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Tribological Evaluation of Date Palm Fruit Syrup–A Potential Environmental-Friendly Lubricant

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Received: 7 June 2017; Accepted: 5 July 2017; Published: 7 July 2017

Abstract: Date palm is one of the most cultivated palms mostly found in the Middle Eastern regions of the world. The date palm fruits are not only nutritionally rich, but also have a good amount of fatty acids such as oleic acid, palmitic acid, and linoleic acids, which have excellent anti-wear and lubricating properties, making it a potentially good candidate to be used as an environmentally-friendly lubricant. This study is a preliminary effort to explore the lubricating properties of date palm fruit syrup by conducting ball-on-disc wear tests on mild steel samples. Different concentrations (50, 75, and 100 vol %) of the syrup in water were tested at a normal load of 50 N and a sliding linear speed of 0.1 m/s. Scanning electron microscopy and optical profilometry were used to characterize the wear tracks and estimate the wear rates. 100 vol % date syrup with a viscosity of 16.95 mPa·s showed excellent results by reducing the coefficient of friction of steel-on-steel from 0.6 (dry conditions) to a value of ~0.1. The depth of the wear track reduced from ~152 μm (dry conditions) to ~11 μm, signifying a considerable reduction in wear.

Keywords: date palm fruit syrup; lubrication; environmentally friendly; tribology; friction; wear

1. Introduction

In the quest to find solutions to the two major challenges of the 21st century (namely, global warming and energy conservation), researchers have been exploring different environmentally-friendly lubrication strategies to reduce friction losses in moving components. The current methods of lubrication for many contacting surfaces in mechanical systems are the use of lubricants with appropriate additives. The lubricant protects against wear, reduces friction, cleans off dirt and residue (detergent), protects against corrosion, and cools. Industrial lubricants are made by adding different additives to base oil to improve its physical and chemical properties. Consequently, lubricating oils have high additive contents (up to 20%), especially detergents and dispersants which constitute 2–15% of oil weight. The function of the additives is to react with the contacting surface and form tribo-films which protect the surfaces from wear. The most commonly used additives among many in the current industrial lubricants used in the automotive/aerospace industry are ZDTP (zinc dialkyl dithiophosphate) and MoDTC (molybdenum dialkyl dithiocarbamate) due to their excellent anti-wear properties, and are added to lubricants to improve their efficiency and reduce friction [1–3].

However, several of the oil additives are toxic environmental contaminants; for example, zinc dithiophosphate and zinc diaryl or dialkyl dithiophosphates (ZDTPs); calcium alkyl phenates; magnesium, sodium, and calcium sulphonates; tricresyl phosphates; molybdenum disulfide; heavy metal soaps; and other organometallic compounds that contain heavy metals [4–6]. Although ZDTPs have a low acute systemic toxicity, they can cause eye damage and skin irritation [4]. Research has shown that prolonged exposure to high concentrations of ZDTPs, calcium alkyl phenates, and magnesium, sodium, and calcium sulphonates had significant effects on the nervous system, the respiratory system causing nose and throat irritation, and also lead to eye irritation [4].

Hence, these additives used in lubricants are one of the major sources of air pollution which cause health hazards and contribute to global warming. Governments around the world are taking necessary steps and passing legislations to control the amount of harmful additives used in lubricants. Moreover, the problem of wear is not totally eliminated, even with the best of additives. Hence, there is an urgent need to explore alternative lubricating strategies or additives for lubricants which are environmentally-friendly and do not pose much threat to the human health without compromising on the overall performance in terms of protecting mechanical systems from wear, friction, and corrosion.

This pursuit of developing environmentally-friendly lubrication strategies led to the development of green lubricants. Researchers have explored different strategies, such as adding environmentally-friendly nano-fillers as additives to the base oil [7–15] on one hand and developing water-based lubrication with extracts from natural resources (natural oils such as vegetable oils [16–20]) on the other for reducing the coefficient of friction and wear in tribological components. In this paper, we plan to take the second approach by developing a water-based environmentally-friendly lubricant by adding date palm fruit extract to it.

