WASTE COOKING OIL AS A SUSTAINABLE FEEDSTOCK FOR BIOLUBRICANT PRODUCTION: TECHNOLOGIES, OPTIMIZATION STRATEGIES, AND PERFORMANCE PROPERTIES

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ABSTRACT

This in-depth study examines the transformation of wasted cooking oils, typically destined for landfills or improper environmental disposal, into improved bio-lubricants through meticulous chemical modifications. Transesterification, epoxidation, and oligomerization are some of the strategic chemical processing routes that can turn these waste materials into lubricants that are more biodegradable, less harmful to the environment, and better at reducing friction than traditional petroleum-based options. Recent technological breakthroughs have significantly enhanced strategies for process optimization. Microwave-assisted and ultrasonic irradiation approaches have greatly shortened processing times from hours to minutes while also improving product quality metrics. This review examines significant research deficiencies and emerging prospects, emphasizing the necessity for enhanced feedstock logistics, improved catalytic system development, and optimized strategic production scale-up to fully exploit the promise of bio-lubricants derived from waste cooking oil.

Keywords: *waste cooking oil, bio-lubricant, transesterification, epoxidation, sustainability, renewable resources, tribology, environmental impact.*

I. INTRODUCTION:

The global transition to sustainable industrial practices has put renewable lubricant alternatives to the traditional petroleum-based products in the spot-light. Traditional mineral oil lubricants, which have been prevalent from the early twentieth century, pose considerable environmental issues, including low biodegradability, aquatic toxicity, and high lifecycle carbon emissions from extraction to disposal. Resource volatility and geopolitical constraints on petroleum supply concurrently generate economic risk, especially for developing economies.[1]

Bio-lubricants, derived from renewable biological feedstocks, offer a viable alternative. These materials demonstrate rapid biodegradability, reduced aquatic toxicity and lifecycle carbon footprints that are 45–67% lower than comparable mineral oil formulations. Recent technological advances indicate that bio-lubricants can match or exceed conventional lubricants in mechanical properties, oxidation resistance, and wear protection, thereby fundamentally changing the traditional sustainability-performance trade-off. [5]

Waste cooking oil is identified as the most strategically beneficial feedstock for the synthesis of bio-lubricants. The valorization of waste cooking oil transforms a problematic waste stream into a valuable industrial resource. Global WCO generation is estimated at approximately 13–15 million tons per year, alongside current collection efforts.

Developed economies possess infrastructure that facilitates rapid business initiation. Market research indicates that the bio-lubricant industry is projected to expand from USD 2.95 billion in 2024 to a range of USD 4.9 billion to USD 7.2 billion by 2033. The industry is projected to expand at an annual rate of 8.5% to 13.7%, significantly outpacing the conventional lubricant market.

The commercialization of bio-lubricants derived from waste cooking oil, while technically feasible, encounters persistent challenges. Standardizing quality is challenging due to variations in feedstock, particularly in developing economies where supply chains are fragmented. Additionally, competing with established mineral oil markets on price remains difficult. Regulatory frameworks, while increasingly beneficial, exhibit inconsistencies across regions and lack full harmonization.

This review integrates contemporary technological advancements and identifies significant strategies for enhancement, facilitating the transition of WCO bio-lubricants from a niche innovation to widespread industrial application.

II. WASTE COOKING OIL: CHARACTERISTICS AND PREPARATION

A. Generation and Availability Patterns

The world has a lot of leftover cooking oil, but it's not used very often. It accounts for 20–32% of all vegetable oil consumed in different parts of the world [3]. Generation mostly comes from restaurants, fast-food chains, motels, and catering industries. They make a lot of trash that may be readily picked up in an orderly method [81]. These enterprises frequently toss away

5 to 20 liters of spent cooking oil every day. This depends on the size of the business, the menu, and how the food is cooked. Commercial sources are attractive places to do systematic collecting operations since they contain trends that can be predicted and larger numbers. Household kitchens only contribute to about 1-3 litres per month and collection is much more expensive as compared to commercial sources. The efficiency of collection changes a lot from one area to another.

In less developed countries with bad infrastructure, it can be as low as 10%. In well-organized European markets with clear regulations and economic incentives, it can be as high as 80% [90]. Collection rates are affected by rules, economic incentives for generators, infrastructure development, public knowledge, and competition from other ways to get rid of or use garbage [84].

