

Comprehensive and Scientific Review on Applications, Advancements and Challenges of Bio-Lubricants

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ABSTRACT

Bio-lubricants have emerged as sustainable and biodegradable alternatives to traditional petroleum-based lubricants. This review summarises the current research on these materials, focusing on their application in areas such as the automotive industry, heavy equipment, hydraulic machinery, metalworking applications, marine industries, and agriculture. Bio lubricants offer advantages such as biodegradability, lower toxicity, reduced environmental impact, but their industrial adoption is constrained by poor oxidative stability, limited low-temperature properties for cold-weather performance, difficulty in achieving viscosity stability across broad temperature ranges and relatively higher raw material and processing costs. Newer advancements through chemical modification processes like transesterification, epoxidation and nanoparticle incorporation have significantly improved performance without giving up environmentally friendly characteristics. Bio-lubricants play a key role in the transition to a green economy in domains like electric vehicles, wind turbine gearboxes. Life cycle assessment studies indicate promising long-term environmental benefits aligning with global sustainable development goals. Future research directions emphasize improving oxidative stability, production through either biotechnological fermentation or recycling waste feedstocks, creating standardized testing protocols (e.g., OECD biodegradability protocols), and advancement of sustainable tribological systems to support environmentally responsible industrial practices.

Keywords: *bio- lubricants, applications, challenges, oxidative stability, chemical modification, life cycle assessment.*

1.INTRODUCTION:

Every year, billions go into the world lubricants market - yet it struggles under growing strain. Moving away from petroleum-derived materials toward greener options that reduce harm to nature - this shift matters more now than environment impact while maintaining

or exceeding performance standards. Bio lubricants, derived from renewable and bountiful natural origins - like vegetable oils, animal fats, and new options including microalgae -Nowadays, certain options are gaining attention to meet this important requirement. Because of growing demands, finding effective solutions has become essential. One key reason drives efforts toward better alternatives. Despite challenges, progress in this area remains ongoing. Recent developments point toward more reliable choices. The need for reliable answers keeps pushing innovation forward. Low fossil fuel supplies push change forward, alongside tighter environmental rules and rising pressure for cleaner energy solutions. Nowadays, stricter pollution rules are shaping choices. People pay more attention when oil leaks harm nature badly sometimes. From now on, handling waste matters will shape how nations tackle climate goals - tied closely to pushes for zero-carbon status worldwide.

Conventional petroleum-based lubricants pose significant environmental hazards, with approximately around half of every lubricant winds up in the environment - either by seeping out, disappearing into air, or being released another way, still lurking in nature after being misused or dumped poorly [1]. Left behind, they taint both land and watery zones. Faced with shrinking supplies, plus harm to plants and animals from toxic waste, some turn to natural fixes instead of synthetic ones [4]. Yet few realize how clean these alternatives can be by design. Fast breakdown happens with these plastics, plus they tend to be less harmful if swallowed and come from natural materials again, which means fewer emissions over time. Footprints [5]. The potential for bio lubricants to achieve biodegradability rates exceeding 90% within 28 days, compared to minimal degradation of petroleum lubricants, represents A change in how materials interact under stress marks a move toward lasting performance [6], [7]. Although natural oils give good advantage, big-scale use of them in lubricants are not popular due to problems around oxidation breakdown. Since ancient times, weak behaviour in cold conditions along with

higher production expenses have often held back the use of this material [8], [9]. Chemical alterations, 3D printing styles, or different raw materials can boost performance of bio-oils. Additive techniques, 3D printing technique, along with changes in starting materials have made bio-lubricants work much better. Some materials give good performance, closing the difference with regular lubricants and revealing fresh opportunities across applications. Work settings influence results across different fields [10], [5]. This comprehensive review examines the current state of bio-lubricant technology and advancements from the work mainly published in recent decade [11]. It covers a wide scope, gathering insights from various fields within that time frame. Bio lubricants function in cars, factories, hydraulic systems, machine shops, boats, and beyond agricultural sectors, while critically evaluating environmental benefits, technical properties, chemical modification strategies exist alongside ongoing difficulties [12]. Emerging trends receive close scrutiny in this overview such as microalgae-made lubricants, turning used kitchen grease into fuel, tiny particle oils, and apps in modern tech like electric cars and windmills [13]. The review aims to provide researchers, industry practitioners, and policymakers with a holistic understanding of bio lubricant potential, limitations, and pathways toward sustainable tribological fixes [14].

II. CHEMICAL CLASSIFICATION OF BIOLUBRICANTS:

Bio lubricants are lubricants made from biological sources that are biodegradable, non-toxic, and have a smaller adverse effect on the environment than fossil-based lubricants [1]. Several categories of bio lubricants exist based on their origin, their chemical structure, and the degree of modification [7]. Bio lubricants can be divided into two groups: natural (unmodified vegetable oils and animal fats) and synthetic (chemically modified derivatives such as esters, epoxides, and polyol esters) [15]. A major difference between natural and synthetic bio lubricants is that many natural bio lubricants will require some form of chemical modification to mitigate inherent limitations compared to their non-biological counterparts and therefore retain their environmental benefit [14] [16]. The scientific community has established criteria for the classification of bio lubricants, which usually require the source of the lubricating substance to be renewable, that it is biodegradable (>60 to 70% degradation within 28 days of manufacture as defined by standard tests [i.e. OECD 301 Series]) and that the substance don't pose an unacceptable ecotoxicological risk [8] [19]. The above criteria are put in place to ensure that bio lubricants provide an actual ecological benefit throughout their entire life cycle, from manufacturing through end use and off to the environment [7] [22].

