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ORIGINAL ARTICLE

Evaluation of boron nitride particles on the tribological performance of avocado and canola oil for energy conservation and sustainability

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Abstract In the present investigation, experiments were conducted using a pin-on-disk apparatus to study the tribological performance of environmentally friendly multi-phase lubricants consisting of natural plant-based liquid lubricants and hexagonal boron nitride (hBN) solid additives. Among the natural plant-based liquid lubricants, a high oleic acid lubricant, such as avocado oil, showed the best tribological performance when compared to other natural plant-based lubricants, which further demonstrated the importance of appropriate natural oil selection for tribological applications. In order to develop an optimal multi-phase lubricant, hBN particles with varying sizes were incorporated as additives in the avocado oil. Experiments revealed that particle additive size with regards to initial surface roughness affects the tribological performance of the multi-phase lubricant. It was found that this multi-phase lubricant with nano-sized additives showed the best performance when compared to multi-phase lubricants with micron-sized and submicron-sized additives. More specifically, the lubricant mixtures had friction reductions from 8 to 64 % for particles ranging from micron-sized to nano-sized, respectively. The wear also decreased in the lubricant mixtures with reductions from 13 to 70 % for particles ranging from micron-sized to nano-sized, respectively. These mechanisms for enhanced tribological performance are discussed in this investigation.

Keywords Friction · Wear · Lubricant · Boron nitride · Environmentally friendly · Avocado · Canola · Oleic acid

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1 Introduction

Pure natural oils have for a long time been known to be good lubricants in lowering friction and preventing wear. Since the beginning of the twentieth century, investigations into the properties of natural oils have received much attention [1–7]. More recently, in an effort to curb the use of toxic petroleum-based lubricants due to concerns of protecting the environment, as a result, we have witnessed a resurgence in natural oils [8–11]. Moreover, the emphasis placed on pure natural oils is a result of the increase in demand for environmentally friendly lubricants that are less toxic to the environment, renewable, and provide feasible and economical alternatives to traditional petroleum-based lubricants [12, 13]. The attraction to natural oils is due to their composition of triacylglycerol made up of esters derived from glycerol and long chains of polar fatty acids that are desirable in boundary lubrication for their ability to adhere to metallic surfaces, remain closely packed, and establish a monolayer that is effective at reducing friction and wear [1, 3–7, 14–19]. Much of the work with natural oils has concentrated on understanding the fundamentals of saturated and unsaturated fatty acids with the bulk of the attention focusing on the use of natural oils as neat lubricants, additives in mineral oils, and most recently carrier fluids for particle additives [1–3, 12, 20–26]. Initial research has shown favorable results where natural oils, such as vegetable oils, were used as carrier fluids for graphite, molybdenum disulfide, or other anti-wear additives in a minimal quantity of lubrication machining scenario. In these studies, the lubricant mixtures demonstrated superior performance in various turning applications by minimizing the coefficient of friction, thereby reducing cutting forces and temperature [27–30]. When compared to mineral and synthetic oils, natural plant oils have a higher lubricity, lower volatility, higher shear stability, higher viscosity index, higher load carrying capacity, and superior detergency and dispersancy [2, 3, 18, 31]. Therefore, natural oils are a good alternative to petroleum-based oils.

Green lamellar powders, such as boric acid (H_3BO_3) and hexagonal boron nitride (hBN), are well-known solid lubricants for their low interlayer friction and ability to form a protective boundary layer and accommodate relative surface velocities [2, 21, 25, 32–34]. These powders are effective in a broad range of applications to lower friction and minimize wear [22, 23, 35–38]. Furthermore, they are environmentally benign and inert to most chemicals, making them an attractive performance enhancing additive to natural oils [2, 24]. Investigations into the size effect of boron nitride and boric acid particulate additives mixed with canola oil were conducted for their effects on friction and wear [22–24]. Canola oil was used as a carrier fluid to circulate the particulate additives during pin-on-disk testing. It was shown that the canola oil with particulate additives demonstrated improved tribological performance when compared to canola oil itself [23–25]. These studies demonstrate that natural oils enhanced with particulate additives can be used as potential biolubricants and as alternatives to toxic petroleum-based lubricants [39]. The aim of the present investigation is to build off the author's previous work using hBN as an additive to natural plant-based oils [24, 40]. This research seeks to select an appropriate carrier fluid that has lower friction and wear than canola oil in order to demonstrate further improvements on the tribological performance when additives are incorporated in the lubricant.

2 Experimental materials and procedures

2.1 Natural oil selection

In a previous investigation, the authors demonstrated the influence of fatty acids on the tribological properties of natural oils as well as the size effect of boron nitride particles on a lubricant mixture [24, 41]. Figure 1a, b shows the results from previously pin-on-disk tests demonstrating the variation of coefficient of friction (COF) with sliding distance and the variation of wear at the completion of the sliding tests for the various natural oils. These results reveal that avocado oil should be evaluated as a carrier fluid with hBN solid particle additives because it had superior tribological properties that surpass all the other natural oils tested in regards to having lower friction and wear. In the previous investigation, the authors evaluated canola oil as a carrier fluid with hBN solid particle additives, and the current work extends this research [23], understanding that the COF and corresponding wear are system-dependent properties that are dependent upon test environment, operating conditions, and surface geometrical configuration. Ambient conditions such as temperature and humidity as well as the type of counterface materials and surface texture also affect the tribological properties of a given lubricant. Despite potential variable differences, previous investigations exemplify a variety of natural oils, such as avocado, canola (rapeseed), corn, olive, peanut, genetically modified (GM) safflower, sesame, and vegetable (soybean), which were considered for their tribological performance. These natural oils were chosen because they represent a variety of saturated, monounsaturated, and polyunsaturated fatty acid compositions within the natural oils that are readily available and inexpensive. In addition, they have viscosity and surface tension properties similar to petroleum-based lubricants used in metal stamping and metal forming applications [12, 42].

