their anti-wear and friction-reducing properties in biolubricants. Research shows that ZnO nanoparticles form a protective film on metal surfaces, preventing direct metal-to-metal contact, which reduces friction and wear by up to 30% and can extend equipment service life by up to 50% under typical conditions. Additionally, ZnO improves lubricant stability under oxidative stress, making it suitable for high-temperature applications. A study showed that ZnO-infused vegetable-based lubricants maintained viscosity and chemical integrity after 100 hours at 150°C, highlighting their reliability for industrial and automotive uses. Al₂O₃ nanoparticles are known for their high thermal and chemical stability, making them particularly effective in high-temperature applications. When incorporated into biolubricants, Al₂O₃ particles exhibit anti-friction behaviour through a "rolling effect," which reduces friction and wear by approximately 35% under elevated loads. In addition, Al₂O₃ enhances the thermal conductivity of biolubricants, helping dissipate heat and reduce lubricant degradation over time.

Studies report that Al₂O₃ nanoparticle-infused biolubricants show a 15% increase in load-carrying capacity, making them highly effective in industrial machinery and automotive applications. CeO₂ nanoparticles provide oxidative stability and reduce emissions, making them suitable for environmentally conscious applications. Their antioxidant properties help prevent lubricant oxidation, thereby extending the lubricant's effective lifespan by up to 40%. Moreover, CeO₂ has self-healing capabilities, as it reacts with wear debris to form protective layers on metal surfaces, which mitigates further wear. This unique feature has proven advantageous in automotive applications, where reduced maintenance and enhanced environmental performance are essential. A study showed that CeO₂ nanoparticles in biolubricants reduced oxidation rates by 25% while increasing wear resistance by 35% compared with conventional additives, underscoring their potential in sustainable lubrication systems. CuO nanoparticles help reduce friction and wear because of their hardness and thermal stability. These nanoparticles create a protective barrier, minimizing surface wear by up to 30%, especially in high-contact scenarios such as gears and engine components.

Furthermore, CuO improves biolubricant dispersion stability, ensuring consistent performance even under fluctuating operating conditions. Research on CuO-infused biolubricants indicates an enhanced anti-wear performance, with a wear scar diameter reduction of approximately 20% compared to conventional formulations. This characteristic is particularly beneficial for engine oils and hydraulic fluids where stability is essential. Carbon-based nanoparticles, including graphene and carbon nanotubes (CNTs), are notable for their mechanical strength, self-lubricating properties, and high thermal conductivity. These nanoparticles reduce friction by forming a tribofilm on contact surfaces, effectively preventing direct metal contact. For instance, graphene nanoparticles have shown up to a 50% reduction in friction when added to base oils, significantly enhancing load-carrying capacity and maintaining stability at high temperatures. Graphene's self-lubricating nature also helps maintain lubricant efficacy over extended periods, making it suitable for high-load and high-temperature applications, including heavy machinery and automotive systems.

2.7. Properties and Performance of Biolubricants

2.7.1. Viscosity

The viscosity of biolubricants is intricately linked to temperature variations and the specific composition of the base oil employed in their formulation. Temperature plays a pivotal role in influencing molecular dynamics within the lubricant, resulting in viscosity changes. Higher temperatures reduce viscosity because molecules move more freely, while lower temperatures increase it. The choice of base oil, sourced from materials such as palm oil, sunflower oil, or olive oil, significantly influences the biolubricant's inherent viscosity characteristics. The unique molecular structures of these base oils, including fatty acid saturation levels, contribute to their intrinsic viscosity and thus determine the lubricant's flow behavior under different thermal conditions (Table 6).

Table 6: Viscosity comparison of different biolubricants at 40°C and 100°C

Biolubricants	Viscosity 40°C	Viscosity 100°C
Castor Oil	220.6	19.72
Jatropha Oil	35.4	7.9
Palm Oil	52.4	10.2
Olive Oil	39.62	8.24
Rapeseed Oil	45.6	10.07
Soybean Oil	28.86	7.55
Sunflower Oil	40.05	8.65

2.7.2. Flash Point

The flash point of a biolubricant, a key safety parameter, is the lowest temperature at which vapors can ignite. This characteristic is closely tied to temperature variations and base-oil composition, which is often derived from sources like palm, sunflower, or olive oil. The molecular structures and saturation levels of fatty acids in these oils influence the biolubricant's volatility and flammability, which are critical safety considerations in industrial applications.