Date palm (*Phoenix dactylifera*) fruit is a naturally-occurring resource with excellent nutritional and medicinal values, and has been a part of staple diets largely in the North African and Middle Eastern regions of the world. In addition to being consumed as a whole fruit, it is also used to make spreads, syrups, and sauces. Researchers have explored the feasibility of using the extracts from the date palm leaves and seeds as anti-corrosive additives in water, and found they to be very effective in inhibiting corrosion in metallic components [21,22]. Date palm fruit extracts as anti-corrosive additives also yielded encouraging results in terms of inhibiting corrosion [23]. Recently, researchers have found that date palm fruits have good amount of nutrients, minerals, and fatty acids. Ogungbenle [22] found that the date palm fruits contain unsaturated fatty acids such as oleic acid (44.51 g/100 g), palmitic acid (23.05 g/100 g), and linoleic acid (11.66 g/100 g), which have proven to be excellent anti-wear and lubricity additives in oils [24–28]. It has been found that oleic acid reacts with iron oxide in steel and forms a thin film of iron oleate which exhibits low friction [26].

Therefore, the motivation of the present study came from the fact that although the date palm fruit is a good source of fatty acids (oleic, palmitic, and linoleic) which are very well known anti-wear and lubricity additives, the feasibility of using the same as a lubricant to protect metallic surfaces from wear and tear has not been explored yet. Hence, the focus of the present study is to investigate the lubricating properties of the date palm fruit syrup in different concentrations with water as a base in protecting the metallic components from wear and tear and to tap its potential of becoming a possible green lubricant.

2. Materials and Methods

Circular mild steel coupons of 25 mm diameter and a thickness of 6 mm were used as metallic substrates. The hardness of the mild steel samples was measured to be ~242 HV. The coupons were uniformly ground and polished to an average surface roughness value of 0.1 ± 0.02 µm to remove the effect of surface topography on the results. Date palm syrup (100%) was bought from the local market. The complete general process followed to extract the syrup from the date palm fruit is shown in the schematic of Figure 1.

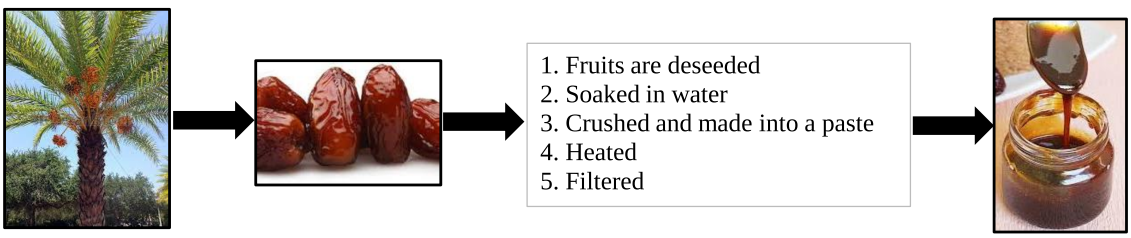

Figure 1. Flow chart of the general process of extracting date syrup from date palm fruit.

Three different loadings of date palm syrup in deionized (DI) water were prepared in terms of volume %. Table 1 shows the various configurations of the date palm fruit syrup in water used for this study, along with the viscosities of each solution. The viscosity of the DI water and the different concentrations of the date palm fruit syrup were measured by using a rotary type viscometer (Rotary viscosimeters "ST-2020", JP Selecta, Barcelona, Spain). A rotating cylinder or disk (spindle) at a selected known speed was submerged into the liquid to be analyzed, and the viscosity was measured by measuring the resistance of the substance according to the flow characteristics of the reference spindle. The instrument calculates the result and directly displays the viscosity that is reported.

Table 1. Configurations of the date palm fruit syrup in water with the corresponding viscosities.