2.2 Lubricant mixture preparation

The tribological performance of the lubricant mixtures was studied by varying the particle size of the hBN powder additives in the base oil consisting of avocado and canola oil. Four hBN particle sizes (70 nm, 0.5 μm, 1.5 μm, and 5.0 μm) were considered to match prior experiments with canola oil and hBN [24]. To quantify and verify the size and shape, the hBN particles were analyzed using a scanning electron microscope (SEM), and the micrographs are shown in Fig. 2. It can be seen in Fig. 2 that the particle sizes observed under SEM do indeed match their average particle size descriptions provided by the manufacturer. It is also shown in the micrographs of Fig. 2 that the sphericity of the particles decreases as the average particle size increases. During each test, 10 mL of the base oil was mixed with hBN particles at 5 % by weight. The individual particles and their mixtures were combined with the base oil using a vortex generator to form a homogenous colloidal mixture.

2.3 Apparatus and parameters

In the pin-on-disk experiment, an oxygen-free electronic copper (C101) pin was made to slide against a 2024 aluminum disk to obtain the friction and wear properties of the natural oil lubricant mixtures [20, 43]. The pin-and-disk materials were specifically chosen to match prior experiments conducted by the authors [2, 12, 23, 24]. The copper pin dimensions were 6.35 mm in diameter and 50 mm in length and had a hemispherical tip. The aluminum disk dimensions were 70 mm in diameter and 6.35 mm in thickness and were polished to a surface roughness having an arithmetic average, Ra, value of 0.3 ± 0.05 μm. Table 1 presents the specified testing parameters used during each pin-on-disk experiment. The experiments were conducted using a Ducom Instrument Material Characterization System mounted with a pin-on-disk module that rotated with a linear velocity of 36 mm/s and a hanging mass cantilever normal load applicator of 10 N, and a linear variable differential transducer to measure wear. The tests traveled a distance of 2100 m under ambient conditions at

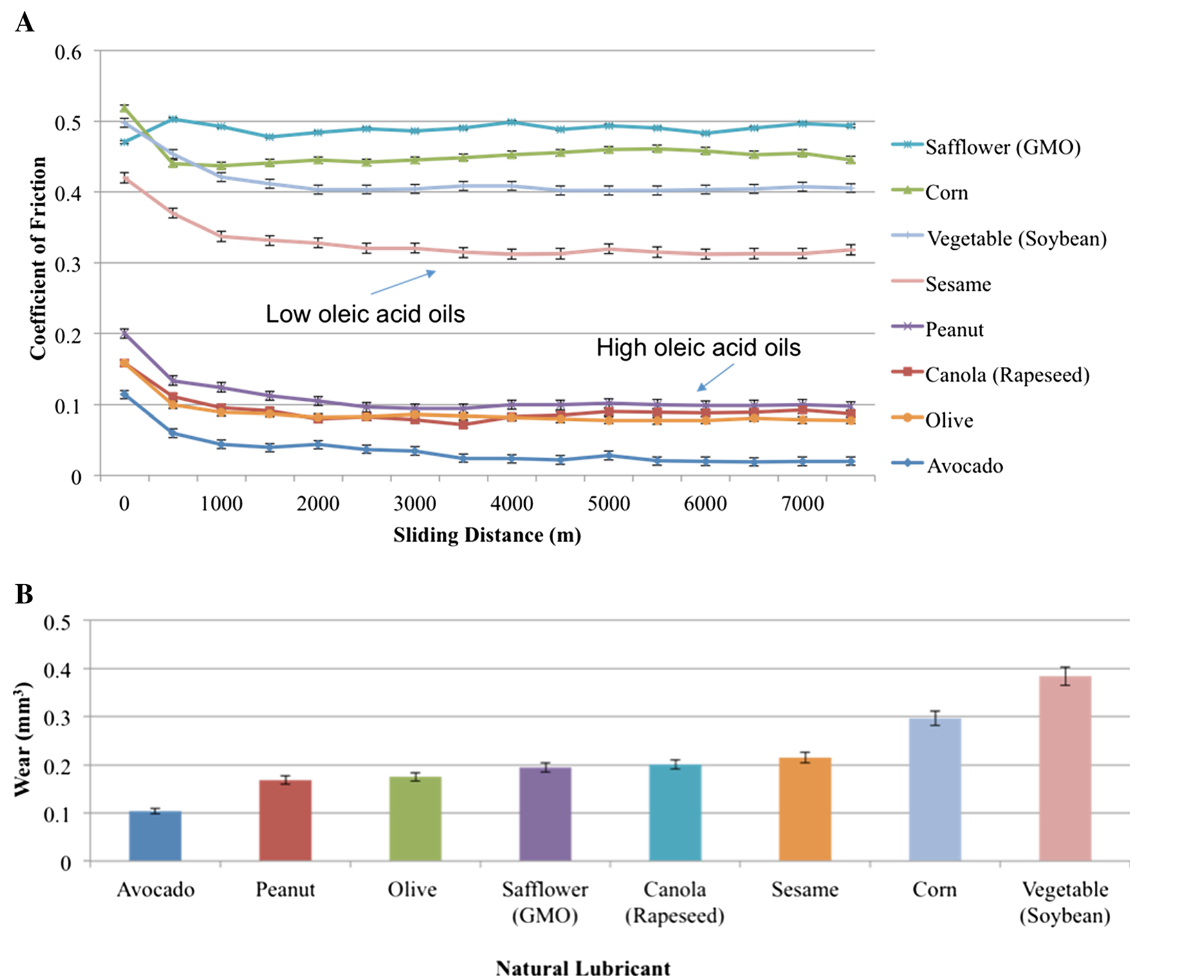

Fig. 1 **a** Variation of the coefficient of friction with sliding distance for natural oils. b Variation of wear for natural oils at completion of tests [41]

room temperature. Prior to each experiment, all test specimens were cleaned with a soap, acetone, and hexane solution in an ultrasonic cleaner. During each of the tests, the disk was completely submerged by the lubricant mixture, thereby continually lubricating the pin-disk interface throughout the duration of the test. Each test was repeated a minimum of three times to ensure repeatability and accuracy of the results.

