A Review on New Trends, Challenges and Prospects of Ecofriendly Friendly Green Food-Grade Biolubricants

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Abstract: The standard operating procedure adopted to health and safety standards for food, beverage, and drug manufacturers are the most priority requirements to keep the business of feeding and healing society on the right track. Biolubricants used in particular should never be allowed to contaminate the raw materials, intermediates, and finished products. The consequences of biolubricant-contaminated products are rarely more acute than in the food processing industry. Therefore the food processing industry presents unique challenges to lubricant formulation engineers, lubricant marketers, plant lubrication engineers, and equipment designers. The food processing and pharmaceutical industries face additional challenges in selecting optimal food-grade biolubricants. Food-grade biolubricants used in these industries have specific requirements, protocols, and performance expectations that exceed typical industrial lubrications. Biolubricants formulated from biobased resources are a new trend in "green" food-grade biolubricants due to their low-cost renewable natural raw materials, biodegradability, environmental friendliness, low toxicity besides their excellent lubrication properties. In this review, the discussion will focus on the future trends, challenges, and prospects of green food-grade biolubricants applicable to the food, beverage, and drug manufacturing industries.

Keywords: biodegradability; chemical modifications; green food-grade biolubricants; non-toxic; plant oils resources.

1. Introduction

Most of the machinery used to prepare and process foodstuffs, cosmetics, tobacco products, animal feed, and pet food and pharmaceutical products require lubricants, greases, and oils for lubrication and heat transfer, power transmission, and corrosion protection of machinery, parts, equipment, and instruments. The industries require more stringent safety and purity specifications in their raw materials or in their final products [1]. Therefore incidental contact between lubricants and food products cannot always be prevented and may contaminate the food products. In all cases where the food products contact cannot be fully excluded, green food-grade biolubricants of known allergen status must be used [2]. The unique feature of the challenges requirements of the food processing industry has motivated the development of food-grade biolubricants. These food-grade biolubricants are formulated to minimize the risks associated with unavoidable and occasional trace contaminations in those final products. Well-defined regulations specify the standards for food-grade biolubricants in certain countries. A new international standard for food processing hygiene will encourage the more widespread regulation and use of "green" food-grade biolubricants throughout the world. Green food-grade

biolubricants should be produced only from biobased raw materials or natural plant oils. It contributes to a safer food supply and sustainable future for the industry. Green food-grade biolubricants must be constituted so that technically unavoidable residues in the processed product are innocuous for health, taste, and odor and do not negatively influence the final products. These food-grade biolubricants must withstand temporal, chemical, thermal and mechanical loads under expected operating conditions [3].

The global market for food-grade lubricants is projected to reach 64.5 kilotons by 2021, registering a compound annual growth rate (CAGR) of 6.7% from 2016. In terms of value, the market for food-grade lubricants is projected to grow at a CAGR of 7%, from the US $182.8 million in 2016 to $256.5 million by 2021 [4]. The demand for food-grade lubricants is extremely intense due to the exponential growth in healthcare, food processing and auxiliary industries such as packaging and leveling.

2. Food-Grade Biolubricants

A food-grade biolubricant is a lubricant used in food-processing areas where there is a possibility of incidental or direct food contact. Food-grade biolubricants protect against wear, friction, corrosion, and oxidation, dissipate heat, transfer power, offer compatibility with rubber and other sealing materials, and promote a sealing effect in some cases [5].

Typical lubrication requirements and challenges in the food and beverage industry include the following: Food-grade biolubricants need to withstand high temperatures prevent the entry of flour dust/salt, etc; Processed food materials are either acidic or alkaline, and lubricants need to be inert and should not affect their performance; Food-grade biolubricants need to meet the requirements of high-speed machinery in food processing and packaging; As there is the possibility of biolubricant getting in direct contact with the food being processed, lubricants need to physiologically harmless, odorless, tasteless, and colorless; Long-term lubrication is desired to ensure maximum productivity.

Furthermore, in different applications environment within the food and drugs business demand lubricants used should highly resist the degradation from the unexpected reaction toward food material or products, chemicals, water/steam. It's also must exhibit inert reaction toward plastics and elastomers container used [6]. The possibility for contamination in the food-products industry environment is even worse if the growth of microorganisms at processing conditions such as bacteria, yeast and fungi occurred. This is another aspect of important lubrication contamination that poses a risk to food-grade lubricants and in industrial environments to be taken into account.

Therefore the selection of appropriate biolubricants is essential for efficient and reliable processing operations [7].

The United State Department of Agriculture (USDA) created the food-grade designations H1, H2, and H3 based on the way they contact food [8]. These categories include as follows: H1 - Biolubricants with incidental food contact (so-called food-grade biolubricants). Lubricants and anti-rust agents or as release agents on gaskets or seals of the food processing tanks are permitted to contact food products. The possibility of incidental food contact is high; H2 – Biolubricants are not permitted to contact food products. The biolubricants are used externally for the lubrication and smoothing at the moving machinery parts; H3 – Soluble biolubricants oils. Biolubricants are permitted to make into contact with food products at certain processing parts such as at hooks and trolleys that can be wash by water or wipe out;

In food production, handling, processing, transport, storage, and sale, the factors contributing to generating human diseases after food consumption must be eliminated. This is why food companies carry out their inspections [9]. Within this self-controlled system, a hazard analysis and critical control point (HACCP) system that serves to identify, evaluate and control significant health hazards posed by foodstuffs are intended to avert the health risks that must be specifically addressed i.e., identified, evaluated, continuously detected and controlled. Accordingly, specific health hazards for consumers - chemical, physical and microbiological - must be identified, and the probability and significance of their occurrence must be assessed. Based on this analysis, the necessary preventive measures with which the identified hazards can be avoided, eliminated, or at least reduced to an acceptable extent must be determined [10]. Such a system is particularly applicable to operations with fixed, constantly repetitive workflows.

3. Food-Grade Biolubricant Trends and Challenges

There are many issues of deep concern when operating a food manufacturing or processing business. Lubricants are used in manufacturing important operational facilities to make them work perfectly and smoot moving, such as in mechanical motors, gears, bearings, conveyors, ovens, steamers, etc. However, the lubricants used can make their way into the final food products produced unintendedly. The lubricants oil and or grease droplets can seep away (seep out through a ball joint) from bearings and conveyors, can seamers, bakery ovens, and other critical points of operation. Lubricants can also be directly incorporated into food through leakage from gearboxes, seals, and shafts (gear lubricants). Foods contaminated with lubricants oil or non-food grade lubricants and grease resulted in food with off-odor and off-flavor. The food smelled of tar and contained very fine iron particles when a worn axle in a gearbox occurred. Plant quality managers and maintenance managers should identify areas of potential lubricant contamination for tight inspection and maintenance.

Despite the excellent properties of high-performance lubricants used on food machinery, food contamination from those lubricants is an ever-present threat. A major accident could cause a company to institute a massive recall that could be devastating to its brand reputation. Lubricant contamination has always been a major concern in the food and beverage processing industries. The lubricants must not pose any toxicity to the final food products or the environment via their biodegradability properties. It is essential for food and beverage companies to use food-grade biolubricants that comply with or exceed government standards and protect brand equity and the environment. Biodegradability is a trending feature of environmentally friendly food-grade biolubricants. The term biodegradability refers to the tendency for a biolubricant to be chemically decomposed in an acceptable time frame by naturally occurring bacteria in soil and water. The decomposing bacteria consume hydrocarbons present in the base oils and additives used in the biolubricant formulation. A series of chemical reactions is required to completely transform hydrocarbons into carbon dioxide (CO_2), which will later be absorbed by plants during photosynthesis, along with water and acceptable amounts of trace minerals. Biodegradation causes biolubricants to dissipate after being released into the environment. The level of contamination in soil is continuously monitored after a controlled release of biolubricant. Therefore, a quality food-grade biolubricant will add to company profitability by reducing maintenance costs and biolubricant consumption. Therefore, future trends in the food processing industry will focus on using 'green' food-grade biolubricants [11].