Amount of Date Palm Fruit Syrup in Deionized (DI) Water (vol %)	Viscosity (mPa·s)
0% (Pure water)	0.91
50%	1.11
75%	3.72
100% (Pure Date Palm Fruit Syrup)	16.95

Wear tests were conducted using a ball-on-disc configuration on a Bruker UMT-3 tribometer (Bruker, Billerica, MA, USA) under dry and lubricated conditions. The mild steel coupons were slid against a AISI 440C stainless steel ball with a hardness of RC-62. Both the ball and the mild steel coupons were cleaned with acetone and dried with a normal stream of air before the test. A normal load of 50 N (Corresponding Hertzian contact pressure of ~2.3 GPa) and a linear sliding speed of 0.1 m/s were used for all the experiments for a constant number of cycles of 25,000 corresponding to a sliding distance of 1000 m. For every test, a measured quantity of each type of solution sufficient to submerge the mild steel sample was used. The lubricant holder was designed in such a way that the region of contact between the rotating mild steel sample and the fixed counterface ball was always flooded with the solution. Three repetitions for each type of solution were performed, and the average value of the coefficient of friction and specific wear rates are reported. All the tests were carried out at a room temperature of 25 $\pm$ 2 °C and a relative humidity of 55 $\pm$ 5%. The images of the counterface ball were recorded with an optical microscope (Meiji, Tokyo, Janpan) after each test to evaluate wear on the counterface ball. A GTK-A optical profilometer (Bruker, Billerica, MA, USA) was used to record the 3D and 2D profiles of the wear tracks after every test to calculate the specific wear rates. Field emission scanning electron microscopy (FESEM, Tescan, Brno, Czech Republic) was used to evaluate the wear mechanisms by imaging the wear tracks after the tests.

For comparison purposes, wear tests were also conducted using an industrial lubricant of SAE 20W50 grade (Viscosity index = 124, Viscosity @ 100 °C = 19.1 mPa·s) under similar conditions.

3. Results

3.1. Variation of Coefficient of Friction under Different Solutions

Figure 2 shows the variation of coefficient of friction for the tribo-pair of mild steel and the AISI 440C stainless steel ball in dry and under different solutions at a normal load of 50 N and a linear sliding speed of 0.1 m/s. Figure 3 shows typical frictional graphs for the tribo-pair under dry and different lubricating conditions. It can be observed that under dry conditions, the tribo-pair exhibited a very high coefficient of friction (COF) of ~0.62. However, under the DI water lubricated conditions, the COF reduced to ~0.38. However, it can be observed that with an increase in the vol % of the date palm fruit syrup in DI water, the COF reduced considerably compared to that of dry and DI water lubricated conditions. The reduction in COF from ~0.38 under pure DI water lubrication to ~0.2 under 50 and 75 vol % of date syrup in DI water can be attributed to the inherent lubricating properties of the date syrup. However, no significant difference in the COF was observed between 50 and 75 vol % of date syrup solution. Meanwhile, for 100% date palm fruit syrup with a viscosity of 16.95 mPa·s, the COF reduced considerably to a value of ~0.1, which is the same as that exhibited under an industrial lubricant (~0.09). This shows the excellent ability of the date palm fruit syrup to provide good lubrication to tribo-pair, which can be attributed to the formation of thin lubricious films by the fatty acids present in it, resulting in low coefficient of friction.

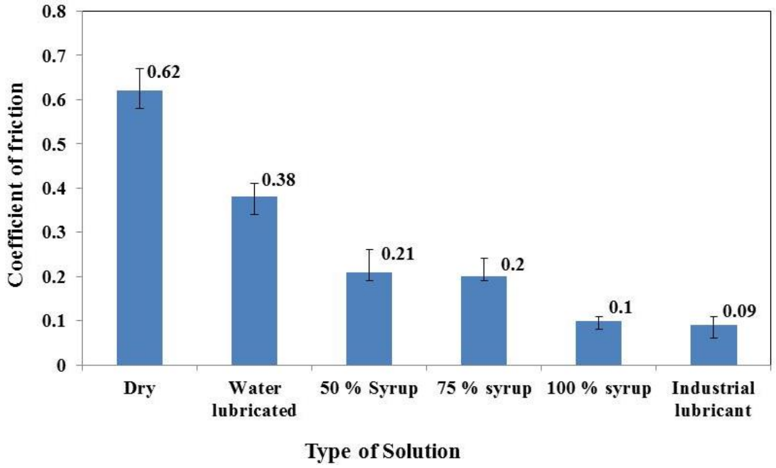

Figure 2. Variation of coefficient of friction in dry and under lubricating conditions with different types of solutions at a normal load of 50 N and a linear sliding speed of 0.1 m/s.