3 Results and discussion

3.1 Effect of fatty acid composition on friction and wear

Figure 3 shows the fatty acid composition for a variety of natural oils. The fatty acid content was retrieved from the US Department of Agriculture's National Agricultural Library, which publishes compositional data in their Nutrient Database. Comparing Figs. 1a, b and 3, the dominant fatty acid that had the greatest impact on the tribological performance was determined to be oleic acid (C18:1) for its ability to form denser monolayers that adsorbed onto the charged metallic surfaces to protect the tribo-interface [15, 31]. By investigating the natural oil composition, it can be speculated that canola oil, which is often considered a preferable alternative to petroleum-based metalworking fluids, may not be the optimal natural oil. The advantage of avocado oil is due to its higher percentage of oleic acid that exhibits superior thermo-oxidative stability as well as the ability to develop resilient monolayers that better protect the pin-disk interface resulting in lower friction and wear [2, 3, 16, 17, 23, 44–46]. For these reasons, it can be speculated that using avocado oil with particulate additives would lead to further improvements in the tribological properties of this class of biolubricants for three reasons: (1) establishment of a superior fatty acid monolayer to lower the friction and wear, (2) enhancement of the thermal-oxidative stability to prevent the lubricant from degrading, and (3) advancement of the particulate additives to further reduce friction and wear. This has led to the current investigation where avocado oil was selected as a carrier fluid (base oil) for mixing with boron nitride powder additives in order to develop a multi-phase lubricant and to study the improvements on the tribological performance.

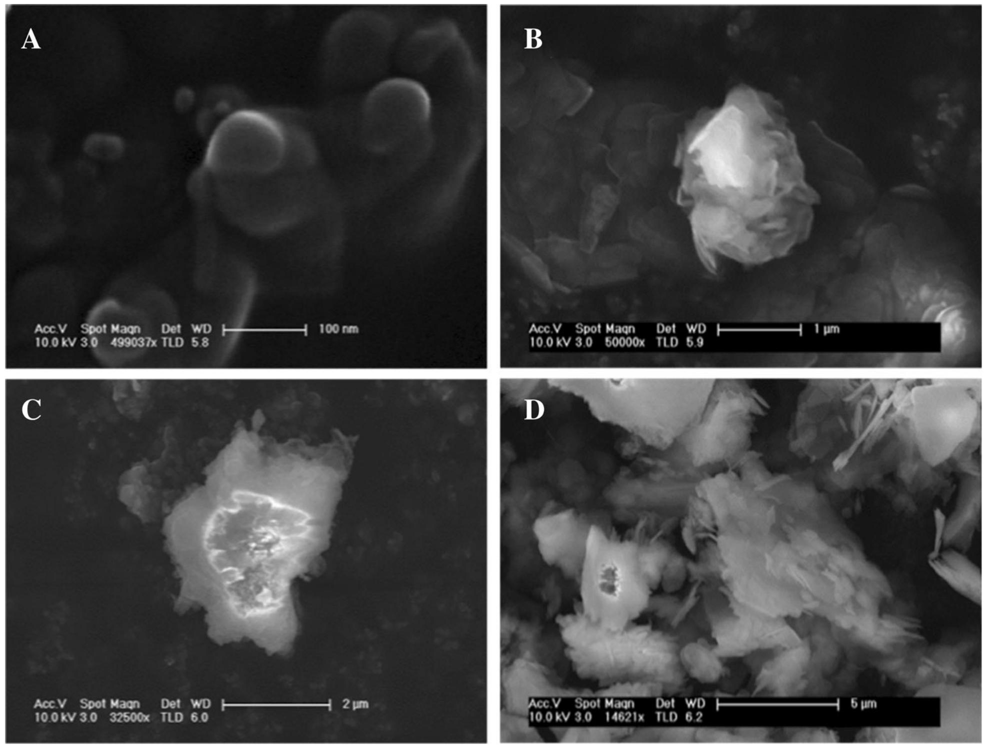

Fig. 2 Scanning electron micrographs of hBN particles with size **a** 70 nm, **b** 0.5 μm, **c** 1.5 μm, and **d** 5.0 μm [24]

3.2 Effect of particulate additive in avocado oil on friction

Figure 4a shows the variation of the COF with sliding distance, and Fig. 4b shows the final COF values at the completion of the tests for avocado oil-based lubricants consisting of hBN particulate additives with varying particle sizes. It was revealed that the COF for the various lubricant mixtures decreases with sliding distance. Among the single particulate mixtures, the 70-nm hBN particles maintained the lowest COF values followed by the 0.5-, 1.5-, and 5-μm hBN particulate mixtures. More still, each of the avocado oil and hBN particulate mixtures maintained a lower COF value than the pure avocado oil. Table 2 shows the final COF values and the percent difference in the COF values in order to measure the influence that the hBN particulate additives in avocado oil have on the tribological performance. In this table, the COF values of the individual particles in avocado oil were compared to the COF value of pure avocado oil in the percent difference calculation. The COF values of combined particulate tests were compared to the COF value of larger particle size to gauge the improvement in tribological performance due to the addition of the smaller particles being present in the combination mixture. It can be seen that the 70-nm hBN particles in avocado oil decreased the COF by 64 % while the 5-μm hBN particles in avocado oil only decreased the COF by 8 % when compared to the pure avocado oil. The influence of the 70-nm particles lowered the COF in the 0.5- and 1.5-μm hBN tests by 20 and 11 %, respectively. The combination of the 0.5- and 1.5-μm hBN as a particulate mixture in avocado oil resulted in a 30 % increase in the COF when compared to the 1.5-μm hBN test. Evaluating the average particle size in the lubricant mixture containing one or two sizes of particulate additives further reveals that there is an 80.5 % correlation coefficient (*R* value) between average particle size and COF (Table 2). This indicates that as the average particle size increases, the COF also increases. This emphasizes the effects particle size and shape have on the tribological performance where smaller particles are more spherical, as shown in Fig. 2a, this allowing the particles to more easily coalesce in the asperity valleys, creating a smoother transfer layer that is less abrasive, where the particles align themselves parallel to the relative motion and slide over one another with relative ease providing lubrication and effectively reducing friction. In

Table 1 Test parameters for the pin-on-disk experiment

Parameter	Selected value
Normal load (N)	10
Sliding velocity (mm/s)	36
Angular velocity (rpm)	21.5
Distance traveled (m)	2100
Duration (hours)	16.2
Environment	Ambient conditions
Lubricant amount (mL) base oil	10
Additives	5 % Wt. hBN
Additive particle sizes	5.0 μm, 1.5 μm, 0.5 μm, and 70 nm

