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Assessing the Potential of Bio-Based Friction Modifiers for Food-Grade Lubrication

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Abstract: The objective of this research is to identify a bio-based friction modifier (FM) with tribological performance comparable to conventional FMs. Promising alternatives to conventional FMs, such as the FMs derived from natural sources, including rapeseed and salmon oil, were selected. Increasing concerns about crude oil prices, environmental impact, and the depletion of fossil resources have further fueled the search for renewable, biodegradable, and environmentally friendly raw materials for lubricants Tribological tests were conducted using a rheometer under non-conformal contact. The normal force, temperature, and sliding speed were varied to simulate conditions such as those found in a food extruder. To simulate cold extrusion applications, water and bio-based FM mixtures were used. The best-performing bio-based FMs were then mixed with a polyalphaolefin to simulate warm extrusion conditions. The results were compared to those obtained from mixtures of a polyalphaolefin and selected conventional FMs. The main finding of this study demonstrated that rapeseed and salmon oils, with a peak coefficient of friction (COF) of 0.16, are the best-performing bio-based FMs for reducing friction. When mixed with distilled water for cold extrusion (case 1) and with polyalphaolefin for warm extrusion (case 2), they performed similarly to the conventional FM, tallow amine, also with a maximum COF of 0.16, and significantly better than polyalphaolefin alone (maximum COF of 0.25). Consequently, rapeseed and salmon oils are suitable bio-based FM candidates to replace conventional FMs in food-grade lubrication.

Keywords: lubricant additives; friction modifiers; rheometer; sustainable; bio based; food-grade lubrication

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1. Introduction

By introducing the EU Ecolabel, the European Commission underlines the focus on using bio-based lubricants [1,2]. Lubricants aim to control friction and wear between rubbing surfaces by supporting loads and removing heat and wear particles, therefore prolonging the system's durability [3]. They consist of a mixture of base oil and additives, the latter typically added in the range between 1 and 30% [4,5]. Additives can be distinguished by their different fields of application; for example, friction modifiers (FMs), antiwear (AW) and extreme pressure additives (EP), viscosity index improvers (VIs), antifoam agents, emulsifiers, detergents, and metal deactivators [6]. FMs aim to reduce friction, especially in boundary and mixed lubrication conditions [3], and work in conditions where AW and EP additives are not yet reactive [7]. In most applications, FM additives are easy-to-shear films that promote friction reduction. In fact, FMs enhance low-friction operation in machine components, which ultimately results in a reduced energy consumption, supporting the usage of sustainable lubrication.

Several types of FMs are used, with organic FMs (OFMs), including free fatty acids originating from vegetable oils and fats, oil-soluble organomolybdenum FMs (MoFMs), and functionalized polymers (PFMs) being the most common ones used recently. However, they are often hazardous for the environment [8]. The first PFMs were developed as viscosity modifiers. Later, their ability to reduce friction by their polar aminic group adsorbing on rubbing surfaces was realized [8]. Further development of the PFMs focused on friction, and their application remained in hydrodynamic and elastohydrodynamic lubrication [8]. The second commonly used FM group, MoFMs, act in extreme conditions (boundary lubrication and high loads) by forming nanocrystals of MoS2 [8]. The MoFMs are only efficient when used in combination with sulfur-containing additives, e.g., EP additives [8]. OFMs, e.g., oleamide, ricinoleic acid, and tallow amine, are amphiphilic molecules that form an adsorbed layer and have their working regime in boundary lubrication [8–11]. The European Chemicals Agency (ECHA) classifies oleamide as an aquatic toxicant in category 4, not requiring any hazard symbol [12,13].

Recent studies focused on the application of novel FMs such as borate esters. According to the European Chemicals Agency (ECHA), borate esters have a low toxicity and are flammable, ricinoleic acid methyl esters fall under aquatic toxicity category 2, and tallow amine falls under acute oral toxicity category 4 and acute aquatic toxicity category 1 [14]. Tallow amine serves as a surfactant in the broad-spectrum glyphosate-based herbicide "Roundup". This substance increases glyphosate's bioavailability and bioaccumulation [13,15].

More and more focus is being put on bio-based lubricants, which do not cause any harm to the environment [16]. The European Commission strongly supported this transition by introducing the EU Ecolabel for lubricants, where a minimum of 25% bio-based carbon content (according to EN 16807) is mandatory for the final product [17,18]. Sustainable lubrication may be achieved by the usage of bio-based natural products, such as plant-based oils, which provide an alternative to conventionally used base oils and additives [19]. There are also sustainable OFMs, with the first ones developed and used in the early 1920s [3]. These were free fatty acids obtained from animal fats and vegetable oils. Oleic acid and linoleic acid can be named as examples [3,13,20]. Nowadays, research mainly focuses on animal fats and vegetable oils, but not on animal oils, when searching for alternative lubrications [19,21]. Due to the different fatty acid profiles of animal fats and oils, this must be considered [22]. Moreover, limited studies on both vegetable oil-based and waste-derived biolubricants, due to their high prices, open the discussion of limited lubrications in water [23].

The usage of water instead of conventional oils as the base medium is gaining importance [24]. Bearings lubricated with water offer considerable benefits for energy efficiency, ecological sustainability, and environmental preservation, according to Xie et al. Consequently, they have already been implemented in water pumps and ships [13,25]. However, next to the expected instability of the bio-based FMs, there is the challenge of evaporation at elevated temperatures when using water-based lubrication [24]. If encountering high-temperature challenges with bio-based FM mixtures in water, potential solutions such as cooling systems or the use of a nitrogen atmosphere may be explored [13,26].