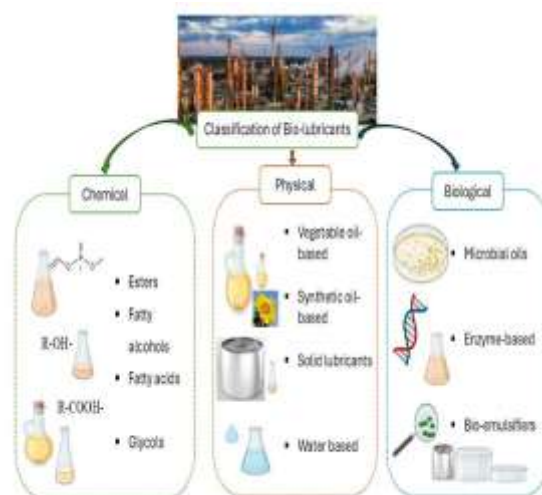


Figure 1. Chemical Classification of Bio-lubricants

III. SUSTAINABLE SOURCES OF BIOLUBRICANTS:

The primary feedstocks for bio lubricant production include vegetable oils (both edible and non-edible), animal fats, and emerging sources such as microalgae and waste cooking oils [6]. Vegetable oils are broadly studied and represent the most commercially viable category of feedstocks, and the most common sources are soybean, rapeseed (canola), palm, sunflower, castor, jatropha, and high oleic variants [7]. The selection of feedstock has a dramatic impact on the physicochemical properties, performance characteristics and sustainability profile of the bio lubricant being developed [19]. Non-edible vegetable oils have received considerable interest due to their ability to alleviate competition in food resources, which is central to the “food vs. fuel” debate surrounding the development of biofuels and bio lubricants [23]. For example, non-edible sources of oil, such as jatropha, karanja and neem, can provide sustainable alternatives that can be grown on marginally productive lands, thus avoiding displacement of food crops [26].

Additionally, waste cooking oils (WCO) are an attractive option for providing feedstock material as they address waste management concerns while providing low-cost feedstock [16]. Current research has shown that WCO can be converted to high-performance bio lubricants using suitable purification and chemical modification technologies [16]. Microalgae have shown significant promise as a next-generation feedstock, due to their high lipid productivity, ability to be cultivated on non-arable land, low freshwater requirements and ability to sequester carbon dioxide [17]. However, there are still significant barriers to the commercial viability of microalgae feedstock, including the existence of high costs for harvesting biomass, inefficiencies associated with lipid extraction and difficulties in scaling production [17].

Figure 2 represents the various sources of bio-lubricants including newly studied waste feedstock like WCO, Biomass and the highly researched microalgal based base.

The common processing generic for the various sources are Transesterification and Hydro-processing, two of most used chemical modification methods.

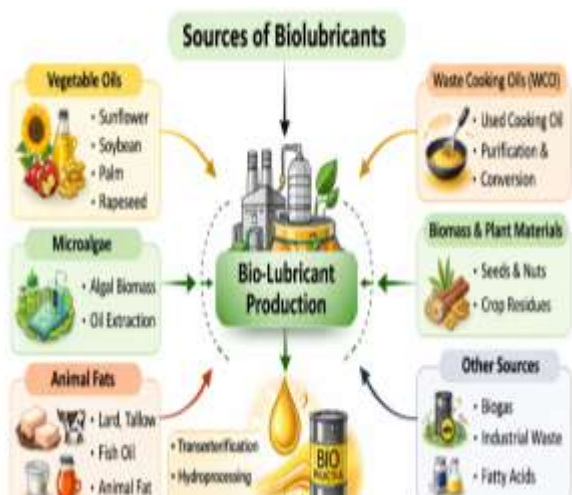


Figure 2. Various Sources of Bio-Lubricants

IV. APPLICATIONS OF BIO-LUBRICANTS:

A. Automotive Applications

The automotive sector represents one of the largest potential markets for bio lubricants, encompassing engine oils, transmission fluids, gearbox lubricants, brake fluids, and greases [6]. Bio lubricants though still new, are starting to deliver well in different car contexts - showing stronger ties to surroundings than before. These high-performance engine oils hold key advantages even when demanding standards must be met [12]. Formulations exist. Best performance in lubrication and shielding from wear often comes from vegetable oil esters, matching or beating some options when it comes to friction control. Emissions are lower when switching from standard mineral oils along with better fuel efficiency [28]. Bio lubricants work well in transmission fluids and gearbox lubricants. Their performance stands out in these fields. Outcomes tend to improve under such conditions because their resistance to viscosity changes, good slip performance, plus strong bonding to many metals make it stand out [8]. They spread power well while shielding surfaces, these materials handle stress without issues even at extreme levels. Under intense pressure, often seen in fluid networks, extreme forces shape behaviour of materials [18].

Studies say chemically altered vegetable oils - like trimethylolpropane esters (TMPE) – match standard limits for car transmission lubricants, with better biodegradability [8], [28]. Still, using bio lubricants in fast, modern cars isn't entirely smooth, though efforts continue, especially where conditions allow better

performance. Especially in today's fuel-efficient engines that go longer between oil changes. Inside these systems, degradation happens through steady chemical reactions instead of sudden events. Even though bio lubricants are better for the environment, their limits mean they do not last as long when temperatures stay extreme for extended periods. Under engines' stressful conditions, oil may need changing sooner because of wearing down [18]. Cars that need oil changes frequently rely on esters tweaked by chemistry - like those built from biology-based materials bring better returns and work easier than plain vegetable oils [16]. Recent gains in additive technologies along with better chemical methods really shape how things progress. Better performance of bio lubricants makes them suitable for car industry [14]. Vehicles powered by electricity need fluids for their transmissions, bearinging, cooling systems, yet cooler than combustion-driven power units, this shift focuses toward blends that fit better with bio-lubricant designs [17]. Their match with existing materials remains key. Biodiesel used in electric cars puts it ahead when it comes to expansion inside a fast-moving sector [17].

B. Hydraulic Fluids

Hydraulic fluids represent a critical application area for bio lubricants, particularly in mobile hydraulic equipment used in agriculture, forestry, construction, and material handling. Machines like harvesters, cranes, tractors, and load carriers run through spaces full of dust, heat, and rough conditions. Because of that, the oils meant to keep them running smooth often face challenges [8]. These spots make it tough for lubricants to do their job properly. Leakages happens often, especially when materials face outdoor conditions. Because of this, breaking down easily becomes important. At the same time, being harmless to living things matters just as much. These traits help avoid risks over time particularly valuable [19]. The use of bio lubricants in these applications significantly reduces spills and leaks of hydraulic fluid carry risks tied to soil and groundwater pollution, as studies have shown [6], [24]. Lately, scientists have worked on creating strong biofluids from vegetable sources - vegetable oils that meet stringent performance requirements while maintaining environmental benefits[24]. These formulations must balance multiple performance criteria including appropriate viscosity, from cold starts to hot operations, performance stays consistent. This material resists breakdown when exposed to light or air. Protection against mechanical stress and chemical decay comes built in. Corrosion slows down under harsh conditions, without extra effort. Seals and hoses fit well when compatibility is considered [24].

