lubricants

Review

Plant-Based Oils for Sustainable Lubrication Solutions—Review

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Abstract: Traditional lubricants, often containing harmful chemicals and synthetic or fossil-derived oils, pose environmental risks by damaging ecosystems and threatening human health and wildlife. There is a growing demand for environmentally sustainable and cost-effective bio-based lubricants derived from renewable raw materials. These bio-based oils often possess natural lubricating properties, making them an attractive alternative to traditional synthetic lubricants. In addition to providing effective lubrication, they offer good biodegradability and minimal toxicity, which are essential for reducing environmental impact. However, the primary challenge lies in optimizing their performance to match or surpass that of conventional lubricants while ensuring they remain cost-effective and widely available. This paper reviews the general requirements for lubricants and explores how plant-based oils can be utilized to meet the diverse lubrication needs across various industries. Further, it highlights different approaches that can be used for further improvements in the area of plant-based lubrication through bio-inspired means, such as the use of estolides, wax esters, or erucic acid, as well as through additions of nanomaterials, such as nanoparticles, nanoclays, or two-dimensional films.

Keywords: lubricants; bio-oils; estolides; wax esters; biodegradability; 2D materials; nanomaterials

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1. Introduction

Introducing a liquid (oil) or semisolid (grease) lubricant into sliding contact is the commonly used and most effective method for reducing friction and wear and prolonging the lifetime of today's moving mechanical systems [1–5]. The use of various additives, such as ionic liquids or tribocatalytically-active nanopowders and coatings, helps to promote the lubrication characteristics of the oils further [6–8]. While being effective from the lubricative standpoint, synthetic lubricants are not appropriate for a range of bio-friendly applications (the food and medical industries) and become a cause for environmental and societal concerns [9,10]. The growing demand for enhanced environmental protection and alternative energy sources has spurred extensive research into using vegetable oils as lubricants for tribological applications [1,11–14].

Vegetable oils and their derivatives are being utilized as substitutes for petroleum oils to mitigate environmental impacts and create a renewable source of lubrication solutions [15–17]. Though the bio-based lubricants market share is currently small relative to the overall global lubricants market, with revenue of USD 2.13 B vs. USD 132.44 B in 2021, it is projected to grow at a higher rate to USD 3.05 B by 2030 [18], and even higher with new regulations [19].

The most common plant-based bio-lubricants currently adopted by the industry include castor oil, soybean oil, palm oil, rapeseed oil, and others [20–25]. Castor oil, for instance, is extensively used across industries for its high viscosity and the significant role of ricinoleic acid in its lubrication performance [26]. Castor oil has also been suggested as a base oil for making 100% biodegradable greases, and oleogels [27,28]. Other noteworthy plant-based oils include rapeseed oil, which improves the tribological performance of lubricants when used as an additive [24,27]. While these oils offer good lubrication properties, they are prone to oxidation and thermal instability compared to mineral oils, often leading to sticky residues upon degradation. Over time, there has been a shift towards plant-based lubricants as they offer a more sustainable and efficient source of renewable oils. Currently, due to the limited availability and higher cost of plant-based oils compared to mineral and synthetic oils, bio-oils are predominantly used in the food and pharmaceutical industries. Nevertheless, substantial efforts are being made to incorporate these bio-lubricants into machinery components.

Plant-based lubricants offer a range of characteristics comparable or superior to those of mineral and synthetic oils (Table 1). In general, they demonstrate good shear stability, comparable density, and miscibility with mineral and synthetic oils, which makes them suitable not only as base oils but also as additives to synthetic lubricants. At the same time, compared to mineral and synthetic oils, plant-based oils offer several benefits, such as reduced volatility, enhanced shear stability, superior lubricating properties, and a significantly higher viscosity index. Additionally, natural oils are less likely to interact with metals that are prone to oxidation and corrosion. As a result, they are actively explored for a range of applications, including in the automotive and manufacturing industries [29].

Table 1. Comparison of properties of mineral oils, synthetic (polyalphaolefin or PAO) oils, and plant-based (or vegetable) oils [30,31].

Property	Mineral Oils	Synthetic (PAO) Oils	Plant-Based Oils
Density, kg·m^{-3} at 20 °C	830 to 910	800 to 850	850 to 950
Viscosity index	100	120 to 140	100 to 200
Shear stability	Good	Good	Good
Pour point, °C	−15	−73 to −30	−20 to +10
Miscibility with mineral oils	n/a	Good	Good
Solubility in water	No	No	No
Oxidation stability	Good	Good	Moderate
Biodegradability	Poor	Moderate	Good

This article reviews the existing knowledge on the lubrication potential of various plant-based lubricants for their application in various automotive and manufacturing systems. For this purpose, the physicochemical characteristics of plant-based oils essential for lubrication performance are first summarized. Then, the state-of-the-art research on improving the lubrication properties of biolubricants is highlighted. This includes both the use of nature-guided modifications of the fatty acid structure and content, such as the addition of estolides, wax esters, or an increase in erucic acid concentration, and the addition of nanomaterials, such as nanoparticles, nanoclays, or two-dimensional (2D) materials, such as graphene, hexagonal boron nitride, metal dichalcogenides, etc.

2. Physicochemical Characteristics of Liquid Lubricants

Liquid lubricants are essential in industrial operations due to their ability to provide several tribological benefits [32,33]. They create a lubricating film that minimizes friction and wear by separating contacting surfaces, dissipates heat generated during friction, cleans and seals contact areas from contaminants, reduces vibrations and noise, and prevents corrosion by forming protective barriers on metallic surfaces [33–35].