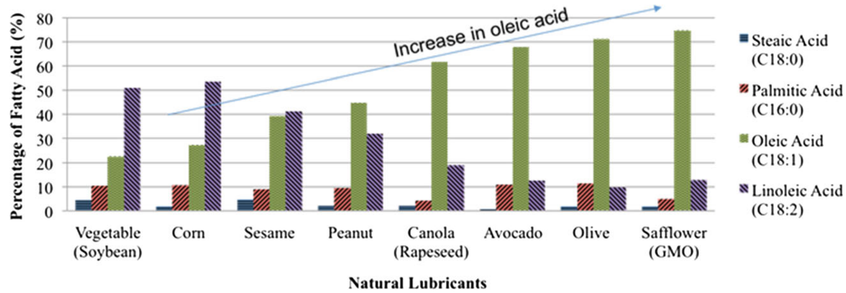

Fig. 3 Fatty acid concentrations of stearic, palmitic, oleic, and linoleic acid in various natural oils [41]

comparison, larger particles have the ability to traverse the asperity contacts and support more of the contact load. However, in this case with a surface roughness and an Ra value of 0.3 μm, their plate-shaped geometry, shown in Fig. 2d, may have been detrimental due to the high stress caused by the interaction between the similar-sized particles and the asperities. This interaction could result in an increase in abrasion resulting in higher friction. Nevertheless, the presence of even the larger particle sizes in the lubricant mixture was still an improvement over pure lubricants with no particle additives.

3.3 Effect of particulate additive in avocado oil on wear

Figure 5a shows the variation of the wear volume with sliding distance for the avocado oil containing particulate additives. It can be seen in the figure that the wear volume increases with sliding distance. Figure 5b shows the wear volume at the completion of the tests. Table 3 presents the average particle size, wear volume, and percent difference in wear volume for the different particulate mixtures in avocado oil. It was revealed in the avocado oil with particulate mixture tests that the 70-nm hBN tests have the lowest wear overall. Within the

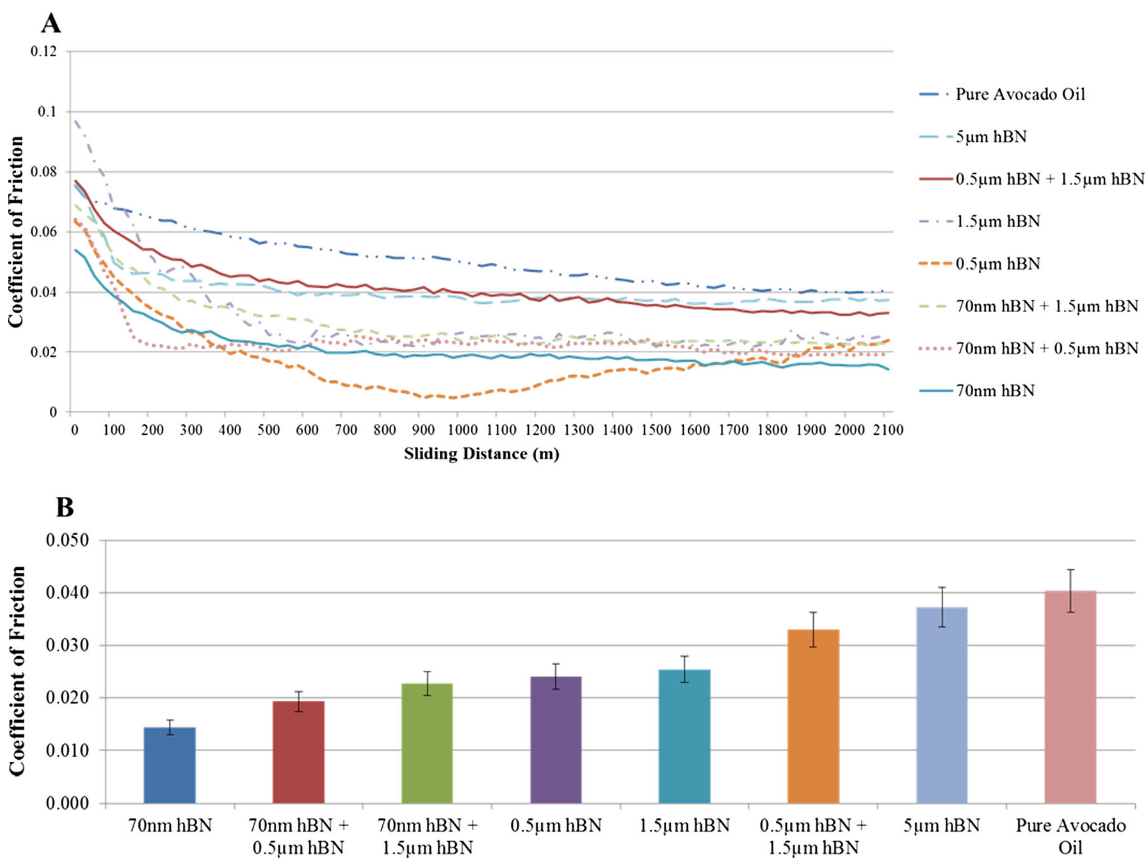

Fig. 4 Coefficient of friction for boron nitride particles in avocado oil **a** variation of the COF with sliding distance and **b** variation of the COF at the end of the experiments

Table 2 Influence of single particle size mixtures and multi-particle size mixtures on the coefficient of friction in avocado oil containing hBN

Particle combination	Average particle size (μm)	COF	Percent difference (%)
	Single particle size mixtures[a]		
70 nm hBN	0.07	0.0144	−64
0.5 μm hBN	0.5	0.0240	−41
1.5 μm hBN	1.5	0.0255	−37
5 μm hBN	5.0	0.0373	−8
Pure avocado oil	0	0.0404	N/A
	Multi-particle size mixtures[b]		
70 nm hBN + 0.5 μm hBN	0.285	0.0193	−20
70 nm hBN + 1.5 μm hBN	0.785	0.0227	−11
0.5 μm hBN + 1.5 μm hBN	1.0	0.0330	30
Correlation coefficient (%)	80.5 %		

[a] Compared to pure avocado oil

[b] Compared to the larger of the two particle sizes

single particulate mixtures, the 0.5-, 1.5-, and 5-μm hBN particles in avocado oil showed a systematic increase in wear with particle size, which was in agreement with the friction results. It was shown that the 70-nm hBN particles in avocado oil decreased the wear by over 72 %, followed by a 63, 50, and 13 % decrease in wear volume for the 0.5-, 1.5-, and 5-μm hBN particles in avocado oil, respectively. When the 70-nm hBN particles were added to the 0.5- and 1.5-μm hBN mixtures, they each had a reduction in wear volume of 39 and 18 %, respectively. The combination of the 0.5-μm hBN with

