Brasenia Schreberi mucilage as a green lubricant additive exhibiting good tribological properties for steel/steel and steel/aluminium friction pairs

Chuan Chen1, Yanqiu Xia1 and Zhengfeng Cao2

1 School of Energy Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, People’s Republic of China
2 School of Advanced Manufacturing Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: 287485237@qq.com

Keywords: BS mucilage, tribology, green additive, tribological property

Abstract
It is still necessary to continue exploring green lubricant additive. This study collected a kind of mucilage from the Brasenia Schreberi (BS) leaves which was an aquatic plant. The BS mucilage was dispersed in synthetic ester (SE) and then employed as a green lubricant under the friction pairs composed of steel/steel and steel/aluminium. The tribological tests of the lubricants were carried out under different friction pairs in details and scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS) were utilized to characterize the worn out surfaces to understand the lubrication mechanisms. The experimental results suggested that as compared with stearic acid (SA) and Ag, BS mucilage in SE could dramatically improve the friction reducing and anti-wear of SE for both steel/steel and steel/aluminium friction pairs. Based on the SEM and XPS analysis of the worn out surfaces, it suggests that the preferable tribological properties of BS mucilage was mainly related to the effective lubricating films including physical adsorption and tribochemical lubricating films in the process of the friction.

1. Introduction

Friction phenomenon takes place when two objects in contact with each other have relative displacement. Wear is the result of friction. Friction leads to significant material waste and energy loss. It has been reported that friction is responsible for about 30% of the total energy losses [1–4]. Lubrication is a technical measure to improve the friction state of the friction pair to reduce frictional resistance and wear. Normally, lubrication technology needs to be achieved through the use of lubricants. Lubricants can form a protective lubricating film to separate two friction surfaces in contact, thereby reducing wear and energy loss [5, 6]. Lubricants have been used for more than a thousand years, since animal oil, water and other fluids have been used as lubricants. With the pursuit of higher reliability of equipment, lower energy loss and economic cost, lubricants have been deeply studied to control the friction and wear. Generally, lubricant consists of base oil and additive. Base oil provides the fundamental properties and additive enhances or endows lubricant more other properties [7–10].

Nowadays, the petroleum-based or synthetic lubricating oil are widely employed in the industry. Although these lubricating oils have superior tribological performances, they are not environmentally friendly. At the same time, currently widely used additives such as MoDTC and ZDDP also contain much sulfur and phosphorus and other elements, which are easy to cause environmental pollution and has strong biological toxicity. With the gradual improvement of environmental awareness, new requirements have been raised for the environmental performance of lubricant. Environmental protection has prompted scientists to explore new environmentally friendly lubricants [11, 12].
At present, scientists have made a lot of efforts, and many related research results have been reported. Vegetable oil has been widely studied as green lubricant due to the good friction properties, biodegradability and non-toxicity, and many researchers have also used various methods to further improve the properties of vegetable oils, such as oxidation stability and tribological properties [13–15]. For example, Kerni et al., investigated the tribological properties of olive oil in boundary and mixed lubrication regimes. Meanwhile, in order to improve the oxidative stability and tribological performance, the olive oil was epoxidized and Cu and h-BN were employed as additives. The results show that epoxidation treatment promotes the formation of O-O-cross linking on the surface, so that the epoxidized olive oil exhibited better friction properties. The addition of 0.5wt% Cu and h-BN could significantly improve the tribological properties of epoxidized olive oil, which was mainly attributed to the protective film formed by the nano-additives on the friction surface [16]. Gupta et al., employed epoxidised canola oil as lubricating oil and evaluated the effect of MoS2 and WS2 as additives on the tribological properties. Their research found that the MoS2 and WS2 could increase the dynamic viscosity. The addition of WS2 and MoS2 could reduce the COF by up to 54.6% and 30%, respectively [17]. D’Amato et al., evaluated the performance of vegetable oil as cutting fluid. The results showed that vegetable oil (Jatropha Curcas L. oil) as cutting fluid could exhibit better refrigeration and tribological properties as compared with dry friction and mineral emulsion lubrication [18]. These studies suggest that vegetable oil have a great potential to be employed as environmentally friendly lubricating oil.