The contamination of food with lubricants is a pressing matter when introducing unharmful bio-based lubricants [27]. As food contact cannot be prevented, the usage of conventional lubricants, greases, and oils is replaced with bio-based lubricants [27]. Tribological studies showed satisfactory results for the application of lubricants in food production machineries, e.g., usage of castor oil, palm oil, and tropical coconut oil in comparison to dry aluminum alloy applications in backward cup extrusion [28]. This trend towards "green" food-grade lubricants is further supported by the low costs of their raw materials and their benign characteristics [27].

Tribological tests are essential to test the functionality of lubricants. OFMs such as oleic acid and glycerol monooleate were already tribologically studied using a ball-on-plates set-up (non-conformal contact), where the coefficient of friction decreased with increasing sliding speed [3,8]. Furthermore, vegetable greases and biopolymer greases were tribologically compared to commercial lubricating greases by using a ball-on-plates set-up [29,30]. An addition of at least 1% of the biopolymer polytetrafluoroethylene (PTFE) to a vegetable oil and lithium stearate mixture proved to significantly reduce the coefficient of friction [29]. Commonly, PTFE is used as an anti-corrosive and anti-adhesive material, being used in the bearings and sliding coatings of machines used in the food industry [29,31,32]. Biopolymer materials, including cellulose, lignin, and Hexamethylene diisocyanate (HMDI)-crosslinked lignocellulose materials, were utilized as lubricant additives. Due to their versatile structure, they are mainly used as ecofriendly thickeners in vegetable oils [17,30,33]. For railway applications, rapeseed oil was directly compared to widely used mineral-based lubricants, where its tribological performance indicated satisfactory results [34]. Further, polysaccharides such as alginic acid showed promising viscosity alteration properties [35] and microalgae could be used for lipid production due to their predominant synthesis of unsaturated fatty acids [13,36]. The oils from microalgae were already successfully used as lubricants when using, among other things, a pin-on-disc tribometer [37,38]. Algae are considered advantageous in comparison to biolubricants from different sources due to their ability to grow in, e.g., wastewater. Further, it would be interesting to see how the double transesterification technique alters the chain length and branching degree [39].

However, the tribological performance of bio-based additives for food-grade applications has not been sufficiently studied until now. For these reasons, this study aims at experimentally evaluating the bio-based FMs in terms of tribological performance. The laboratory test conditions were selected to simulate those of slow-speed components in the food industry, i.e., extruders or two-roll presses. Initial tests aimed to evaluate the different bio-based FMs in water lubrication. Further, the performances of the most effective bio-based additives were compared to those of conventional FMs in commonly used lubricants. This systematic assessment showed that bio-based additives such as rapeseed and salmon oil can be used as FMs in biolubricants (water) and perform similarly to the conventionally used FMs in conventional base oils for food industry-oriented applications.

2. Materials and Methods

2.1. Tribological Tests

The experimental tests were carried out using the tribological set-up of an MCR302 rheometer (Anton Paar GmbH, Graz, Austria), which consists of a ball-on-plates configuration (non-conformal contact, see Figure 1). The normal force (F_N) is applied on the rotating ball pressed against the steady plates, mounted at a 45° angle. The test temperature can be controlled in the range from −20 to 200 °C. The sliding speed of the 100Cr6 ball (6.35 mm radius R) can vary from 1×10^{8} to 1.41 m/s on the 1.4301 stainless steel plates ($15 \times 6 \times 3$ mm). The torque (T) on the rotating shaft is measured and used for calculating the coefficient of friction, abbreviated in this manuscript as COF:

$$COF = \frac{T}{F_N \times R}$$

The tribological tests were carried out at a constant temperature and load but varying sliding speeds (Stribeck curves). Different temperatures were tested depending on the lubricant (see Sections 2.1.1 and 2.1.2), whereas the normal load ($F_{N,Tribo}$) of 5 N per plate (F_N = 10.6 N) and the sliding speed between 1×10^{8} and 0.1 m/s (300 points with logarithmic steps) were utilized for all tribological tests. Every speed step in the Stribeck curve was maintained constant for 1 s, giving a total of 300 s for every Stribeck curve measurement.

Three repetitions on the same surfaces were carried out for each lubricant and amounts between 0.7 and 1 mL were utilized.

Note that the 1st run was considered as a run-in and not considered for the data evaluation. The results of the 2nd and 3rd runs were used for calculating the mean COF and the standard deviation values of the individual samples; see one example in Figure 2.

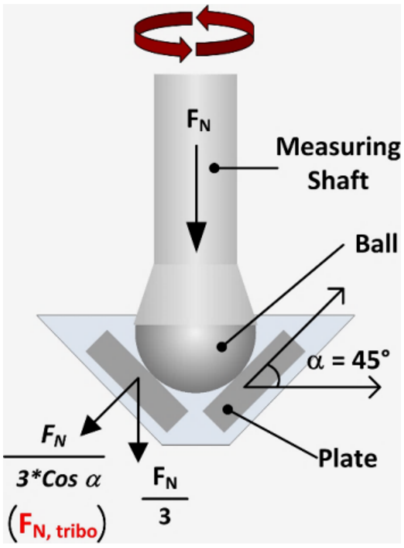

Figure 1. A schematic view of the ball-on-plates configuration of the MCR302 rheometer, Reprinted with permission from Anton Paar GmbH [40].