2.7.3. Influence of Catalysts

In biolubricant synthesis, catalyst selection is crucial and strongly influences reaction efficiency and outcome. Common catalysts such as sodium methoxide and chloric acid are widely used in esterification and transesterification processes, which are vital steps in converting natural oils into biolubricants. Sodium methoxide, a strong base, facilitates transesterification reactions and plays a key role in converting triglycerides in natural oils into biodiesel and glycerol. Conversely, chloric acid catalyzes esterification, facilitating ester formation, a fundamental step in biolubricant synthesis. Additionally, lipase, a biocatalyst in biolubricant synthesis, supports sustainability by offering an eco-friendly alternative to chemical catalysts. Lipases, instrumental in esterification and transesterification reactions, enable the conversion of triglycerides into biodiesel and glycerol. Their remarkable specificity allows for precise control over biolubricant composition, enhancing overall product quality. Notably, lipases operate under mild reaction conditions, minimising energy requirements and aligning with the broader objective of developing green, environmentally conscious biolubricant production methods.

2.7.4. Yield

Biolubricant yield is a critical parameter that directly affects the economic feasibility and efficiency of the production process. Various factors influence the yield, including the type of oilseed used, the molecular weight of the oils and esters, the choice of catalyst, and the specific viscosity characteristics of both the base oils and the final biolubricants. The choice of oilseed plays a pivotal role in determining the yield of the resultant biolubricants. For instance, palm oil, with a molecular weight of 463.07 g/mol, yields a biolubricant with a viscosity of 4.59 cSt at 40°C when reacted with trimethylolpropane (TMP) using sodium methoxide as a catalyst. This process achieves an impressive yield of 98.5%. Similarly, jatropha oil, having a higher molecular weight of 733 g/mol, also produces a biolubricant with a yield of 98% under the same catalytic conditions. These high yields indicate the efficiency of the transesterification process and the favorable molecular characteristics of these oils. Soybean oil, with a notably higher molecular weight of 920 g/mol, has been successfully converted into biolubricants using both neopentyl glycol (NPG) and trimethylolpropane as intermediates, facilitated by lipase from *C. rugosa*. The process demonstrates yields of 100% and 84% for the respective biolubricants, highlighting the versatility of soybean oil as a feedstock. The lipase-mediated process not only improves yield but also supports sustainability goals by reducing the environmental impact of chemical catalysts (Table 7).

Table 7: Comparative synthesis conditions and physicochemical properties of different biolubricants

Oil (Molecular Weight)	Ester (Molecular Weight)	Catalyst	Oil Viscosity @40°C cSt	Biolubricant Viscosity @40°C cSt	Biolubricant Flash Point °C	Yield %
Palm Oil (463.07)	Trimethylolpropane (221.61)	Sodium Methoxide	52.13	4.59	150	98.5
Jatropha Oil (733)	Trimethylolpropane (221.61)	Sodium Methoxide	36.97	4.6	185	98
Soybean Oil (920)	Neopentyl glycol (NPG)	Lipomod™ 34MDP Lipase from <i>C. rugosa</i>	60	21.10	152	100
	Trimethylolpropane (TMP)	Lipomod™ 34MDP Lipase from <i>C. rugosa</i>	60	25.2	150	84
Castor Oil (Jatropha Curcas L. oil)	9-Octadecenoic acid (Z) -, 2-hydroxy-1- (hydroxymethyl) ethyl ester.	Chlorate Acid Catalyst	220.6	217.25	268	66%