B. Physical and Chemical Property Evolution

Heating vegetable oil modifies its chemical and physical properties in a big way through a sequence of intricate thermal, oxidative, and hydrolytic events [3]. These changes cause free fatty acids to form, mono- and diglycerides to form, oxidation products to form, and polymerized compounds to form.

Temperatures from 160-190C make it easier to break down molecules, the properties of waste cooking oil differ significantly based on the original oil source, the frying method, the duration of usage, and the storage conditions [3]. Acid readings usually show between 1.32 - 15.4mg KOH/g.

The viscosity changes a lot when you cook. For instance, kinematic viscosity values go from 4.2 to 190.2 mm^2/s, which is a lot broader than the ranges for virgin oils [3]. These increases occurs because polymerization makes molecules that are bigger and thicker. Too much viscosity might make processing hard, although small increases can actually aid some lubricant uses.

The water content in used frying oil varies from 0.18 to 1.9 wt%, indicating contamination during food processing [3]. These water levels may not seem like a major deal, but they can really mess with chemical modification processes, especially those that use alkaline catalysts that are sensitive to water content.

The peroxide values, which vary from 5.6 to 23.1 meq/kg, illustrate how much oxidative deterioration occurred when the product is used and stored [3]. These compounds can make oil unstable and make lubricants work worse if they aren't treated properly during processing. Some oxidation products, on the other hand, may be helpful like natural antioxidants.

As the heat breaks down the material, the colour changes from bright yellow to dark brown or black. This means that conjugated compounds and carbonyl groups are formed [3].

C. Pre-treatment and Purification Technologies

It is very necessary to properly pre-treat used cooking oil before manufacturing high-quality bio-lubricants [3][16]. The major goals are to get rid of food particles, water, and other things that could come in the way of chemical alteration activities or make the final product less good. The challenge is to achieve these objectives in a cost-effective manner while preserving essential oil components.

The first step in treatment is physical filtering, which removes food particles and suspended materials that could cause difficulties with processing or quality later on [3]. Different sorts of pollutants require different filtration systems. This is because the oil is handled differently by the generators and the food that is fried. This first stage keeps the equipment clean and makes the future phases of fine filtering easier. Coarse filtration is a suitable choice for collecting sites because it is affordable and straightforward to use.

Fine filtering with cellulose filters or membrane systems can get rid of particles as small as 5 μm, which is clear enough for the next step in chemical processing [14]. Fine filtering costs more than coarse filtration, but it is important to keep the quality of the product the same and stop the catalyst from losing its effectiveness in downstream operations. When picking a filtration medium, you need to think about the temperature of the oil, the flow rates, and the projected number of contaminants.

It is highly crucial to get rid of water since it can inhibit many chemical modification reactions from happening, especially transesterification procedures that use alkaline catalysts [3]. When done at lower temperatures (60–80 °C), vacuum distillation removes water with the least amount of damage to the oil's parts [16]. This strategy works effectively for huge companies that can afford to buy vacuum cleaners. But when you look at the economy, you need to think about how much energy it takes to heat and make a vacuum, and you need trained workers to keep things going well.

Another technique to get rid of both water and tiny particles at the same time is to use centrifugal separation [14]. Because they have a strong enough gravitational attraction, high-speed centrifuges can separate phases depending on variations in density. This technology works best on emulsified water that can't be removed by letting it settle. However, it can be expensive to buy and keep up. The water could also be removed by using activated alumina or molecular sieves to soak it up. This is especially helpful for uses that don't need much water [14]. These materials just soak up water, not oil. But the need to replace or renew absorbent materials makes things more complicated and expensive, therefore this method is better for high-value uses.

III. CHEMICAL MODIFICATION ROUTES FOR BIO-LUBRICANT PRODUCTION

A. Transesterification Processes and Optimization

Transesterification has emerged as the most extensively studied and commercially viable chemical modification technique for converting waste cooking oil into bio-lubricants [3][11]. This process involves triglycerides reacting with alcohols to form fatty acid esters that have very different viscosity, pour point, and thermal stability qualities than standard lubricants.