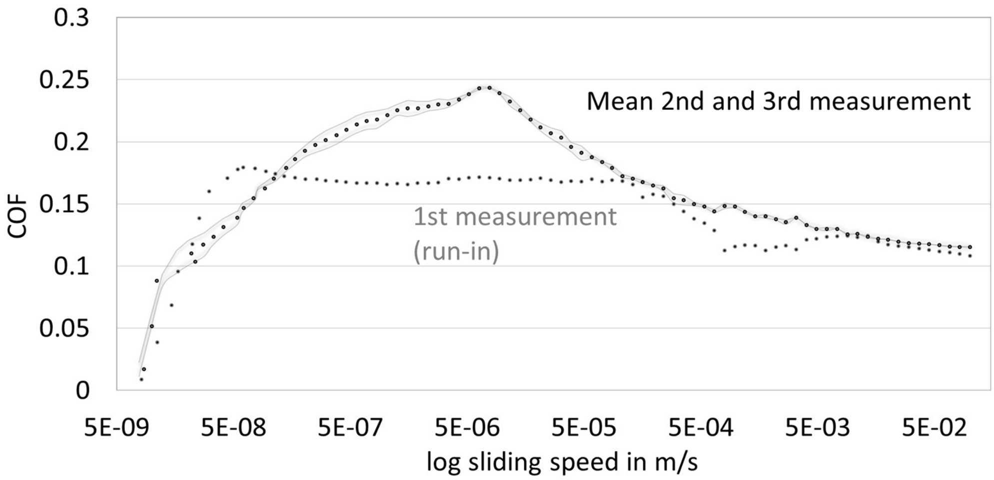

Figure 2. The sliding speed (logarithmic scale) versus the COF, an exemplary depiction of the 1st run (run-in) and the mean values of the 2nd and 3rd run, including the standard deviation of PAO8 at 80 °C.

This research focused on the simulation of cold and warm extrusion. Cold extrusion (30–60 °C) is generally adopted for pasta and confectionery (e.g., chewing gum), whereas warm extrusion (70–130 °C) is utilized for producing indirectly expanded snacks (i.e., fried products), semi-finished products, meat analogs, and modified starch [41]. The lubricant samples and test conditions used for the two use cases are presented in the following.

2.1.1. Breakaway Torque

The transition from a static state to a kinetic state of motion is characterized by (sub-) micron-scale relative displacements. In general, real-life systems tend to deform elastically/plastically prior to the onset of motion (i.e., the breakaway point), see Figure 3 [40].

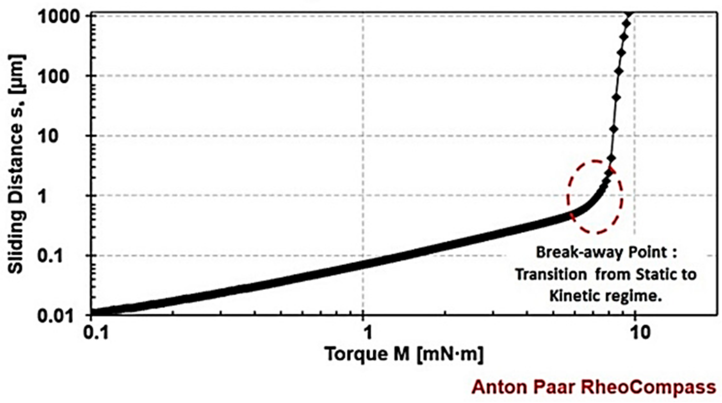

Figure 3. The breakaway torque, with permission from Anton Paar [40].

The breakaway force is defined as being the highest point of static friction (i.e., friction without movement), and is the turning point to kinetic friction. It thereby helps to understand the start of the sliding speed versus the friction (Stribeck) curves [40].

2.1.2. Use Case 1—Cold Extrusion

Due to the low temperatures involved in cold extrusion (30 to 60 °C) [41], water could be used as a base lubricant and an environmentally friendly potential alternative to the conventional base oils for this application [41]. After comparing different bio-based FMs with literature research [13], the following five were used as additives in water; see Table 1. Both rapeseed oil and salmon oil underly the EU Ecolabel for lubricants, where a minimum of 25% bio-based carbon content (according to EN 16807) is mandatory for the final product [14]. Agar, alginate, and hydroxypropyl methyl cellulose were chosen as bio-based FMs in powder form to ensure their complete dissolution and homogenization in water. Meanwhile, salmon and rapeseed oil were selected as emulsion bio-based FMs, as tribologically active substances do not need to dissolve in the carrier liquid [13].

Table 1. The bio-based FMs at 1 wt% in distilled water.

Concentration	Sample	Lubricant	Test Temperature
1 wt%	Salmon oil	Distilled water	30 °C
	Rapeseed oil		
	Agar		
	Alginate		
	Hydroxypropyl methyl-cellulose (HPMC)		

After the initial tribological tests in water (see Section 2.1), the best-performing bio-based FMs were used as pure lubricants (fully flooded test cell) and as "limited" lubrication (dipping the materials in oil). These advanced tribological tests aimed to evaluate the effect of water on the tribological and wear performance by comparing the bio-based FMs alone to the bio-based FMs mixed in water.

2.1.3. Use Case 2—Warm Extrusion

For the warm extrusion application (70–130 °C), water cannot be used as a lubricant. Therefore, a standard customary market polyalphaolefin PAO8 was used as the base lubricant. Four conventional FMs were selected after literature research and toxicologically assessed [41]. The bio-based FMs performing best in water lubrication, namely salmon oil and rapeseed oil, were then added to the PAO8 for comparison with the conventional additives; see Table 2.