Key properties of lubricants that are critical for efficient friction and wear reduction in tribological contacts include density (which affects the lubricant's ability to provide sufficient lubricative film thickness), viscosity (which determines the flow characteristics and resistance to motion within the lubricant), thermal conductivity (which influences the lubricant's ability to dissipate heat generated during movement), specific heat capacity (which affects the lubricant's ability to absorb heat), flash point (the temperature at which it produces vapor that can ignite), pour point (the lowest temperature at which the lubricant remains fluid), oxidative stability (which prevents degradation of the lubricant over time), and vapor pressure (which influences the evaporation rate of the lubricant) [33,36]. These properties influence the lubricant's ability to reduce friction, manage heat, maintain stability under varying temperatures, and protect surfaces from wear and corrosion.

This COF behavior for the lubricated contact can be described by the Stribeck curve (Figure 1), summarizing the coefficient of friction behavior as a function of the Hersey number or lubricant gap parameter.

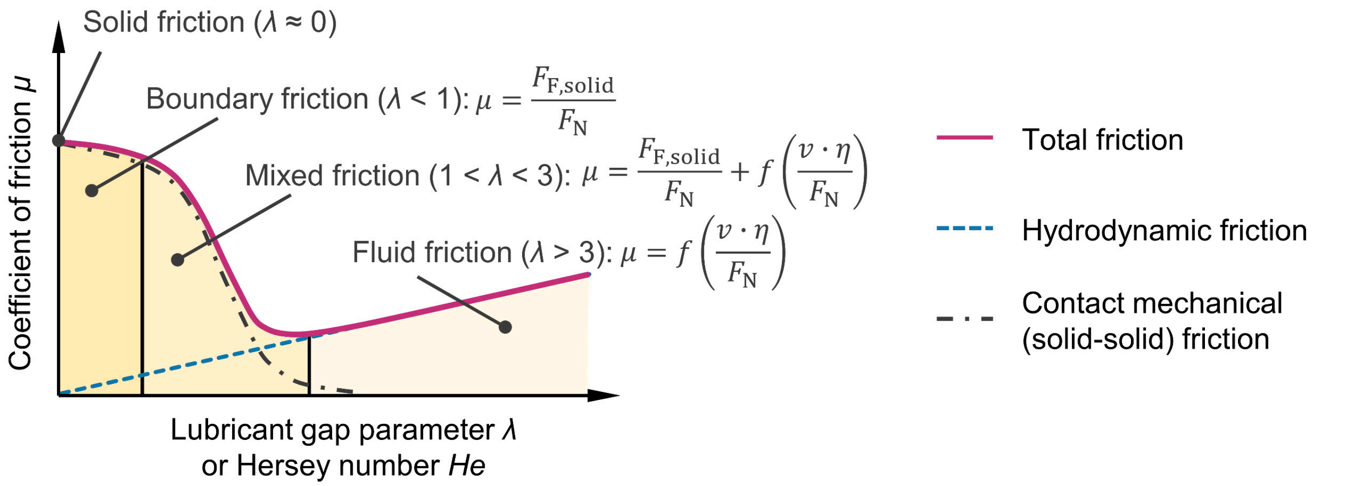


Figure 1. Stribeck curve describing the COF as a function of the Hersey number. The physical meaning of the Hersey number is the separation of two sliding surfaces provided by the thickness of the lubricating film. Reproduced with permission from [33].

Upon a decrease in the thickness of the film (decrease in Hersey number), one can expect a reduction in the thickness of the lubricating film. In this case, the system is in the regime of boundary lubrication (i) with direct contact created between the asperities. Once the thickness starts to increase (the Hersey number increases), the surfaces become partially separated by the fluid while some asperities still remain in contact, leading to a so-called regime of mixed lubrication (ii). Upon reaching elastohydrodynamic regime (iii), when the Hersey number approaches 1 (or ~1 μm in terms of the film thickness), the surfaces are completely separated by the fluid film, and the sliding is governed by the shearing between the liquid layers. With a further increase in the thickness of the film, the friction slightly increases as more energy is dissipated for moving the liquid in the hydrodynamic lubrication (iv) regime.

3. Plant-Based Oils and Their Evaluation

Numerous lubricants produced by the petroleum industry perform effectively in particular conditions. However, synthetic oils and their derivatives, while effective as lubricants, are often unsuitable from safety and compatibility viewpoints, especially when used in eco-friendly applications such as those in the food and medical industries, where cross-contamination can lead to negative health effects [37]. Consequently, there is an increasing demand for sustainable and cost-effective bio-based lubricants made from renewable raw materials. The growing concern about the potential release of non-biocompatible lubricants into the environment makes plant-based lubrication very attractive also for applications involving open systems, such as sawing and harvesting tools [19,38,39] or when operating in close proximity to marine and groundwater [40–42].

Nature has inspired the development of improved, more environmentally friendly lubricants. Plant-based lubricants can be divided into non-edible and edible oils (Table 2). Bio-lubricants contain fatty acids that form a thin protective film at the contact points between surfaces, reducing wear and improving oxidation resistance. Sourced from renewable materials, bio-lubricants are environmentally friendly, biodegradable, and have low toxicity for both ecosystems and humans.