Recent advances in materials have suggested strong potential for hydraulic use with better heat and structural performance. These changes could reshape how systems operate over time. Vegetable oils without change tend to

stay more stable against oxidation than they do [19]. Nowhere else has the push for cleaner liquids spread so widely - bio lubricants actually hold a strong foothold here, thanks in part to Driven by both eco-focused rules and practical gains, projects often shift toward greener zones. Where nature is fragile, choices tilt toward sustainability like woods, rivers, or farmed soil, eco-friendly fluid choices [24]. Some operators choose them simply because they care about nature's balance [6]. The development of bio-based hydraulic fluids that meet ISO VG32 and other industry standards has become more feasible due to advances in materials science and sustainable technology. Standards now gain wider use because they work well in real-world settings [16], [24]. Challenges for bio-based hydraulic fluids include maintaining performance under extreme operating conditions. Under different conditions, these materials help keep hydraulic setups stable over time while staying affordable. Even so, scientists today explore better materials for reactions using standard fluids [24]. Still, work continues on fine-tuning what goes into these processes with updates, each method still faces hurdles because new challenges keep appearing alongside old ones. From hydraulic systems to broad industrial use, bio lubricants work across many fluid applications [12].

C. Metalworking Fluids

Metalworking fluids - MWFs - are liquids applied during tasks like cutting, grinding, drilling, or shaping metal. These fluids serve more than one purpose when used in mechanical processing. Bio lubricants find meaningful use across various sectors one key application being their role in cooling systems. Beyond that they perform tasks such as cooling, lubrication, chip removal, and corrosion protection during metal machining processes [29]. Using vegetable oil metalworking fluids offers several advantages like superior lubricity improves alongside reduced tool wear. Surface quality gets better while safety for workers enhances because temperatures stay lower toxicity and reduced mist formation [21]. Research has shown that vegetable oils are effective at lowering heat generation, friction, and tool wear and tear, which has led to their successful use as metalworking fluids in a variety of machining operations [6], [18]. Vegetable oil molecules adhere well to metal surfaces due to their polar nature. Surface traces function by forming thin layers that protect material and machines as they are sculpted away during cutting. Operations see changes with vegetable oil-based cutting fluids [18].

According to research, these fluids enhance performance in specific scenarios. Despite their widespread use, they still have difficulties in intricate configurations. Environmental factors and machine characteristics have a significant impact on performance. Previous research suggests improved outcomes in controlled environments. However, inconsistent results continue to limit widespread

adoption. When cutting metal, water occasionally outperforms conventional oil-based coolants, but it rarely equals their ease of use or finish quality. According to some laboratory tests, plain water can cut steel just as well under certain circumstances, even though greasy liquids still lead in smoothness and accuracy. Along with long-term benefits for both people and the environment, these changes also result in increased well-being and practical gains [21].

Bio lubricants possess uses in metal processing, such as lubricants for cutting tools or fluids for cooling during operations. Interesting qualities can be found in lubricants and mold-release agents, such as high-oleic sunflower oil [6, 8]. The seamless replacement of mineral oils in leather and textile processes demonstrates the adaptability of lubricants based on vegetable oils [16]. According to these findings, using bio lubricants in metalworking operations lowers worker exposure to harmful fumes and mists, enhancing occupational health and safety [21], [29]. One of the challenges in creating vegetable-based metalworking lubricants is making sure that there is enough ox-bitter weather won't shorten the product's shelf life when cutting tasks involve heat. Even in extremely hot or cold temperatures, its defense against wild microbes remains robust. Performance is just as important for wet emulsions as maintaining prices competitive with products made from alternatives derived from oil [29]. Additive packages, antimicrobial, blending antifoams with additives like antioxidants, corrosion inhibitors, biocides, thermal stabilizers, crobials, and extreme pressure additives, are essential for optimizing bio lubricant performance in metalworking applications [14], [29].

D. Industrial applications

Bio-lubricants are being used inside gears, starting with bearings, then circulating systems, next in compressors, finally in the turbines [13]. These oils often improve sliding performance, reduce friction, while keeping their thickness stable under heat changes plus handling heavy loads [1]. Industrial gear oils made from natural bio lubricants handle friction control well, especially under pressure. Reducing friction helps machines last longer while cutting down on repairs needed over time [6], [18]. Compressor oils work well with bio lubricants, especially when made from synthetic esters due to better heat management, higher ignition points, good resistance to breakdown from oxygen exposure. Epoxidated oils have improved heat stability. At 260 degrees Celsius, their performance matches tough compressor needs [19]. When bio lubricants are involved, outside exposure drops when air and gas compressors are designed to lower pollution chances without sacrificing performance. Starting and running equipment falls into these categories.

Bearing and circulating oil systems in industrial facilities often work better when lubricants show

enhanced slip properties and anti-wear properties of bio lubricants, potentially reducing energy consumption through lower friction losses happen too, thanks to how veg oil lubes handle flow [17]. Their strong viscosity index keeps performance steady. Even when conditions shift - like cold temperatures altering oil viscosity - the system keeps lubrication steady. Performance remains constant in the face of fluctuating thermal conditions, guaranteeing steady behaviour.

This setup is defined by operating under initial conditions plus increased heat [1], [2]. Industry occasionally uses these materials in odd ways, such as filling transformer tanks with silent, non-conductive fluids. Because they resist burning, decompose naturally, and manage electricity well, bio lubricants can occasionally stand out [8], [19]. The creation of bio-lubricant compositions for use in power transformers tackles Every time oil spills from a transformer, the balance of nature and safety regulations become entangled. Wider ecological pressures combine with what occurs in the field. Spills disturb the environment while drawing attention to stringent standards. With every incident, growing awareness and real-world needs are brought into focus [18].

E. Marine and Aviation Applications

Marine environments rely heavily on bio-lubricants due to the high degree of hazard posed to them from conventional lubricants. The introduction of lubricant leaks and spills into aquatic systems adversely affects marine life. The release of hazardous fluids from external combustion engines into the open ocean adds chemicals to the ocean's ecosystem. The effects on nature resulting from the discharge of oil, stern tube grease, and hydraulic fluids used in the marine industry can all be detrimental to the life found in the water. Bio-lubricants have the ability to break down quickly and have low toxicity coatings, which make them a good candidate for marine applications and can also serve as a means to minimize the impacts on the environment from everyday lubricant leaks or spills. Engine testing in the marine environment has indicated that lubricating oils made from vegetable oil-based products function effectively. The solutions must address friction control, surface protection, and rust resistance as well as meet the required specifications.