The term biolubricant has been ascribed to all lubricants derived from biobased raw materials such as plant oils, animal fats, or other environmentally benign hydrocarbons. Biolubricants are intended to be biodegradable and non-toxic to humans and other living organisms, particularly in aquatic environments where the impacts are more detrimental. In the global lubrication market, the rise of biolubricants results from new environmentally-friendly (green biolubricants) initiatives for protecting the environment from toxic substances. Plant oil-based biolubricants, which have existed for a long time, are renewable and mostly biodegradable and can be considered promising substitutes for conventional lubricants. However, the limitation of direct use as base oils due to their low oxidative, thermal and hydrolytic stability, a wider range of kinematic viscosities and poor low-temperature behaviors can be mitigated by specific chemical modifications, additive formulations, and blending with mineral oils. However, these mitigations resulted in some increased cost of production, toxicity, and decreased the biodegradability. Thus, developing a cost-effective biobased biolubricant with a revolutionary combination of biodegradability and high lubrication properties is a major challenge [12].

3.1. Sources of food-grade biolubricants.

Biolubricants are suitable for alternative energy applications because of their widespread sources. The types of biolubricant feedstocks may differ from country to country and highly depend on geographical locations. Biolubricants can be made from different crop oils. Although more than 350 oil-bearing crops are known, only palm, soybean, sunflower, coconut, safflower, rapeseed, cottonseed, and peanut oils are considered potential alternative biolubricants. Table 1 shows the oil content of specific non-edible and edible seeds with a high prospect to be used for biolubricants raw materials [13]. Palm oil, in particular, is the main feedstock for the production of food-grade biolubricants in Malaysia. Malaysian palm oil production contributes nearly half of the world's palm oil production annually. However, less than 10 percent of the annual production has been used for non-food products such as biolubricants and biodiesel. Moreover, soy, sunflowers, canola, corn oils have been used to formulate food-grade biolubricant in many European countries, Canada and USA.

Non-edible oils, however, such as *Jatropha*, castor, neem, rubber, jojoba, and karanja have received worldwide interest for the production of biolubricants in specific applications [14]. Nowadays, the separation technology has reached an advanced level to separate the minor or trace non-edible constituents from these oils. Therefore the oil derivatives such as their fatty acids and fatty acid methyl esters are plausible for producing food-grade biolubricants.

Table 1. The oil content of some non-edible and edible oil seeds.

No.	Non-edible seeds	Oil content (%)	Edible seeds	Oil content (%)
1	Rubber	40-50	Soy	18-23
2	Neem	30-50	Palm	30-60
3	Karanja	30-50	Peanut	45-55
4	Castor	45-60	Olive	45-70
5	Mahua	35-50	Corn	48-50
6	Linseed	35-45	Coconut	63-65
7	Moringa	20-36	Canola	35-50
8	Rapeseed	38-46	Sunflower	35-42
9	Jatropha	40-60	Cottonseed	15-20
10	Jojoba	45-60	Palm kernel	41-45

3.2. Physicochemical properties of food-grade biolubricants.

Biolubricating oils must pose specific properties that enhance their performance and suitability for various applications in the food industry. Some of these food-grade biolubricants properties are described below:

3.2.1. Oxidation stability.

Oxidation stability is an important trait in the field of lubrication and should be properly controlled. Oxidation or oxidative stability is the ability to prevent the oxidation process from forming its oxide derivatives. In general, oxidative stability increases when the temperature rises. Most contaminants and water presence, ruff metal surfaces, high temperature and pressure are major contributors to the oxidation process. The untreated oils with low oxidative will oxidize rapidly and turn thick due to the polymerizing process [15]. The oxidation stability of food-grade biolubricants is influenced by the level of unsaturated bonds. Biolubricants with a higher level of unsaturated fatty acids are more easily oxidized. The presence of a double bond in the carbon chain structure serves as an active area for the oxidation reaction. Thus, the more double bonds in the carbon chain of a food-grade biolubricant, the more susceptible the lubricant is to oxidation [16]. The amount and the composition of unsaturated fatty acids in food-grade biolubricants need to be in ratio balance with saturated fatty acid composition to produce suitable and required lubrication properties.

3.2.2. Hydrolytic stability.

The resistance of biolubricants to chemical attacks, whether H_2O is involved as a reactant or a product, is another parameter to be considered regarding food-grade biolubricant stability. Generally, food-grade biolubricants are formed by esters, which are prone to hydrolysis from their respective fatty acids and alcohol contents. The saturation ratio improves hydrolytic stability. Similarly, saturated dicarboxylic or fatty esters were shown to be highly stable due to steric effects [17]. The hydrolytic stability of food-grade biolubricants is boosted when short-chain alcohols are used in the construction of biolubricants molecules. This resistance can be further upgraded by using branched alcohols as in the main esters biolubricants structure. The use of glycerol as the alcohol-based in ester food-grade biolubricant results in poor hydrolytic stability due to the presence of β-H in the esters backbone. It is not comparable to that shown in monoesters biolubricant which formed by using branched structure alcohols.

By replacing glycerol with polyhydric alcohol results in high hydrolytic stability in food-grade biolubricants. Despite hydrolytic stability causing physicochemical food-grade biolubricant properties to deteriorate, this parameter is key to obtaining biolubricants with high biodegradability and fewer negative environmental effects.

3.2.3. Viscosity and viscosity index.

One of the most important properties of a food-grade biolubricant is viscosity, which expresses the resistance of a biolubricant to flow. Viscosity is directly related to temperature, pressure, and lubricant film thickness. High viscosity indicates a thicker lubricant film, and low viscosity suggests a thinner film. This is usually tested using the kinematic viscosity method based on ASTM D445, which is measured at 40 and 100°C. The viscosity index (VI) of a food-

grade biolubricant measures the change in the biolubricant viscosity with a change in its temperature. The viscosity of a biolubricant is inversely proportional to its temperature. Therefore, a machine that operates over a wide temperature range will require a food-grade biolubricant with a higher viscosity index. The higher the viscosity index, the lower the effect of temperature on the lubricating product's viscosity [18]. Furthermore, branching compound affects on the VI values, as increased branching favors a lower viscosity index, whereas the increased length of the carbon chain has an adverse effect by increasing the VI [19]. Given that, the food-grade biolubricant may be formulated by the combination of branched alcohol such as TMP and a short or medium chain of plant fatty acids.

3.2.4. Pour point.

The pour point (PP) is the lowest temperature at which liquid flows or pours. In biolubricants, the pour point is directly related to the viscosity index. The pour point is an important characteristic for equipment that operates in a cold environment or handles cold fluids [20]. The pour point of food-grade biolubricants should be low to prevent them from becoming solid/waxy in cold weather, especially in winter. To improve (lower) the pour point, a fatty acid with a shorter chain length and increased degree of branching alcohols can be applied. Diesters of fatty acids have excellent pour points for lubrication purposes, ranging between -70°C and -40°C, while polyol esters have to pour points ranging between -60 and -15°C [21]. Furthermore, the presence of -C=C- bonds decreases the pour point. However, these food-grade biolubricants are more susceptible to oxidation processes to oxidation processes. A suitable pour point is normally contributed by short aliphatic carbon chains saturated fatty acids. An increase in the aliphatic carbon chain's length causes a higher pour point due to increases in a more compact molecular arrangement. In-plant oils, the aliphatic chain of 16 and 18 saturated carbon atoms cause them to become solid at room temperature and suitable for grease. Whereas for unsaturated carbon chain causes them to be liquid. However, the position of the -C=C- unsaturated bond in the aliphatic carbons does not affect the pour point property. Its stereoisomer conformation greatly influences the pour point behavior either in *cis-* or *trans-* configuration form, whereas the -C=C- unsaturated bond position has a slight effect. The cis-configuration has been observed to have a lower pour point than hydrocarbons with *trans-* configuration chains [22]. Plant fatty acids' right and balanced composition is the key to achieving before the formulation of food-grade biolubricants has been made.