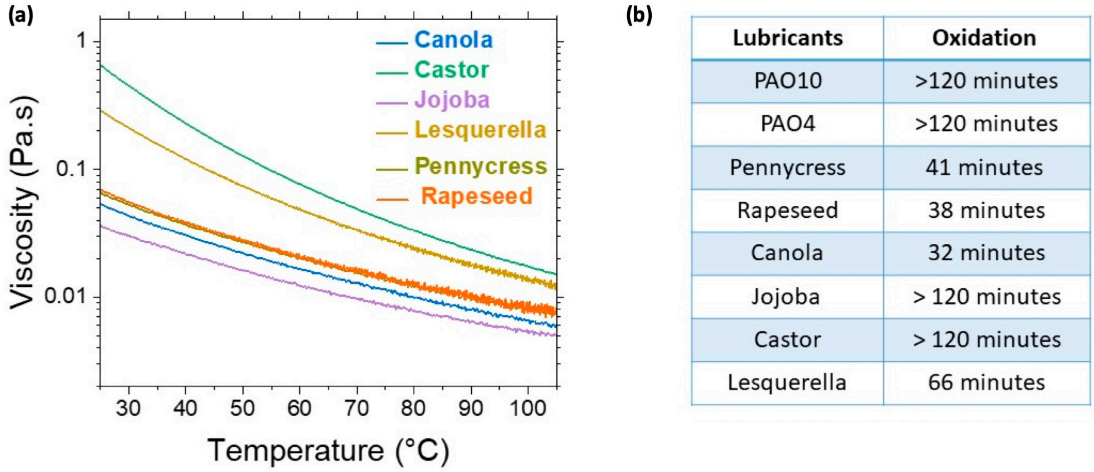
Table 2. Physicochemical properties of plant-based oils. Data adapted from [16,41,43–47].

Oil	Density at 25 °C, kg/m^3	Kinematic Viscosity at 40 °C, cSt	Oxidation Stability at 110 °C, h	Cloud Point, °C	Flash Point, °C
Non-edible oils					
Karanja	918	4.8	6	9	150
Castor	898	15.25	1.2	−14	260
Neem	885	5.2	7.2	−6	44
Jatropha	878	4.82	2.3	3	136
Tobacco	887	4.25	0.8	n/a	166
Mahua	850	3.4	n/a	n/a	210
Edible oils					
Coconut	805	2.75	35.4	0	325
Sunflower	878	4.45	0.9	3	252
Linseed	890	3.74	0.2	−4	178
Soybean	885	4.05	2.1	1	325
Peanut	882	4.92	2.1	5	177
Olive	892	4.52	3.4	n/a	318
Rice bran	886	4.95	0.5	0	318
Rape seed	880	4.45	7.5	−3	252
Palm	875	5.72	4.0	13	165

Prior studies tried to summarize the structural and functional characteristics of widely available biolubricants [10,46,48–50]. Figure 2 summarizes comparative studies for dynamic viscosity and oxidation induction time (OIT) at 120 °C for 2 h for a selection of bio-oils [51]. The typical trend of viscosity decrease with temperature increase was observed for all the samples. This is attributed to the increase in distance between the molecules that weakens the intermolecular forces and makes the resistance needed for the oil to change shape or movement lower at higher temperatures. Among the six oils, castor oil showed the highest viscosity, and jojoba oil showed the lowest viscosity at all temperatures. The viscosities of the bio-oil candidates studied in Figure 2 were, in general, higher than for the polyalphaolefin oil PAO4 (viscosity at 40 °C is 0.018 Pa s) but lower than PAO10 (viscosity at 40 °C is 0.0554 Pa s) baselines, with the exception of castor and Lesquerella [52]. This highlights that bio-oils, without any modifications, already offer a range of characteristics suitable for different applications. Under heavy loads, a higher viscosity is necessary to provide a superior hydrodynamic/hydrostatic lubricant film that protects the surface from wear and tear. Lower viscosity, meanwhile, is essential for easier flow and replenishment of the lubricants in low-load contacts.

Notably, both castor and jojoba oils demonstrated equally good oxidation resistance (>120 min at 120 °C) tested with Oxidation Induction Time (OIT) analysis (Figure 2b) [51]. This oxidation resistance is in line with the oxidation resistance of synthetic oils, PAO4 and PAO10. The rest of the oil samples—pennycress, rapeseed, canola, and Lesquerella—demonstrated much shorter OIT values, indicating their relative susceptibility to oxidation at 120 °C [51].

When tested at boundary lubrication regime [51], the wear rates of steel surfaces lubricated with rapeseed, jojoba, castor, or Lesquerella oils at 25 °C were significantly lower—by an order of magnitude—compared to those lubricated with synthetic PAO4 and PAO10 oils at the same temperature (Figure 3). Even as the temperature increased to 100 °C, the bio-oils outperformed the synthetic options, with rapeseed and castor oils demonstrating the lowest wear rates. At 150 °C, the wear rates for all oils decreased further. At 200 °C, rapeseed, jojoba, and PAO10 oils showed the best performance, exhibiting lower wear rates than the other oils, including PAO4.



Lubricants	Oxidation
PAO10	>120 minutes
PAO4	>120 minutes
Pennycress	41 minutes
Rapeseed	38 minutes
Canola	32 minutes
Jojoba	> 120 minutes
Castor	> 120 minutes
Lesquerella	66 minutes

Figure 2. (**a**) Dynamic viscosity analysis of bio-oil samples, (**b**) Oxidation Induction Time (OIT) analysis at 120 °C for 2 h. Adapted with permission from [51].