Table 2. The conventional FMs at 1 wt% starting from the least to the most toxic, oleamide, borate ester, ricinoleic acid methyl esters, and tallow amine. The best-performing bio-based FMs at 1 wt%, namely rapeseed and salmon oil.

FMs	Concentration	Sample	Lubricant	Test Temperature
Conventional	1 wt%	Oleamide	PAO8	80 °C
		Borate ester		
		Methyl ricinoleate		
		Tallow amine		
Bio-based	1 wt%	Salmon oil	PAO8	80 °C
		Rapeseed oil		

2.2. Sample Characterization

The samples were characterized following the methods of previous work [13] yet underwent additional analysis and evaluation.

The stainless steel plates depicted clear wear, which was microscopically analyzed using a metallurgical microscope (Carl Zeiss AG, Jena, Germany) at a consistent scale of 200 µm. To determine the purity of the samples, two physical–chemical methods were employed: infrared spectroscopy using attenuated total reflection (ATR) and elemental analysis via inductively coupled plasma optical emission spectrometry (ICP-OES).

The infrared spectroscopy was performed using a Bruker Tensor 27 FT-IR spectrometer (Bruker Optics GmbH, Ettlingen, Germany). The samples were positioned on a diamond ATR crystal and pressed with a consistent and reproducible force. The resulting infrared spectra were processed (e.g., baseline correction) and analyzed using the “OPUS” software (Version 5.0, Bruker Optics GmbH, Ettlingen, Germany). Figures A2 and A3 present the interpretation of the ATR measurements of the best-performing bio-based FMs, salmon oil and rapeseed oil [42].

As an initial step for the ICP-OES measurements, all the samples were digested using a microwave method (Anton Paar Multiwave Pro GmbH, Graz, Austria). The elemental analysis was further conducted (Thermo Fisher Scientific iCAP 7400 Duo spectrometer, Waltham, MA, USA). Appendix B contains the results of the elemental analysis using the ICP-OES, indicating that no detectable impurities were found in both the conventional and bio-based FMs.

3. Results and Discussion

3.1. Tribological Tests

3.1.1. Breakaway Torque

In Section 2.1.1, the breakaway torque measurements are explained. Figures 4 and 5 show the breakaway torque results and help to explain the beginning of the Stribeck curves of case 1 and case 2, namely elastic/plastic deformation and the onset of macroscopic movement (breakaway point). The elastic/plastic deformation was excluded from the Stribeck curves of case 1 and case 2.

In Figure 4, the bio-based reference (distilled water) reached the breakaway point with higher torque than the best-performing bio-based FMs (rapeseed oil). Furthermore, for the distilled water, the torque initially fluctuated after the breakaway point and then drastically decreased from 35 mN m to 20 mN m.

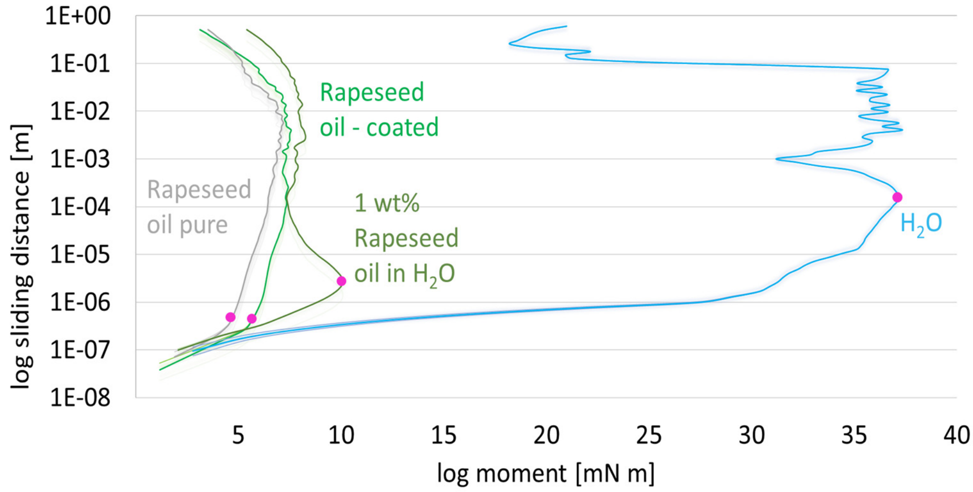

Figure 4. The breakaway point in the pink circle, the mean torque curve including the standard deviation of 1 wt% rapeseed oil in distilled water, the limited lubrication and pure rapeseed oil in distilled water, and distilled water at 30 °C.

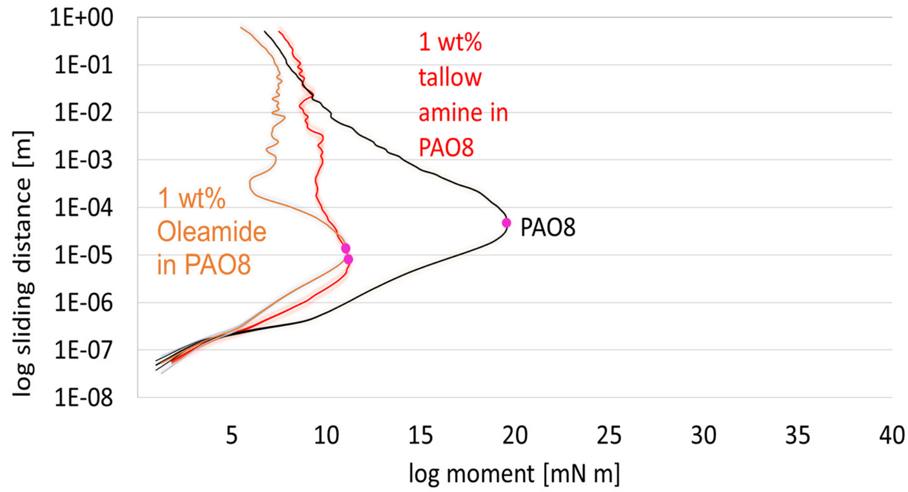

Figure 5. The breakaway point in the pink circle, the mean torque curve including the standard deviation of the best-performing conventional FMs (oleamide and tallow amine) and of the conventional reference PAO8 at 80 °C.