3.2.5. Flash point and fire point.

The flashpoint of a food-grade biolubricant is the lowest temperature at which the biolubricant oil can be ignited by an external source, while the fire point is the temperature at which biolubricant combustion can be sustained for at least five minutes after the ignition source has been removed [23]. Flash and fire points identify food-grade biolubricant volatility and fire-resistance properties. Both flash point and fire point measurements are based on the ASTM D92 method. Food-grade biolubricant should not formulate from the raw materials with a flash point lower than 38°C (100 F) due to safety handling issues. Thus, the flammability of the chosen raw materials for formulating food-grade biolubricant is determined by their flash point and fire point value [24].

3.2.6. Cloud point.

The cloud point (CP) is the temperature at which the first sign of wax formation for a food-grade biolubricant can be detected, i.e., the temperature at which the first sign of haziness is observed. The wax crystals formed can clog filters and openings, thereby leaving deposits on surfaces of equipment such as heat exchangers and increasing the viscosity of the food-grade biolubricant. To prevent filter clogging, the temperature must be maintained above the cloud point [25]. Food-grade biolubricant should be formulated from the raw materials with low cloud points by carefully choosing the right ratio between unsaturated and saturated fatty acids and alcohol.

3.2.7. Biodegradability.

Biodegradation materials by a biological process are one of among three important processes that convert or break down materials that enter into the environment. The other two processes are physical or weathering breakdown and chemical or sometimes referred to as photooxidation process. Biodegradation is the chemical breakdown or degradation of materials through biological means by living organisms or their enzymes in the optimal environment condition. The organisms play an important role in degradation, including bacteria, yeast, protozoans and fungi. The final breakdown materials molecules for nourishment are typically yielding clean carbon dioxide and water. Simple certain materials chemical structures such as aliphatic hydrocarbon esters are more susceptible to microbial breakdown compared to others. Plant oils and synthetic aliphatic esters are generally biodegradable more rapidly compared to any mineral oils under the same conditions due to their simple non-aromatic composition. Materials biodegradation can be occurred in both aerobic and anaerobic environments. In the environment where oxygen is present, an aerobic breakdown degradation will occur in soil or water, whereas where oxygen is absent, anaerobic breakdown degradation will occur in deep sediments or groundwater. In wastewater treatment plants successful biodegradation process is important to ensure the materials have been a breakdown into less toxic compounds. Therefore it required both aerobic and anaerobic processes to be involved efficiently. In contrast to other environmental processes, such as hydrolysis or photochemical reactions, materials break down is unique requiring specific degradation agents that the end product is often the complete conversion form of the simple organic or inorganic products such as carbon dioxide and water. The complete breakdown in biodegradation process is referred to as "ultimate biodegradation" or "ultimate mineralization." In general, a single alteration of the maternal materials compound dumped in the environment is sufficient for "primary break down". This is due to the biodegradation in natural environments is caused by the rigorous continuous actions of numerous microbial populations with different metabolic capabilities and efficiency. Thus, in the end, complete degradation is often can occur with time factors.

A food-grade biolubricant is classified as biodegradable if its percentage of degradation in a standard test exceeds a certain marked level [26]. In general, biolubricants based on plant oils exhibit better biodegradability follows by their derivatives, synthetic esters, other oils, and mineral oils, as shown in Table 2.

Table 2. Biodegradability of some lubricant base stocks.

Types of base stocks oil	Biodegradability (%)
Mineral oils	20-40
Polyalphaolefins	75-90

Types of base stocks oil	Biodegradability (%)
Waxier	70-95
Plant oils	90-98
Esters	75-100
Polyols	70-100
Trimelliates	0-70
Polyethylene glycols	70-80

Biodegradability is primarily influenced by the base oil of the biolubricant. It depends on the chemical structures of its organic compounds or oleochemicals. The chemical composition of a base oil change during the application of the biolubricant, that is, when it is introduced to factors such as air, temperature, metals, humidity, and pressure [27]. In other words, biodegradability hinges on how the chemical structure of the base oil changes during service [28]. The raw material used sustainability is determined based on its pollution properties and origin. The bio-based products are disintegrated completely into CO_2 and water after being discharged via several pathways at the end of their life span. Since equal amounts of CO_2 are released and taken up by plants in the atmosphere during the life cycle of oleochemicals, the carbon cycle of this product is said to be closed. That is, this product does not have any effect on the CO_2 balance in the atmosphere. In contrast, the opposite effect of mineral-oil-based products, which increases the CO_2 in the atmosphere and causes global warming [29]. Therefore, these products indirectly pollute the environment. Atmospheric CO_2 synthesized by the leaves of green plants is photosynthetically assimilated to make up part of the organic carbon loading in oleochemicals' lifecycle. The plants store excess energy from the organic molecules as oil. Hence, triacylglycerols can be extracted from the plant biomass directly. After an oil-splitting reaction, the ester bonds in the extracted triacylglycerols are hydrolytically cleaved, and alcohol glycerol and fatty acids are produced. The fatty acids and glycerol can be readily used or can undergo further oleochemical processing to form the raw materials for food-grade biolubricants. Once the end of life is reached, disposal of biolubricants will be done through discharge into the environment via wastewater (majority of instances), landfills (fewer instances), or burning (fewer instances). These biolubricants will disintegrate into CO_2 and water regardless of the discharge pathway taken. Microorganisms present in wastewater treatment plants or landfills or incineration will ensure that these biolubricants biodegrade. As the oleochemical carbon life cycle is closed, meaning that it does not affect the atmospheric carbon balance. Figure 1 shows the life cycle of biobased biolubricants in more detail.
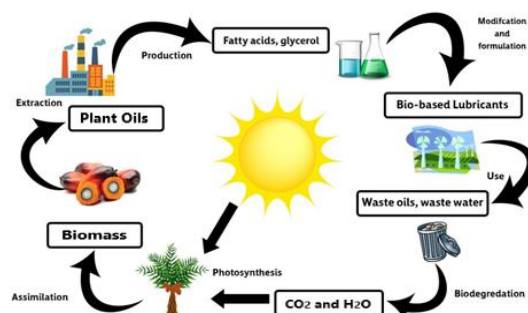
Figure 1. The life cycle of biolubricants.

3.2.8. Tribological properties.

Tribology is the science and engineering of the interactions between two surfaces in relative motion. Tribology includes the study of friction, lubrication, and wear, and it has

become the foundation for selecting suitable biolubricants for a particular application. Friction is the resistance to relative motion between two bodies in contact. It is not a material property but a system property. Wear is the gradual removal, damage, or displacement of material on solid surfaces. Biolubricant is the control medium for friction and wears by introducing a friction-reducing film between moving surfaces in contact. This protecting film normally depends on the biolubricant lubrication properties, has several functions, including reducing friction, preventing wear, protecting equipment from corrosion, controlling temperature and contamination, transmitting power, and providing a fluid seal [30].