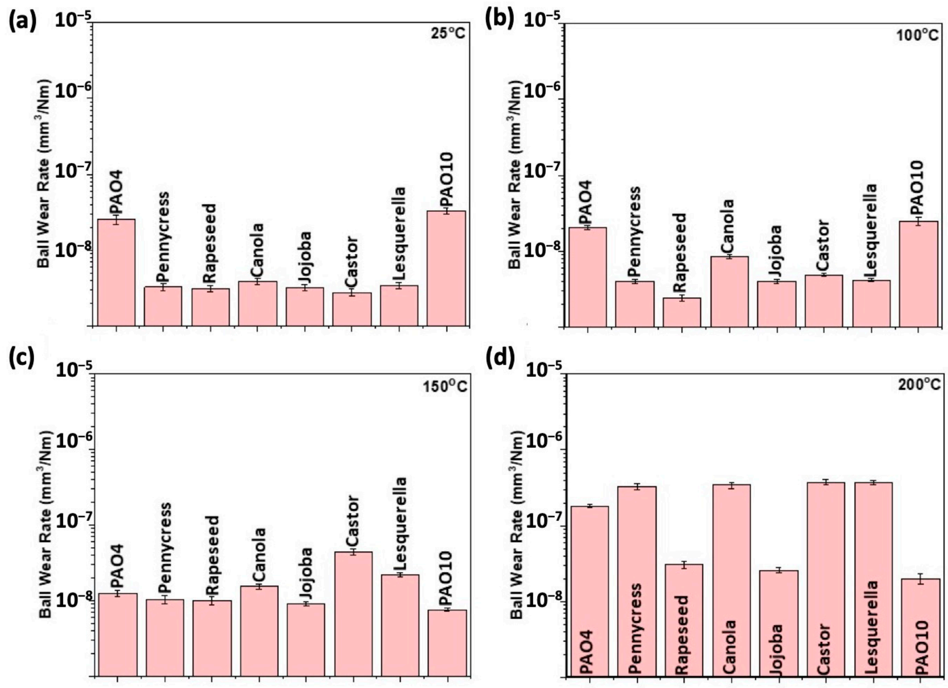


Figure 3. The ball wear rate of 52100 steel surface used in reciprocating tribology tests for the six bio-lubricants and synthetic oils at (**a**) 25 °C, (**b**) 100 °C, (**c**) 150 °C, (**d**) 200 °C. The tests were performed at a 10 N load. Reproduced with permission from [51].

These results suggested that, though unable to provide good thermal stability at elevated temperatures, bio-oils still can be very efficient for applications that are limited to lower temperatures [53,54]. Alternatively, their stability and lubrication characteristics can be improved by additional routes reviewed below.

4. Novel Approaches for Lubrication Property Improvements

Different approaches have been considered for a while to further enhance the lubrication characteristics of plant-based lubricants. Among them, the most common either focus on enhancing the natural lubricity of fatty acids through chemical (by chemically modifying the structure of esters) or biological (by modifying the plant genome to affect the resulting oil) routes or on adding lubrication-enhancing materials.

Recent research has highlighted the advantageous properties of certain lipid molecules. Most bio-lubricants are composed of fatty acid (FA) esters that form a thin film at the contact points between surfaces, thereby reducing wear and oxidation while extending the lifespan of lubricated surfaces. Specifically, it has been demonstrated that triacylglycerol (TAG), wax esters, and erucic acids, all containing long-chain fatty acids, enhance oxidation stability and lubrication efficiency. This understanding has facilitated advancements in designing bio-lubricants through genetic modification techniques.

Bio-lubricants offer a broad spectrum of physical and chemical characteristics, which can be further improved through additional treatments such as genetic modifications or synthetic alterations. In recent years, research aimed at understanding the performance origins of bio-lubricants has become more streamlined. Various studies have focused on the impact of long-chain molecules and their structures on the oxidation resistance and tribological performance of bio-lubricants. As a result, a number of approaches for improving the properties of bio-oils through enhancing their FA content have been proposed.

Alternative to nature-guided approaches, multiple studies have focused on enhancing the lubrication characteristics of bio-oils with the introduction of nanomaterials, such as two-dimensional (2D) materials (e.g., graphene), nanoclays (e.g., bentonite nanoclay), or nanoparticles (e.g., titanium oxide). While this route often implies the use of inorganic modifications, the selection of nanomaterials still allows for sustaining good biocompatibility of the bio-oils. Figure 4 summarizes the possible approaches for such improvements, which are evaluated in further detail below.