Marine engine oils are very effective in protecting against rust damage in extreme saline conditions. Natural oil-based lubricants are the products to be used when lubricating underwater equipment. The need to switch to bio-lubricants will continue to increase under the growing environmental regulations, particularly for sensitive ecosystems. Areas that are impacted by this change are coastal waterways, ports, and protected marine areas.

Nonetheless, there are a limited number of bio lubricants that can be used for aviation due to the

extreme operating environment experienced by the oil in aviation. The extreme conditions faced by an engine include both cold ambient temperatures when the engine is starting and flying at high altitudes, along with operating at high pressure, experiencing large temperature variations and operating under continuous excessive load. Therefore, all of the components that make up an aircraft must operate flawlessly under extreme conditions and through all phases of an aircraft operation. Weather conditions are an example of different types of environmental conditions, but also the way scientific research is conducted is affected by the requirement for high level reliability of aircraft systems and the amount of regulation in the aviation sector. Throughout all that research continues to seek new biotechnology alternatives and potential future uses of biobased lubricants beyond just aviation inside of the aviation industry. Some examples of biobased lubricants include hydraulic fluids and fluids used in low-pressure applications.

Through the creation of biobased lubricants, this is facilitating and will facilitate an expansion of the usage of biobased lubricants into a wider variety of aircraft systems, including ground support equipment and other facilities [19]. Also, the potential of biobased lubricants to be used with new marine technologies comes about as hybrid and electric marine technologies continue to develop innovations in propulsion systems. The ongoing urgency to transition to hybrid and electric marine propulsion systems opens opportunities for the marine transportation industry to expand. At the same time, the marine transportation industry is in the early stages of a transition as result of the emergence of new drive technologies for marine propulsion systems. The trend towards the environmentally friendly propulsion system must continue as this can help contribute towards achieving the levels of marine environmental impact reduction that have been targeted. As a result, the usage of friendly lubricants are fitting into the broader scope of sustainability goals [17].

F. Agricultural Equipment

Agriculture is an ideal application domain for bio lubricants due to the rough use of machinery and direct contact with soil, crops, and water resources. Tractors, harvesters, planters, and some farming machines work in places with dirt and water make oil spill likely, or settings full of dust that sticks easily. They possess danger of oils leak [6], [8]. When biodegradable lubricants are used in farming machines, this method lowers chances of dirt and water getting polluted - keeping things safe, maintaining crop health which is associated with soil balance and nature's stability [15]. Chainsaw oils and bio-lubricants work well together due to similar properties. With vegetable oil formulas used often in forest work [6], [18], their performance stands out as they are made from common ingredients and

handle tough tasks well. Their role grows as needs shift across different regions. Applications involve total-loss lubrication systems where the lubricant is continuously dispersed. Around here, folks often check what's in food scraps before they break down. Since nature shapes these processes, turning into compost matters a lot [6]. Oil-based lubricants for chainsaws work well but break down fast in woodland dirt, says research.

Reducing exposure to nature remains central, especially when aiming to lower ecological effects [18]. Tractors, harvesters, and irrigation systems are examples of agricultural machinery with hydraulic systems take advantage of bio-based hydraulic fluids that protect the environment without sacrificing functionality [8], [24]. Support for the use of bio lubricants in agricultural applications comes from regulatory requirements in certain jurisdictions as well as environmental stewardship concerns [15] [24]. Another appropriate use for bio lubricants is in two-stroke engine oils found in power tools and small agricultural equipment; formulations of these oils have been shown to provide efficient lubrication and lower emissions when compared to traditional two-stroke oils [19]. A wide range of equipment types and operating conditions are being addressed by the ongoing development of bio lubricant formulations for agricultural applications [19].

G. Other Uses

Electric cars, wind turbines, and other cutting-edge technologies that support sustainability goals are examples of emerging uses for bio lubricants. With operating conditions that are frequently more compatible with current bio lubricant formulations than internal combustion engines, electric vehicles require lubricants for transmission systems, bearings, and thermal management systems [17]. Electric vehicles are especially well-suited for bio lubricants due to their lower operating temperatures and decreased oxidative stress, which could hasten adoption in this quickly expanding market segment [17]. Another promising application area is wind turbines, where hydraulic fluids and gearbox lubricants are necessary for blade pitch control and other systems [5]. Biodegradable lubricants are especially appealing because of the environmental sensitivity of many wind farm locations, such as offshore installations and isolated terrestrial sites [17]. The alignment of sustainable lubrication practices with renewable energy generation is supported by the compatibility of bio lubricants with wind turbine applications [5, 17]. Additional new uses include food-grade lubricants for machinery used in food processing, where bio lubricants' non-toxic properties offer safety benefits in the event of unintentional food contact [8]. The market potential and adaptability of bio-based lubrication technologies are being demonstrated by the ongoing development of customized bio lubricant formulations for niche applications [14]. Figure 3

summarises the applications of bio-lubricants in different industrial sectors.

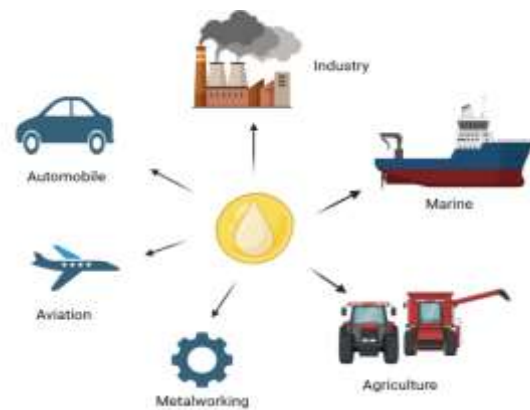


Figure 3. Different industrial applications of bio-lubricants

V. RECENT ADVANCEMENTS AND EMERGING TRENDS:

A. Microalgae-Derived Bio lubricants

Microalgae have emerged as a promising next-generation feedstock for bio lubricant production, offering several advantages over terrestrial oil crops [17]. Microalgae can achieve high lipid pro-Some plants pack in up to half their body weight as fat, while needing less space and resources than crops like soy or corn. One study found certain types reach lipid levels between 20 and 50 percent of total mass [17]. Cultivation might grow where land isn't farmed, using salty water or treated waste instead, sidestepping rivalry with regular crop producing food while cutting down on freshwater use is a key benefit of growing microalgae [17]. Cultivating these tiny algae also comes with extra advantages not seen elsewhere which is carbon capture through these microorganisms, turning lubricant creation into a carbon-reducing process. These conditions often arise alongside CO₂ sources like those released from power plants [17].