POME oil	POME oil methyl ester Trimethylolpropane.	Hepatopancre as Lipase from Pacific White Shrimp	43	48	164	83.5 - 97
Sunflower Oil	Epoxidised sunflower oil	TiO ₂ /SiO ₂ , NbVO/SiO ₂ , polyoxometal ates, sulfated/SnO ₂	40.05	44.79 8.78 @100°C	Pour Point = - 9	-
	Estolide Sunflower oil	Acid catalyst (H ₂ SO ₄) An oxidant (HClO ₄)	40.5	102.4 17.7-42.5 @100°C	-	-
Olive oil	Epoxidized Olive oil	TiO ₂ /SiO ₂ , NbVO/SiO ₂ , polyoxometal ates, sulfated/SnO ₂	39.68	-	Pour Point = - 28 to -11	-
	Estolide Olive oil	Acid catalyst (H ₂ SO ₄) An oxidant (HClO ₄)	39.68	271.8-518.6 33.5-60.2 @100°C	-	-

In contrast, castor oil, which contains a specific ester characterised as 9-octadecenoic acid, yields a biolubricant with a lower efficiency of 66% when chloric acid is used as the catalyst. This lower yield can be attributed to the complexity of the molecular structure and potential steric hindrance, which may impede the catalytic action during synthesis. The production of biolubricants from palm oil mill effluent (POME) also showcases the impact of feedstock composition on yield. Utilising trimethylolpropane and lipase derived from Pacific white shrimp, POME oil methyl ester achieves a yield ranging from 83.5% to 97%, demonstrating effective conversion even from waste materials. For sunflower and olive oils, yields can vary significantly depending on the extraction and catalytic processes used. Epoxidised sunflower oil yields are less defined, with a viscosity of approximately 44.79 cSt at 40°C but no specified yield percentage. Estolide formulations using acid catalysts such as H₂SO₄ and oxidants like HClO₄ have not reported precise yields (Tables 6 and 7, indicating a need for further investigation. Overall, oilseed selection, the molecular weights involved, and the catalytic methods used are fundamental in determining the yield and efficiency of biolubricant production. Optimising these parameters can significantly improve the economic viability and environmental sustainability of biolubricant synthesis.

3. Applications of Biolubricants

The evolving landscape of biolubricants, derived from renewable sources, represents a significant advancement toward sustainable practices across various industrial applications. These alternatives not only show environmental responsibility but also deliver improved performance across diverse sectors, aligning with the growing global demand for eco-friendly solutions. In engine oils, where the push for higher efficiency and lower environmental impact is paramount, biolubricants play a pivotal role. Utilising resources like castor, palm, and coconut oils as substitutes for conventional mineral oils has revealed their potential benefits. For instance, castor oil has been shown to reduce volatile organic compound emissions by 5% while improving lubricity, highlighting its environmental benefits and potential to mitigate health concerns associated with emissions from traditional engine oils. Hydraulic fluid applications further underscore biolubricants' advantages. Vegetable oils, particularly soybean oil, are recognized for their superior power-transmission properties, resulting in faster response times and more efficient energy utilization. Major industry players, including Mannekote et al. [38], actively endorse hydraulic systems that use environmentally friendly vegetable oils, ensuring adherence to rigorous pump test standards and confirming their efficacy in the sector.

Metalworking oils represent another domain where biolubricants demonstrate significant benefits, including improved thermal stability, rust resistance, and emulsifiability. These attributes extend tool life and support stable emulsions even at elevated temperatures. Integrating biodegradable vegetable oils into metalworking fluids, along with additives such as emulsifiers, fungicides, and antioxidants, has been shown to increase tool life by up to 40%, with substantial improvements in surface finish and accuracy. The expanding market for biolubricants spans transmission oils, chainsaw oils, greases, and insulating oils. Despite ongoing challenges such as the limited commercialisation of bio-based transmission oils and the need for bio-based thickeners in greases, research and development initiatives continue to drive innovation in these sectors. For example, canola- or sunflower oil-based insulating fluids have been shown to increase transformer loading by up to 20%, illustrating the potential

of biolubricants in industries traditionally dominated by mineral oils. The manifold advantages of biolubricants position them as sustainable solutions that promote environmentally conscious lubrication practices without compromising performance or efficacy.