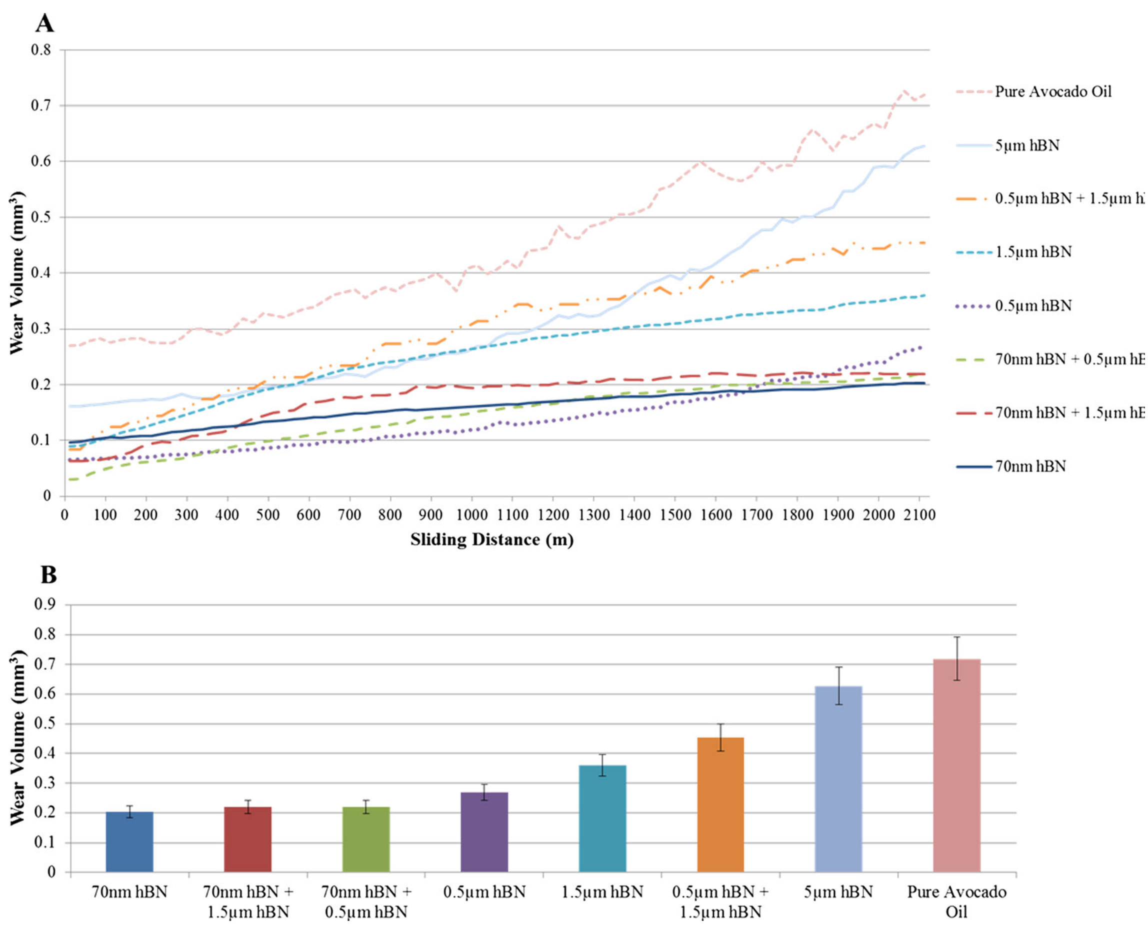

Fig. 5 **a** Variation of the wear with sliding distance and **b** variation of the wear at the end of the experiments for boron nitride particles in avocado oil tests

Table 3 Influence of single particle size mixtures and multi-particle size mixtures on the wear volume in avocado oil containing hBN

Particle combination	Average particle size (μm)	Wear volume (mm^3)	Percent difference (%)
	Single particle size mixtures[a]		
70 nm hBN	0.07	0.2028	−72
0.5 μm hBN	0.5	0.2683	−63
1.5 μm hBN	1.5	0.3600	−50
5 μm hBN	5.0	0.6280	−13
Pure avocado oil	0	0.7191	N/A
	Multi-particle size mixtures[b]		
70 nm hBN + 1.5 μm hBN	0.785	0.2190	−18 (83 %)
70 nm hBN + 0.5 μm hBN	0.285	0.2202	−39 (−68 %)
0.5 μm hBN + 1.5 μm hBN	1.0	0.4537	26
Correlation coefficient (%)	88.9 %		

[a] Compared to pure avocado oil

[b] Compared to the larger of the two particle sizes

the 1.5-μm hBN particles revealed a 26 % increase in wear volume. The 70-nm hBN particles dominated the performance of the particle additives in avocado oil, revealing the importance of allowing smaller particles to coalesce in the asperity valleys and establish a thin smooth lubricious transfer film that can simultaneously lower the friction and minimize the wear.

An investigation into the average particle size (Table 3) of the lubricant mixtures reveals a stronger correlation coefficient (*R* value) of 88.9 % between average particle size and wear volume, when compared with the correlation coefficient between average particle size and COF of 80.5 %. With regards to the wear volume results, a larger average particle size will have a higher wear volume with an 88.9 % dependency. This demonstrates the effects of particle size and shape on the tribological performance where smaller more spherical particles have a greater affinity for minimizing wear. Larger particles still lower wear when compared to a lubricant mixture with no particle additives, but not to the same degree as smaller particles because the larger particle size and plate-shaped geometry tends to behave detrimentally by acting as a third-body abrasive particle that can damage the softer disk surface by plastic deformation [47].