The process of transesterification is based on the chemistry of nucleophilic substitution at the carbonyl carbon of triglyceride molecules [3]. From a stoichiometric perspective, one mole of triglyceride reacts with three moles of alcohol to produce three moles of fatty acid alkyl esters and one mole of glycerol. However, real-world applications almost never achieve theoretical stoichiometric conditions due of constraints on equilibrium and side reactions.

In industry, more alcohol is added to finish the reaction and make up for the alcohol that is lost during processing. Most of the time, this is done with 6–9 molar ratios [11]. This method is cheap when the price of not fully converting and the chance of alcohol recovery and recycling systems is considered.

The parameters of the reaction have a considerable effect on both the rate of conversion and the quality of the outcome [3]. The best reaction rates occurred between 50 and 75 degrees Celsius. This also keeps delicate parts from becoming damaged by heat. Higher temperatures speed up reaction kinetics, but they can also generate unwanted side reactions and the evaporation of alcohol. But responses are too sluggish for commercial usage at lower temperatures.

The length of the reaction can be anything from 30 minutes to several hours, depending on the type of catalyst, how well the alcohol is mixed, and how much conversion is needed [11]. The challenge lies in achieving an optimal equilibrium between rapid processing, which reduces equipment dimensions and capital expenditures, and complete conversion, which enhances yield and product quality.

New ways to mix and create catalysts are making reactions happen faster while maintaining the conversion rates high.

Methanol reacts faster because its molecules are smaller and more likely to bond with other molecules. This is helpful for things that need to be done quickly. But ethanol generates lubricants that perform better in the cold and break down faster, which might make the longer reaction times worth it.

2-ethylhexanol and other higher alcohols generate products with superior viscosity indices and oxidative stability, but they need harsher reaction conditions and special handling [12]. These high-quality alcohols could be a good deal for high-value lubricant uses where greater performance makes higher raw material prices worth it, as on boats or in airplanes.

Separating and purifying the products is one of the hardest stages of transesterification [11]. Fatty acid esters, glycerol, unreacted alcohol, catalyst residues, and various by-products are all in the reaction mixture. It is a complex multiphase system that is difficult to separate with basic methods. For high-performance lubricants, traditional methods don't always work effectively to obtain the purity levels needed.

The usual way to separate things is to let them settle by gravity and then wash them with water. This process takes a long time and makes a lot of waste, which is terrible for the environment [3]. As time goes on, more and more firms are employing newer separation technologies that are better for the environment and more efficient. But these new ways cost extra to set up.

Membrane separation removes glycerol and polar molecules while retaining essential ester products [12]. Ceramic or polymeric membranes with the correct molecular weight cutoffs can separate objects without the heat stress that occurs with distillation. But when you look at the costs of membrane fouling and replacement in economic studies, you have to remember that some contaminants might make membranes work worse.

B. Epoxidation Reactions and Applications

One of the most beautiful ways to alter a molecule is by epoxidation. It adds epoxide functional groups to chains of unsaturated fatty acids, which makes them significantly more stable at high temperatures and less likely to alter fast [31][36]. This improvement is especially helpful for uses at high temperatures where standard bio-lubricants don't work well. It opens up new markets that renewable lubricants couldn't reach before.

In standard epoxidation methods, peracids produced on-site, like performic or peracetic acid, are utilized to add oxygen to unsaturated sites in two phases [3][31]. The first step is to mix carboxylic acids and hydrogen peroxide to generate peracids. Next, oxygen is moved to double bonds in a method that doesn't change the stereochemistry.

This approach achieves a lot of conversions, but it has to be extremely careful about the conditions of the reaction so that the oxirane ring doesn't open, which would lose the performance benefits [42]. The challenge is in maximizing epoxidation while minimizing side reactions that lead to ring opening. These processes can create hydroxyl groups and increase the viscosity.

Formic acid systems are now the dominant way to epoxidize used cooking oil because they are more selective and work at lower temperatures than acetic acid systems [31][36]. Formic acid has a reduced molecular size, which makes it easier for mass to transfer in systems with more than one phase. It is also less reactive, which means that ring-opening processes are less likely to happen. Most of the time, these benefits make up for the fact that supplies cost a little more.