3.2.8.1. Friction reduction capabilities.

It is known that plant oils provide good lubrication properties through their ester functionality. The polar head of the fatty ester chain attaches to the metal surface by a chemical process, which results in the formation of a monolayer film. The nonpolar end of the fatty acid chain points away from the metal surface, which reduces the coefficient of friction. Most studies have shown that even though crude plant oils improve the coefficient of friction and decrease the surface wear. The triacylglycerol structure provides desirable qualities for boundary lubrication because its long fatty acid chains are completely separated from its ester polar head. This results in a high-strength lubricating film. The protecting film interacts strongly with the metal surface, thus reducing friction and wear. Furthermore, most of the food-grade biolubricants produced from palm oil-based and their fatty acids derivatives have shown strong boundary lubrication properties. For example, the comparison of tribological properties of palm oil olein (POo) exhibits a low friction coefficient of 0.2 μ at 40°C and shows good friction coefficient of 1.2 μ at 100°C. This shows that POo has better lubrication properties even at high temperatures. On the other hand, coconut oil lauric acid derivative (dodecanedioic acid) based green food-grade biolubricant of di-2-ethyhexyl dodecanedioate (D2EHD) shows quite low friction coefficient of 0.11 μ at 40°C and 0.17 μ at 100°C [31].

3.2.9. Toxicity.

Toxicity is an important property when considering biolubricant usage. With up to 50% of all lubricants entering the environment via waste streams, spills, normal usage, and improper disposal, biolubricants can introduce toxicity to plants, animals, and humans. These effects are more severe in aquatic ecosystems due to their high sensitivity. The aquatic toxicity of lubricants to various species is measured using different standard test methods, as shown in Table 3. Food-grade biolubricants should not pose any toxicity to the final food products and the environment. This is necessary for the food processing industries to use the green food-grade biolubricant.

Table 3. International standard toxicological test methods.

Test Type	Species used	Standard test method and duration	Ref.
Short term tests (Acute tests)	Algae	72 h-OECD 201 (72 h)	[32]
	Daphnia	48 h-OECD 202/1 (48 h)	[33]
	Fish	96 h-OECD 203 (96 h)	[34]
	Bacteria	30 min -OECD 204 (30 min)	[35]
Long term tests (Chronic tests)	Daphnia	21 Days- OECD 202/2 (21 days)	[33]
	Fish	14 days-OECD 204 (14 days)	[35]

4. Development of Plant Oils as Base Stocks for Green Food-Grade Biolubricants

Plant oils are known as natural lubricants oil for many applications, including in food processing. However, food-grade biolubricants use in the food processing industry poses unique lubrication challenges. For example, large-scale food processing requires machinery such as pumps, mixers, tanks, hoses, pipes, chain drives, and conveyor belts. All the machinery used in food processing facilities faces many of the same tribological and lubrication challenges found in other non-food processing plants. Green food-grade biolubricants must offer similar protection levels for machinery internal moving metals surface to prevent friction, wear, corrosion, heat and corroded material deposits. They must also offer high oxidative, hydrolytic and thermal stabilizes with good pumpability at operational conditions. At certain specific applications within food and drug manufacturing facilities demand high-end green biolubricants. It resist degradation and performance well if in contact with food products, chemicals, water and steam, and bacteria. However, most of the raw materials used to formulate green food-grade biolubricants that effectively address these challenges in conventional industrial applications are not usable in food applications for safety reasons. Given these challenges, alternative safer raw materials must be used, such as cheaper and renewable ester compounds of plant oils. However, plant oils' drawbacks must be overcome if they are to be used directly as green food-grade biolubricants via low-cost and reliable modification processes. Plant oils are composed of triacylglycerols (TAGs) of fatty acids [36], as shown in Figure 2.
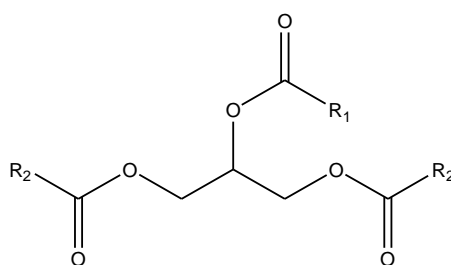
R$_1$, R$_2$, R$_3$= Acyl group (C$_8$- C$_{22}$)

Figure 2. Chemical structure of triacylglycerol.

A higher percentage of unsaturation leads to more environmentally acceptable plant oil biolubricants. Plant oils can be classified as edible or non-edible. The common edible oils are coconut, olive, soybean, sunflower, palm, peanut, canola, and corn oils. Since they are used for foods and formulate food-grade biolubricants, their demand is always very high. Their usages to produce non-food products are in adequate conflict of common interest. Therefore the non-edible oils have great advantages over edible oils to produce biolubricant. The non-edible plant oils, such as rubber, neem, castor, mahua, karanja, jatropha, linseed oils, etc., are comparatively less expensive and thus have a competitive advantage for the production of biolubricants. However, high-end and 'know how' technology formulation are required and needed to separate the unintended impurity before producing food-grade biolubricants [37].

The presence of an adsorbed surface film of long-chain and polar fatty acyl groups from plant oils on a sliding surface provides good boundary lubrication, thereby reducing friction and wear [38]. The use of plant oils for basestock lubricants offers several advantages. Table 4 summarizes some of the unique characteristics of plant oil base stocks for biolubricant.

Table 4. The characteristics and the benefits of plant oil as based stocks biolubricants.

Advantages characteristic	Benefits
Renewable natural resources	Sufficient supply, cheap materials, and environmental safe
High lubricity	Lower friction losses, better fuel consumption
Low volatility	Reduce exhaust emissions
High viscosity index	Use for wide temperature range biolubricants
High boiling temperatures	Less emissions and loss to the environment
High detergency	Eliminate the requirement of detergent additives
High flashpoints	Increase safety for operators and reduce risk of fire hazards
Non-toxic and rapid biodegradation	Reduce toxicological and environmental hazards/pollution
Oil mist and oil vapor reduction	Leads to less breathing of oil mist into the lungs
Good skin compatibility	High cleanliness and less dermatological at work place

4.1. Limitations of plant oils as base stocks for green food-grade biolubricants.

The use of plant oils for green food-grade biolubricants application is limited by their inherent properties [39], such as: Poor low-temperature properties due to the presence of saturated fatty acids; Poor hydrolytic stability, making them susceptible to hydrolysis in the presence of moisture, resulting in the formation of corrosive products; Limited resistance to oxidation due to the presence of mono- and polyunsaturated fatty acids in plant oils; Poor thermal stability and susceptibility to oxidation, restricting their use in their native form and limited to 150°C; Unpleasant odor, poor compatibility with paints and sealants, flushing propensity because of high viscosity, and filter-clogging tendencies;

These inherent properties of plant oils limit their applications, as base oils' choice requires meeting certain technical viabilities. These shortcomings can be overcome using different methods of modification, as listed in Table 5. Some of the development and modification processes toward plant oils to meet the requirement to have good lubrication properties are discussed in the following section.

Table 5. The available methods used for improving the lubrication properties of plant oils.

Process/Method	Remarks
Blending	- Mixing of two or more plant oils to achieve the required properties.
Fractionation	- Separating oils into two or more fractions depending on the end-use requirements.
Domestication of wild crops	- Conversion of wild crops to crops that can be cultivated commercially.
Genetic modification	- Modifying the crop by genetic engineering to get the desired properties.
Chemical modification	- Hydrogenation- increasing the saturation portion to increase desire properties. - Esterification/transesterification of fatty acids with different alcohol moiety. - Epoxidation, oxirane ring opening, esterification with different types of fatty acids. - Oxidation of unsaturation to produce dicarboxylic acids, esterification with different alcohol moiety. - Oligomerization/mild polymerization to produce estolide.