The lipid composition of microalgae can be influenced through cultivation conditions, including light levels, water access, plus heat or cold levels shape how much fat forms in plants. The acidity of oils from microalgae can vary under various conditions. Some microalgae species already have high levels of acid and also high amounts of fatty acids with one unsaturated bond compared to how well they do under cold temperatures [17]. One approach to modifying microalgae is through genetic modification, aiming to enhance lipid levels. In the future, customized bio-lubricants will likely be produced from specific feedstocks [17]. Despite the benefits of using microalgae oils in lubricants other obstacles still exist when using microalgae oil as a lubricant, one significant obstacle to produce this oil at a reasonable cost is the cost of harvesting biomass and extracting its lipids, thus making it financially challenging for producers. Micro algae cells usually grow in low density in a culture, being between 2 and

20 microns in diameter, and have relatively low density as they float around in the mid-to-top of the volume in which they are grown [17]. Harvesting and de-watering microalgae cells require large amounts of energy, due to the energy-intensive nature of these processes. Extracting lipids from microalgal cells often presents difficulties due to cell walls being tough to break down, while the use of standard solvent-based extraction techniques presents additional environmental impacts. Research on green solvents and more efficient extraction methods denotes the clear shift in how microalgae make lipids - scaling back takes less toll on nature [17]. Using microalgae polysaccharides to make bio lubricants - especially ones with low - When it comes to heat-based methods, this approach stands out as a growing area of study - potentially making processes more environmentally friendly. Even though methods exist to turn microalgae fats into bio lubricants, more effort still required. Developing lubricant mixes using polysaccharides has been explored recently [17].

B. Waste Cooking Oil Valorization

Used cooking oil stands out as a key material for making bio-lubricants - offering a practical path forward by handling large amounts of waste streams through efficient processing routes. Waste management struggles come alongside delivering affordable raw materials [16]. The value from waste materials gets used. WCO for bio lubricant production offers dual environmental benefits: preventing water pollution while creating long-term solutions. Lubricants [16] from restaurants and food processing sites comes WCO in big amounts, providing a distributed feedstock source that can support regional bio lubricant production. Researches have demonstrated that WCO can be effectively converted into high-performance bio lube using chemical methods. [16]. Molecular distillation is one such method used to separate WCO and provide with better slip and wear resistance. Chemical modification by double transesterification using Trimethylolpropane (TFATE) forms a result of 85.7% satisfying ISO VG32 standards. Purification at 120°C yields WCOs rich in acidity along with unsaturated and saturated fats [16]. These acid blends serve as effective lubricants [16]. Chemically altering waste cooking oil (WCO) occurs via transesterification, epoxidation, and hydrogenation which all modify WCO's structure in different ways; additionally, adding a few types of additives will enhance performance under high-temperature stress and provide additional performance characteristics to WCO-based lubricants which will allow for effective utilization for high-stress applications; however, the most effective catalysts will differ by application [16]. Some prior methods of converting oils involve variable quality (uneven) catalysts; however, this variability will support the more sustainable production of oil due to the recovery/reusability of catalysts [16]. Nonetheless, there are still issues regarding the quality of input in the

form of uneven amounts of contaminants and/or difficulty in handling the products of degradation of WCO to deal with/what to do with what is left after fermentation of the WCO - therefore, a proper methodology on solid removal of the residual materials from WCO must be established [16]. The concepts of circular economy will dictate the future direction of the development of WCO-derived bio-lubricants by converting waste into usable products [16]. Future research must address how to efficiently acquire the raw materials for the creation of downstream products; currently, multiple teams are developing or commercializing different raw materials. The definition of quality standards of WCO feedstocks must be consistent between governmental departments; processing methods need to be developed so that costs are contained; and there have been many positive advancements in technology that have allowed for the potential for handling the variability in feedstocks [16]. At this time WCO is being deliterized in integrated systems, and the current systems for waste are capable of mitigating to support the production of eco-friendly lubricating oils sourced from renewable biomass. These biobased feed stocks already move through collection channels, opening paths toward greener fluid alternatives without heavy capital and production scales [16].

C. Nano-Bio lubricants

Nano-bio lubricants, which combine bio-based oils with nanoparticle additives, represent a sustainable shift in tribology focuses on better performance without harming the environment [13]. The addition of nanoparticles to bio lubricants shows clear improvements in performance. Improvements in tribological performance mean lower friction coefficients along with reduced wear rates over time. Different kinds of nanoparticles have been looked at like from metals like oxides to carbon-rich compounds and tiny particle metals, different traits show up depending on structure and use characteristics [13], [28]. The mechanisms by which nanoparticles enhance lubrication include filling surface asperities to smoothing out bumps, these form protective layers on metal areas - working like tiny sliders to ease friction. Friction drops when materials roll instead of slide against each other. Heat moves faster too, carried away by better conductivity. Heat transfers better with these particles [28]. How well they work varies by amount used and their spread in size. Depending on how it's used and what kind of base oil is involved, adjustments need to be made - this part demands precise tuning [13], [28]. Getting nano-bio lubricants made is hard when nanoparticles stay clumped instead of spreading evenly. Agglomeration prevention during storage and usage, and health and environmental risks are all well-known issues based on the work conducted thus far on base oils. However, there is still ongoing research into solving all these issues. There's also a lot of interest in green

alternatives where the negative effects can be reduced while still maintaining efficacy. That has become the primary driver of many scientific investigations [13]. Changing the particle structure of the nanoparticles is one of the most researched areas currently. One of the typical ways of stabilising the particles is by using disperse agents/surfactants, although determining which agent to use is sometimes difficult because it depends on the material under consideration. When picking materials, make sure they meet rules about breaking down naturally [13]. Nano-bio lubricants face hurdles that must be overcome, showing real results stands out as key. With better energy and cost traits than regular bio-lubricants, these new versions stand out [28],[32].