The normal parameters for the reaction include temperatures between 50 and 60 °C, formic acid-to-unsaturated sites molar ratios between 1.5 and 2.0, and hydrogen peroxide concentrations between 30 and 50% [36]. Reaction periods normally range from 4 to 8 hours, depending on the type of oil and how much epoxidation is needed. But process intensification technologies help get shorter durations.

The level of epoxidation lets you change the properties of lubricants to fit different needs [31]. The best relative conversion to oxirane (RCO) values are between 50 and 80 percent. This is because they make the material more stable at high temperatures while still preserving the flow properties that are needed. More epoxidation makes things thicker and may lead them to gel.

Research on optimizing processes using statistical experimental design has revealed significant factors influencing the efficacy of epoxidation [31][36]. The most crucial thing is the temperature. The optimal range is usually between 50 and 55 °C, which keeps the reaction speed and selectivity in check. Higher temperatures make both the desirable epoxidation and the unfavourable ring-opening reactions happen faster. This means that it's very crucial to keep the temperature just right.

C. Oligomerization and Estolide Formation

Oligomerization reactions are maybe the most advanced means to alter molecules. They make estolides by putting together chains of fatty acids to make lubricants that operate well at low temperatures and are more stable at high temperatures [44][3]. These branched ester structures mix the renewable nature of bio-based feedstocks with performance that is as good as or better than that of synthetic lubricants.The methods used to manufacture estolides depend a lot on the fatty acid content of the starting materials [3]. Carboxylic acid groups are added to double bonds in unsaturated fatty acids through olefin addition methods. This occurs through acid-catalyzed electrophilic addition processes. Saturated fatty acids require alternative pathways, typically including hydroxyl-functionalized intermediates that eventually undergo condensation reactions.

The reaction's parameters have a large effect on how well estolides are created and what they are like, thus they need to be carefully tuned [3]. Acid catalysts like perchloric or sulfuric acid speed up oligomerization when the temperature is between 80 and 120 °C. Perchloric acid systems are better for keeping products stable and are lighter in color than sulfuric acid systems. But because of safety worries about working with sulfuric acid systems, they are often suited for business use. The estolide number (EN) tells you how much oligomerization has happened, which has a direct effect on the properties of lubricants and how well they work [3]. Most programs perform best when the EN number is between 1.5 and 3.0. If the values are too high, the substance may become excessively thick or gel, which makes it less functional.

IV. CATALYST SYSTEMS AND PROCESS OPTIMIZATION

A. Homogeneous Catalysts and Mechanistic Considerations

Homogeneous catalysts are still the best choice for research and commercial usage of bio-lubricants because they are very active, very selective, and easy to use [3][15]. These catalysts are in the same phase as the reactants, which lets the molecules get close to each other and speeds up the reaction. This also makes the conversion more efficient, even when the conditions aren't too harsh.

Alkaline homogeneous catalysts, particularly sodium and potassium hydroxides and their corresponding alkoxides, have exceptional effectiveness in transesterification processes [3]. Sodium methoxide is the most active alkaline catalyst; under the ideal conditions, it changes 95% to 98% of its substrate in 30 to 60 minutes. Alkoxide ions that are extremely basic are very nucleophilic, which means they quickly target triglyceride carbonyl carbons, which makes ester exchange easier.

But alkaline catalysts are particularly sensitive to how much free fatty acids and water are in the feedstocks for waste frying oil [3]. When free fatty acids and basic catalysts react with each other, they create soap products that make it difficult to separate the products and make the catalysts less effective. When the water content is more than 0.3%, hydrolysis happens, which makes more free fatty acids. This can cause a chain reaction that makes the catalyst work even worse.

Some examples of acid homogeneous catalysts are sulfuric, hydrochloric, and phosphoric acids. They can handle a lot of free fatty acids and speed up both esterification and transesterification reactions at the same time [3]. Sulfuric acid is the most active mineral acid catalyst, but it normally takes 3 to 6 hours for the reaction to attain the right amount of conversion. In acid-catalyzed reactions, the carbonyl oxygen gets a proton, which makes it more electrophilic and easier for nucleophiles to attack.