4.2. Genetic modification and modified cultivation of plant oils.

Genetic engineering has provided notable advances over the years and has benefited the agricultural sector to the maximum extent. The major advances are in terms of increased yield and resistance to herbicides. Genetic engineering has also been used to modify the fatty acid profiles of some plant oil crops for added value. The earliest report states that the genetic modification of rapeseed oil began in the late 1960s, and a new variant with a very low quantity of erucic acid (approximately 3%) was licensed in 1968. Other efforts were made to genetically modify various oil crops to suit the demands of industrial lubrication applications, including high oleic sunflower oil (HOSO), which contains over 90% oleic acid, which has excellent pour point property. Canola oil, a genetically modified version of rapeseed oil, has excellent oxidation stability, even without further modification, and is suitable for various biolubricant

applications [40]. Most of the plant oils with a high ratio of unsaturated fatty acids toward saturated fatty acids are suitable to be used as raw materials to formulate green food-grade biolubricants. For example, oils with strong boundary lubrication properties such as high oleic sunflower oil (HOSO), canola and palm olein are suitable raw materials for manufacturing green food-grade biolubricants [33].

4.3. Chemical modification of plant oils.

Biolubricant research has focused on solving the deficiencies of natural and synthetic oils while seeking to understand the relationship between chemical composition and molecular structure. For example, biolubricants synthesized from branched fatty acids such as isostearic acid exhibit superior low-temperature behavior, such as a low pour point, low viscosity, high chemical stability, and high flashpoint. Isostearic acid is procured from the thermal isomerization of polyunsaturated C_{18} fatty acids with subsequent hydrogenation. The branching points are limited to the interior portion of the molecule. Similarly, 12-hydroxystearic acid derived from ricinoleic acid by hydrogenation can also be used. As previously discussed, removing the double bonds and the glycerol molecules from the triacylglycerols enhances biolubricant performance [41]. The foregoing discussion on the development and enhancements of biolubricants provided an overview of the molecular structure and physical constraints that must be considered when evaluating their performance.

Plant oils' inherent limitations as biolubricants basestock can be overcome via several chemical manipulations and enhancement routes to improve their physicochemical properties, thereby maintaining and even improving specific properties for various applications. Some of the development of the chemical modifications of plant oils to produce relievable food-grade biolubricants are summarized below:

4.3.1. Esterification/transesterification reactions.

Plant oils are prone to oxidation in the acyl ester moieties of triacylglycerols or backbone of glycerol moiety. Transesterification reactions involve the glycerol moieties of the triacylglycerols being replaced by a long and/or branched-chain alcohol, while esterification reactions involve fatty acids of natural oils reacting with long-chain alcohols to form their respective esters for biolubricants application [42]. The esterification/transesterification reactions are carried out using mineral acids (HCl, H_2SO_4, or p-toluensulfonic acid). Despite the high yield of mineral oils, these processes also exhibit some drawbacks related to product separation and high acid corrosivity. Considering these disadvantages, heterogeneous mineral acids and solid catalysts were developed as sustainable alternatives to perform the esterification and transesterification processes. These reactions require basic catalysts such as calcium oxide, CaO to obtain full transesterification conversion. However, high temperatures are required to activate and catalyst regeneration steps [43]. The physicochemical and lubrication properties of synthetic esters biolubricants are directly related to the types of acids and alcohol used in the esterification/transesterification processes. In general, synthetic esters perform better lubrication properties compare to their respective plant oils or triacylglycerols. Thus, the respective synthetic esters exhibit good low-temperature behavior, high flash point, low volatility and high oxidative stability than their respective plant oils (Table 6).

Table 6. Physicochemical and lubrication properties of plant oils and their respective synthetic ester biolubricants.

Name	Viscosity @ 40 $^\circ$C (cSt)	Viscosity 100 @ $^\circ$C (cSt)	Viscosity index	Pour point ($^\circ$C)	Flash point ($^\circ$C)
Castor	220.6	19.72	220	-27	250
Castor/TMP	20.94	4.47	127	-	-
Castor (modified)	210	20.5	240	-53	270
Jatropha curcas	35.4	7.9	205	-6	186
Jatropha/TMP	43.9	8.71	180	-30	315
Palm	52.4	10.2	186	-5	-
Palm/TMP	47.9	9.0	176	-2	355
Palm Oil/TMP	61	14	158	8	290
Olive	39.62	8.24	190	-3	318
Olive/PE	63.08	12.00	190	-24	-
Rapeseed	45.60	10.07	180	-12	252
Rapeseed/alcohols	7.8–38.2	2.7–8.4	205–224	$^-$31.3 - $^-$18	-
Rubber	49	31.5	271	-30	281
Rubber/TMP	13.3	8.6	283	-40	310
Soybean	28.86	7.55	246	-9	325
Soybean/alcohols	10.3–432.7	3.0–34.4	45–195	-	-
Sunflower	40.05	8.65	206	-12	252
Sunflower/octanol	7.93	2.74	226	-3	-

Both acidic and basic catalysts are suitable to enhance the esterification and transesterification processes. Mineral acids such as HCl, H_2SO_4, or H_3PO_4 are widely used to catalyze esterification/transesterification reactions with good conversion. However, these acid-catalyzed processes promote disadvantages toward the corrosion of the reactor. The isolation and purification of the obtained biolubricants also become tedious jobs. Bearing in mind these factors, heterogeneous solid acid catalysts such as ion-exchange resins or oxides such as Al_2O_3, ZrO_2, TiO_2, Nb_2O_5, Ta_2O_5, WO_3, zeolites, and heteropolyacids have been proposed and reported as potential alternatives catalysts to replace traditional mineral acids [44]. However, the transesterification process under acidic conditions is rarely used for even commercial thought has been extensively studied at the laboratory scale. The use of basic catalysts for esterification/transesterification processes gives more insight and advantages. The use of alkalis or alkaline earth oxides, hydroxides, alkoxides, or carbonates have been reported to have higher yields, up to 98% in many cases with less catalyst and shorter reaction times than the solid acid catalysts [45]. Therefore base-catalyzed process has been adopted for commercial used. This is due to the advantages of base-catalyzed reaction proceed approximately 4000 times faster and requires lower temperatures.

4.3.2. Partial/selective hydrogenation.

The multiple double bonds in the plant oils increase their susceptibility toward oxidation attacks. The hydrogenation of plant oils is an important process in the oil and fat and oleochemical industries to modify the oil's physical characteristics for specific uses and increase its stability in terms of oxidation and decomposition [46]. Plant oils are complex mixtures of triacylglycerols with 12-22 carbon atoms, which may have 0-3 double bonds in each of the hydrocarbon chains [47]. By selective hydrogenation, unsaturated fatty acids can be transformed into single unsaturated fatty acids without increasing the substance's saturated part. Natural fats and oils often contain multiple unsaturated fatty acids, such as linoleic and linolenic acids, which seriously impair the oil's aging stability even if they are present in very small quantities. By selective hydrogenation, the easily oxidizable compounds are transformed into more stable components. This significantly improves the aging behavior of the oils and

promotes their use as biolubricants. It is desirable to selectively hydrogenate polyunsaturated acids to the monoenic level [48]. However, during hydrogenation, monoenic acids, originally present or formed as products, may isomerize to form *cis-* and *trans*-acids. *The cis*-isomer remains liquid at ambient temperature compared to the *trans*-isomer. The selective hydrogenation of plant oil must lead to a minimum of 80% *cis*-oleic acid to meet the industrial needs of biolubricants [49].

In the industrial hydrogenation process, nickel catalyst deposited on silica support is largely used [50]. The hydrogenation of different plant oils has also been commenced by using catalysts containing copper [51] or copper chromite [52]. These types of catalysts require above 150°C reaction temperature and high hydrogen pressure. Jovanovica *et al.* (1998) had performed the tallow hydrogenation and selective hydrogenation of sunflower seeds and soybean oil by using nickel catalyst supported on natural silicate diatomite [50].