D. Green Chemistry and Sustainable Catalysis

Using green chemistry ideas in making bio lubricants matters a lot. Lately, a shift has emerged toward cleaner production methods in manufacturing, driven by environmental concerns [14], [20]. Instead of focusing only on efficiency, green chemistry pushes further, aiming to reduce harm while respecting natural systems. Designing chemical products and processes so they use fewer or no harmful ingredients, cutting down on waste helps boost energy efficiency while turning to renewable materials for production [14]. Bio lubricants inherently aligns with several green chemistry principles through the use of renewable, plant-based materials helps make eco-friendly items while reducing reliance on synthetic sources [22]. Heterogenous catalysis is slowing making strides in bio-lubricant production. Catalyst recovery becomes easier, product cleaning gets less complicated. The entire process is simplified by reducing the number of steps required [14]. For instance, some of the old-school methods of producing catalysts, which often involve a lot of trial and error, still produce successful results. Improvements in methods have been made and wastage reduced as a result of these improvements [20]. A few have replaced liquid-form acid and base with solid-form acid/base like metal oxide or zeolite to improve on the cleanliness of the processes behind esterification/transesterification when using biocatalysts in tandem with conventional catalysts. Biocatalysts provide a major improvement over conventional methods of catalyzing reactions, as they can be used to make multiple ingredients in the same vessel for a cleaner reaction than can be done with traditional a method [20]; the goal is to provide improved mixing systems, stable performance, and greater catalyzing power for biodiesel production through the employment of different types of catalysts which possess different properties. Research continues into alternate methods of catalyzing reactions used in biodiesel production. Use of lipase-based catalysts for creating bio-lubricants represent another aspect of green chemistry. Lipase is one type of enzyme that will drive a specific reaction to create bio-lubricants, while at the same time, catalyzing (driving) an efficient, well-separated, low-energy reaction [20]. There are certain

limitations presently with respect to the use of lipase-based catalysts, however, due to high cost, slow reaction rates, and a lack of understanding as to how to enhance enzyme performance through changes (trapping) to enzymes have made progress in creating new ways to improve trapping different types of lipase enzymes in matrices for use as catalytic agents. This type of research is largely conducted by multiple laboratories working independently on separate projects but at the same time with a common goal of increasing overall enzyme performance. Enzymes pulled from clean, sustainable sources often make processes work better while staying within budget [20]. Instead of traditional methods, turning to biological catalysts changes how things run. Recyclable enzyme setups are improving through innovation, helping sustainable manufacturing move forward [20]. Solvent-free or minimal-solvent processes for bio lubricant production reduce environmental impacts and simplify downstream processing [14]. These improvements sometimes come from upgraded systems that make existing tools work smarter integration of renewable energy sources, such as solar or wind power, into bio lubricant production. Still, these upgrades do more than help save energy - they also improve how long systems last [22].

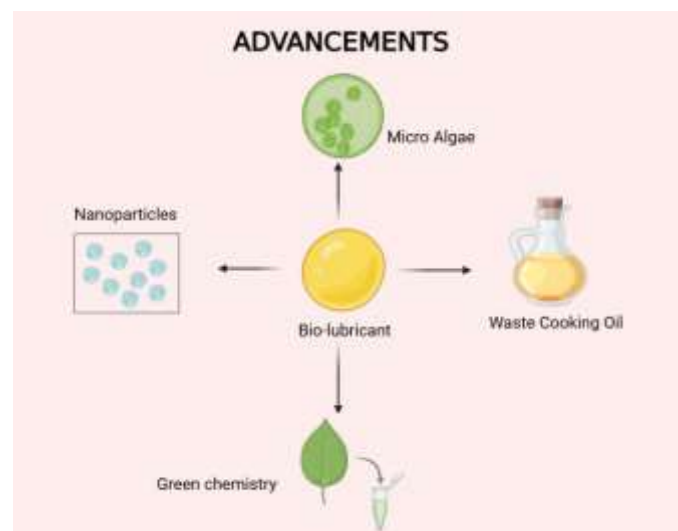


Figure 5. Recent advancements in the field of Bio-lubricants

VI. CHALLENGES AND TECHNICAL BARRIERS:

A. Oxidative and Thermal Instability

Oxidation together with heat sensitivity now stand as main hurdles in scaling bio lubricant technology Bio lubricants are gaining more use, especially where extreme heat or heavy stress applies [5], [9]. Vegetable oils contain fatty acid chains that include unsaturated types, holding active double bonds. These bonds allow chemical reactions to occur, shaping their behaviour under heat and light. Over time, Bio-lubricants tend to break down through oxidation resulting in harmful changes in their structure. This breakdown often results in new compounds forming within the mixture and can

also form byproducts which are undesirable. Acids, peroxides, aldehydes, and polymeric compound weaken bio-lubricant's performances [1]. This fundamental chemical limitation has generally restricted bio lubricant use in engines, especially during high temperatures. Higher heat speeds up oxidation, driving reactions. When temperature rises by 10 degrees, its length often doubles [6]. Heat cracks the oil's shield near engine cores, where molten films stall in loops hotter than boiling water - exposed, worn thin by friction that never lets up. Heat from red-hot metals changes how oils hold their shape when mixed with fuel leftovers. What stays stable in raw plant extracts depends on what surrounds them during reaction phase, insufficient for reliable long-term operation [17], [18].

High wear has been observed in testing olive and soybean oils at 150°C and shows how poorly they work without changes. Heat affects the behaviour of oils, heat induces breakdown and lead to changes in material nature and properties.[6] Heat breaks down molecules and it stresses ester bonds in triglycerides [2]. The chemical connection between hydrophilic and hydrophobic functional groups on the ester molecules has an incredible reaction to heat. Ester bonds can be broken down by thermal degradation when fats are exposed to heat. In some cases, polymerization of polyunsaturated fats can occur, joining one fat molecule to another. Polymerization of fats produces larger molecules and results in a higher viscosity. As temperature increases, chemical reactions that create larger molecules occur [3] and eventually take over the movement of all liquids. The surface of the liquid experiences many bumps caused by the breaking down of larger molecules and the lubricant ability is diminished by pressure [4]. To counteract the effects of heat and chemical sensitivity, multiple solutions are needed. Many of these solutions involve making chemical changes, such as decreasing the unsaturation level, producing strong antioxidants and developing thermal stabilizer additives. These additives will be beneficial additions, but the proper selection of feedstocks is critical because the type of fatty acid affects the effectiveness [7],[9]. If there are many ways to make improvements but no way to provide longevity in oxidation, then the task of matching thermal stability to synthetic lubricants will not be easy for many materials to achieve. [10].