The conventional reference (PAO8) reached the breakaway point with a higher torque than the best-performing conventional FMs; see Figure 5. Moreover, the conventional reference (PAO8) decreased drastically after the breakaway point from 20 mN m to 10 mN m. Ultimately, the conventional reference (PAO8) reached a similar torque as the best-performing conventional FMs (oleamide and tallow amine).

Interpreting the breakaway torque measurements, both the bio-based (distilled water) and the conventional (PAO8) reference need substantially more torque than the mixtures with bio-based and conventional FMs to reach the end of the elastic/plastic deformation and the onset of macroscopic motion. This additional need for torque, and consequently for force, leads to additional energy consumption. Therefore, the usage of a contained amount of the bio-based FMs (1 wt%) in distilled water and of the conventional FMs in PAO8 significantly reduces the energy consumption in applications such as extruders and two-roll presses.

3.1.2. Use Case 1—Cold Extrusion

Figure 6 compares the frictional performance of the bio-based reference lubricant (distilled water) and the bio-based FM mixtures in distilled water at 30 °C.

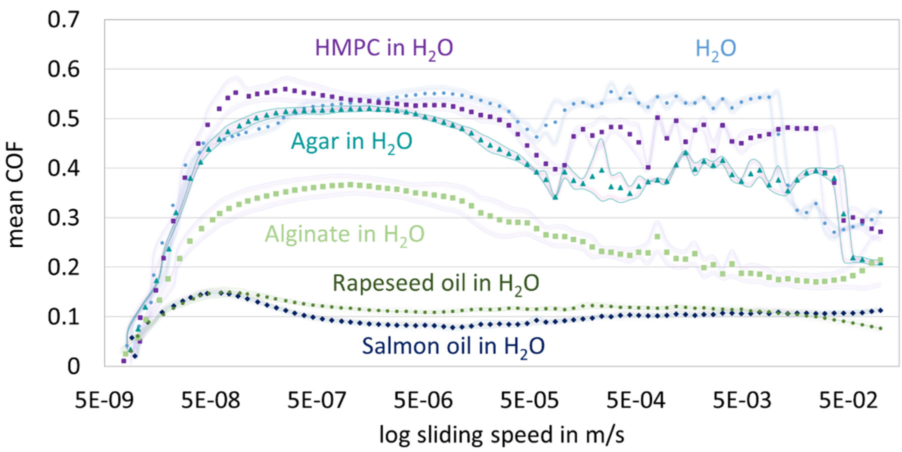

Figure 6. The sliding speed versus the COF, the mean curve including the standard deviation of the bio-based reference distilled water, and of the 1 wt% bio-based FMs in distilled water at 30 °C.

Overall, the addition of bio-based FMs in water reduced friction when compared to distilled water. The rapeseed and salmon oil showed the best frictional reduction (COF ≈ 0.1), followed by the alginate, agar, and HMPC.

The COF of the distilled water was around 0.5, but abruptly decreased to values around 0.3 for higher speeds. Agar and HMPC only brought contained friction reduction, and the COF trend was quite like that encountered for the pure distilled water (a drop in the COF at higher speeds). A yellowish change in color was observed after the tribological testing of the HPMC in distilled water, indicating either oxidation reactions and/or possible mechanical stress of the tribological test. A sedimentation process of the agar was detected for the distilled water-mixed agar, possibly due to inadequate bonding between the water and agar [13]. The two components were prepared and homogenized at room temperature (20 °C), and then heated while stirring with a magnetic stirrer (at 90 °C) until completely dissolved [43]. However, the test temperature, being 30 °C, did not ensure sufficient linkage. Contrary to the distilled water, the COF of the alginate in water decreased steeply with the increase in speed, starting from around 0.35 at slower speeds and dropping to values around 0.2 at higher speeds. The rapeseed and salmon oil added to water presented a quite constant COF around 0.1 for the different speeds tested.

The frictional results of the two best-performing FMs (rapeseed and salmon oil) were compared to those obtained from the pure lubricant (fully flooded test cell) and as limited lubrication (dipping the materials in oil).

Figure 7 compares the bio-based FMs in 30 °C 1 wt% mixtures in water and as pure samples in two conditions: fully flooded and limited lubrication. For the pure samples, 1 mL oil was evaluated. For the limited lubrication samples, the plates and ball used in the tribological test were merely immersed in the rapeseed and salmon oil [13]. The pure and limited lubrication conditions for the salmon and rapeseed oil cannot significantly be distinguished. The COF increased steadily from values around 0.08 up to 0.1 until the speed of 0.005 m/s, whereas the COF decreased to roughly 0.04 at higher speeds.