The hydrogenation of palm olein at low temperature and pressure with sizes ranging from 1.3 to 3.0 nm polyvinyl pyrrolidone (PVP)-stabilized Pt colloids was reported as an effective catalyst [53]. They reported that the initial hydrogen consumption rate was high due to the hydrogenation of the linoleate and slowed down after that for the hydrogenation of oleate. The rate of the diene much more significantly influences the monoene by the particle size of the Pt clusters used. The higher the rate for the diene and hence the higher the selectivity for the smaller the average particle size of Pt. It was found to be due to the partial hydrogenation of the diene rather than the isomerization of the monoene in *trans*-isomer formation. In another report, Pt and Pd catalysts showed different hydrogenation rates toward the double bonds of polyunsaturated soybean oil by using PVP-stabilized Pt and Pd colloids (particle sizes ranging from 1.5 to 3.1 nm) as catalysts at 35°C and at atmospheric pressure. The Pt catalyst showed lower oleate selectivity, end up with higher yields of the saturated product but a lower percentage of the *trans*-isomer than the Pd catalyst [54]. The selectivity towards oleate increases while the selectivity and activity towards linoleate decrease with an increase in the mean particle size.

As an intermediate *trans*, *trans*-linoleate was detected for the Pt catalyst with a larger particle mean size. The continuous hydrogenation of sunflower seed oil was carried out in a novel three-phase catalytic membrane hydrogenation reactor by Veldsink (2001) [55]. The reactor consisted of Pd as the active catalyst impregnated in membrane provided a catalytic interface between the oil and the gas phase (H_2). It was found that the three-phase catalytic membrane reactor, intraparticle diffusion limitations and interfacial transport resistances did not impact the hydrogenation reaction. Instead, oleic and elaidic acid was not hydrogenated in the presence of linoleic acid over the Pd catalyst and under selective conditions. This is due to the hydrogenation process run under kinetically controlled conditions. The initial formation of stearic acid was caused by the direct conversion of linoleic acid into stearic acid by a shunt reaction.

The hydrogenation of various oil have been reported, and a summary has been presented in Table 7. The temperature and amount of catalyst used to increase the catalyst activity, selectivity, and *trans*-fatty acid content. However, its decreases with H_2 pressure and agitation. To improve the hydrogenation process, many critical factors need to be taken into accounts such as mass and heat transfers, the transport of H_2 and triacylglycerols to the catalyst surface, the efficient solubilization of hydrogen in the oil, the homogeneous distribution of the active catalyst throughout the reactor, and the available surface of the catalyst [56]. In tallying to the process conditions, the contributing to *trans*-fatty acid and saturated fatty acid production

ratio during hydrogenation is an important factor to be highlighted. The dispersed metal's choice of the solid support and its surface characteristics is important in the catalyst formulation. This is to avoid and minimize the side reaction occurring during catalytic hydrogenation by producing *trans*-fatty acids. The catalysts design with tailored characteristics producing higher selectivity toward saturated product formation instead of lower selectivity with *cis* configurations formation is important.
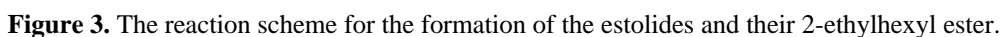
Table 7. Detail of hydrogenation of some plant oils by various researchers.

Oil	Catalyst	Temp.	Particle size	Pressure	Reaction time	Catalyst loading
Soybean	Ru nanoparticles	353 K	1.13-17.22 nm	1.5 MPa	12 h	-
Soybean	PVP-stabilized Pt and Pd colloids	35°C	1.5-3.1 nm	Atmospheric pressure	90 min	-
Palm olein	PVP-stabilized Pt colloids	5°C	1.4-2.9 nm	Atmospheric pressure	90 min	-
Edible vegetable	Supported nickel catalyst	150-160°C	-	-	-	-
Sunflower and soybean	Nickel catalyst supported on diatomite	195-200°C	-	1.5 Mpa	180 min	0.33 wt.%
Ethyl esters of sunflower	Pd/SiO$_2$ catalyst	40°C	0.10-0.04 mm	10 bar	-	0.3-1.5 wt.%
Rapeseed	Cu/SiO$_2$ catalyst	-	-	20 or 6 bar of H$_2$	-	8-9 wt.%
Sunflower	Novel three-phase catalytic membrane, Pd as the active catalyst	74°C	5 nm pores	5 bar H$_2$ pressure	-	-
Sunflower and canola	Pd/SiO$_2$ catalyst	110°C	6.8 nm pores	5 atm	60 min	1 wt.%

4.3.3. Oligomerization/estoloides.

Oligomerization is a modification of double bonds of unsaturated fatty acids that engage two or more fatty acid molecules attached to the residual alkyls. Estolides are oligomers and formed when one fatty acid links to the site of unsaturation of another fatty acid to form oligomeric esters. The secondary ester linkages formed are more stable toward hydrolysis than triacylglycerols (plant oils/fats), with better physical properties for use as food-grade biolubricants [57].

The estolide number (EN) is defined by the estolide molecule or the average number of fatty acids with repeating monomer units, *n* less than 10 [58]. A series of complex estolides based on oleic acid and saturated fatty acids (butyric through stearic acids) using 0.4 equivalents of perchloric acid at 45 or 55°C has been produced with yields varied between 45% and 65% after Kugelrohr distillation [59]. The EN was found to vary with reaction temperature and the type of saturated fatty acids. Estolide with higher degrees of oligomerization (EN = 3.3) is found for shorter saturated fatty acids of butyric and hexanoic acids. Whereas the lower degree of oligomerization for saturated stearic acid (EN = 1.4). These oleic acid-based estolides display better oxidative stability than plant oil-based fluids when blended with a small amount of oxidative stability packaging. Oleic acid with oleic or linoleic acids will react with each other at temperatures of 210-250°C in the presence of catalysts of layered aluminosilicate or montmorillonite, producing a complex mixture of C$_{36}$ dicarboxylic acids (dimeric fatty acids), C$_{54}$ trimer fatty acids, and C$_{18}$ monomer fatty acids [60]. When these oleic estolides were reacted with 2-ethylhexanol producing high yields of the resultant ester [61], as shown in Figure 3. The pour point of the estolide 2-ethylhexyl esters decreased to -39°C, as the carbon chain length of the saturated capping material increased from C-4 to C-10. The mid-chain saturated estolide 2-ethylhexyl esters of C-6 to C-14 showed superior pour point properties

compared to others. The viscosity index for the free acid estolides ranged from 122 to 155. On the other hand, the 2-ethylhexyl esters estolide had slightly higher indices ranging from 172 to 196. Therefore these estolide esters demonstrated superior pour point and were more suitable as a base stock for biodegradable biolubricants and functional fluids compare to the common commercial fluids.

Figure 3. The reaction scheme for the formation of the estolides and their 2-ethylhexyl ester.

Moreover, oleic acid and lauric acid were treated with perchloric acid at 60°C to produce complex estolides of 45-75% after purification by Kugelrohr distillation [62]. Further esterification of the saturated oleic estolides with 2-ethylhexanol was executed to obtain the analogous ester with high yields. The estolide number (EN) contributed an important role in viscosity; viscosity increased with higher EN. The free acid estolides were exhibited several hundred centistokes (141 to 170) more viscous than their resultant esters estolide 2-ethylhexyl (159 to 232 cSt). These new reasonably low-cost coco-oleic estolide esters exhibited superior pour point (-36°C) suitable as a base stock for biodegradable lubricants and functional fluids.

The oxidative stability has been estimated for both coconut-oleic estolide 2-ethylhexyl ester (coco) and oleic estolide 2ethylhexyl ester (oleic) by using a rotating bomb oxidative test (RBOT) [63].

Table 8. Physicochemical and lubrication properties of plant oils based estolides.