In the direction of environmentally friendly lubricating additives, many researchers have also made a lot of efforts. Feng et al., extracted surface waxes from three different pine leaves and used them as lubricant additives. The results indicated that the three kinds of leaves waxes were mainly composed of alkanes, alcohols and acids, and they could exhibit superior friction properties as lubricant additives for steel/steel and steel/ aluminium friction pairs [19]. Zhang et al., found that CaCO3 as a green additive could significantly improve the load-carrying performance, as well as the friction reduction and wear resistance of poly-alpha-olefin lubricating oil. The XPS analysis of the worn surface indicated the lubricating protective film composed of CaCO3, CaO and iron oxide were responsible for the enhanced tribological properties [20]. Khan et al., synthesized aminoguanidine salt-based deep eutectic solvents (DESs) through a single-step facile approach and employed DESs as environmentally-friendly additive in SN 150 base oil. The results showed that the DESs could reduce the wear volume and COF by 94% and 30% for steel/steel friction pairs, respectively. The analysis of the worn surface indicated a lubricating protective film was generated on the worn surface to enhance the tribological performances [21]. Although there have been many researches about green lubricants, with higher and higher requirements for environmental protection, it is still necessary to continue exploring green lubricants.

In this work, our attention is mainly focused on the green lubricant additives. Brasenia Schreberi (BS) is a kind of water plant, which belongs to the Nymphaeaceae and family. It has been consumed as a food and employed in medical industry [22–24]. Meanwhile, many researches also have been conducted about the chemical compositions of BS mucilage and the related results suggest that the BS mucilage is mainly composed of alcohols, alkanes, olefines, esters and acids [25]. In this study, the BS mucilage is collected to be employed as an additive and the synthetic ester (SE) was employed as the base oil because of its environmentally friendly and degradable performances. Steel and aluminum are widely used as friction pair materials in the industry. In order to study the adaptability of the lubricants for different friction pairs, the tribological behaviors of the lubricants are evaluated under steel/steel, steel/aluminium friction pairs in detail. The worn out surfaces are also investigated by scanning electron microscopy (SEM) and multifunctional X-ray photoelectron spectroscopy (XPS) to probe the related mechanisms.

### 2. Experimental section

#### 2.1. Materials

Synthetic ester (SE) was selected as the based oil because of its environmentally friendly and degradable performances, which was provided by the Zhongcheng Petrochemical Co., Ltd. Table 1 lists the properties of the SE. The fresh BS was collected at Shizhu County in Chongqing Province (Longitude 108° East, latitude 30° North). The mucilage was carefully obtained from the fresh BS by a scraper and was transferred into a beaker. The beaker was placed in a heat oven at 40 °C for 12 h to remove the water. Then, the BS mucilage was obtained.

| Item                     | Kinematic viscosity 40 °C | Viscosity index 100 °C | Condensation point | Flash point |
|--------------------------|----------------------------|------------------------|--------------------|-------------|
| Synthetic ester          | 25.32 cSt                  | 2.74 cSt               | 136                | <60 °C      |
| Synthetic ester          | 25.32 cSt                  | 2.74 cSt               | 136                | 252 °C      |

Table 1. Typical properties of the synthetic ester (SE).
as a lubricant additive. Meanwhile, the stearic acid (SA) and solid nanoparticle Ag were used as the contrastive additives.

2.2. Preparation and measurement of the lubricants
The lubricant additive including BS mucilage, stearic acid (SA) and Ag particle were ultrasonically dispersed in the base oil of synthetic ester. The concentration was 0.5wt%, 1.0 wt %, 1.5 wt % and 2.0 wt %. The BS mucilage was characterized by a Fourier transform infrared spectrometer (FT-IR, Thermo Fisher Scientific). The kinematic viscosity of pure SE, BS mucilage and SE + BS mucilage were also measured (SVM-3000, Anton Paar).