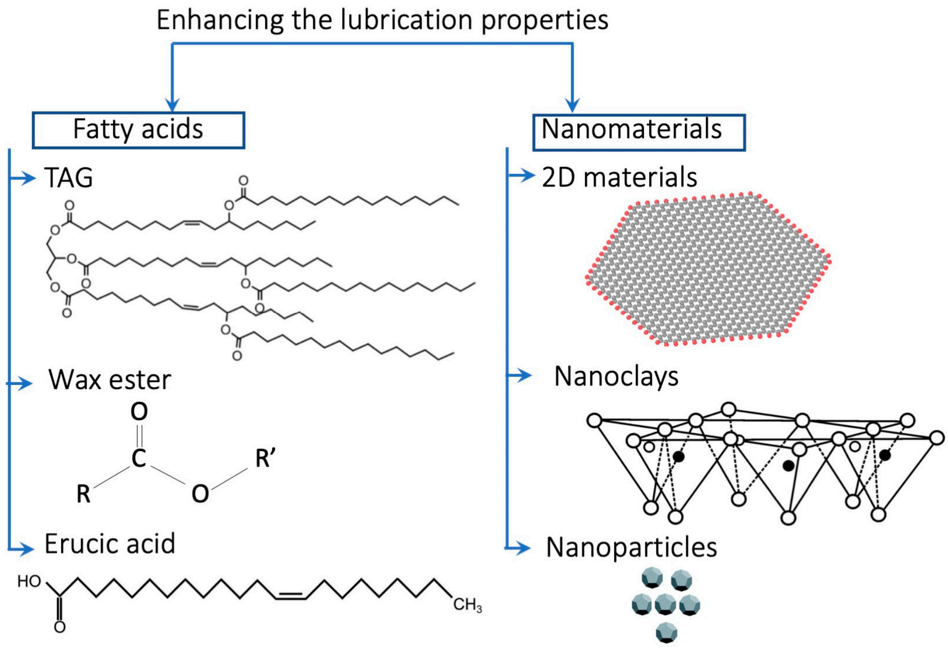


Figure 4. Approaches for improving the lubrication characteristics of plant-based lubricants reviewed below are divided into two groups, affecting the fatty acid structure through the introduction of TAG estolides (the example of TAG estolide from Orychophragmus violaceus seed oil is presented), wax esters, or erucic acid, and with the use of nanomaterials such as 2D materials, nanoclays, or nanoparticles.

4.1. TAG Estolides

Recent studies have reported the analysis of seed oil from Orychophragmus violaceus (OV), also known as the February orchid, which belongs to the Brassicaceae family [55,56]. This oil exhibits superior physical properties and shows promise in prototype lubricant formulations [55,56]. Previous studies have indicated that OV oil is, in major, made of natural estolides, triacylglycerol (TAG) estolides (Figure 4), known for their excellent lubricating qualities [57–59]. Additionally, the plant produces very long-chain di-hydroxy fatty acids, such as 7,18-OH C:24 fatty acids with one or two double bonds, through enzymatic processes. This contrasts with the shorter-chain hydroxy fatty acids (FAs) found in castor oil, which have only one hydroxyl group. Estolides are particularly valued for their outstanding oxidative stability, lubricity, and performance at low temperatures compared to other bio-based oils [55,60]. The beneficial effect of long-chain FAs has been seen when comparing canola and rapeseed oils [51], which are both composed of triacylglycerols. Rapeseed oil has a higher erucic acid content in comparison to canola oil, with higher polyunsaturated FA content. Since the erucic acid (22:1) is relatively more viscous than shorter-chain and polyunsaturated FA, it is believed to be responsible for overall better thermal stability and oxidation resistance of the rapeseed oil [51].

Identifying the estolide composition of O. violaceus oil has provided valuable insights for enhancing the lubricity of castor oil [60]. Specifically, Romsdahl et al. [60] demonstrated that while capped estolides or TAG estolides with nonhydroxy fatty acids (FAs) at the terminal ends reduced friction and wear of steel surfaces tested at room temperature, uncapped estolides, or TAG estolides with hydroxy FAs at the terminal end of the estolide branch chain, provided better lubrication characteristics at elevated temperatures [60]. By creating the oil blends with estolides, the lubrication properties of the castor oil were enhanced over a range of temperatures (Figure 5). Interestingly, the mass-spectroscopy analysis (ESI-MS) indicated the fragmentation onset only at 300 °C, suggesting the improved resistance of estolides to oxidation.