4. Challenges Faced by Bio-Lubricants

Despite these advantages, biolubricants face multifaceted challenges that hinder widespread adoption. One major obstacle is their poor oxidative stability, particularly at elevated temperatures, which leads to chemical modifications that adversely affect their physicochemical properties. The low thermo-oxidative stability of unsaturated vegetable oils further complicates matters, as these oils are prone to chemical degradation that can compromise biolubricant performance over time. Additionally, feedstock variability and seasonality add complexity, resulting in different chemical compositions in starting vegetable oils. Selecting suitable non-edible oils is crucial to avoid disruptions in the food chain and to prevent potential issues such as price speculation and social imbalances. Looking ahead, the prospects of biolubricants hinge on addressing these challenges while improving lubrication performance and ensuring non-toxic formulations compared with traditional mineral oils. Stringent environmental regulations are expected to drive the development of more sustainable formulations across various sectors, including engine oils, hydraulic fluids, compressor oils, and insulating fluids.

Overcoming the challenge of securing reliable, cost-effective vegetable oils is vital to biolubricants' competitiveness. Government involvement is essential, requiring policies that encourage the cultivation of non-edible oil crops and incentivise the production of lubricants with higher bio-component proportions and lower degradation and toxicity than mineral oils. Limited adoption of biolubricants may also stem from lubricant manufacturers' reluctance to invest in modifying their production chains. Governments must play a critical role in facilitating this transition by providing the necessary support and incentives. The scientific community is actively working to optimise biolubricant synthesis processes. Various innovative methods, including mechanochemical treatments, microwaves, ultrasound, and enzymatic processes, are being explored to enhance efficiency under mild conditions. Furthermore, nanoparticles show promise for improving the physicochemical properties of biolubricants by minimizing asperity contact and wear; however, concerns about potential nano-object release and associated risks continue to highlight the challenge of developing safe, nanoparticle-free biolubricants.

5. Conclusion

The integration of biolubricants into various industrial applications signifies a pivotal transition towards more sustainable practices in lubrication technology. As industries face increasing pressure to reduce their environmental footprints, biolubricants offer a compelling alternative to traditional mineral oils, with renewable origins and reduced ecological impact. This review highlights the multifaceted benefits of biolubricants, including lower emissions, enhanced biodegradability, and improved performance across applications ranging from engine oils to hydraulic fluids and metalworking processes. Despite these advantages, adopting biolubricants still faces challenges. Key issues such as poor oxidative stability, variability in feedstock quality, and limited commercialisation of certain biolubricant formulations continue to hinder widespread acceptance. The susceptibility of unsaturated vegetable oils to oxidation, particularly at high temperatures, creates significant barriers to performance and longevity. Additionally, dependence on seasonal crop yields can create supply and price volatility, undermining the overall stability of biolubricant markets. To foster biolubricant growth, stakeholders across the supply chain—from agricultural producers to lubricant manufacturers—must collaborate to develop innovative solutions. This includes advancing research into alternative, non-edible feedstocks that do not interfere with food supply chains, thereby mitigating the socio-economic impacts of food price fluctuations. Government policies that incentivize the cultivation of such crops and support research and development in biolubricant technologies will be crucial to building a robust, sustainable biolubricant industry.

Moreover, as technology advances, exploring novel synthesis methods, including enzymatic processes and green chemistry approaches, offers an opportunity to improve biolubricant efficiency and environmental performance. The ongoing development of formulations that incorporate additives or nanotechnology can further improve their physicochemical properties, making them competitive with conventional lubricants. The future of biolubricants also lies in addressing safety concerns related to nanoparticle use and ensuring formulations remain non-toxic and environmentally benign. As the scientific community works to develop safe and effective biolubricants, maintaining transparency in production processes and product formulations will be essential to foster trust among consumers and industries alike. The transition towards biolubricants is not merely a response to regulatory pressures; it is a necessary evolution in the pursuit of sustainable industrial practices. By capitalising on the potential of biolubricants, industries can not only comply with environmental regulations but also gain a competitive edge through enhanced performance and reduced environmental impact. As the market continues to evolve, collaboration among researchers, manufacturers, and policymakers will be pivotal to overcoming existing challenges and fully realising the promise of biolubricants as a cornerstone of sustainable lubrication practices. The path ahead requires innovation,

commitment, and a shared vision for a greener future, where biolubricants play a central role in promoting both environmental sustainability and industrial efficiency.

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