Two-step techniques that use acid pre-treatment followed by alkaline transesterification make the most of both types of catalysts while limiting their downsides [26]. The first stage, acid-catalyzed esterification, decreases the amount of free fatty acids to less than 1%. This makes the succeeding processes operate well with alkaline catalysis. This approach produces a high overall convers

B. Heterogeneous Catalysts and Sustainability

Heterogeneous catalysts alleviate the challenges of separating and recovering reactants in homogeneous systems by being in different phases. This makes it easy to separate them by filtering or decanting [27][19]. Heterogeneous catalysts are normally less active than homogeneous ones, but they are better for reusability, less waste, and easier product purification, which can make the whole process cheaper.

Calcium oxide (CaO) is one of the most researched heterogeneous base catalysts for producing bio-lubricants [28]. Calcium oxide (CaO) is manufactured from cheap limestone or calcium compounds that are thrown away by factories. It works well for transesterification and can withstand more water and free fatty acids than other alkaline catalysts. This strategy is especially good for big projects because calcium supplies are inexpensive and easy to get.

When calcium carbonate breaks down into calcium oxide at 800–900 °C, it leaves behind relatively basic surface sites [28]. These fundamental sites prepare alcohol molecules to attack triglyceride molecules. But as they react with CO_2 in the air, CaO catalysts slowly lose their ability to work because they wash away active sites. It's crucial to know how catalysts stop working so that they can stay operating well.

Heterogeneous acid catalysts, including ion-exchange resins and solid acids, enhance the processing of high free fatty acid feedstocks while maintaining the separation advantages of heterogeneous systems [19][21]. Amberlite resins are great for both esterification and transesterification at the same time. They work like homogenous acids, but they are considerably easier to clean. Polymer matrices give catalysts a stable base and a lot of space to spread out across.

Zeolite-based catalysts are particularly stable at high temperatures and can choose the correct shape for manufacturing bio-lubricants [66]. The optimum Si/Al ratios in modified H-ZSM-5 perform great for esterification operations, giving 99% yield even at low temperatures. Microporous structures act like molecular sieves, which makes it easier to get the things you want and harder to make the things you don't want.

V. PROCESS INTENSIFICATION TECHNIQUES

A. Microwave-Assisted Processing Revolution

One of the most promising approaches to speed up the process of manufacturing bio-lubricants is to use microwaves. It has a lot of benefits, such speeding up the reaction pace, utilizing less energy, and making the product better [61][62][63].The quick temperature rise ensures heat is spread evenly. This speeds up reaction kinetics and cuts down on processing times, which can make a business a lot more profitable.

Dipolar rotation and ionic conduction in polar materials are what make microwave heating operate [62]. Because methanol and other alcohols used in transesterification are polar, they are highly good at absorbing microwaves. This makes the heat more concentrated, which speeds up the processes considerably faster than conventional heating can. This selective heating utilizes less energy than regular heating methods and makes processes work better.

Microwave-assisted transesterification of waste cooking oil is much faster, with response times falling from 60–120 minutes to 2–5 minutes while preserving the same or greater conversion rates [61][63]. Rapid heating makes the temperature in reaction mixtures more equal and gets rid of hot spots that could cause local overheating and product breakdown.

Research on process optimization indicates that the optimal microwave power densities for producing bio-lubricants range from 2 to 4 W/g [79]. When the power level is too high, it can cause too much heating and unwanted side effects. When the power level is too low, it doesn't speed up the process as much as normal processing. Pulsed microwave irradiation gives you more control over the speed of heating and the evenness of the temperature, which lets you fine-tune the conditions for processing.

When microwave heating is used with the best catalyst systems, the two technologies work together to make performance better than either one could do alone [63]. Heterogeneous catalysts perform better in a microwave because they have superior mass transfer and surface activation effects that get around the issues that solid catalysts normally have.

B. Ultrasonic Enhancement and Cavitation Effects

Another effective method for speeding up the production of bio-lubricants is ultrasonic irradiation. It works by employing sonic cavitation to speed up the movement of mass and produce high-energy regions in certain places [59][62]. In relatively small places, cavitation bubbles form and break down, generating conditions that are exceedingly extreme, with temperatures above 5000 K and pressures over 1000 atm.

The main benefits of ultrasonic processing are that it makes it much easier to mix reactants that don't combine and spread catalysts throughout reaction mixtures [59]. The manufacturing of bio-lubricants often requires complex multiphase systems in which oil, alcohol, and a catalyst must be very close to each other for the reaction to work well. Ultrasonic cavitation creates fine emulsions with a considerably greater interfacial area. This speeds up reaction rates and makes conversion more efficient.