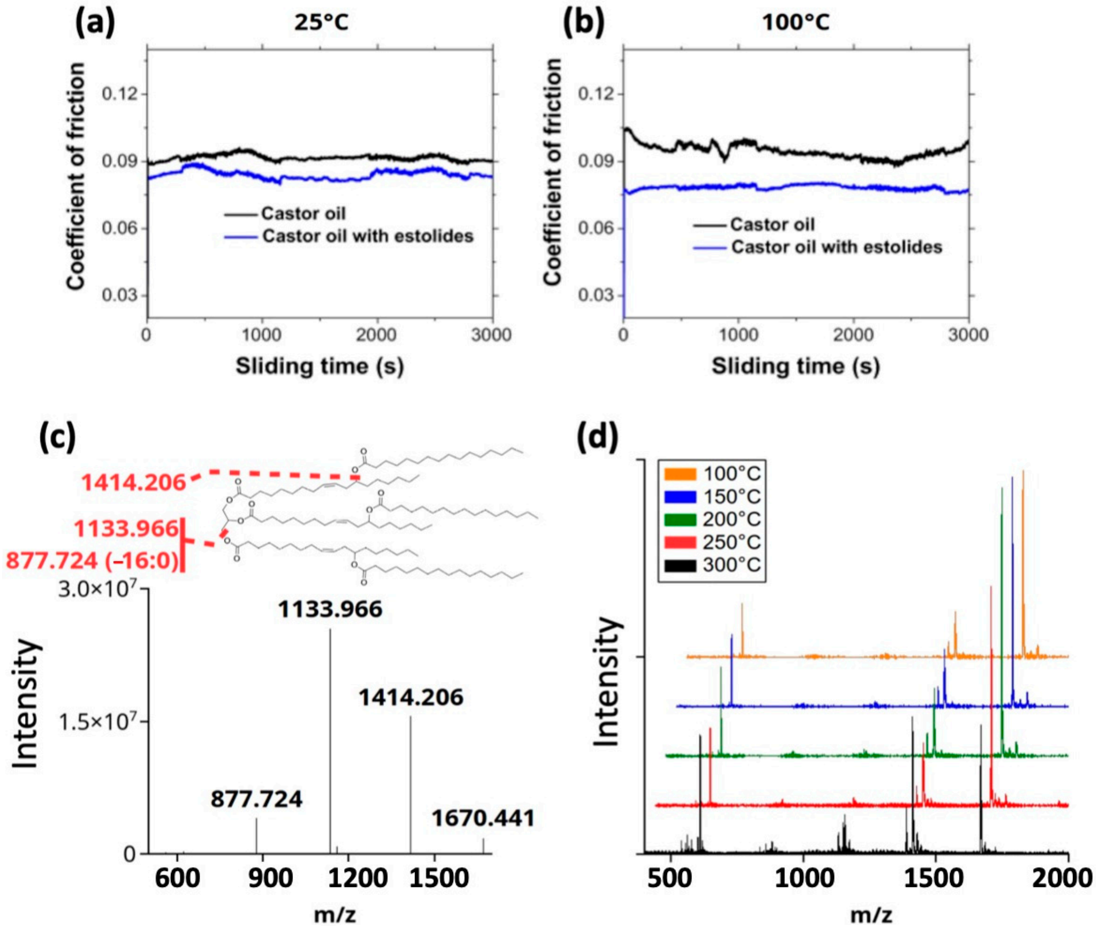


Figure 5. Lubrication properties of synthetic castor estolides. Coefficient of friction results for castor oil with estolides (blue) and unmodified castor oil (black) at 25 °C (**a**) and 100 °C (**b**). (**c**) MALDI–MS/MS confirmed the structure of synthetic castor estolides with esterified 16:0. (**d**) ESI-MS of synthetic castor estolides showed fragmentation of the esterified 16:0, unlike the fragmentation of hydroxy TAG of unmodified castor oil. Adapted with permission from [60].

Under heavy loads, lubricants with higher viscosity are essential to create a robust hydrodynamic or hydrostatic film that protects surfaces from wear. Commercially available synthetic solutions, such as synthetic esters and estolides, can increase the base viscosity of both petroleum-based and biodegradable lubricants while maintaining sustainability [61–64]. However, producing these high-viscosity synthetics requires multiple petroleum resources, resulting in a higher carbon footprint and costly manufacturing processes. Consequently, they are typically reserved for high-value applications. Due to its impressive viscosity, OV oil offers a promising alternative for sufficient viscosity enhancement and superior lubricating performance, potentially replacing synthetic esters and estolides.

4.2. Wax Esters

Jojoba oil, commonly utilized in cosmetic and pharmaceutical applications [65], comprises highly stable liquid wax esters [66] predominantly made up of mono-unsaturated very long chain (VLC) fatty acids and fatty alcohols. VLC fatty acids and fatty alcohols add significantly to the oil's thermal and oxidative stability, enhancing its effectiveness and value as a bio-lubricant [67,68]. Unlike conventional vegetable oils, which are composed of triacylglycerols (TAG) with fatty acids attached to a glycerol backbone, wax esters in jojoba oil are formed by linking one fatty acid to one fatty alcohol via an ester bond [69]. This unique structure makes wax esters highly desirable for non-food applications, including cosmetics and personal-care products, due to their excellent lubricating properties [70]. However, their higher cost compared to conventional plant oils limits their use as lubricants and protective coatings [70,71]. Additionally, the inconsistent supply of jojoba-derived wax esters due to the plant's requirement for arid environments underscores the need for expanded bio-based wax ester production. Efforts to produce wax esters in genetically engineered oil crops have shown promise [72,73]. One alternative source is Crambe oil, which contains a high level of monounsaturated erucic acid and low levels of di- and tri-unsaturated fatty acids, making it suitable for various industrial applications, including lubrication [74]. Transgenic Crambe plants have now been developed to produce seeds with varying amounts of wax esters mixed with a larger proportion of TAG, providing a potential new source of bio-based lubricants [75].

The lubrication properties of conventional Crambe oil can be enhanced by incorporating wax esters purified from genetically modified Crambe seeds (Figure 6). In their study, Shirani et al. [76] reported that while no improvement was observed at room temperature, significant friction and wear reductions were reported at elevated temperatures. Specifically, it was shown that adding 15 wt% of wax esters to Crambe oil improves its temperature stability, as confirmed by tribology, QCM, and FTIR analyses. QCM studies show that at temperatures above 100 °C, the properties of the wax esters dominate, indicating higher stability and lower temperature sensitivity of the mixtures. This results in slower viscosity change rates and better mechanical resistance during heating, making the mixtures more effective as lubricants [76].