The tribological behaviors of the lubricants are evaluated using a ball-on-disk friction and wear tester. The friction pair is made of steel (AISI 52100, hardness 590–610 Hv, surface roughness 0.05 um) and aluminium (2024, hardness: 160–170 Hv, surface roughness 0.05 um). The frequency was 2–5 Hz and the stroke was 5 mm. The applied loads for steel/steel and steel/aluminium friction pairs is 50–200 N and 20–50 N, respectively. Before and after each tribological test, the ball and disk were ultrasonically washed in acetone for 10 min. Every tribological test for different lubricant was continued for 30 min and was conducted for three times to get the more responsible results.

When friction test is over, the pictures and widths of wear scar were obtained by an EVO-18 scanning electron microscopy (SEM, ZEISS) and an optical microscopy, respectively. A PHI-5702 multifunctional X-ray photoelectron spectroscopy (XPS, American Institute of Physics Electronic Company) was used to detect the chemical state of the worn out surfaces. The reference binding energy was C1s (284.2 eV).

3. Results and discussion

3.1. Analysis of the BS mucilage
As shown in figure 1(a), it can be seen that the mucilage is colorless, transparent and tightly adheres to the BS leaves. Figure 1(b) depicts the FT-IR curve of the BS mucilage to characterize the chemical composition. The peaks at 3726 cm⁻¹ belongs to the O–H stretching vibration bands and 3289 cm⁻¹ belongs to the C–H stretching vibration bands. The peak at 1764 cm⁻¹ belongs to the C=O adsorption vibration band. The peaks at 1592 cm⁻¹ and 1163 cm⁻¹ belong to the C–O bending vibration band. Similar to the reported FT-IR results by the literatures [23–25], the FT-IR spectra confirmed the BS mucilage is mainly composed of alcohols, alkanes, olefines, esters and acids. Table 2 depicts the kinematic viscosity of SE, BS and SE + BS. It can be found that the BS mucilage possesses a higher kinematic viscosity than SE under both 40 °C and 100 °C. With the increasing BS concentration from 0.5wt% to 2.0wt%, the kinematic viscosity of lubricant increases by 15.1% and 13.5% under 40 °C and 100 °C, respectively.

| Kinematic viscosity | SE  | BS  | SE + 0.5wt% BS | SE + 1.0wt% BS | SE + 1.5wt% BS | SE + 2.0wt% BS |
|---------------------|-----|-----|----------------|---------------|---------------|---------------|
| 40 °C               | 25.52 | 47.36 | 26.21          | 27.15          | 27.94          | 29.37         |
| 100 °C              | 2.74  | 9.25 | 2.83           | 2.91           | 3.02           | 3.11          |

Figure 1. Appearance picture (a) and FT-IR spectra (b) of the BS mucilage.
3.2. Tribological properties of lubricants under steel-steel friction pair

The tribological performances of the lubricants are greatly affected by the concentration of the additives. When the additive concentration is too low, the lubricant cannot form a sufficient lubricating film on the friction surface, which will lead to increased wear. However, if the additive concentration is too high, competitive adsorption will occur on the friction surface, which also will increase the wear [2, 26, 27]. Therefore, in order to optimize the concentration, the detailed tribological performances of the SE containing various additive concentrations for steel-steel friction pair were investigated and the results were depicted in figure 2 (a) and (b). It can be found that the pure SE exhibited relatively higher COF and wear width than other lubricants, indicating that the addition of the three kinds of additive all can enhance the friction reducing and wear resistance abilities of pure SE. Among the three kinds of additives, the BS mucilage exhibited relatively lower COFs and wear widths under all the additive concentrations than other lubricants, indicating BS mucilage possessed the best tribological properties. Importantly, the optimum concentration of BS mucilage was 1.5wt%. At this time, it exhibited the lowest COF and wear width. As compared with pure SE, it reduced the COF and wear width by 29.6% and 22.4%. The good tribological properties of BS mucilage was mainly attributed to the sufficient lubricating film formed by physical adsorption and chemical reactions on the worn surfaces [19, 24, 28]. Therefore, the optimal concentration of the three kinds of additives was 1.5 wt%, and in the following experiments for steel/steel friction pair all the concentration of the additive was adjusted as 1.5wt%.