3.4 Surface analysis

Figures 6, 7, and 8 show the scanning electron micrographs of the pins tested against the aluminum disk using various avocado particulate mixtures. It can be seen in Fig. 6 that the worn surfaces of the pins all have a relatively similar and small worn surface area. Figure 6 represents the worn surfaces of the 70-nm hBN in avocado oil; 70-nm and 1.5-μm hBN combination in avocado oil; and 70-nm and 0.5-μm hBN combination in avocado oil. The diameter of the worn pin surfaces is in agreement to their corresponding wear volumes as they all had a wear volume of approximately 0.21 ± 0.01 mm^3 as shown in Table 3. Figure 7 shows the SEM images of the pins tested for the 0.5-, 1.5,- and 0.5- and 1.5-μm combination hBN mixtures in avocado oil. These micrographs show an increase in surface damage and wear track diameter when compared to the micrographs shown in Fig. 6. This is expected as the friction and wear increased for each of these multi-phase lubricants. In Fig. 7b, the darker colors are not wear marks, but remnants of oil residue in the surface roughness. In Fig. 7c, wear debris can be seen to have accumulated on the edge of the worn surface, whereas in Fig. 7a, e the wear debris has separated from the worn surface. This could be an effect of the presence of the 0.5-μm hBN particles being present in the lubricant mixture and minimizing the abrasion that occurred in the tribo-interface. The micrograph shown in Fig. 8 reveals the worn surface for the 5-μm hBN particles in avocado oil and the pure avocado oil tests. The presence of the larger 5-μm hBN particles revealed a smoother surface in Fig. 8a, b when compared to the pure avocado oil micrographs shown in Fig. 8c, d which corresponds to the moderately lower friction and wear results shown previously.

3.5 Comparison of canola and avocado oil as base lubricants

The ability of smaller hBN particles to systematically improve the tribological properties of the avocado oil demonstrates the importance of choosing an appropriately sized boron nitride particle to enhance lubricity and minimize wear on the tribo-interface [47]. A comparison of the tribological performance of canola oil (from previously published work) with hBN particulate additives and avocado oil with hBN particulate additives is shown in Fig. 9 [24]. It can be seen in Fig. 9a that avocado oil with hBN particle additives has a lower COF value than canola oil with particle additives has. Figure 9b shows a similar comparison for wear volume between canola oil and avocado oil each with hBN particle additives. It can be seen in Fig. 9b that avocado oil has comparable or generally

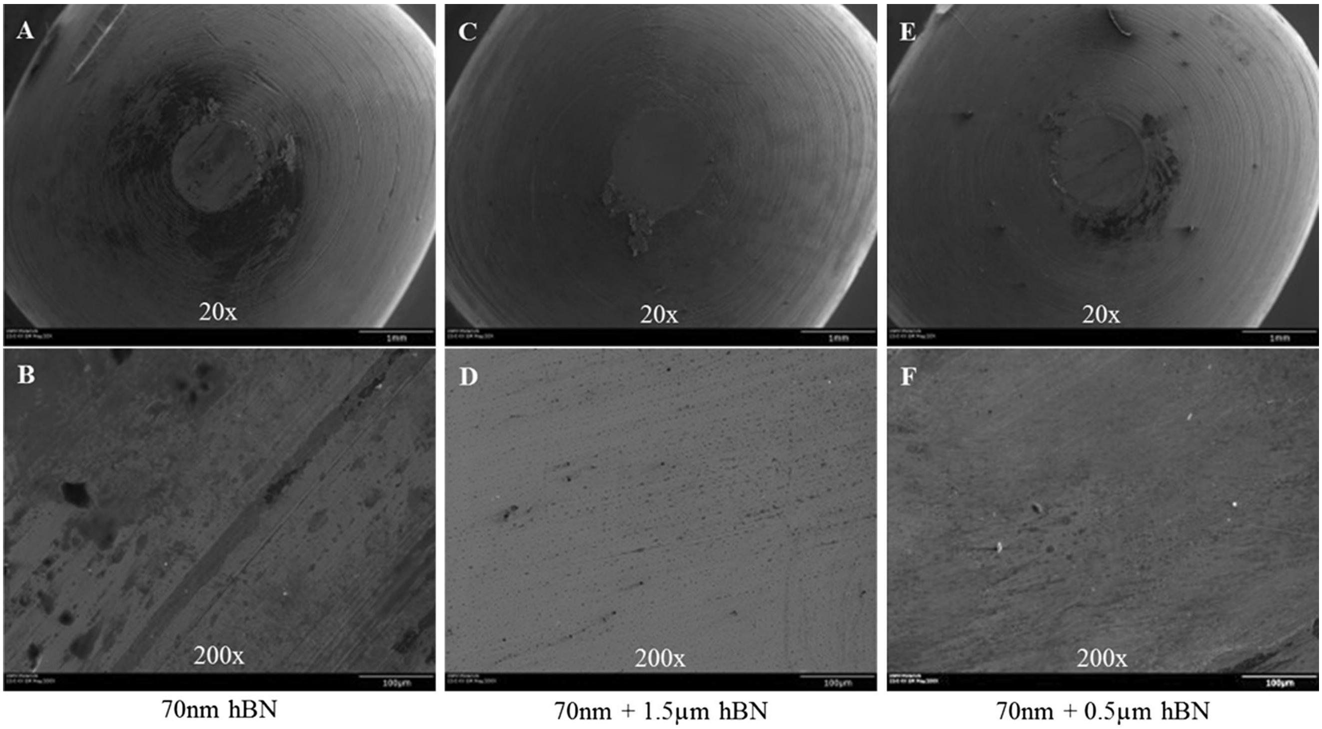

Fig. 6 SEM images of pin worn surface for various particulate mixtures in avocado oil **a**, **b** 70 nm hBN; **c**, **d** 70 nm + 1.5 μm hBN; and **e**, **f** 70 nm + 0.5 μm hBN

lower wear volume than canola oil has. Table 4 quantifies the comparison between the COF and wear results for canola and avocado oil in detail. The friction results for the avocado oil single hBN particulate additive mixtures had between 56 and 80 % lower COF values than their corresponding canola oil particulate mixtures. Comparing the correlation coefficients (R value) between particle size and friction, the avocado oil and the canola oil revealed strong dependencies of 93.5 and