B. Low-Temperature Limitations

Most vegetable oils struggle under cold conditions, which diminishes their overall performance, making them less useful overall. Many lubricants operate slower through rough weather, particularly when the machines are operating cold or sitting for extended periods. As vegetable oils become colder, they will develop a cloudy appearance and eventually settle and get frozen depending on the temperature. Similar to the freezing point of vegetable oils will occur as saturated fats

develop into a crystalline structure; this occurs between approximately -10 degrees Celsius and 10 degrees Celsius [8]. On the other hand, unlike the lubricants made from oils, silicones behave differently when stressed. Silicone lubricants can reshape and stretch or flow when pressure is applied as well as create unique combinations of new formulations. Fluid behaviour is also altered at temperatures beyond -30 degrees Celsius. Vegetable oils crystallize at high temperatures because of the crystallization process. Hydrogenation also tends to favour the unsaturated form of fats; however, saturated chains (C16:0 or C18:0) will remain in the system and continue to form clusters and stick together.

Poor cold flow is present in oils containing high levels of unsaturated fats. When there is an increase in the temperature behaviour of a lubricant mixture, it is primarily due to the amount of saturated components in the mixture. Clouds consist of molecules that are arranged in a manner similar to the way crystalline wax becomes solidified into crystalline form when it cools to its melting point. A syfy (not an absence of) cohesive molecular mass begins to form into a substantial mass when the liquid solidifies and is difficult to pour. Hydraulic fluids that do not exhibit viscosity or flow easily (flow rate) are significant contributors to how they perform in low temperature applications [18]. Prevention of corrosion while maintaining low-temperature properties is one of the most significant challenges in the chemistry of materials. One of the major challenges with bio-lubricants is the long time it takes to degrade their properties since they break down naturally [9]. There are several things that can be done to increase the longevity of lubricants; for example-Oils with high levels of saturated fats have extreme difficulties in processing during their conversion to hydrogenated (non-hydrogenated) oils regardless of the branding of such oils. Additionally, oils maintain fluidity at lower temperatures despite the increase in viscosity as opposed to solidified oils maintaining viscosity when heated [16]. There is also a high degree of variation in the degree to which the majority of unsaturated oils break down due to their chemical structures as evidenced by [6], [18]. Chemical alterations to improve low-temperature conditions can include the use of branched fatty acids to inhibit crystal development, or through fractionation or targeting specific high-melting components in a fluid. This approach follows one region to another, different methods shape how *Jatropha* oil transforms. Cold climates affect flow rates while distribution impacts output. Additives that slow crystallization play a role too [14], [16]. Transforming it via transesterification yields synthetic esters with carefully selected fatty acid compositions can optimize low-temperature, performance improves under certain conditions even when keeping other useful traits intact [8], [20]. At low temperatures, synthetic oils often fall short when matched against those from petroleum roots. Many bio

lubricants are made from similar formulations found in research papers [9], [18].

C. Cost Competitiveness

Even though they're made from renewable sources, bio lubricants tend to cost more than standard oil-derived ones. Bio lubricants face a major hurdle entering most markets [6], [18]. Their cost runs higher by 30 to 40 percent. Pricier than standard lubricants, certain bio-based mixes ring up two to four folds higher in cost [27]. That higher expense comes from a mix of influences including feedstock prices, along with chemical tweaks and handling costs, plus tiny manufacturing volumes, then a few more factors like specialized additives needed [8], [19]. Costs tied to feedstocks make up a large part of what it costs to produce bio lubricants – especially edible vegetable oils get used now more than before [6], [22]. Food needs, fuel demands, and lubricant uses fight for the same resources. When demand rises for vegetable oils made from certain plants, market values often climb - particularly if crop supplies are tight amid seasonal shifts in farming patterns. Cultural tastes shift, prices waver because of it [26]. Instead of regular oil, scientists test non-food sources like used kitchen grease. Lowering feedstock expenses is possible with these options, yet each could need further treatment to reach the desired outcome. Quality that meets established criteria will continue to be accepted by consumers [16].

Chemical changes occur during transesterification, epoxidation and hydrogenation – each one causes a chemical change to the oils used to produce bio-lubricants [14]. Running heavy costs are attributed to producing bio-lubricants [16],[20]. Production of bio-lubricants requires the use of specialized machinery to perform these complex processing operations. Compared to traditional methods of producing bio-lubricants, current methods require distinctive measures for each component (e.g.; management methodology; catalyst type (i.e.; biocatalysts and/or chemical), energy input/consumption, purification steps/requirements) that have been developed to produce bio-lubricants at a higher cost than producing petroleum-based lubricants due to the more straightforward refineries utilized to produce the latter [20].

With advancements in the performance of new catalysts, the production of bio-lubricants represent the opportunity for these to be the most viable and least costly alternatives for lubricant manufacturers as a result of using raw materials with catalysts that can be reclaimed and reused, thus making a significant reduction in costs in relation to petroleum-based lubricants through providential decision-making based upon what factors [14],[20] are used to produce bio-lubricants. Typically produced on a smaller scale than petroleum-based lubricants; lower production volumes result in greater proportional increases in the costs of bio-lubricants than would occur if larger amounts were

produced [22]. Until production volumes of the respective goods sufficiently increase, the relative costs of production of these items will decline; however, with technology continuing to advance regarding the production of bio-based lubricants, the market competitiveness of manufacturers will also continue to improve [22]. Although creating a price parity with petroleum lubricants will not be feasible, the environment requires protection beyond the support that can be generated by free-market economies [22].