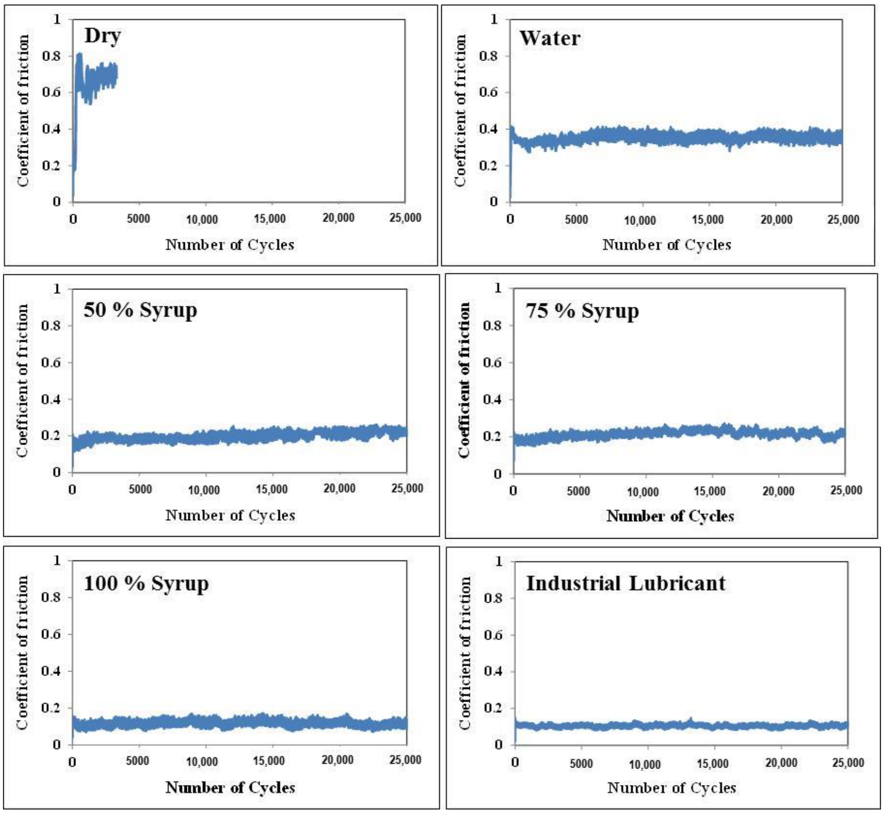

Figure 3. Typical frictional graphs for dry and lubricated conditions under different solutions at a normal load of 50 N and a linear sliding speed of 0.1 m/s.

3.2. Wear under Dry and Lubricating Conditions with Different Solutions

Figure 4 shows the contour plots and 2D optical profiles for the wear tracks for all the conditions considered. Figure 5 shows the scanning electron microscopy (SEM) images of the wear tracks at lower and higher magnifications for the different conditions. Figure 6 shows the optical images of the stainless steel counterface balls after the wear test.