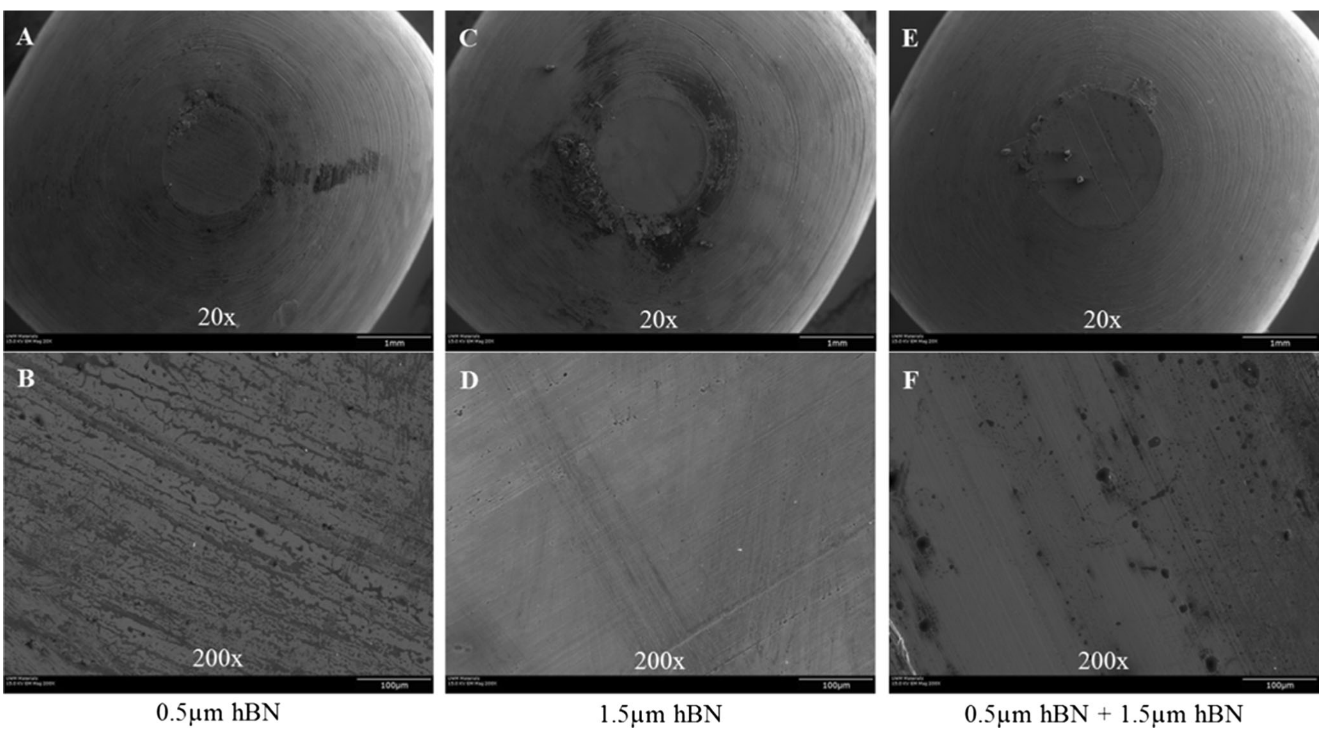

Fig. 7 SEM images of pin worn surface for various particulate mixtures in avocado oil **a**, **b** 0.5 μm hBN; **c**, **d** 1.5 μm hBN; and **e**, **f** 0.5 μm + 1.5 μm hBN

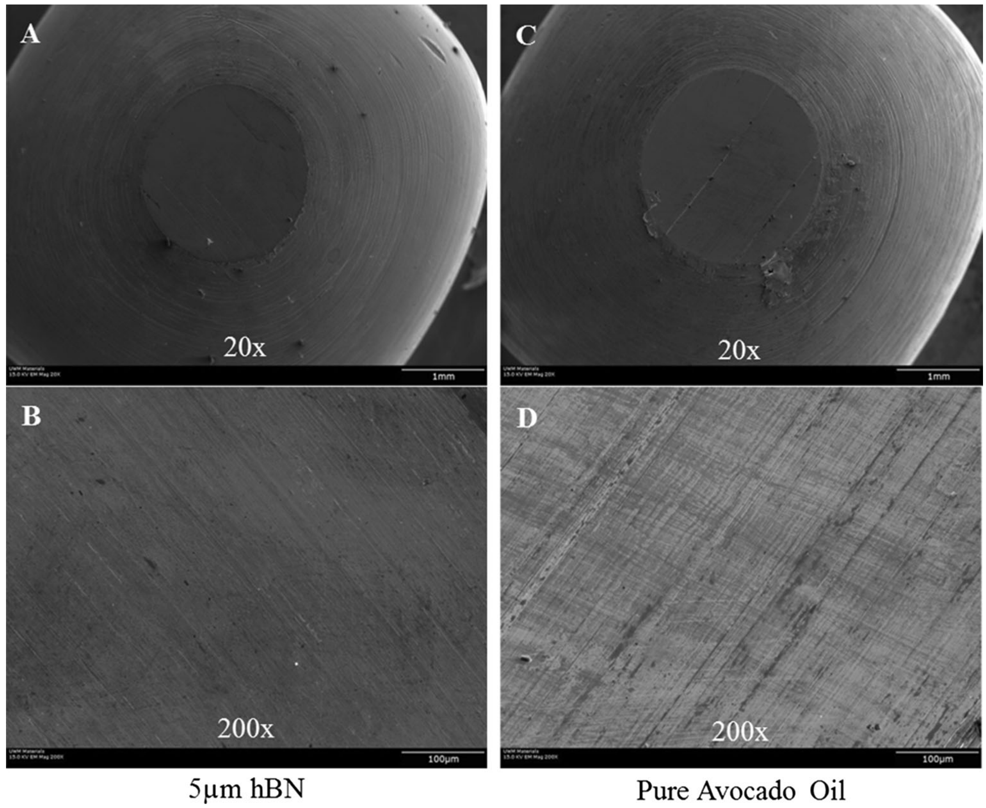

Fig. 8 SEM images of pin worn surface for various particulate mixtures in avocado oil **a**, **b** 5 µm hBN and **c**, **d** pure avocado oil

91.6 %, respectively. This indicates that smaller nano-sized particulate additives have the greatest effect on lowering friction and enhancing the lubricant for both natural oils despite having differences in fatty acid composition. Inspecting the wear volumes showed that the two oils have similar results with a 20 % difference when the 70-nm hBN particles are combined with the lubricants. The avocado oil had a 70 and 46 % lower wear volume for the 0.5- and 5-µm hBN particles, respectively, and a higher wear volume for the 1.5-µm hBN particles. The 1.5-µm hBN particles on average had a higher wear volume for the avocado oil than the canola oil which could be attributed to some experimental variance and particle-to-surface roughness interactions. Nevertheless, comparing the correlation coefficient between particle size and wear volume reveals an R value of 99.6 and 66.7 % for the avocado oil and the canola oil, respectively. Interestingly, the avocado oil shows a strong correlation with a systematic decrease in wear volume as particle size decreases from micron-