Name	Viscosity @ 40°C (cSt)	Viscosity @ 100°C (cSt)	Viscosity index	Pour point (°C)
Castor	220.6	19.72	220	-27
Estolide castor /2-ethylhexanol/lauric acid	51.4	9.99	183	-
Estolide castor /2-ethylhexanol/butanethiol	56.0	10.6	144	< -54
Olive	39.62	8.24	190	-3
Estolide olive	271.8-518.6	33.5-60.2	168-199	-
Estolide olive /2-ethylhexanol/linear alcohols	55.2-108.9	102.5-15.3	163-189	-33 to -9
Estolide olive /2-ethylhexanol/branched alcohols	62.5-209.3	11.1-29.9	149–192	-39 to -24
Sunflower	40.05	8.65	206	-12
Estolide sunflower	102.4-425.3	17.7-42.5	153-185	-

The oxidative stability was drastically increased for coconut-oleic estolide 2-ethylhexyl ester with 3.5% oxidative stability. However, the viscosity index (VI) of coconut-oleic estolide

2-ethylhexyl ester had slightly lower, ranging from 161 to 174 compared to oleic estolide 2-ethylhexyl ester ranged from 179 to 190. Never the less these two estolide esters have demonstrated far superior oxidative stability and are of reasonable cost. They were more suitable as a base stock for biodegradable lubricants and functional fluids than current commercial, plant-based materials. Generally, the obtained estolide has an improved lubricity, thermo-oxidative stability, viscosity index, and a decreased pour point as a biolubricant [64] (Table 8).

4.3.4. Epoxidation.

The number/degree of unsaturation in plant oils contributes an important role in oxidative stability. This unsaturation functionality is susceptible to hydrolytic degradation or thermo-degrade during the oxidation process [65]. The hydro-or/and thermo-oxidative stability and also other physicochemical properties can be enhanced through the chemical modifying process towards the alkene groups or by incorporating alkyl side chains [66]. The epoxidation is an important method of modifying unsaturation at -C=C- bonds to obtain food-grade biolubricants with optimal pour point, high oxidative stability and higher adsorption to metal surfaces, higher viscosity, better lubricity with high viscosity index [67]. Table 9 shows the physicochemical and lubrication properties of some modified epoxidized plant oils. The epoxidation of unsaturated bonds takes place via alkyl hydroperoxides, using peroxy acids, dioxiranes, or peracids as peroxide sources. To prevent the corrosive nature of the reaction medium's heterogeneous solid catalysts are used as sustainable mild alternatives catalysts in epoxidation process. Such suitable catalysts are acidic ion exchange resins or transition metal-based catalysts (TiO_2/SiO_2, $NbVO/SiO_2$, polyoxometalates, sulfated/SnO_2) [68].

Table 9. Physicochemical and lubrication properties of some modified epoxidized plant oils.

Name	Viscosity @ 40°C (cSt)	Viscosity @ 100°C (cSt)	Viscosity index	Pour point (°C)
Castor	220.6	19.72	220	-27
Epoxidized castor /acid	95.15	16.5	189	-26
Jatropha curcas	35.4	7.9	205	-6
Epoxidized *Jatropha curcas*/ Formic acid	146.15	10.2	139	0
Olive	39.62	8.24	190	-3
Epoxidized olive /acid	-	-	95-215	-11
Soybean	28.86	7.55	246	-9
Epoxidized soybean/alcohols	195.6-23.4	16.4-20.9	86-113	-18
Sunflower	40.05	8.65	206	-12
Epoxidized sunflower /acid	44.79	8.78	180	-9

The epoxidized oils products still display poor low-temperature properties; it is necessary to modify these epoxidized oils to improve their physicochemical and lubrication properties via esterification or re-esterification reactions or by alkylation, acylation, acyloxylation, amino alkylation, cooligomerization, hydroaminomethylation, or hydroformylation [69]. Figure 4 shows the use of epoxidized plant oils as starting materials to synthesize biolubricants with different physicochemical properties. Several authors have reported that these consecutive reactions improve low-temperature properties, lubricity, viscosity indexes, and thermo-oxidative stability and reduce the friction coefficient [70]. Both esterification and acetylation reactions were carried out using homogeneous acid catalysts (H_2SO_4) mixed with alcohols [71]. However, the potential side effect corrosion from the reaction medium has led to the use of solid acid catalysts such as cationic exchange resins or sulfated-SnO_2 for mild conditions of these reactions [68].
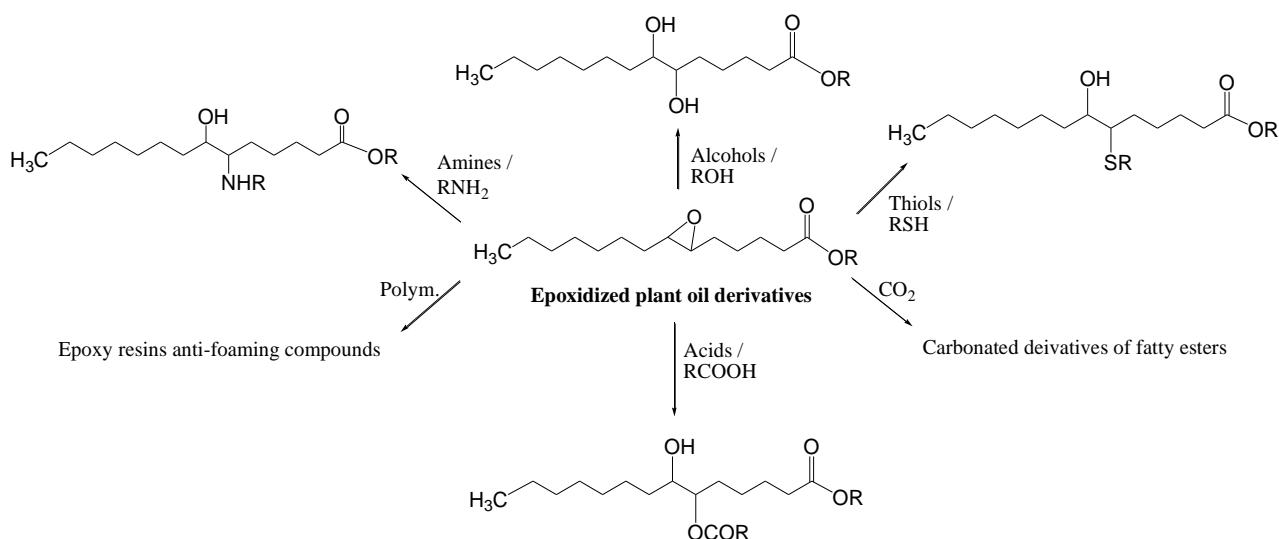
Figure 4. The epoxidized plant oils as starting materials to synthesize several biolubricants.
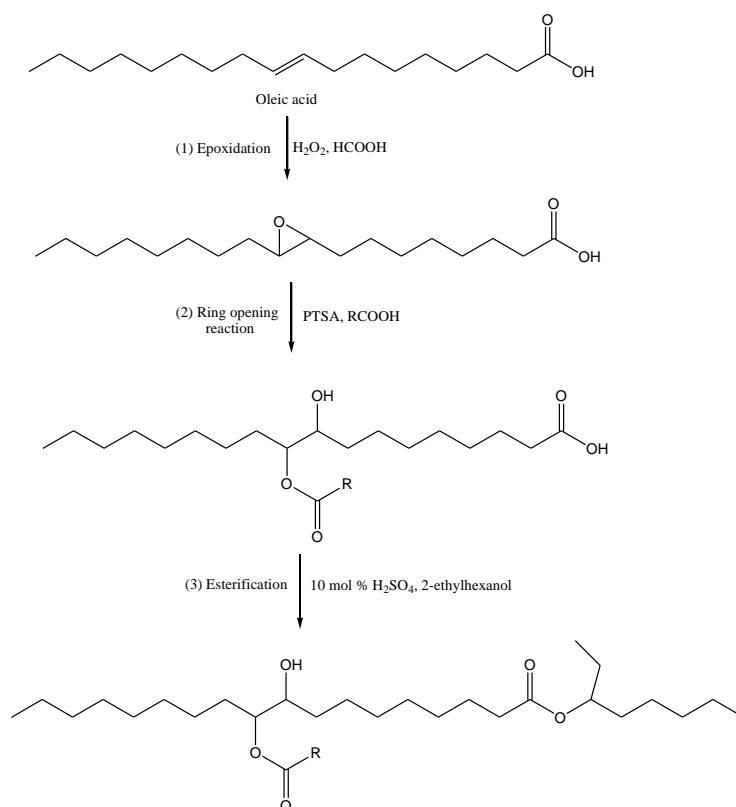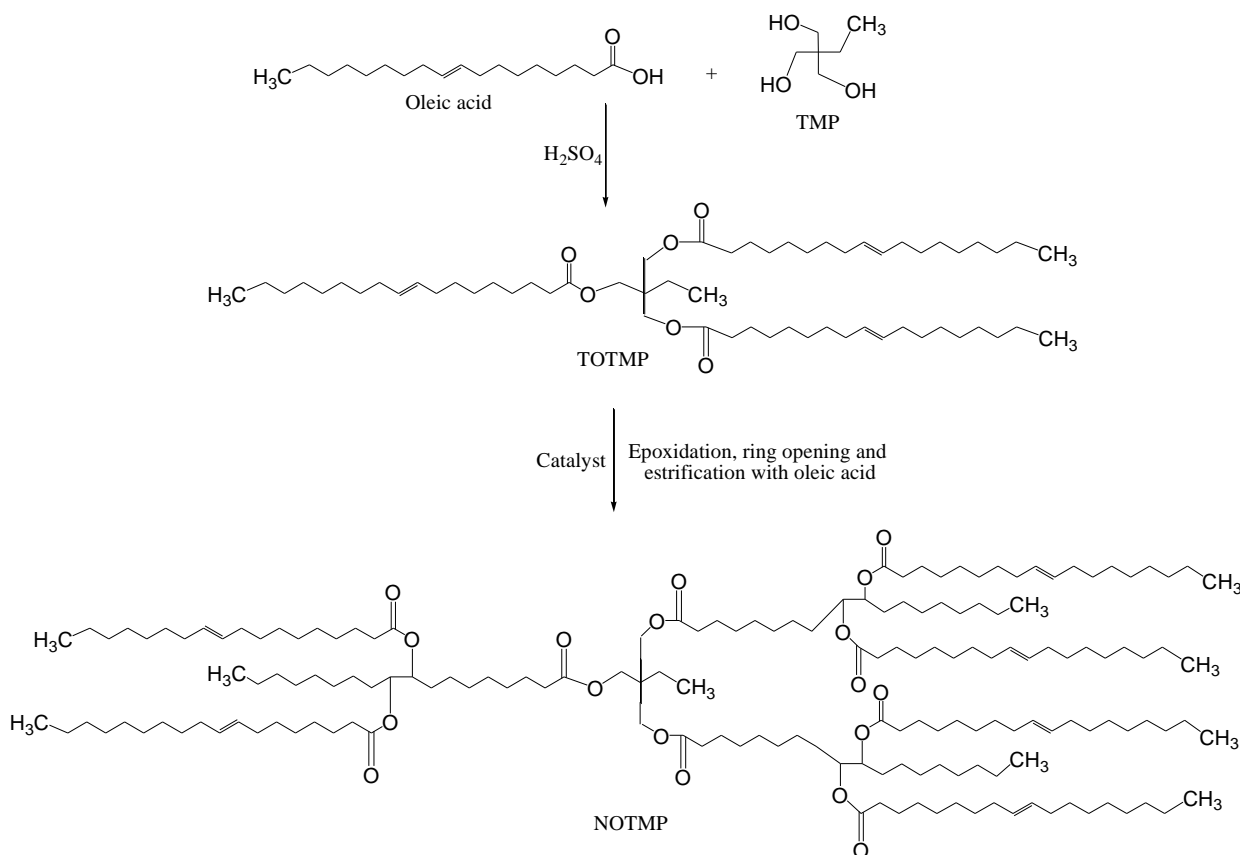