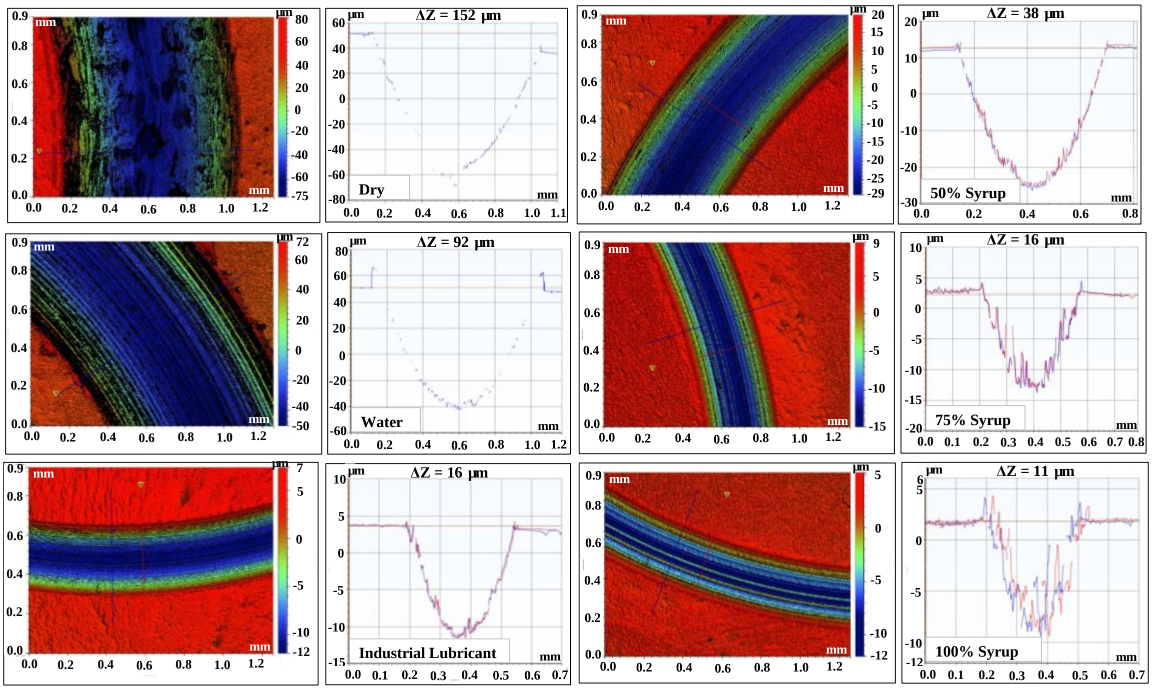

Figure 4. Typical contour plots and 2D wear profiles for dry and lubricated conditions under different solutions at a normal load of 50 N and a linear sliding speed of 0.1 m/s.