It is very important to choose the proper frequency since it has a huge impact on how well cavitation works and how well the process works [59]. Ultrasound at low frequencies (20–40 kHz) creates cavitation bubbles that are bigger and break apart more forcefully. This makes the mechanical effects stronger, which helps with mixing and mass transmission. At higher frequencies (40–100 kHz), bubbles are formed that are smaller and more stable. This makes the treatment less harsh and helps retain the quality of the product.

To get the most out of a system without using too much energy or causing damage to the equipment, it is vitally crucial to optimize power density [59]. The optimal power levels for creating bio-lubricants are usually between 0.1 and 0.5 W/mL. This has enough cavitation intensity to work without making the product too hot or breaking up the emulsion, which could affect the quality of the product.

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VI.PROPERTIES AND PERFORMANCE EVALUATION

A. Physical Properties and Performance Metrics

The physical characteristics of bio-lubricants derived from spent cooking oil significantly influence their efficacy and applicability across several industries [30][33]. By understanding these properties and how they relate to molecule structure, it is feasible to make lubricants that match certain performance demands in a logical way. This makes it possible to enter new markets and use it in new ways.

Viscosity is perhaps the most significant thing that determines how well a lubricant functions. It has a direct impact on how well it can pump, how well it can create films, and how much energy it needs in mechanical systems [30]. At room temperature, bio-lubricants are usually thicker than mineral oils. For instance, the kinematic viscosity values range from 8 to 45 mm^2/s at 40°C, depending on the molecular structure and how much the chemical structure has been modified. This higher viscosity is usually good for border lubrication since thicker layers protect better.

Epoxidized bio-lubricants have a viscosity that is 20–40% higher than oils that haven't been modified. This is because polar interactions between epoxide groups and larger intermolecular forces [41]. Higher viscosity can make pumping harder in cold conditions, but it also makes it better at moving big loads and protecting against wear in harsh situations. Many users are fine with these trade-offs.

The viscosity index (VI) tells you how quickly viscosity changes when the temperature changes. Bio-lubricants are good at keeping temperatures stable, hence higher values are better [30]. The viscosity index (VI) of regular bio-lubricants is between 180 and 220, which is a lot higher than the VI of mineral oils (95–110) and synthetic hydrocarbons (120–140). This special feature lets it work as a lubricant at a wide range of temperatures without the need for expensive viscosity improver additives.

B. Tribological Performance Excellence

The tribological characteristics of bio-lubricants are what make them work as lubricants. They include lowering friction, keeping things from wearing out, and moving loads [30][33][40]. In real life, these features have a direct effect on how effectively equipment functions, how much energy it uses, and how often it needs to be maintained. This is why they are so vital for getting people to buy things and making them happy.

Tests of the coefficient of friction (COF) reveal that bio-lubricants always operate better than mineral oils when there is boundary lubrication [30][33]. The COF value for bio-lubricants is 0.08–0.12, while the value for regular lubricants is 0.12–0.16. Fatty acid esters have a polar nature that helps them cling to metal surfaces better. This creates boundary lubricating films that work better to cut down on friction and energy expenditure.

Standardized tests, such as four-ball wear and pin-on-disc tests, reveal that bio-lubricants are very good at preventing wear [40]. Wear scar widths that are usually 15–30% smaller than those of mineral oil controls suggest that the surface protection is superior. Chemical reactions with metal surfaces generate protective tribofilms that make materials less likely to wear down. Scientists are still trying to figure out how this works.

VII. ENVIRONMENTAL IMPACT AND LIFE CYCLE ASSESSMENT

A. Life Cycle Assessment Methodology

Life cycle assessment (LCA) provides a comprehensive methodology for evaluating the environmental impacts of bio-lubricant production from waste cooking oil throughout all stages of its life cycle [25][27][34]. The methodology encompasses the acquisition of raw materials, their transportation, processing, utilization, and eventual disposal at the conclusion of their lifecycle. This allows for a quantitative comparison with conventional petroleum-based alternatives, revealing both apparent and latent environmental advantages.