Figure 3 depicts the different tribological performances of the lubricants under increasing applied load. It can be seen that all the COFs and wear widths decreased with the applied load increasing. The reason may be attributed to that increasing applied load lead to increasing contact pressure and Joule heat in the contact area, which in turn promotes the physical and chemical reactions occur between worn surface and lubricants to form a much sufficient and dense lubricating film, thereby enhancing the tribological performances [29]. Meanwhile, the tribological performances of the pure SE were in a sharp contrast with those of the SE containing additives under all the tested loads, indicating all the additives greatly improved the friction reduction and anti-wear abilities of pure SE. BS mucilage exhibited the lowest COFs and wear widths among all the lubricants at all the loads. The biggest reduction in COFs and wear widths was about 30% and 23.7% under 200 N, respectively. These results indicated BS mucilage possessed the best friction reduction ability, which may be attributed to the
fact that BS mucilage can form a denser and more sufficient lubricating protective film than other lubricants under different loads [19].

Figure 4 further depicts the tribological performances of the lubricants under different frequencies for steel/steel contact pair. Observing the figure 4, all the additives made a great reduction in the COFs and wear widths as compared with pure SE. Meanwhile, with the frequency ranging from 2 to 5 Hz, all the lubricants exhibited a slow increase in COFs and wear widths. It also can be found that BS mucilage exhibited the biggest reduction in COFs and wear widths, which indicated that BS mucilage could generate a high-performance lubricating film on the friction surface at various frequencies [28]. Therefore, BS mucilage possessed a superior friction reduction and anti-wear abilities for steel/steel contact pair under various frequencies.

3.3. Morphologies of the worn surfaces of steel disc
Wear surface damage can further reflect the tribological properties of the tested lubricants. Therefore, the pictures of the worn out surfaces on steel disc were obtained by an EVO-18 SEM and figure 5 depicts the results. As shown in figure 5(a), the pure SE lubricated worn surface was much rough and there were many grooves and wear debris, implying a sever wear taken place [30]. Figure 5(b) depicts the picture of the worn surface lubricated by SE + SA and it can be seen that the number of the grooves and wear debris was smaller than pure SE, indicating the SA as additive could form a lubricating film between the contact surfaces to improve the anti-wear ability of SE. From the figure 5(c), it could be seen that the SE + Ag lubricated worn surfaces was obviously different from others. It was reported that Ag nanoparticle could exhibited the ‘rolling effect’ to reduce the shear stress and exhibit ‘mending and polishing effect’ to form a deposited lubricating film between the friction interfaces, thereby improve the tribological performances. Therefore, it was easily found that some grooves, adhesion and polishing areas on the SE + Ag lubricated worn surfaces. Meanwhile, some plastic deformation also appeared [31, 32]. As a sharp contrast, the worn surface lubricated SE + BS mucilage was the smoothest, with only a few small scratches on the surface, which may be attributed to that BS mucilage generated a high-performance lubricating film through the physical adsorption and chemical reactions during the friction process [23]. The SEM analysis of the worn surfaces indicates that BS mucilage exhibited the best wear resistance performance among all the tested lubricants and this conclusion was also supported by the results shown in figures 2–4.