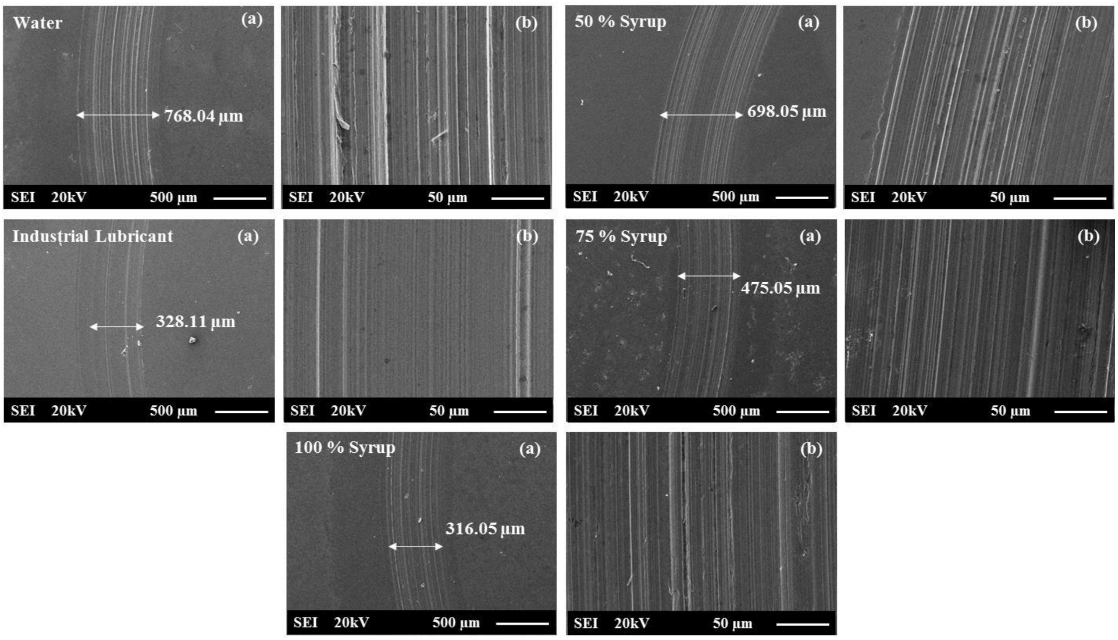

Figure 5. Scanning electron microscopy (SEM) images at (**a**) Lower magnifications; (**b**) Higher magnifications of the wear tracks for lubricated conditions under different solutions at a normal load of 50 N and a linear sliding speed of 0.1 m/s.

3.2.1. Effect of Different Syrup Loadings on the Wear of the Tribo-Pair as Compared to Dry and Water Lubricated Conditions

Firstly, it was observed that the wear decreased significantly from the dry conditions as compared to that of the case where the date palm fruit syrup was used as a lubricant in different concentrations. This is clearly evident from the depth and the width of the wear track profile, whereby the depth of the wear track reduced from ~152 µm (the test was run only for 3500 cycles) for the dry condition to values of ~38, 16, and 11 µm for 50%, 75%, and 100% loadings of the syrup in DI water, even after 25,000 cycles of test. This clearly shows the ability of the syrup in providing lubrication to the metallic surfaces and reducing the wear and tear of the tribo-pair.

Secondly, it was observed that as compared to the tests run under pure 100% DI water lubrication, the date palm fruit syrup showed lower wear for all three cases. This is evident from the examination of the 2D wear track profile depths (Figure 4), whereby the depth of the wear track reduced considerably from ~92 µm after a test of 25,000 cycles for DI water lubrication as compared to that of ~38, 16, and 11 µm for 50%, 75%, and 100% loadings of the syrup in DI water. Moreover, the width of the wear tracks also reduced significantly, as can be seen from Figures 4 and 5, signifying the effectiveness of the syrup in providing a good lubrication between the metal surfaces, leading to reduced wear. Upon observation of the optical images of the counterface stainless steel ball for the case of DI water lubrication as shown in Figure 6, a significant amount of wear scar is noticed when compared to that of the surfaces of the balls that were run under the different loadings of the syrup. This again signifies the better capability of the syrup in protecting both the surfaces of the tribo-pair against wear as compared to that of water.

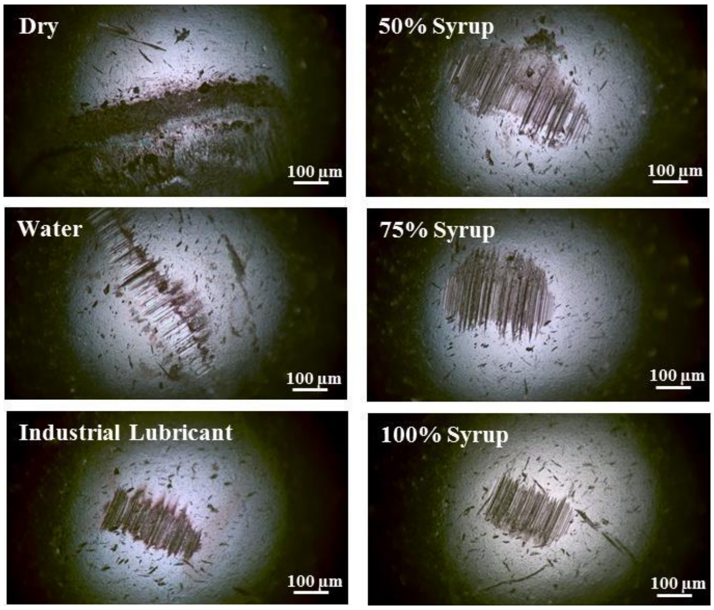

Figure 6. Optical images of the stainless steel counterface balls after the wear test for dry and lubricated conditions under different solutions at a normal load of 50 N and a linear sliding speed of 0.1 m/s.