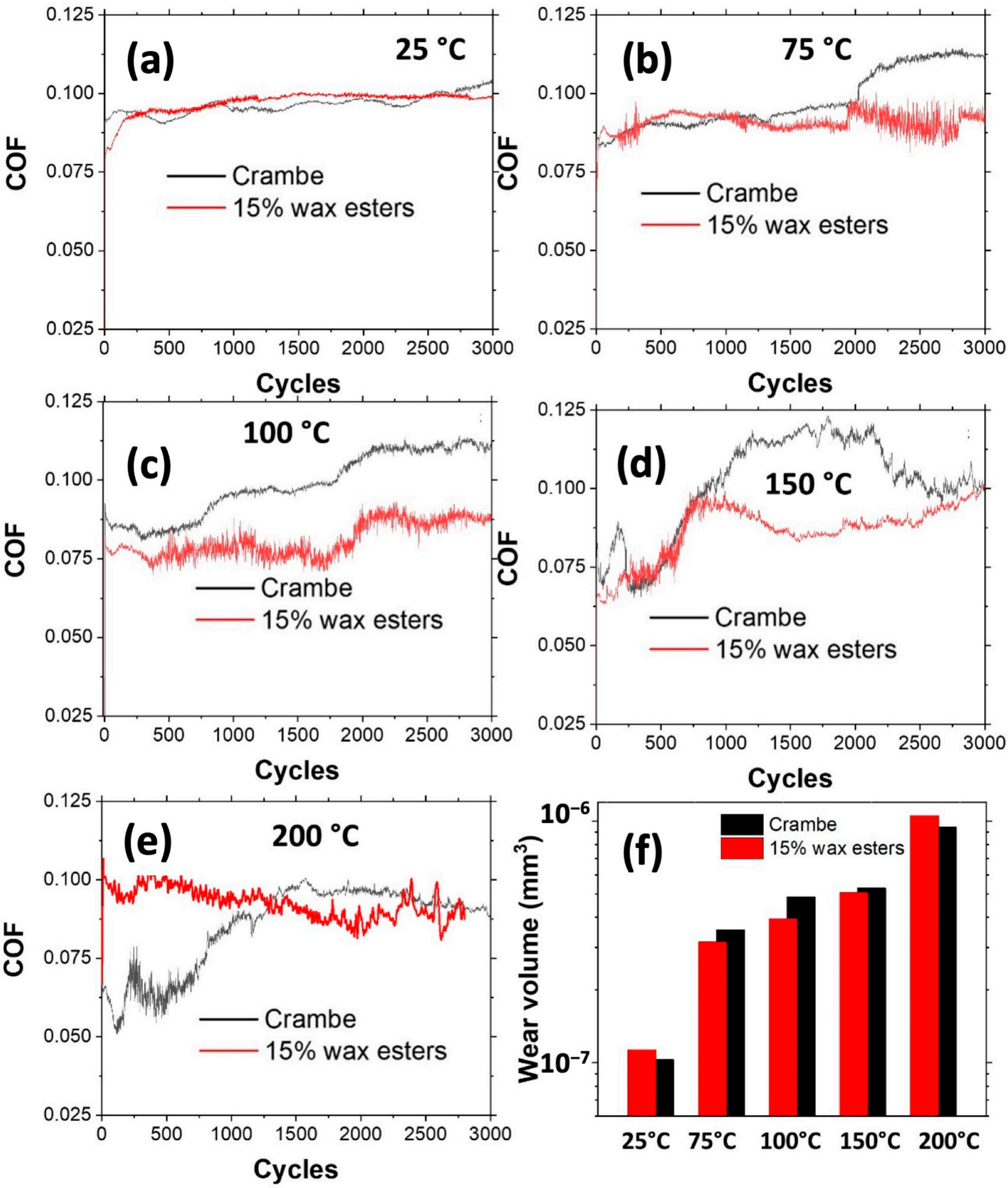


Figure 6. Coefficient of friction behavior for Crambe oil and Crambe oil with 15 wt% wax esters at (**a**) 25 °C, (**b**) 75 °C, (**c**) 100 °C, (**d**) 150 °C, (**e**) 200 °C and (**f**) the calculated wear volume based on the contact area over the counter body. Reproduced with permission from [76].

4.3. Erucic Acid

Another viable approach that was considered for improving the lubrication characteristics of plant-derived oils is related to genetically modifying the plants to affect the structure of the resulting oils. Prior studies [51] indicated that very long-chain fatty acids (VLC FAs), such as erucic acid and eicosenoic acid (C20:1 cis), may significantly enhance the lubricating properties of the oil. A comparison between the performance of wild-type pennycress oil, containing approximately 36% erucic acid and 10% eicosenoic acid, and the seed oil from the pennycress fatty acid elongase1 (fae1) mutant, which contains only 3% of these VLC FAs, suggested that an increase in VLC FAs content led to increases in both viscosity and oxidation induction time (OIT) values. As a result, the steel surfaces lubricated with oil with higher erucic acid content experienced lower friction and wear over a range of tested temperature conditions. Consequently, analysis of the wear tracks formed during the tests suggested that not only does the high erucic acid oil show a smaller degree of wear, but it also provides better protection of surfaces from oxidation, as confirmed by a lower O: Fe ratio.

4.4. Nanomaterials

Apart from the natural approaches for modifying the structure and properties of the bio-oils, nanomaterials offer a new perspective for improvement through the incorporation of nanoparticles, nanoclays, or 2D-material platelets [77–81]. Multiple studies demonstrated that the use of nanomaterials in biolubricants helps to improve their mechanical, thermal, and tribological properties, leading to more efficient friction and wear reduction, increased thermal stability, and enhanced oxidation resistance.

Among the nanoparticles dispersed in biolubricants, the most common are zinc oxide, aluminum oxide, silicon oxide, titanium dioxide, and zirconium dioxide [80,82,83]. Such selection is based not only on their lubrication enhancement potential but also on the requirement of minimum toxicity added to the biolubricants. In these cases, the improvements are observed at very low concentrations of additives. For example, the addition of titanium dioxide nanoparticles to palm oil biolubricant was optimized at 0.1 wt% [84], while the addition of zirconium dioxide to canola oil needed 0.5 wt% [85]. It should be noted that the size of added nanoparticles plays a crucial role in the performance of lubricants. As the nanoparticles usually aid in lubrication by reinforcing the surfaces and separating the contacting interfaces [86], their size should be comparable to the roughness of the lubricated components [87].