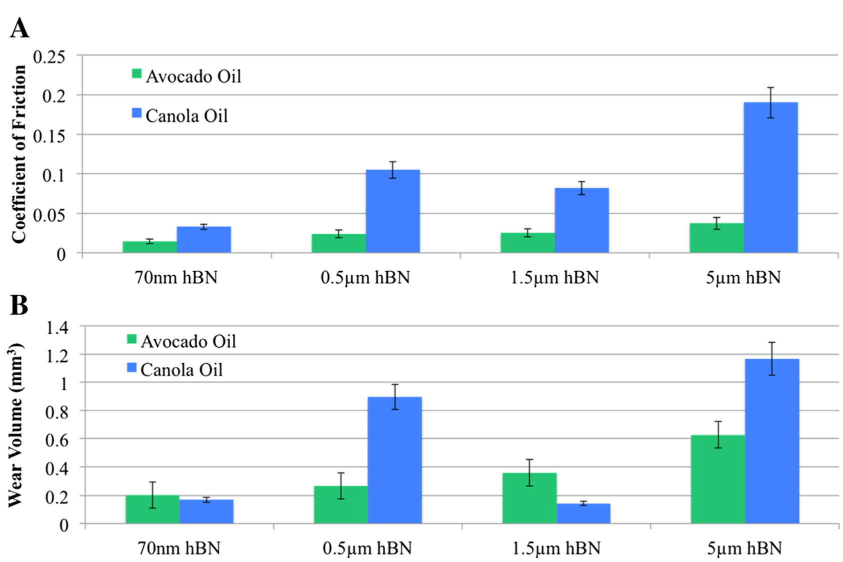

Figure 9 Variation of **a** coefficient of friction and **b** wear volume at the end of the experiments for the avocado oil and canola oil hBN particulate mixtures

Table 4 Comparison of COF and wear volume results for avocado and canola oil with hBN particulate additives

Lubricant mixture	Avocado oil COF	Canola oil COF	Percent difference (%)
70 nm hBN	0.0144	0.033	−56
0.5 μm hBN	0.024	0.105	−77
1.5 μm hBN	0.0255	0.082	−69
5 μm hBN	0.0373	0.19	−80
Correlation Coefficient between particle size and COF (%)	93.5 %	91.6 %	
Lubricant mixture	Avocado Oil Wear Volume (mm^3)	Canola Oil Wear Volume (mm^3)	Percent difference (%)
70 nm hBN	0.2028	0.1686	20
0.5 μm hBN	0.2683	0.8953	−70
1.5 μm hBN	0.36	0.1442	150
5 μm hBN	0.628	1.1671	−46
Correlation Coefficient between particle size and wear volume (%)	99.6 %	66.7 %	

to nanometer-size. The canola oil shows a low to moderate correlation between particle size and wear volume which is due to the variability in its wear volume. This is speculated to be caused by the increase in surface damage as a result of the less effective fatty acid monolayer in the canola oil due to the lower oleic acid content. Overall, the performance of the avocado oil is more consistent and demonstrates clear discernable trends in performance as observed by the friction and wear analysis and substantiated by the strong dependencies between particle size, friction, and wear results that were quantified with the high (strong) correlation coefficients (*R* values). By optimizing the particle size of the boron nitride and selecting a bio-based fluid that has high oleic acid such as avocado oil as a carrier fluid, an enhanced and more effective multi-phase lubricant mixture can be developed, thereby improving system efficiency by substantially lowering the friction as well as preventing surface damage and surface roughness by minimizing wear in the tribo-interface.

4 Conclusions

In this research, the effect of fatty acid composition in natural oil on the tribological performance was investigated. It was shown that avocado oil with its high amounts of oleic acid would be the optimal natural oil-based lubricant for tribological applications. The results of this study using avocado oil as a carrier fluid extend previous research by the authors which illustrates the importance of choosing the appropriately sized boron nitride particle to enhance the lubricity and minimize wear of the tribo-interface. Generally, by selecting smaller particles or reducing the overall average particle size when combining particulate additives of different sizes, lower friction and wear values can be achieved. By optimizing the particle size of the boron nitride and selecting a high oleic acid bio-based natural oil, such as avocado oil with its ability to develop superior fatty acid monolayers that adsorb onto the charged metal worn surfaces to act as a carrier fluid, a colloidal solution can be established that does not degrade or separate. This in turn allows for a sustainable natural plant-based lubricant to be developed that has properties that will lower friction and wear, thereby improving a systems energy economy through conservation. The following conclusions can be drawn from the current research.

- Natural oils with higher levels of oleic acid, such as avocado oil, exhibit superior tribological properties (i.e., lower friction and wear) when compared to natural oils with lower amounts of oleic acid, such as canola oil.
- Nano-sized particles were shown to offer the best tribological performance when compared to micron- and submicron-sized particles in natural oils. This is a result of the colloidal solution not degrading over time, and therefore, it is able to continuously maintain the hBN particulate additives in the lubricating interface.
- Particle additives that are larger than the asperities carry a portion of the load between the contacting asperities, resulting in an overall decrease of friction and wear; however, these larger particles are also more abrasive, causing higher wear that has the potential to cause a rougher surface finish and greater surface damage.
- Nano-sized particles where shown to be more spherical which aided to their lubricity. In natural oils, nano-sized particles were able to coalesce in the asperity valleys creating a superior protective transfer film between the contacting surfaces that thwart friction and wear. The nano-sized particles' ability to improve the tribological performance remains to exist in mixtures containing submicron- and micron-sized boron nitride particles.
- When comparing canola oil to avocado oil with hBN particulate additives, avocado oil demonstrated significantly lower COF values with less surface damage and reduced wear when using nanometer- and submicron-sized hBN particulate additives.
- When developing multi-phase lubricants, they can be optimized by choosing carrier fluids that reduce friction in boundary lubrication through monolayer adhesion and by selecting appropriate lamellar solid particle additives that are nonabrasive, smaller than the initial surface roughness, and can coalesce in the surface asperities.

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