D. Feedstock Variability and Supply Chain

The inconsistency of the raw materials used to make bio-lubricants is a major problem. The differences in the various materials can be very significant for a number of important characteristics. There are no greater inconsistencies than when using vegetable material since there are so many types of vegetables, the geographical conditions they were grown in and how the weather varies during the growth of that crop & when it is harvested will all have a bearing on the volumes of material produced. Additionally, how vegetable materials are processed will influence the consistency of the end product. Due to these issues, bio-lubricants will generally also have varying degrees of quality. The variability of these materials makes it impossible to maintain consistency and meet specifications are complicated to manage. Another important aspect; is the fatty acid composition of the different vegetable oils will affect the extent and degree to which the oil's unique properties shift when creating a batch of bio-lubricants made from vegetable oils. Unlike other additives; differences in the vegetable oils used in bio-lubricants can differ anywhere from 10 to 20 or more in the fatty acid composition when comparing separate batches of vegetable oils. There are many more factors that need to be considered when producing bio-lubricants; the distance between where the feedstock is harvested, the route taken by the feedstock, storage capacity and duration of storage would contribute to additional problems with producing bio-lubricants. The seasonality of agricultural harvesting has a direct impact on supply patterns therefore will often impact the price of food. Many types of vegetable oils will see a decrease in value due to the chemical breakdown caused by oxidation.

In order to manage the products produced by oxidation, care should be taken to ensure that all this information is properly tracked and managed appropriately. Depending on the conditions described in references, some vegetable oils may require stabilization while being stored. The majority of plant-based oils being used to produce food, fuel and lubricants make it difficult for the suppliers to compete for these resources. This clash shapes how crops get used. Ethical and practical issues arise, especially around edible oils - think about how common ones are used [6], [26]. The “food” vs fuel debate - a challenge for biofuels too -

affects how people see bio lubricants, grow about pulling farm efforts away from feeding people [6], [26]. New plans form using plants and waste that are not typically used for food can help fix current issues, yet brings fresh challenges. Cultivation, harvesting, and treatment bring difficulties tied to biology and handling methods [16], [26]. Even when demand is high, using local materials might limit how much bio lubricant is available - especially in areas with tough growing conditions. Across regions, movement of goods might need shipping over great distances - this often raises expenses while adding pressure on the environment [22]. The development of diverse feedstock options, including oil crops and microalgae locally might boost supply chain stability while cutting down on shipping needs [17].

E. Technical Barriers to Industrial Adoption

Beyond the specific technical limitations discussed above, several broader technical barriers imply bio lubricants slowly gain ground in factories, yet uneven standards hinder wide acceptance. Testing methods remain scattered, limiting consistency across sites. When building bio-lubricants, lacking dedicated performance standards makes the process harder than it needs to be market accepted [5]. Several current lubricant standards focus on petroleum-based systems only. At times, standards can overlook certain products while failing to assess how well bio lubricants perform. Unnecessary obstacles could also be added by their standards. For bio-lubricants, meeting these standards may be difficult [22]. When we use older machines, sometimes they don't fit perfectly with what we have already connected. Sometimes the seal will slip on something, or the hose has a crack; or the items wear out incorrectly because they are not designed together, and this mismatch continues to cause problems long after being installed. In general, biodiesel matches well when we work with the most common types of construction materials. However, if these materials are subjected to higher operational temperatures, they will begin to soften (in the case of plastic) or warp (in the case of metal) [24]. The vast majority of the time, bio-lubricants do not cause damage to any equipment made from multiple materials; however, at the same time there has been an increase in swelling or degradation of elastomer and seal components of lubrication systems due to changes in the original materials [24]. There is ample opportunity to use biodiesel in existing machinery as long as the machinery does not need any changes, which would allow a person to use biodiesel as a straight replacement for different types of fuels [24]. The limited amount of both long-term performance and field data available on bio-lubricants creates a larger hurdle for individuals who would be using bio lubes when there are level of demand for their respective applications [22]. Equipment manufacturers will be similarly impacted by these same types of hurdles. A worker will be unwilling to use a lubricant with superior

performance until they have established reliability through documented performance under pressure.

The reluctance to change will continue as long as their current procedures feel comfortable and secure; therefore, documented evidence of reliability under pressure must also be provided to build trust and provide long-term consistent performance [29]. Another issue with bio-lubricants is microbial growth, particularly in water-contaminated systems or metalworking when starting with liquid mixtures known as emulsion fluids. Incorporating antimicrobial agents is Complex; this requires paying close attention to how everything interacts during the formulation process. The decomposition of bio-lubricants occurs naturally due to being made from natural ingredients, such as vegetable oils or additives. While these characteristics provide ecological benefits, they pose challenges regarding the microbial breakdown during usage or storage. The rate of microbial breakdown is greatly affected by how well the composition is balanced with the resistance to microbial growth throughout the service life. Therefore, careful selection of additives during production and formulation work is necessary, along with the refinements identified in [14], [19].



Figure 4. Challenges of Bio-lubricants

VII. CONCLUSION:

In summary, bio-lubricants have the potential to play an important role in achieving worldwide sustainability goals and moving towards environmentally-friendly tribological system applications. Despite the hurdles presented by technical and economic challenges, bio-lubricants continue to illustrate the improving viability of bio-lubricants as both an alternative (from petroleum-based lubricants) and the necessary next step toward sustainable practices in industrial operations given large environmental advantages, continuing technological progress and increasing consumer acceptance by increased biodegradability rates, substantial reduction in toxicity levels, mitigation of large carbon footprints and sourcing from renewable feedstocks that eliminate resource depletion concerns, lower toxicity emissions

and increased workplace safety. Recent advances in chemical modification methods and additive formulations have significantly improved the limitations of bio-lubricants.

Bio-lubricants are also important in reducing contamination of our environment, impacting the effects of climate change, conserving finite resources, and protecting ecosystem and human health. Bio-lubricants are anticipated to continue capturing market share in multiple applications, as research continues to develop, volume of production increases, and enabling policies are developed will result in the lubricant industry being transformed to a sustainable state. Policy creation should be focused on creating and incentivizing a comprehensive regulatory structure related to the use of biodegradable CBDs in applications requiring environmentally sensitive materials and/or provide for the carbon pricing mechanisms in bio-lubricant end-user applications. There are high growth markets for bio-lubricants in electric vehicles and wind turbines, because their operating temperatures are lower than those of internal combustion engines, and therefore they are very well aligned with environmental concerns. There must be a concerted effort from all stakeholders, including researchers, industry, and policymakers, to advance the use of bio-lubricants.

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