Another route suggested the use of nanoclays as dispersions in designing eco-friendly lubricants [88–91]. Specifically, Biswas et al. [91] evaluated the lubrication performance of sunflower oil reinforced with different concentrations of halloysite clay nanotubes. At low contact pressures, 1.5 wt.% of nanoclays in sunflower oil demonstrated the largest reduction in friction and wear, while at high pressures, the optimized concentration of nanoclays reduced to 0.05 wt.%, providing significant reductions in both friction and wear, and to 0.10 wt.%, increasing load-carrying capacity. In another study, halloysite clay nanotubes and montmorillonite nanoclay reduced friction and wear of corn and peanut oils, which was attributed to the smoothing of worn surfaces produced by the nanoclay additives [89]. Further, it was demonstrated that nanoclays can be combined with or replaced by nanocellulose to improve the yield stress of castor oil-based biolubricants under the varied electrical potential [90]. In addition to just serving as additives to oils, nanoclays demonstrated great promise as thickeners toward the design of biodegradable greases [92].

Special attention should be given to another class of nanomaterials that have been intensively studied over the last years as a potential additive to biolubricants: two-dimensional (2D) materials [93–96]. Significant advancements in synthesis and understanding of their structure–property relationships enabled the use of 2D nanomaterials, such as graphene, transition metal dichalcogenides, boron nitride, and MXenes, under a wider range of conditions [97–100], showcasing their significant potential in enhancing the friction and wear properties of various substrates. In lubricated conditions, 2D materials are often added to base oils to promote their lubrication characteristics within the contact area. During sliding, 2D materials act as shearing films or nano-roller bearings, potentially transforming the friction mode from sliding to rolling and regulating lubricant flow to reduce frictional losses. Further, 2D materials can initiate tribo-chemical reactions and form beneficial tribo-films in the contact area. These tribo-films may exhibit low shear resistance due to weak interlayer interactions, such as van der Waals or electrostatic forces, which allows them to transfer to the opposing surface and create a tribo-layer interface with improved frictional properties. When the oil supply is low, the presence of such tribo-films may help to prevent the onset of scuffing failure [101].

The use of 2D materials such as graphene has been evaluated for improving the lubrication characteristics of bio-oils as well. Mushtaq et al. [93] reported that the addition of 0.5 wt% of graphene to Jatropha oil resulted in ~44% decrease in both friction and wear rate of steel-on-steel tribo-pair, which was attributed to the formation of a protective graphene-rich tribo-layer on the sliding surfaces. In another study, the addition of graphene nanoplatelets helped to enhance the lubrication characteristics of palm oil-based biolubricants [96]. Omrani et al. [102] reported significant reductions in the coefficient of friction, up to 84%, for canola oil when adding less than 1.5 wt% of graphene nanoparticles. Since the prior work reported graphene to be non-toxic and safe for biomedical applications [103], its use is not expected to cause any biocompatibility or environmental friendliness concerns.

Overall, the prior studies suggest that nanomaterials demonstrate great promise as additives in biolubricants, enhancing their lubrication performance while maintaining low toxicity. These additives, even in small concentrations, significantly improve friction and wear characteristics, making them valuable for sustainable lubrication solutions. This provides an additional or alternative route to the chemical and metabolic engineering of plant-based lubricants, suggesting that environmentally friendly biolubricants can meet or exceed the performance of traditional lubricants.

5. Conclusions and Perspectives

Various vegetable oils, including rapeseed oil, palm oil, moringa oil, passionfruit oil, and rubber seed oil, have demonstrated outstanding performance when tested as hydraulic fluids [104–106]. Castor, palm, rapeseed, and coconut oils demonstrated performance similar to conventional oils in two- and four-stroke engines [107–109]. Meanwhile, soybean, Karanja, and coconut oil were reported to improve thermal stability and resistance to oxidation in metalworking fluids [110–112].

Vegetable oils typically exhibit lower oxidative stability compared to petroleum-based and synthetic oils, primarily due to the presence of unsaturated bonds in their carbon chains. This issue can be somewhat mitigated through chemical modifications that convert unsaturated fats into saturated ones or by adding antioxidant compounds. Recent studies suggest that the great oxidation resistance of some oil candidates, such as in particular OV oil that is superior to many other commercially available bio-oils, may offer a solution to the existing problem of bio-oil stability. Low oxidative stability of the oils can be suppressed by manipulating the structure of the oil, for example, by increasing the erucic acid content. Alternatively, the addition of synthetic esters or plant-derived wax esters can help to improve the friction and wear-reduction characteristics of biolubricants by increasing their thermal stability and resistance to oxidation.

With a wide range of plant-based oils currently under study and the ongoing expansion of the library of bio-based lubricants, these options may offer solutions to many critical industrial needs. In light of recent advances in environmentally friendly mechanical assemblies, such as electric vehicles [113], the search for new advanced lubrication solutions has become even more critical [114]. Toward this goal, not only nature-guided lubrication improvement solutions can be used, but alternative approaches, such as the use of nanoparticles, nanoclays, or 2D films, may further enable easier adaptation of lubrication from renewable resources.

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