3.4. Tribological properties of lubricants under steel-aluminium friction pair
In order to evaluate the adaptability of the lubricants for different friction pairs, the tribological performances of lubricants for the steel/aluminum friction pair were further investigated. As shown in figures 6(a) and (b), with the raising additive concentration, all the COFs and the wear scar widths gradually decreased. The addition of additives all significantly lowered the COFs and wear widths. The biggest reduction in COFs (29.8%) and wear widths (19.1%) was achieved by SE + 2.0wt BS mucilage. Different from steel/steel friction pair, the optimum concentration of additive was 2.0wt% for steel-aluminium friction pair, which may be attributed to the different sensitivity of additive for different friction materials [33]. Among all the additives, the BS still mucilage exhibited the best friction reduction and anti-wear performances. This result shows that the SE + BS mucilage is also very suitable for the lubrication of steel-aluminum friction pairs.

The tribological performances of the lubricants for steel-aluminium friction pair under different loads was investigated and figure 7 gives the experimental results. Different from the steel-steel friction pair shown in figure 3, the COFs and wear widths of steel-aluminium friction pair gradually increased with the increasing load, which may be attributed to the different hardness between steel and aluminum. Aluminum has a lower hardness
Figure 5. SEM of the worn surfaces under different lubricants lubrication for steel-steel friction pair at 200 N, 5 Hz and RT. (a) SE, (b) SE + SA, (c) SE + Ag and (d) SE + BS mucilage.

Figure 6. COFs (a) and wear widths (b) of the lubricating oil containing different concentrations of additives for steel-aluminium friction pair at 20 N, 5 Hz and RT.

Figure 7. COFs (a) and wear widths(b) of the lubricating oil containing 2.0wt% additive for steel-aluminium friction pair at different loads, 5 Hz and RT.
than steel, therefore, aluminum is prone to deformation in the friction process under the action of high load, resulting in a poor tribological performances [34]. However, observing all the experimental data, the COFs and wear widths of the SE + BS mucilage were still the lowest under all the tested load conditions, indicating SE + BS mucilage could also generate a good lubricating film to separate the friction interfaces, thereby exhibiting superior tribological properties for steel-aluminium friction pair at different loads [23].

Figure 8 also depicts the tribological performances of different additives for steel-aluminium friction pair at various frequencies. Obviously, the COF and wear scar widths also slowly increased with the frequency ranging from 2 to 5 Hz. Among the additives, SE + BS mucilage still exhibited lower COFs and wear scar widths, indicating that BS mucilage could effectively separate the friction interface to exhibit a better friction reduction and anti-wear abilities than others for steel-aluminium friction pair at different frequencies [28].

3.5. Morphologies of the worn surfaces of aluminium disc

Figure 9 displays the damage pictures of the worn out surfaces on the aluminium disc to further contrast the tribological performances of different additives. Obviously, a large number of grooves and wear debris appeared on the worn surface lubricated by pure SE and SE + SA, implying severe wear existing in both lubrication conditions of SE and SE + SA. Different from the SE + Ag lubricated steel disc shown in figure 5(c), only some grooves and wear debris appeared on the worn surface of the aluminium disc. This may be related to the low hardness of aluminum [34]. The wear surface under the lubrication of SE + BS mucilage was the smoothest and there were only very shallow grooves and a few adhesion areas, indicating that SE + BS mucilage could exhibit superior tribological performances for steel-aluminium friction pair. The reason may be lie in that SE + BS could form sufficient lubricating film through physical adsorption and chemical reactions [23]. These results were also consistent with the experimental data shown in figures 6–8.

3.6. Analysis of the lubrication mechanism

XPS is an effective facility which could be employed to probe the possible lubrication mechanisms. Figure 10 gives the XPS curves of the C1s, Fe2p and O1s of the worn out surface on steel disc. The peak located at 284.2 eV belongs to C1s which is usually to be used as the reference binding energy [5]. The peaks of 724.8 and 710.8 eV belongs to Fe2p, which imply that Fe$_2$O$_3$ and Fe$_3$O$_4$ were generated by tribochemical reactions during the friction process [35, 36]. The wide peak of O1s ranging from 530.0 to 531.5 eV is attributed to the C-O and Fe-O compounds, which indicates that some complex organic compounds adsorbs on the friction surface [37, 38]. The XPS analysis suggests that complex chemical reactions and physical adsorption taken place on the SE + BS mucilage lubricated worn surfaces during the friction process to generate an effective lubricating film to improve the tribological performances of the friction pairs.