According to the curve progressions, the bio-based references and the 1 wt% bio-based FM in distilled water all seem to be working in the expected working range of the FMs, namely the mixed lubrication regimes, where AW and WP additives are not yet reactive. Furthermore, the existence of wear was visible for all the samples, indicating the initial boundary lubrication.

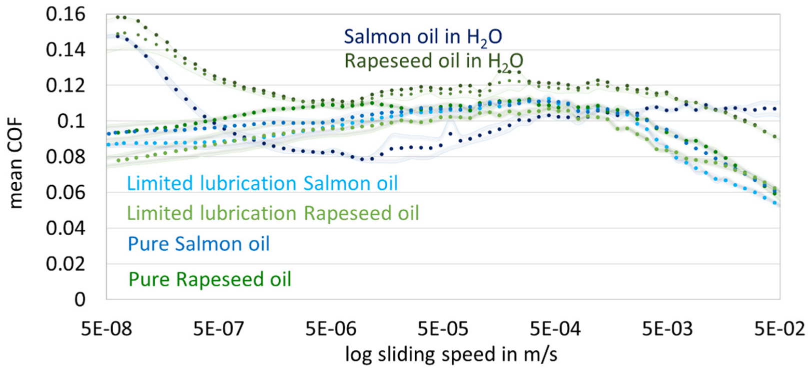

Figure 7. The sliding speed versus the COF, the mean curve including the standard deviation of the bio-based FMs (rapeseed and salmon oil) in water, limited lubrication, and pure bio-based FMs tested at 30 °C.

3.1.3. Use Case 2—Warm Extrusion

This sub-chapter depicts the results of the tribological tests of the conventional versus the bio-based FMs, both at 1 wt% in oil lubrication (PAO8) at 80 °C; see Figure 8.

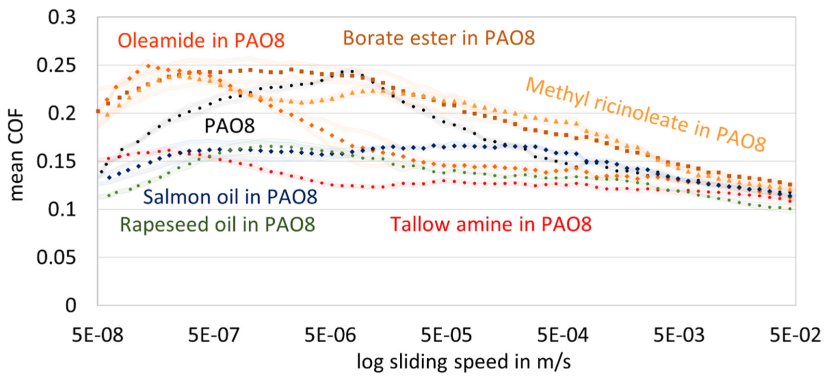

Figure 8. The sliding speed versus the COF, the mean curve including the standard deviation of the bio-based versus the conventional FMs and the conventional reference PAO8 at 80 °C.

The COF of the reference PAO8 started from approximately 0.15 at the minimum speed, rising to 0.25 at roughly 5×10^6 m/s, and then decreased to values around 0.1. It must be noted that all the mixtures showed COFs between 0.1 and 0.12 at higher speeds. The addition of oleamide and borate ester to the PAO8 generally increased the friction compared to the reference lubricant. Furthermore, the COF results of these two conventional FMs presented a similar trend to the PAO8, with the maximum COF shifted for the lower speed.

The oleamide in PAO8 showed a high COF (≈0.25) at the lower speed (5×10^7). However, the friction constantly decreased with the increment of the sliding speed, being, for a wide interval, lower than the unadditivated PAO8 (5×10^7 until 5×10^4). Tallow amine exhibited the best frictional results within the conventional FMs with COFs around 0.15 and 0.1 at lower and higher speeds, respectively.

When comparing the salmon and rapeseed functional materials (FMs) in PAO8 with the tallow amine in PAO8 under identical conditions, they exhibited comparable performance.

Evaluating both the conventional and bio-based FMs in PAO8 at 80 °C, and in distilled water at 30 °C, it is evident that the rapeseed oil and salmon oil FMs can achieve COF values as low as the tallow amine, being the top-performing traditional FM [13].

3.2. Characterization of Samples after Tribological Tests

Figure A1 depicts the wear scars of the best performers (bio-based FMs) and worst performer (water), measured by a reflected light microscope. A bigger wear scar was observed for the worst performer (water) when comparing it to the conventional oil PAO8.

Thus, PAO8 fulfills the expected wear-reducing effect. Moreover, the wear scars of the 1 wt% tallow amine in PAO8 and the 1 wt% rapeseed and salmon oil in distilled water are comparable. In conclusion, the Stribeck curves and the reflected light microscope images indicate that adding just 1 wt% of salmon or rapeseed oil significantly improved both the antiwear and friction properties in comparison to distilled water.

The wear scar images obtained with the reflected light microscope (see Figure A1) suggest that even with only 1 wt% of the salmon and rapeseed oil in water, lubrication is effective enough to produce a wear scar comparable to that produced by pure oil samples. This indicates the potential to replace oil-based lubrication with an environmentally friendly, water-based system by incorporating as little as 1 wt% bio-based FM. This transition could also be more cost-effective, as the water and oil mixtures demonstrate equivalent performance within a confidence interval of 0.05.

In summary, the sample characterization analysis demonstrates correlations between the wear and friction of the conventional and bio-based FMs.