The definition of the functional unit has a big effect on the results of the LCA and how well studies can be compared [27]. The functional unit for most bio-lubricant life cycle assessments (LCAs) is one kilogram or one liter of finished lubricant. Other studies, on the other hand, utilize service-based metrics like lubricant-kilometers for cars. Using the same functional unit every time lets you compare research and technologies in a useful way, but you need to be careful to note any differences in performance.

B. Carbon Footprint Analysis

A carbon footprint assessment indicates that bio-lubricants emit significantly fewer greenhouse emissions compared to petroleum-based counterparts. Most of the time, the cuts are between 29% and 67%, however this depends on how they are made and the restrictions of the system [29]. These benefits stem from the fact that biomass feedstocks may be used again and again and don't normally need as much energy to process. Bio-lubricants grow increasingly tempting as carbon pricing schemes spread around the world.

VIII. COMMERCIAL APPLICATIONS AND MARKET ANALYSIS

A. Application Sectors

There are a lot of various ways that businesses can employ bio-lubricants generated from leftover cooking oil. Every industry has its own needs for performance, reasons for following the rules, and trends in adoption [66][68]. The biggest market category is automotive applications, which include engine oils, transmission fluids, hydraulic fluids, and gear lubricants [66][68]. The car industry is highly interesting because it is so vast and growing swiftly. Over 40 million metric tons of lubricants are utilized around the world every year. But bio-based solutions have a hard time entering into the market because of tight performance standards and OEM clearance processes.

B. Market Size and Growth Projections

The global market for bio-lubricants has developed quickly, growing from \$2.95 billion in 2024 to \$4.9 billion to \$7.2 billion by 2030–2033, with compound annual growth rates (CAGR) of 8.5% to 13.7% [66][68][77]. The general lubricants market only grows by approximately 2–3% per year, so this growth is far higher. This illustrates that the market really likes eco-friendly options, which is thanks to both legislative requirements and voluntary actions to be more environmentally friendly.

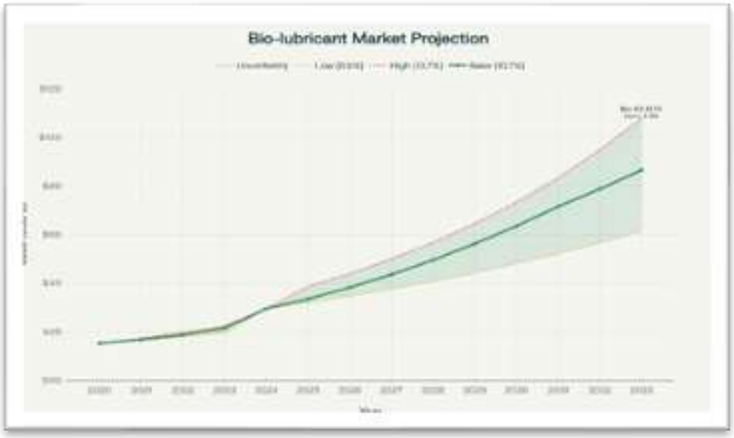

Figure 1. Biolube Market Projection in the next decade

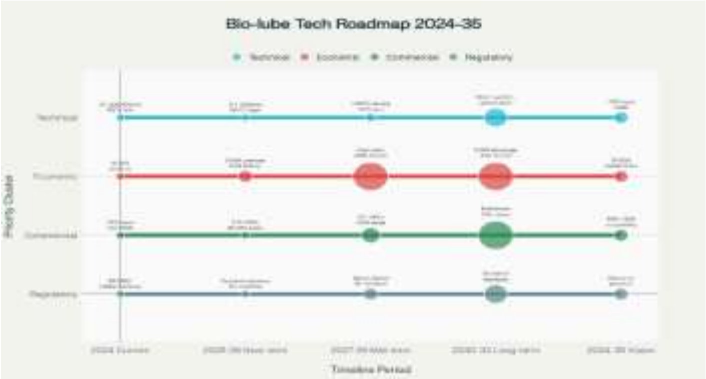

Figure 2. Biolube Technology road map till date

IX.REGULATORY FRAMEWORK AND STANDARDS

A. International Standards and Certification Programs

Bio-lubricants have a lot of laws that come from international standards, regional rules, and volunteer certification programs. These rules are aimed to make sure the products are high-quality, beneficial for the environment, and easy to find in stores [46][67][69]. These frameworks are vital for manufacturers because they help customers make smart choices and make sure that businesses meet the rules in different parts of the world.