A series of tribological tests show that BS mucilage dispersed in SE could effectively enhance the tribological properties of friction pairs. The enhanced lubrication mechanisms can be explained from following aspects. Related researches reveal that BS mucilage is a mixture and its composition main consists of alcohols, alkanes, olefines, esters and acids [23–25]. When BS mucilage is used as lubricant, these long-chain components will fracture to form a lot of short-chain components under the action of contact pressure and friction interface interaction. And these short-chain components usually carry negative charge [19, 28, 34]. Meanwhile, in the process of friction, electrons on the metal surface are easy to escape, so that the metal surface usually carries positive charge [39]. It is well known that positive and negative charges could attract each other. Thus, the genitive short-chain components could tightly adsorb on the worn surface to form a lubricating film to improve the tribological properties [19, 28]. Apart from the physical adsorption lubricating film, there is also
Figure 9. SEM of the worn surfaces under different additives lubrication for steel-aluminium friction pair at 50 N, 5 Hz and RT. (a) SE, (b) SE + SA, (c) SE + Ag and (d) SE + BS mucilage.

Figure 10. XPS spectra of C1s (a), Fe2p (b) and O1s (c) on the worn surface of steel disc under the lubrication of the SE + BS mucilage.
existing a tribochemical lubricating film to enhance the tribological performances. During the friction process, the temperature of the friction zone rises with the friction behavior continuing, which could promote chemical interactions occur between the BS mucilage and the fresh metal surface to form a tribochemical lubricating film [40]. This point is confirmed by the results shown in figure 10, where complex chemical reaction occurs on the friction surface, resulting in the tribochemical lubricating film composed of Fe₂O₃ and Fe₃O₄ and so on to improve the tribological performances [35, 36]. In a word, based on the tribological test, SEM and XPS analysis, the BS mucilage could effectively generate complex lubricating films including adsorption and tribochemical lubricating films on the worn surface to improve the tribological performances.

This paper aims to investigate the tribological performances of BS mucilage as green additive for steel/steel and steel/aluminium friction pairs. Taking into account the environmentally friendly and excellent tribological characteristics of BS mucilage, it has great potential as an environmentally friendly lubricant additive. In the future work, we will further investigate the thermal stability, oxidation resistance of BS mucilage, as well as the effect on the friction and rheological properties of lubricants.

4. Conclusion

In this work, a kind of mucilage was collected from the BS leaves and employed as a green lubricant additive. The detailed tribological performances of BS mucilage was evaluated under the steel/steel and steel-aluminium friction pairs. The main conclusions can be summarized as follows:

(1) The addition of BS mucilage increased the kinematic viscosity of lubricant and when the BS mucilage was 2.0wt%, the kinematic viscosity of lubricant increased by 15.1% and 13.5% under 40 °C and 100 °C, respectively.

(2) BS mucilage exhibited superior tribological performances for steel/steel friction pair under different applied loads and frequencies. The optimal concentration of BS mucilage was 1.5wt%, which could reduce the COF and wear width by 29.6% and 22.4%.

(3) BS mucilage also weas suitable for steel/aluminium friction pair. However, due to the different sensitivity of lubricant for different materials and the low hardness of aluminum, the optimal concentration of BS mucilage for steel/aluminium friction pair was 2.0wt%, which reduced the COF and wear width by 29.8% and 19.1%, respectively.