Figure 5. The modification processes of oleic acid by epoxidation, ring-opening, and esterification.

The unsaturation functional group points in plant oils or their fatty acid, such as oleic and linoleic acids, are interesting to start the modification process to produce biolubricants. Modification processes such as epoxidation, ring-opening with oleic acid, followed by esterification with branched alcohol to produce an excellent biolubricant have been reported [72]. Figure 5 shows the respective modification process. Introducing the mid-ester group and the branched ester group at the end of the biolubricant molecule reduces the pour point and increases the viscosity index properties. Another technique of modification of oleic acid's unsaturation was by the esterification of oleic acid with polyhydric alcohols such as trimethylopropane (TMP) to produce trioleate TMP (TOTMP). Further intensive modification of TOTMP by further reactions of epoxidation, ring-opening and esterification to produce even better biolubrication. Figure 6 shows the unique modification processes towards the oleic acid

to produce nonaolate TMP (NOTMP) food-grade biolubricants [34]. Therefore, thorough chemical modification reactions toward plant oils or plant oils derivatives are plausible for producing green food-grade biolubricants.

Figure 6. The oleic acid modification processes to produce food-grade biolubricant.

5. Green Food-Grade Biolubricants – Future Prospects

Future prospective green food-grade biolubricants must perform at par as normal lubricants. They must protect against wear, friction, corrosion, and oxidation besides dissipating heat and transfer power. They must also be compatible with rubber and other sealing materials and provide a sealing effect in some cases. Also, different applications within the food and drug industries demand that green food-grade biolubricants resist degradation from food products, chemicals, and water/steam and exhibit neutral behavior toward plastics and elastomers. These green food-grade biolubricants must also comply with food/health and safety regulations and be physiologically inert, tasteless, and odorless, and internationally approved. Green food-grade biolubricants can be subjected to intense environmental contaminants due to leakages from food products. Therefore, future green food-grade biolubricants should not pose toxicity issues. The growth of unexpected microorganisms such as bacteria, yeast, and fungi is another important aspect of lubrication contamination that poses a risk to green food-grade biolubricants. Therefore the green food-grade biolubricants should retain self-antimicrobial properties to overwhelm this condition. Since these can be a risk in industrial environments, the opportunity for contamination in the food production environment is even grander to be overcome. The green food-grade biolubricants must not pose any toxicity to the final food products or the environment via their biodegradability properties. Alternatively, safer raw materials must be used, cheaper and renewable ester compounds of the abundant plants' oil-based to produce "green food-grade biolubricants. Therefore, food and beverage companies

need to use green food-grade biolubricants in the future that not only are in compliance with or exceed government standards but also protect brand equity and the environment. Thus, developing cost-effective biobased green food-grade biolubricants with revolutionary combinations of high-end lubrication properties remains a major challenge and a motivating goal.

6. Conclusions

Beverage and food-associated processing plants, nowadays, are getting more progressive and efficient. Selecting and implementing premium quality green food-grade biolubricants are very important steps to ensure a safe working environment and products, efficient and hygienic processing facility. Green food-grade biolubricants used are designed to be resistant to a wide range of food materials, pH levels, metals, plastics, and other packaging containers. Therefore specially formulated green food-grade biolubricants are vital and produced in highly tailored, physiologically harmless, odorless, tasteless and colorless forms. Given these circumstances, recommended green food-grade biolubricants are obtained from plant oil-based biolubricants which are renewable, environmentally friendly, biodegradable, less toxic, and cheap in production.

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Conflicts of Interest

The authors declare no conflict of interest.

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