3.2.2. Effect of Different Syrup Loadings on the Wear of the Tribo-Pair

It can be observed from Figure 4 that the wear decreases with an increase in the vol % of date palm fruit syrup in DI water. On examining the 2D wear track profiles in Figure 4 and the SEM images of the wear tracks in Figure 5, it can be observed that both the wear track width and the wear track depth reduced with an increase in the vol % of the syrup in DI water. This reduction is attributed to the increase in the viscosity of the solution, leading to an improvement in the ability of the syrup solution to provide effective lubrication to the tribo-pair. However, upon close examination of the SEM images of the wear tracks as shown in Figure 5 and the 2D profiles of the tracks as shown in Figure 4, a significant amount of perturbance is observed with an increase in the quantity of the syrup in the DI water solution. This is attributed to the remnants of the viscous syrup on the wear track. Moreover, it can also be noticed from the counterface ball images shown in Figure 5 that the size of the scar mark on the ball surface reduced with an increase in the concentration of the syrup in the solution, again proving the effectiveness of the date palm fruit syrup in providing good lubrication to the trio-pair.

3.2.3. Performance of the Date Palm Fruit Syrup Solution as Compared to an Industrial Lubricant

It can be observed from the 2D profiles of the wear tracks (Figure 4) for the industrial lubricant and the 100% syrup that the depth of the wear track is actually slightly lower for the 100% syrup (~11 µm) as compared to the case of industrial lubricant (~16 µm). Even the wear track width is lower for the 100% syrup (~316 µm) as compared to that of the industrial lubricant (~328 µm), signifying the fact that the 100% syrup is very effective in providing proper lubrication to the tribo-pair, leading to reduced friction and reduced wear.

4. Conclusions

The present study was undertaken with the main focus of investigating the feasibility of using the date palm fruit syrup as an environmentally-friendly lubricant which has also been found by many earlier studies to be very effective as a corrosion inhibitor [23]. Hence, ball-on-disc wear tests were conducted on mild steel samples under various conditions, and it was observed that the date palm fruit syrup was very effective in reducing the friction and wear between the tribo-pair of mild steel coupons and a hard stainless steel ball. The syrup was found to be very effective in all its forms—i.e., as an additive to DI water or as 100% syrup—in reducing the friction and wear as compared to the dry sliding and tests carried out under DI water lubrication. However, with an increase in the vol % of the syrup in DI water, the performance improved whereby the 100% syrup showed comparable performance to an industrial lubricant.

Date palm fruits were found to contain unsaturated fatty acids such as oleic acid (44.81%), palmitic acid (23.05%), and linoleic acid (11.66%), which have proven to be excellent anti-wear and lubricity additives in oils [24]. The anti-wear properties of the fatty acids result from the interaction of their polar group (–COOH) with the metallic surface, leading to a surface film formation which helps in reducing the metal-to-metal contact and thus resulting in a significant reduction in wear and tear of the contacting surfaces [29,30]. Hence, the good tribological performance of the date palm fruit syrup is attributed to the presence of fatty acids such as the oleic acid, palmitic acid, and linoleic acid, which form thin anti-wear and lubricious films on the steel surface, helping in the protection of the steel surface from wear and tear.

Hence, the present study opens up various opportunities for some interesting future studies whereby the date palm fruit syrup can be explored and modified by some environmentally-friendly additives to further improve its performance.

Acknowledgments: The author gratefully acknowledges the financial support by the Deanship of Scientific Research (DSR) at King Fahd University of Petroleum & Minerals (KFUPM) through Project No. FT161011.

Author Contributions: Abdul Samad Mohammed was responsible for this novel research right from the conceptualization to the designing, conducting and analyzing the experiments. He was also responsible for drafting the results in the paper format.

Conflicts of Interest: The author declares no conflict of interest.

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