(4) Based on the SEM and XPS analysis of the worn surfaces, the such superior tribological performances of BS mucilage was mainly attributed to the effective lubricating films including physical adsorption and tribochemical lubricating films in the process of the friction. These lubricating films could effectively separate the friction interfaces, thereby reducing friction and wear. Taking into account the superior tribological performances, BS mucilage has great potential as an environmentally friendly lubricant additive.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Chuan Chen https://orcid.org/0000-0001-6207-1910
Zhengfeng Cao https://orcid.org/0000-0002-0716-8418

References

[1] Matta C, Joly-pottuz L, Bouchet M I D B, Martin J M, Kano M, Zhang Q and Goddard W A 2008 Superlubricity and tribochemistry of polyhydric alcohols Physical Review B 78 085436
[2] Cao Z, Xia Y and Chen C 2018 Fabrication of novel ionic liquids-doped polyaniline as lubricant additive for anti-corrosion and tribological properties Tribol. Int. 2018 446–54
[3] Shaﬁ W K, Raina A and Haq M 2018 Friction and wear characteristics of vegetable oils using nanoparticles for sustainable lubrication tribology-materials Surfaces & Interfaces 12 1–17
[4] Holmberg K, Andersson P and Erdemir A 2012 Global energy consumption due to friction in passenger cars Tribol. Int. 47 221–34
[5] Cao Z and Xia Y 2018 Synthesis and tribological properties of polyaniline functionalized by ionic liquids J. Mater. Sci. 53 7060–71
[6] Zhou Y and Qu J 2017 Ionic liquids as lubricant additives: a review ACS Applied Materials & Interfaces 9 3209–22
[7] Mannekote J K, Kailas S V, Venkatesh K and Kasthavayini N 2017 Environmentally friendly functional fluids from renewable and sustainable sources - A review Renew. Sustain. Energy Rev. 81 1787–801
[8] Schaf T W and Prasad S V 2013 Solid lubricants: a review J. Mater. Sci. 48 511–31
[9] Wu L X, Xia Y Q, Xiong S Z, Wu H and Chen Z S 2021 Effect of ionic liquids modified nano-TiO2 as additive on tribological properties of silicone grease Mater. Res. Express 8 105011
[10] Xia Y Q, Chen C, Feng X and Cao Z F 2021 Synthesis and tribological study of core-shell Ag@polyaniline as lubricant additive in lithium-based complex grease Industrial Lubrication and Tribology 73 1091–7
[11] Shaﬁ W K, Charoo M S and Haniel M 2021 Effect of fatty acid composition on the lubricating properties of bio-based green lubricants Tribology and Sustainability (Boca Raton, FL: Taylor & Francis Group) ch 14
[12] Nagendra Pratama P and Kaul S 2012 Development of eco-friendly/ biodegradable lubricants: an overview Renew. Sustain. Energy Rev. 16 764–74
[13] Lathil P S and Bo M 2007 Green approach for the eco-friendly biodiesel base stock from epoxidized vegetable oil Appl. Catalysis B 69 207–12
[14] Fox N J and Stachowiak G W 2007 Vegetable oil-based lubricants - A review of oxidation Tribol. Int. 40 1035–46
[15] Ranjan N, Shende R C, Kamara M and Ramaprabhu S 2020 Utilization of TiO2/g-C3N4 nanoadditive to boost oxidative properties of vegetable oil for tribological application Friction 9 275–87
[16] Kern I, Rauna A and Haq M 2019 Friction and wear performance of olive oil containing nanoparticles in boundary and mixed lubrication regimes Wear 426–427 819–27
[17] Gupta G, Haq M, Rauna A and Shaﬁ W K 2021 Effect of epoxidation and nanoparticle addition on the rheological and tribological properties of canola oil Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology ITR2020 1–9
[18] D’Amato R, Wang C, Calvo R, Vališek P and Ruggiero A 2019 Characterization of vegetable oil as cutting fluid Procedia Manufacturing 41 145–52