4. Conclusions

In this study, bio-based FMs were experimentally evaluated and compared to conventional FMs under two different test conditions: In one, slow-speed components in the cold application for the food industry using water lubrication with a selection of bio-based FMs. In the other, a warm application using oil lubrication with the best-performing bio-based FMs compared to the conventional FMs. The following findings were obtained:

1. The performed tests of all the conventional FMs in oil mixtures and the best-performing bio-based FMs in both oil and water mixtures underline the working range of FMs, namely in the boundary and/or mixed lubrication regimes.
2. The worst performer (distilled water at 30 °C) and the best performers (pure and limited lubrication of the rapeseed and salmon oil in water at 30 °C) depict wear formation, indicating the initial boundary lubrication.
3. The friction and wear characteristics of the best-performing bio-based FMs (salmon oil and rapeseed oil) in 1 wt% water mixtures and in pure lubrication (without water) are comparable. Thus, the 1 wt% bio-based FM water mixtures should be considered from a sustainable point of view. However, relubrication must be considered since the minimal concentration of oil could lead to a reduced service life of the machine.
4. The best bio-based FMs (salmon oil and rapeseed oil) in PAO8 possess the frictional characteristics to replace the best conventional FM (tallow amine) in PAO8.
5. By interpreting the breakaway torque results, both the bio-based (distilled water) and the conventional (PAO8) references need substantially more torque than the mixtures with the bio-based and conventional FMs to reach the end of the elastic/plastic deformation and the onset of macroscopic motion. Therefore, the usage of the bio-based FMs (1 wt%) in distilled water and of the conventional FMs (1 wt%) in PAO8 can significantly reduce energy consumption in applications such as extruders and two-role presses.

In conclusion, this research represents a crucial step toward developing more sustainable food-grade lubricants, demonstrating that bio-based FMs can achieve friction performance comparable to conventional FMs. Nevertheless, it is important to emphasize that the products' stability has yet to undergo comprehensive testing. This could be part of a further study, including an oxidation test, rancidity, foam formation, and generally temperature resistance and low-temperature applications.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Conflicts of Interest: Authors Rosa Maria Nothnagel, Guido Boidi, Rainer Franz and Marcella Frauscher was employed by the company AC2T research GmbH. The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

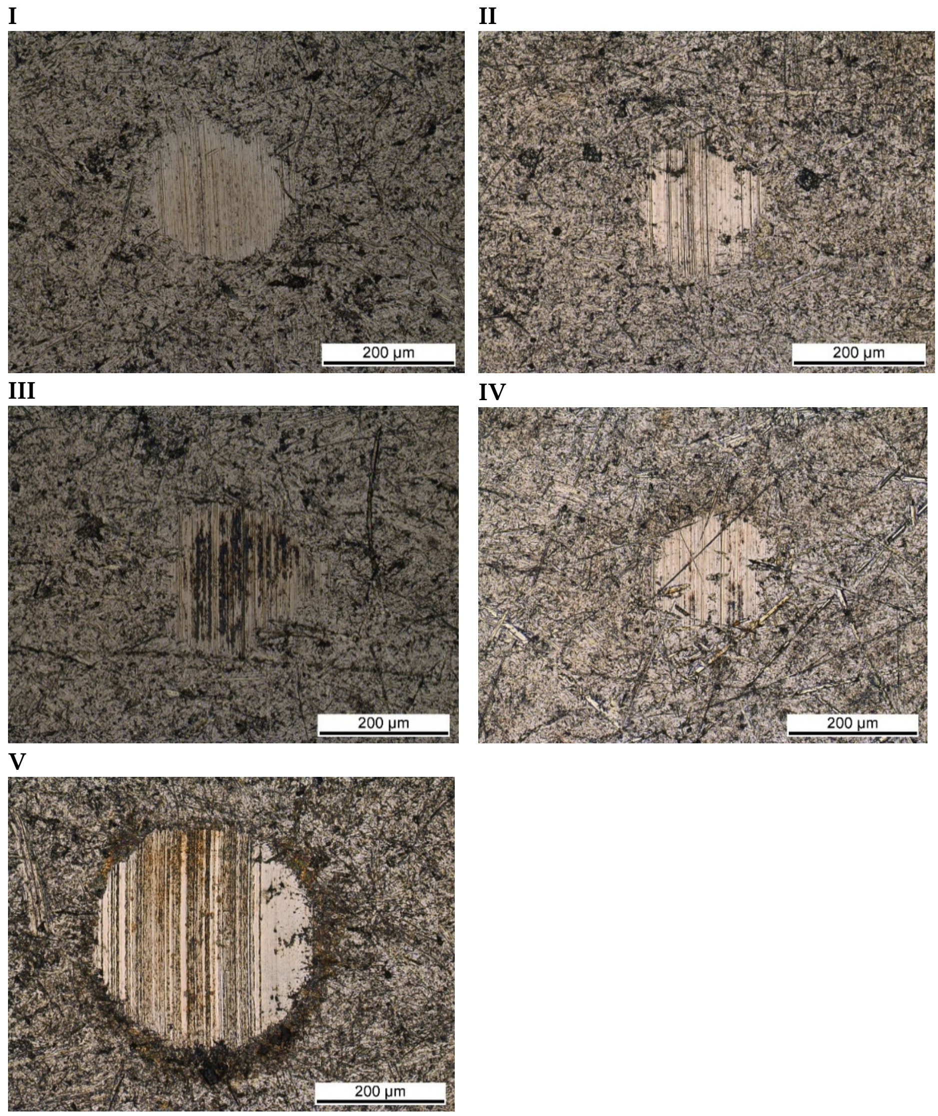

Figure A1. The wear on stainless steel plates of the best performers (the bio-based FMs in water) and the worst performer (water): pure salmon oil 30 °C wear (**I**), 1 wt% salmon oil 30 °C wear on stainless steel plates (**II**), pure rapeseed oil 30 °C wear on stainless steel plates (**III**), 1 wt% rapeseed oil 30 °C wear on stainless steel plates (**IV**), and water 30 °C wear on stainless steel plates (**V**) modified accordingly [13].