The European Committee for Standardization (CEN) has developed tight requirements for bio-based lubricants through EN 16807. This standard sets out the rules and standards for putting bio-lubricants into groups [46][67]. According to ASTM D6866 or EN 16640, this standard states how to check for the minimum amount of bio-based carbon that must be present. The standard is what you need to do to obey the laws and make claims in European Union marketplaces.

X. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

A. Technical Challenges

Even though bio-lubricant technology has improved a lot, there are still some technical issues that stop it from being utilized by a lot of people and performing at its best [76][79]. We need to perform focused research and development in a number of areas, such chemistry, materials science, and engineering, to fix these challenges. In these sectors, it is tremendously helpful for academics and industry to work together. When utilized in high-temperature environments, bio-lubricants still have a lot of problems with thermal stability [76][79]. Epoxidation and branching are two chemical modifications that make bio-lubricants more resistant to heat and high temperatures. However, they still don't operate as well as synthetic hydrocarbons when the temperature climbs over 200°C. Ester linkages make it simpler for thermal breakdown to develop, which makes the viscosity go up and causes deposits to build up that could affect the performance of equipment.

B. Economic and Commercial Barriers

Bio-lubricants aren't used more often since they cost more to create, usually 30–40% more than ordinary lubricants [66][76]. There are many reasons why this is a bad deal, such as the high cost of feedstock, the difficulty of processing, and the limits of scale.

XI. CONCLUSION AND FUTURE

Making bio-lubricants from spent cooking oil is a terrific example of how protecting the environment, making scientific progress, and making money can all work together. This in-depth study demonstrates that we are at a pivotal juncture in the growth of lubrication technology, where long-lasting alternatives are expected to become economically viable.

The technical achievements documented in this evaluation demonstrate that critical scientific and engineering challenges have been largely overcome. Transesterification, epoxidation, and oligomerization are chemical modification methods that have gone from being interesting lab experiments to industrial processes that can make lubricants that often work better than traditional petroleum-based lubricants in important ways. Microwave and ultrasonic technology have been cost effective to factories.

The greatest news is that the market is doing well, with annual growth rates of 8.5% to 13.7%, which are far higher than the growth rates for the whole lubricants sector. Customers understand that bio-lubricants are better for the environment and often operate better. Regulatory frameworks are becoming more friendly to renewable alternatives, which should make them more widely used in various industries.

But there are still huge concerns that make people less hopeful. In many circumstances, it's still challenging to discover economic competitiveness because prices are 30–40% more than the norm for the market. Issues in the supply chain make it harder to use feedstock to its full potential, while issues with technology make it harder to use feedstock in the most challenging operating conditions. Researchers, corporations, and government officials all need to stay committed to solving these problems.

In the next ten years, bio-lubricants will undoubtedly go from being a promising choice to a common technology. For things to go well, catalyst systems, process optimization, and supply chain development need to keep growing better. New technologies that fix problems and cut costs could make people more willing to adopt them than we think is conceivable right now.

Bio-lubricants add more value to circular economy frameworks than just how well they operate as products. Waste-to-value conversion exemplifies resource efficiency principles and advances sustainable development objectives—qualities that are increasingly sought after as societies navigate resource limitations and environmental issues.

Research priorities should focus on disruptive technologies that address critical limitations. Changing chemicals in more advanced ways using controlled polymerization processes could lead to bio-lubricants that work better. Separation technology can help continuous production systems save a lot of money. You might have more possibilities for sourcing supplies and make the supply chain more stable if you develop alternative feedstocks.

In conclusion, bio-lubricants manufactured from recycled cooking oil are a well-known technology with clear business prospects and demonstrated benefits. There are still some challenges, but the mix of environmental benefits, government assistance, and better technology makes it probable that development and use will keep going. To be successful, you need to perform focused research to get around economic and technological barriers, build solid supply chains, and encourage people to buy your product. Bio-lubricants created from leftover cooking oil can assist the environment and the economy by turning waste into something valuable. All you need is the correct amount of money and determination. This shift is excellent for both businesses and the community.

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