[19] Feng X, Cao Z F and Xia Y Q 2017 Leaf-surface wax extracted from different pines as green additives exhibiting excellent tribological properties Mater. Res. Express 4 115305
[20] Zhang M, Wang X B, Fu X S and Xia Y Q 2009 Performance and anti-wear mechanism of CaCO3 nanoparticles as a green additive in poly-alpha-olefin Tribol. Int. 42 1029–39
[21] Khan A, Singh R, Gupta P, Gupta K and Khatri O P 2021 Aminoguanidine-based deep eutectic solvents as environmentally-friendly and high-performance lubricant additives J. Mol. Liq. 339 116829
[22] Frogde J D, Thomas G L and Pauley G B 1990 Effects of canopy formation by floating and submerged aquatic macrophytes on the water quality of two shallow Paciﬁc Northwest lakes Aquatic Botany 38 231–48
[23] Li J J, Liu Y H, Luo J B, Liu P X and Zhang C H 2012 Excellent lubricating behavior of brine shreberi mucilage Langmuir 28 7997–8002
[24] Li P, Liu Y, Yang Y, Chen Z, Li J and Luo J 2014 Mechanism of biological liquid superlubricity of brine shreberi mucilage Langmuir 30 3811–6
[25] Misaki A, Kirkwood S, Scalletti J V and Smith F 2011 Structure of the extracellular polysaccharide produced by Xanthomonas oryzae. Canadian Journal of Chemistry 40 2204–13
[26] Ngo D, He X, Luo H, Qu J and Kim S H 2020 Competitive adsorption of lubricant base oil and ionic liquid additives at air/liquid and solid/liquid interfaces Langmuir 36 7582–92
[27] Yang G, Zhao J, Cui L, Song S Y, Zhang S M, Yu L G and Zhang P Y 2017 Tribological character and mechanism analysis of borax ester as a lubricant additive in different base oils RSC Advances 7 7944–53
[28] Feng X, Hu Y C, Cao Z F and Xia Y Q 2019 Leaves based lubricant additive towards improving tribological properties Journal of Renewable Materials 7 441–9
[29] Xiao L, Björklund S and Rosén B G 2007 The influence of surface roughness and the contact pressure distribution on friction in rolling/sliding contacts Tribol. Int. 40 694–8
[30] Cao Z and Xia Y 2017 Study on the preparation and tribological properties of fly ash as lubricant additive for steel/steel pair Tribol. Lett. 65 104
[31] Zhang M, Wang X B, Fu X S and Liu W M 2009 Investigation of electrical contact resistance of Ag nanoparticles as additives added to PEG 300 Tribol. Trans. 52 557–64
[32] Cetin M H and Kılıncarslan S K 2020 Effects of cutting fluids with nano-silica and borax additives on milling performance of aluminium alloys J. Manuf. Processes 50 170–82
[33] Wang Z, Xia Y and Liu Z 2011 Study the sensitivity of solid lubricating additives to attapulgite clay base grease Tribol. Lett. 42 141–8
[34] Feng X, Hu Y and Xia Y 2019 Tribological research of leaf-surface wax derived from plants of Pinaceae. Lubrication Science 31 1–10
[35] Rivera N, García A, Fernández-González A, Blanco D, González R and Battez A H 2019 Tribological behavior of three fatty acid ionic liquids in the lubrication of different material pairs J. Mol. Liq. 296 111858
[36] Elsheikh A, Yu J, Sathyamurthy R, Tawfiq M, Elsheikh A, Yu J, Sathyamurthy R, Tawfiq M, Shinde R C, Kamaraj M and Ramaprabhu S 2020 Utilization of TiO2/nano-TiO2 as additive on tribological properties Journal of Renewable Materials 7 441–9
[37] Battez A H, Gonzalez R, Viesca J L, Blanco D, Asedegbega E and Osorio A 2009 Tribological behaviour of two imidazolium ionic liquids as lubricant additives for steel/steel contacts Wear 266 1224–8
[38] Minami I 2009 Ionic liquids in tribology Molecules 14 2286–305
[39] Wei J X, Cai M R, Feng Z and Liu W M 2014 Candle soot as particular lubricant additives Tribol. Lett. 53 521–31
[40] Antusch S, Dienwiebel M, Nold E, Albers P, Spicher U and Scherge M 2010 On the tribochemical action of engine soot Wear 269 1–12