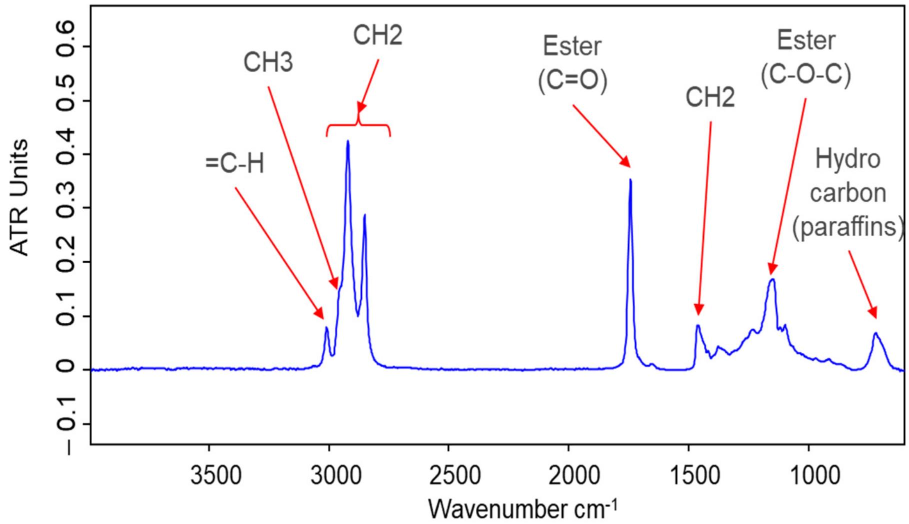

Figure A2. An ATR Spectrum of the best-performing bio-based FM in water: salmon oil modified accordingly [13].

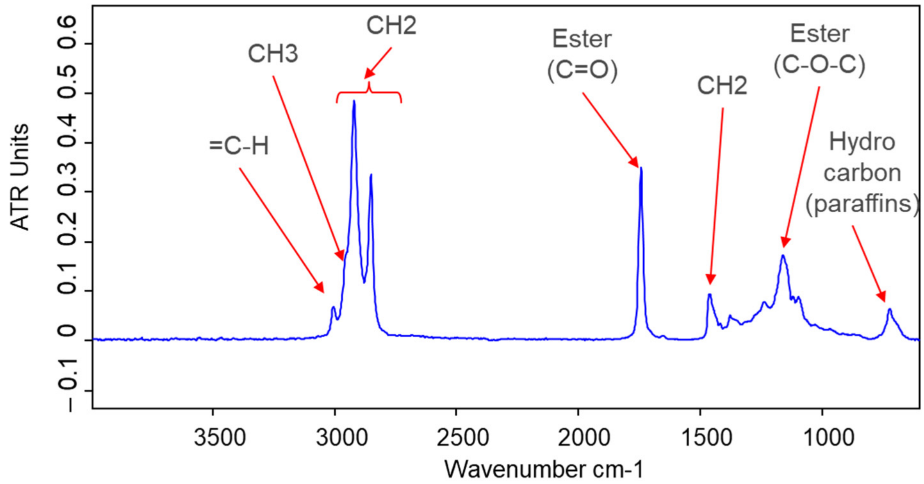

Figure A3. An ATR Spectrum of the best-performing bio-based FM in water: rapeseed oil.

Appendix B. The ICP-OES Results for the Conventional and Bio-Based FMs; Elements below 10 ppm Were Excluded (Co, Cr, Cu, Li, Mn, Mo, Ni, Sb, Sn, Ti, V, W, Zn); Both Modified Accordingly [13]

Table A1. ICP-OES results for the conventional and bio-based FMs (Al, B, Ba, Ca, Fe, K).

Name	Al	B	Ba	Ca	Fe	K
Hydroxypropyl methylcelullose	5	<5	<1	11	14	<10
Agar	11	144	1	3100	22	286
Alginic acid calcium salt from brown algae	154	<5	30	>14,500	147	250
Salmon oil	<5	<5	<1	<5	<1	<10
Rapeseed oil	<5	<5	<1	5	<1	<10
Borate ester	26	>12,600	<1	16	<1	<10
Tallow amine	<5	<10	<1	10	<1	<10
Oleamide	<5	<5	<1	30	<1	<10
Methyl ricinoleate	<5	<5	<1	<5	<1	<10

Table A2. The ICP-OES results for the conventional and bio-based FMs (Mg, Na, P, Pb, S, Si).

Name	Mg	Na	P	Pb	S	Si
Hydroxypropyl methylcellulose	2	3330	<10	<10	16	10
Agar	992	5000	49	<10	5290	33
Alginic acid calcium salt from brown algae	827	2040	75	<10	316	140
Salmon oil	<1	<10	<10	<10	<10	<10
Rapeseed oil	<1	<10	<10	<10	<10	<10
Borate ester	2	65	<10	<10	<10	<10
Tallow amine	<1	<10	<10	<10	<10	<10
Oleamide	1	<10	<10	<10	<25	<10
Methyl ricinoleate	<1	<10	<10	<10	50	<10

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